

Introduction and Techno-economic Background

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1.1 Potential for PV Energy Generation as Part of a Renewable Energy Mix

Climate change became one of the major drivers for changing the balance of energy generation and supply in the latter part of the 20th century and the beginning of the 21st century. The increase in carbon dioxide (CO₂) concentration in the atmosphere over the past century to a figure approaching 400 parts per million (ppm) is taking it closer to the historical 450 ppm concentration where there was virtually no ice on the planet. The Intergovernmental Panel on Climate Change (IPCC) has set a maximum increase in global temperature of 2 °C which Hansen *et al.*¹ argue can only be achieved if atmospheric CO₂ falls to 350 ppm to avoid irreversible loss of the ice sheet. Meinshausen *et al.*² put a figure on cumulative CO₂ emissions into the atmosphere of 1000 Gt between 2000 and 2050 would yield a 25% probability of exceeding the 2 °C threshold in global warming.

The world electricity supply is heavily dependent on coal, gas and oil, accounting for 62% of the total for Organisation for Economic Co-operation and Development (OECD) countries in the period January to April 2012,

according to the International Energy Agency (IEA).³ In the same period the balance was made up of 19% nuclear, 14% hydro and a mere 5% for other renewable energy such as wind, solar and geothermal. However, this small contribution from renewable energy has been increasing and was up by 1% on the same period the previous year. Vries *et al.*⁴ have analysed the potential mix of wind, solar and biomass (WSB) to 2050 and concluded that this could be achieved at an energy cost of 10 US cents per kWh of energy, displacing fossil fuel electricity generation.

Although the annual growth of the photovoltaic (PV) sector has been in the range of 30 to 40% over the past 20 years, it is still at an early stage of potential development both in terms of capacity and price. A number of different scenarios exist to predict the future renewable energy mix that will displace combustion of fossil fuels.⁵ For example, the World Business Council for Sustainable Development (WBCSD) predicts 50% electricity generated from renewable energy sources by 2050 with 15% generated by solar PV.⁶ Other scenarios give a range for renewable energy generation from 31% from the IEA to a number of studies predicting 50%, including the German Advisory Council on Climate Change, Greenpeace and Shell's sustainable development plan. All the scenarios consider PV solar energy to be a significant part of the energy mix though the extent of penetration into the energy mix changes according to the different scenarios. Looking beyond 2050 the proportion of renewable energy and in particular PV solar energy will continue to grow and the German Solar Industry Association predicts that the proportion of PV solar electricity generation will increase to over 50% of the mix by the end of the century. In a separate study by Fthenakis *et al.*⁷ which looked at the potential for combined PV and concentrator solar power (CSP) in the USA, it was predicted that all the electrical energy could be produced from the Sun combined with compressed air energy storage.

In 2011 over 25 GW of PV was installed worldwide, taking the cumulated PV installations to over 50 GW. Most of these installations are based on crystalline silicon (c-Si), but the share of thin film PV has grown over the past decade and currently stands at between 10 and 15%.

In terms of climate change there is a carbon cost in manufacture based on the dependence of electricity used in PV module manufacture on fossil fuel sources. The melting of silicon to form the c-Si requires a temperature of over 1400 °C. In contrast, thin film PV uses processing temperatures below 600 °C and therefore will require less energy. Peht⁸ carried out a lifecycle analysis of c-Si PV module manufacture. With the current German energy mix, where there is 566 g of CO₂ per kWh of electricity, this leads to an emission of 100 g of CO₂ equivalent per kWh of electricity generated over the lifetime of the PV module. As the proportion of non-fossil fuel energy sources in the energy mix increases this could be halved to 50 g of CO₂ equivalent per kWh. This compares with around 10 g of CO₂ equivalent per kWh for onshore wind and 1.5 MW hydropower. Other factors that will reduce this carbon emission are the efficiency of solar energy conversion and processing temperatures. Thin film PV is currently less efficient than c-Si, roughly 10% compared with 15%

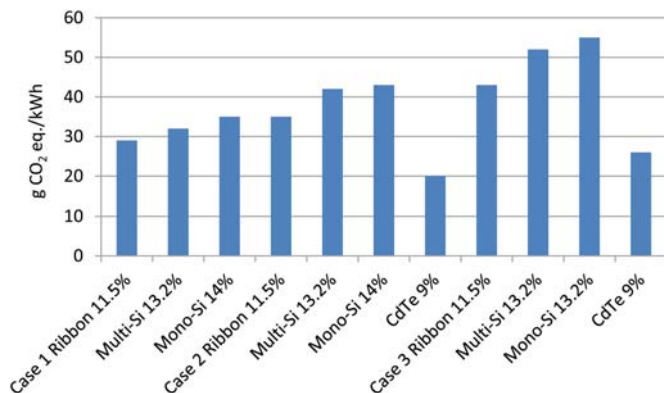


Figure 1.1 Lifecycle emissions (g CO₂ equivalent per kWh) from different types of silicon modules compared with thin film CdTe for: Case 1 – the current geographically specific production of Si; Case 2 – emissions for upstream electricity used in production in Europe; and Case 3 – emissions for equivalent production in the USA (after Fthenakis *et al.*⁷).

but the process energy per square metre is less, which leads to an overall reduction in CO₂ emission. Fthenakis *et al.*⁷ estimated that less than 20 g CO₂ equivalent per kWh was emitted for 9% efficient cadmium telluride modules.

Figure 1.1 illustrates that cadmium telluride (CdTe) thin film PV is very competitive in terms of environmental emissions compared with other technologies. Recent improvements in efficiency in thin film CdTe modules to more than 12% would reduce carbon emissions to less than 15 g CO₂ equivalent per kWh. From these estimates it is clear that the adoption of thin film PV modules will make an impact on reducing carbon emissions in PV module manufacture.

In this book we examine the materials challenges for inorganic thin film PV that will influence both the environmental impact and the economic payback, as discussed later in this chapter.

1.2 Historical Development of Thin Film PV

Observation of the photovoltaic effect goes back to Becquerel, first published in 1839.⁹ However, practical devices were only realised with the development of high purity silicon for semiconductor devices and the first demonstration of a silicon PV cell at Bell Labs in 1954.¹⁰ The initial devices had a conversion efficiency of 6%, but this rapidly improved and established silicon solar cells as a source of power for the early satellites. By 1980 c-Si cells had reached 16% AM1.5 (air mass) efficiency and have continued to improve to the present day with record efficiency of 25%.¹¹

Although the global PV market is dominated by c-Si, there has been rapid growth of other PV cell and module technologies that offer a very wide choice of PV materials, each with its potential advantages and disadvantages

compared with the silicon benchmark. For c-Si, the development of cast multi-crystalline silicon has provided a cheaper alternative to single crystal silicon with only a small penalty in loss of efficiency. By 2004 multi-crystalline silicon single cell record efficiency had exceeded 20%.¹²

The earliest thin film PV dates back to the late 1960s with the emergence of amorphous silicon (a-Si) on glass substrates as a much cheaper and lower energy option than the crystalline silicon cells.^{13,14} The first a-Si solar cell reports date back to 1976¹⁵ but have never achieved the efficiency of the c-Si counterparts. This is discussed in more detail regarding the fundamental properties in Chapter 2 and in further detail in Chapter 3. In many respects, the history of a-Si has established a cheaper alternative to c-Si and led the way for the emergence of other thin film materials. The techno-economic trade-off between cost of manufacture and module efficiency is discussed later in this chapter and provides a context for the remainder of the book. Single junction a-Si cells have now achieved over 10% stabilised efficiency¹⁶ and over 12% when combined in a tandem cell with a micro-crystalline junction.¹⁷ Early applications of a-Si solar cells were seen in consumer products where the low cost and monolithic integration were important but longer term stability was not as important as for larger scale power applications. Monolithic integration of a-Si onto glass has enabled a range of architectural applications to be explored that would have been difficult or impossible to achieve with c-Si.

The origins of CdTe PV cells goes back to a $\text{Cu}_2\text{Te}/\text{CdTe}$ cell reported in 1976 by Cusano.¹⁸ This sparked a rapid increase in the possibilities for compound semiconductor thin film PV that included, around the same time, the first interest in the Chalcopyrite structure of copper indium diselenide (CIS) with the work of Wagner *et al.*¹⁹ on single crystal material and Kazmerski *et al.*²⁰ on thin film PV. Further developments on CIS thin film PV led to alloying with gallium to form CIGS where indium can be substituted with gallium to change the bandgap of the absorber. For both CIGS and CdTe cells the absorber is p-type and the preferred n-type heterojunction material has become cadmium sulphide. Although early commercialisation of thin film PV was with a-Si, the more complex polycrystalline chalcogenides have shown the potential to achieve higher module efficiencies and good long-term stability. Large-scale thin film module manufacture of CdTe and CIGS modules has been demonstrated by First Solar and Solar Frontier, respectively. The significance of manufacturing volume in the cost of module manufacture is discussed in Section 1.4 along with the significance of continual improvements of module conversion efficiency.

The past 20 years have seen the development of many alternative materials and designs for PV solar cells suitable for a range of different applications. The drive for low cost materials and low temperature processing has generated a huge amount of research in dye sensitised solar cells (DSC) and organic photovoltaics. The DSC owes its origins to photoelectrochemical cells and the origins of this go back to Becquerel.⁹ The principal of these

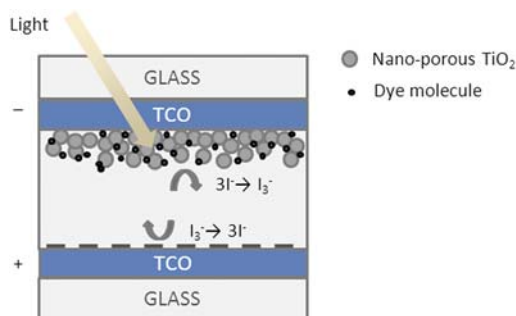


Figure 1.2 Schematic of a dye sensitised solar cell where an incident photon will excite an electron in an absorbing dye molecule which is attached to the surface of a TiO₂ particle that can then pass into the transparent conducting oxide (TCO). The charge neutrality of the dye is restored through the iodide redox process at the back contact.

cells²¹ is the release of an electron from a suitable dye such as ruthenium organometallics into the conduction band of anatase TiO₂. The dye is regenerated from the counter electrode with an iodide redox couple and is shown schematically in Figure 1.2. The highest efficiency achieved for laboratory cells is achieved 11%.²² Commercial exploitation of this highly manufacturable process has been demonstrated by G24i Power amongst others. In the case of G24i Power the DSC is deposited onto a plastic sheet in a roll to roll process. These cells perform particularly well under low light intensity and are being marketed for consumer products.

A further development of organic semiconductors as an alternative to their inorganic counterparts was the formation of polymer blends that can separate the excitons formed when light is absorbed in organic semiconductors.²³ This is essentially a room temperature process and represents a very low carbon footprint. The excitons are strongly bound so separation of the electron–hole pair is not as easy as with inorganic semiconductors and can only occur at the interfaces. This is made more difficult by the short excitonic diffusion length which is around 10 nm. Hence the success of polymer blends which create a large interface area between the electron donor and electron acceptor polymers to improve collection efficiency. These cells have shown rapid progress over the past 10 years with only 3% efficient cells in 2002 rising to 10% in 2012.¹¹ These cells are still very much in the research phase, but are likely to be part of the PV materials mix in future generations of PV device applications.

The highest efficiency PV devices are based on III–V epitaxial materials. The highest efficiency single junction cell is not c-Si, as one might expect, but GaAs with a world record efficiency of 28.3%,¹¹ not too far off the Shockley–Queisser limit described in Chapter 2. These high efficiency cells require very high quality epitaxial layers, which are achieved through lattice matching of each of the layers in the structure. By lattice matching to Ge

substrates, it is possible to produce a triple junction of lattice matched layers of InGaP and InGaAs to cover the blue and red parts of the spectrum, respectively, with the infrared covered by a junction formed with the Ge substrate.²⁴ These triple junction cells have been developed as high performance solar cells for space but there is now increasing interest for use with concentrators (lenses or reflectors) for terrestrial power generation.²⁵ The III–V cells are covered in greater detail in Chapter 8. The efficiency of these cells has been increasing rapidly in the past 10 years going from 35% in 2002 to 41.6% in 2009²⁶ for around 500 suns concentration. In December 2012, Solar Junction beat its own previous world record of 43.5% to achieve a National Renewable Energy Laboratory (NREL) verified efficiency of 44% at 947 suns. This shows the same kind of rapid increase over the past decade as the newer organic PV at the other end of the efficiency scale and reflects the advanced semiconductor engineering of epitaxial III–V semiconductors. The challenge for thin film PV moving forward is to find a similar surge in performance. This book explores new developments that could lead to such rapid progress for thin film amorphous and polycrystalline PV.

1.3 The Role of Inorganic Thin Film PV in the Mix of PV Technologies

There is now a wide variety of PV materials and devices that appear to be competing for the same space of low cost per Watt peak (W_p). Conibeer²⁷ has described the generations of PV devices according to their potential to reduce the cost per W_p . This is reproduced in Figure 1.3 showing the expected trend lines for the three generations of PV materials. The first generation is the currently dominant crystalline silicon cells which are relatively high cost but also high efficiency single junction cells. The second generation is the thin film inorganic monolithic modules that are much cheaper to produce per square metre but are also lower efficiency than the crystalline silicon cells. Both first and second generations are single junction cells which have a theoretical upper limit as explained in Chapter 2. The third generation seeks to breach this single junction limit through either multi-junction cells or other devices that can capture the energy from hot electrons. The cost per square metre is similar to the second generation but achieves a lower cost per W_p through gaining higher efficiency.

Organic PV (OPV) cells are also sometimes referred to as third generation. These can be single or multi-junction but offer the potential for even lower cost per square metre than thin film inorganic PV, largely because of lower deposition and processing temperatures. The limits to OPV efficiency are not understood in the same way as for inorganic PV so how far OPV can go in terms of low cost and high efficiency is not known at this point.²⁸

Inorganic thin film PV bridges between second and third generation PV. The cost per square metre is less than for crystalline silicon but has the potential to achieve the same single junction efficiency. There is also the

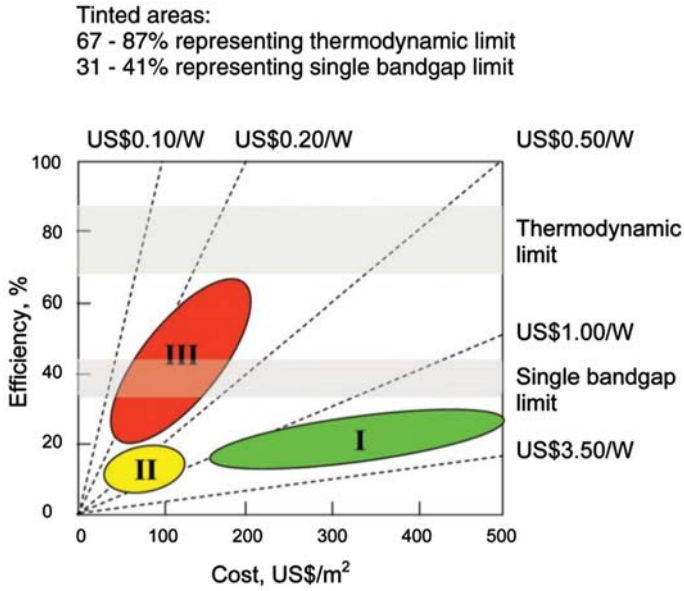


Figure 1.3 Schematic showing the relationship between cell efficiency and cost for the three generations of solar cells, with the dotted lines showing the trajectories for different cost per W_p (after Conibeer²⁷).

potential for inorganic thin film PV to incorporate third generation PV concepts to achieve higher efficiency. In this respect the way has already been shown with III-V triple junction cells, but these are high quality single crystal and to truly achieve the potential of third generation PV this would have to be achieved with the lower cost fabrication of inorganic thin films.

Inorganic thin film PV has had to compete with a more mature and larger scale c-Si PV industry, but this scale is now being achieved by some of the thin film PV manufacturers and the significance of this is discussed in the next section. There are other aspects of inorganic thin film PV that can make this class of solar materials attractive over crystalline silicon. The absorber materials are direct bandgap semiconductors so requiring far less material to absorb the available solar radiation than for c-Si. This property is described in Chapter 2. Another advantage is the temperature coefficient of efficiency whereby the efficiency of all PV devices will decrease as the modules get hotter, but the coefficient for thin film PV is approximately half that of c-Si so will have advantages when being operated in hotter climates. Finally the monolithic integration of cells in a thin film module gives greater flexibility over the appearance of the module, making it look more uniform and giving it aesthetic advantages over c-Si modules for building integrated applications.²⁹

An example of the potential for thin film PV in architectural design is shown in Figure 1.4, which shows the 85 kW_p CIS array on the technology centre of the OptIC building in St Asaph, North Wales. The curved façade



Figure 1.4 The 85 kW_p thin film PV façade at the OpTIC building in St Asaph, North Wales, generating 70 MWh of electricity per year. The modules are Shell ST36 CIS and the total array area is 1176 m².

effect is actually created from a series of flat panels and strings are aligned with panels of similar elevation to avoid losses as the elevation of the Sun changes during the day. This façade has been in operation now for 10 years and the CIS thin film panels continue to perform well with similar output to their initial performance.

1.4 Costs of Photovoltaics and Recent PV Industry Developments

The cost of PV systems, defined as an integrated assembly of PV modules and other components by convention called Balance of System (BOS), has been steadily decreasing over time. There are different metrics for the costs of PV, which can be measured in terms of:

1. Factory gate costs of individual PV system components (PV module and BOS components), *i.e.* the cost of producing them (\$ per W_p). Cost trends and dynamics at component and, in particular, module level are global as they can be manufactured and traded in the global market and their technological development is affected by worldwide R&D efforts. It is important to differentiate production costs from the price charged to the final end customer, which is the production cost plus the company's mark-up (price–cost margin). Indeed, PV module prices are also affected by market forces such as demand–supply dynamics and levels of market competition, as further discussed later in this section.
2. Cost of investing in a PV system, *i.e.* CAPEX (\$ per W_p installed) made of PV modules cost and BOS costs. The latter refers to all PV system components and cost elements other than the modules, thus

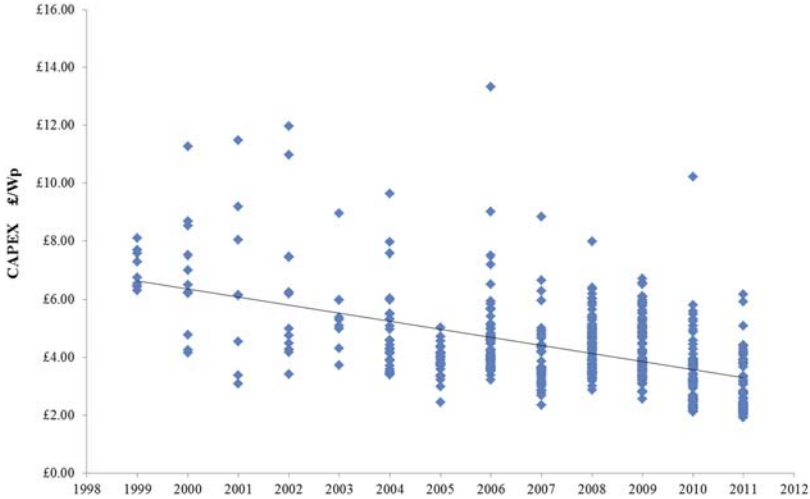


Figure 1.5 PV system price across European countries. Diamonds represent PV system price installed in several European countries over the last decade (Germany, Italy, Spain, Netherlands, Belgium, Austria, Greece, France and the UK). Data are converted to 2011 British pounds, accounting for currency exchange rates and inflation. Source: ref. 33.

including technical components such as inverter, mounting structures, cables and wiring, battery (for off-grid systems), metering (for grid-connected applications) as well as installation, design and commissioning costs. PV system CAPEX vary across market segment (and system size), system types and countries (Figure 1.5). They do not scale linearly with system size and thus tend to be higher in residential markets compared with medium size commercial systems and large utility scale systems. They also differ across countries (as affected by national market size and implementation conditions) and across PV system types (with, for example, building integrated PV systems being more expensive than standard rooftop applications). Despite this variability, PV system CAPEX has been decreasing over time across segments and countries, and is expected to further reduce (see also discussion below). Historically this has resulted from a combination of progressive reductions in module costs (discussed below) and BOS costs.³⁰⁻³³

3. Generation cost, usually calculated as the levelised cost of electricity (LCOE) (\$ per kWh). LCOE is generally defined as the discounted lifetime PV system CAPEX divided by the discounted lifetime generation of the PV system. It is thus a function of initial capital cost (CAPEX), lifetime of the system, operational and maintenance costs, discount factor and location of the plant, which defines the lifetime generation of the system. LCOE varies considerably according to the type of PV system assumed (being a function of PV system CAPEX) and is very location and

country specific (as PV electricity generation is strongly dependent on climatic conditions and irradiation levels). In 2011, LCOE was estimated to range between 0.25 \$ per kWh and 0.65 \$ per kWh in the USA and to average around 0.203 € per kWh in Europe.³⁴

The following discussion focuses on the costs of the PV module, being the major contributor to the total PV system costs (ranging from 35 to 55% depending on the PV system type and application^{35,36}) and being at the centre of most of the available cost reduction and PV roadmapping literature.^{37–40} Indeed, analysis and evolution of PV module production costs over time can also help to shed light on future research and technology development priorities as well as in defining successful policy support to emerging technologies and energy technology strategies.³³

PV module prices have experienced sustained reductions over time. The price dropped from about 90 \$ per W_p in the 1970s to about 5 \$ per W_p in the early 2000s.^{41,42} The impressive PV market growth of the last decade (worldwide cumulative installed capacity increased from 1.4 GW in 2000 to over 67 GW in 2011⁴³), coupled with continuous industrial and R&D developments over time, allowed further price reductions.^{33,37–40,44} In particular, PV module prices have dropped dramatically in the last couple of years, falling by about 45% between mid-2010 and March 2012 (Figure 1.6).⁴¹

Such impressive historical reductions reflect the development and deployment of c-Si technologies, which still account for the majority of the PV market (about 87% in 2011⁴⁵). Indeed, as estimated by the experience curves literature, c-Si module technologies have shown an historical learning rate of the order of 20% (ranging from 18 to 22% depending on studies and reference dataset used³³). In other words, this means a reduction of about 20% in c-Si module prices for every doubling of production capacity (see also Figure 1.7).

The recent dramatic drop in c-Si prices is due to a combination of the following factors (see ref. 33 and 46 for more details):

1. There has been a reduction in the production costs of c-Si PV driven mainly by a combination of: technological development (in particular increase in production cell efficiency) and optimisation of production processes; reduction in the cost of input materials, in particular a drop in silicon feedstock prices due to market oversupply resulting from production capacity expansion triggered by the polysilicon bottleneck experienced by the PV industry in the mid-2000s (see also below); and a massive increase in the scale of production, driven in particular by the fast expansion of the Chinese PV industry production capacity (by 2010 China accounted for 57% of worldwide capacity ramping up from only 8% in 2005⁴⁶).
2. A sustained oversupply situation in the global PV market (annual PV production capacity has been higher than worldwide annual installation, *e.g.* in 2012 it was 50 GW compared with 29 GW in 2010⁴⁷) which, combined with a slowdown in PV demand in key European

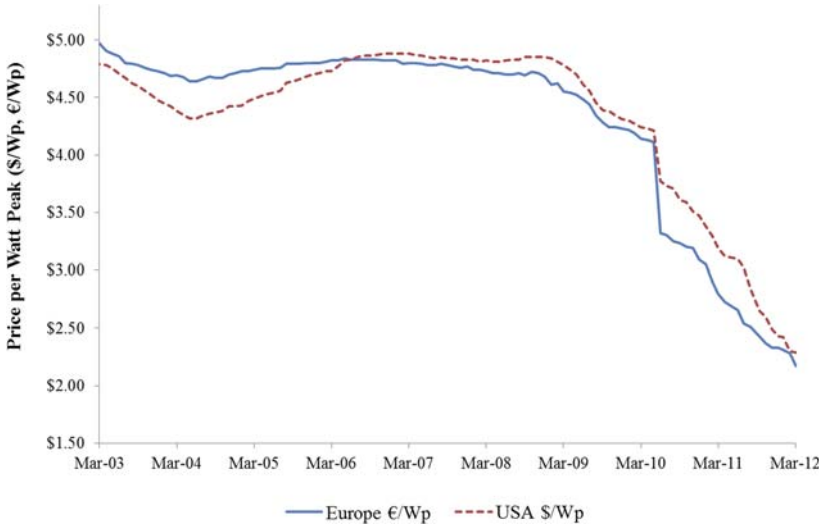


Figure 1.6 PV module retail price index, 2003–2012. The figures presented are average retail prices in Europe and the USA based on a monthly online survey. They encompass a wide range of module prices, varying according to the module technology (with thin film modules generally cheaper than c-Si), the module model and manufacturer, its quality, as well as the country in which the product is purchased. For example, in March 2012 average retail module prices were 2.29 \$ per W_p in the USA and 2.17 € per W_p in Europe, respectively, but the lowest retail price for a c-Si solar module was 1.1 \$ per W_p (0.81 € per W_p) and the lowest thin film module price was 0.84 \$ per W_p (0.62 € per W_p). Source: ref. 41.

countries (such as Germany and Italy, major drivers of PV market growth of the last decade years), has put strong downward pressure on c-Si module prices, reducing manufacturers’ margins considerably and triggering worldwide industry consolidation, with several companies have gone out of business since late 2011 to date (both along the c-Si supply chain and among thin film PV manufacturers).

Crystalline silicon PV module prices vary depending on the cost structure of the manufacturer, module quality and efficiency as well as country of production and market features. Nonetheless, average c-Si module prices are reported to be 0.77 € per W_p from Germany and at 0.56 € per W_p from China in June 2013 (which compares with an average market price in Europe of 1.95 € per W_p in March 2010).⁴⁸ Production costs of c-Si also vary according to manufacturer and its cost structure, ranging between 1.03 and 0.60 € per W_p .^{49,50}

Such recent developments in c-Si costs and prices were largely unexpected and not predicted by the PV cost reduction literature available.³³ The same literature had placed considerable hope in the potential of thin film

technologies to deliver higher cost reductions than c-Si^{37,38,51-54} for the following reasons.

- They use semiconductor materials which are better absorbers of light than c-Si, allowing much lower material thickness thus reducing costs.
- Their unit of production is more flexible and not constrained by the wafer dimensions, thus allowing larger unit of production (at least as large as a conveniently handled sheet of glass might be). This reduces manufacturing costs allowing large scale continuous production and diversity of use. Roll-to-roll deposition on stainless steel for a-Si technologies are already in production. Flexible substrates, such as stainless foils and polymer films, are even more suitable for roll-to-roll deposition.⁵⁵
- They have the potential for lower energy use in the production process and product recovery, therefore showing a lower energy payback period than c-Si technologies.^{51,55,56}

Such potential can be harnessed provided the expected increases in cell and module efficiency and large-scale production capacity are achieved.^{37,57} Indeed, significant investment went into inorganic thin film PV in mid-2000s when the PV industry experienced the silicon feedstock bottleneck. This caused an increase in feedstock prices and consequent inversion of the historically negatively sloped experience curve for c-Si module prices (see Figures 1.6 and 1.7). Since then, the production capacity of thin film PV facilities has increased from few MWs to approaching 1 GW, and turnkey production lines with high cost reduction potential have been developed. One company in particular, First Solar, managed to increase its production capacity of CdTe modules from 20 MW in 2005 to above 1 GW by the late

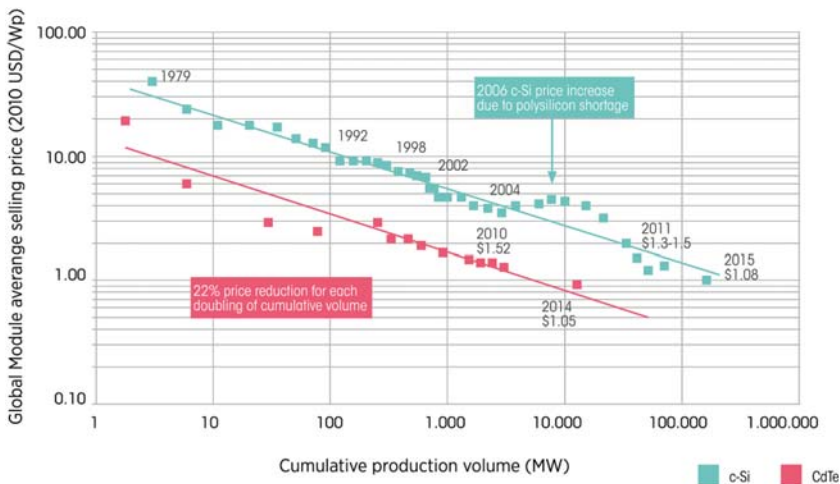


Figure 1.7 The historical PV module price experience curve, 1979–2011. Data points after 2011 are estimated. Source: ref. 50.

2000s.^{58,59} It was the first manufacturer to reduce unit production costs below the 1 \$ per W_p threshold in 2009⁶⁰ (see also Figure 1.7). Similarly, Solar Frontier, a CIS manufacturer approached a production capacity of 1 GW by 2011.⁶¹ Thin film PV modules are currently the cheapest in the market with average market prices ranging from 0.39 € per W_p for a-Si to 0.57 € per W_p for CdTe in June 2013.⁴⁸

However, despite the considerable technological developments introduced in this chapter and further discussed in Chapters 3, 5 and 6, flat plate thin film PV have not yet achieved module efficiencies comparable with c-Si technologies. This limits their ability to compete in the worldwide market against the incumbent and more mature c-Si, as lower module efficiency makes them less suitable for area constrained applications (such as most rooftop applications) and implies higher area related BOS costs (such as cabling and mounting structures) which partially offset their lower module prices when PV system CAPEX are considered. Indeed several thin film companies have gone out of business during the market consolidation recently experienced by the worldwide PV industry. Among these are the more innovation driven companies (e.g. Solyndra, United Solar, Soltecture, Odersun), targeting novel and niche applications for thin film PV technologies such as on flexible substrates or semi-transparent modules suitable for, for example, building integrated solutions or rooftop applications with weight-bearing limitations.

1.5 Role of Materials Cost and Efficiency in Cost of Thin Film PV

The importance of increasing production scale for the reduction of the unit costs of thin film PV technologies is pointed out in the previous section. However, when production scale increases then the input materials cost share also increases (as shown for example for CdTe and CIGS in Figures 1.8

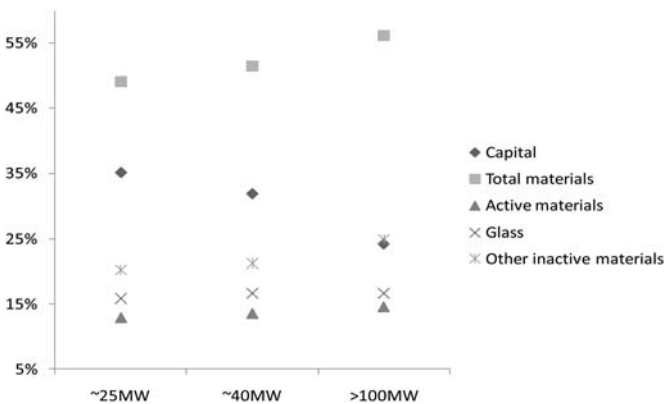


Figure 1.8 CdTe module production cost share for increasing scale of production. Source: ref. 73.

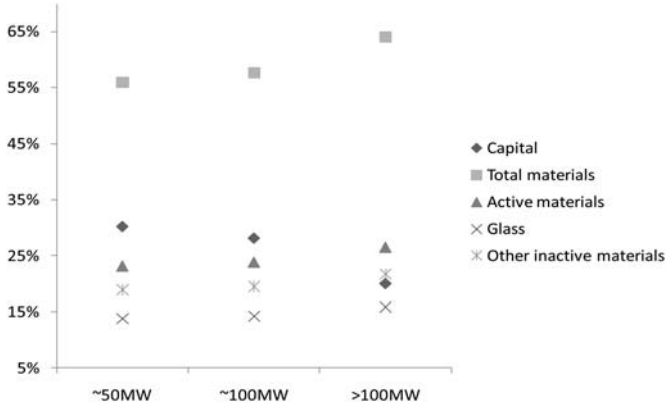


Figure 1.9 CIGS module production cost share for increasing scale of production. Source: ref. 73.

and 1.9), indicating the need to optimise materials use in order to achieve further cost reductions. An efficient use of input materials is particularly relevant for CdTe and CIGS technologies, as concerns over scarcity (and consequent high price) of key active materials, tellurium (Te) and indium (In), have been highlighted as potential barriers to future market expansion and cost reductions of those thin film PV technologies relying on them. Indeed, due to increased demand for both materials over the past decade, Te and In prices have experienced increased volatility since mid-2000s, causing unprecedented price highs. Driven by exponential demand coming from the liquid crystal display (LCD) screen industry, the price of indium increased dramatically from 85 \$ per kg at the beginning of 2003 to 830 \$ per kg by the end of 2004,⁶² then rose again above 750 \$ per kg in 2011⁶³ after years of volatility. Similarly, the tellurium price experienced an increase of more than 300% in 2005, reaching an annual average price of around 230 \$ per kg (from about 35 \$ per kg in 2004), due to supply shortfall caused by demand increases from China and solar cell manufacturers outside China.⁶⁴ Tellurium prices have been fluctuating since, reaching values above 200 \$ per kg in 2010⁶⁵ and above 400 \$ per kg in 2011 (the average price in late 2011 was around 300 \$ per kg).⁶⁶

In the past decade several contributions in the literature have attempted to estimate the potential of thin film PV technologies using scarce materials such as Te and In to expand their production capacity in the future and to contribute to the global warming mitigation challenge. A review of such literature points out the differences in methods and assumptions taken by the various contributors as well as the uncertainties behind critical materials resource assessment and currently available figures for Te and In production and reserves.⁶⁷ In particular, the potential to expand production of In and Te is unclear, since data are poor and reporting has been reduced. Resource data are largely absent and the economics of production is

complicated by the fact that Te and In are mostly extracted as byproducts of other primary metals, *i.e.* copper and zinc. Moreover, future In and Te demand coming from thin film PV is also subject to uncertainties as materials usage in a PV cell can vary and demand will also depend on future expansion of the PV sector as well as the relative share of thin film PV technologies in the overall PV technology mix. Such uncertainties translate into a wide range of estimates of the impact of Te and In supply constraints on potential future expansion of CdTe and CIGS.⁶⁷ The literature review highlighted how, in order to reach conclusive answers on such potential constraint, more analysis and research is needed to better estimate future availability of In and Te. Future availability scenarios should take into account the temporal and economic nature of In and Te extraction and recovery, and their future demand and production expansion should be better understood. Indeed, the relevant literature has been increasingly trying to address such questions.⁶⁸⁻⁷¹

Thus, whether CdTe and CIGS technologies can be considered sustainable solutions in the long term under scenarios of low availability of In and Te materials and very high PV market growth, or rather medium term stepping stones for other PV technologies to come is still an open question. The answer is linked to In and Te future production expansion, to PV market developments and to the future mix of PV technologies available to satisfy PV demand growth. This includes the development of thin film PV technologies based on alternative more abundant materials. Among those, kesterite-based thin film devices such $\text{Cu}_2\text{ZnSn}(\text{S},\text{Se})_4$ (CZTSSe) and $\text{Cu}_2\text{ZnSnS}_4$ (CZTS) solar cells, where indium and gallium are replaced by the readily available materials zinc (Zn) and tin (Sn). This is discussed in detail in Chapter 6.⁷²

Nevertheless, recent evidence on In and Te availability and the comparison of estimated maximum annual production achievable by CdTe and CIGS against forecasts of future PV market size seem to indicate that the availability of In and Te is unlikely to constrain CdTe and CIGS technologies *per se* in their ability to scale up production and to supply a significant proportion of future PV market growth.^{67,70,71} However, a possible cause of concern for CdTe and CIGS is the impact of an escalation of In and Te price on their production costs and their cost-competitiveness in the wider PV market.^{68-70,73-75}

Recent contributions have assessed the impact on CdTe and CIGS production costs of increases in In and Te prices. The absolute maximum In and Te prices which keep CdTe and CIGS technologies cost competitive is debated in the literature, as the calculations vary over time and across models due to high variability of materials prices themselves as well as of the production cost structure assumed (other production cost drivers such as, for example, the prices of other materials, cost of capital and production capacity utilisation also change over time). However, the estimates available clearly show how active materials account for an increasing production cost share of CdTe and CIGS when In and Te prices increase (see, for example,

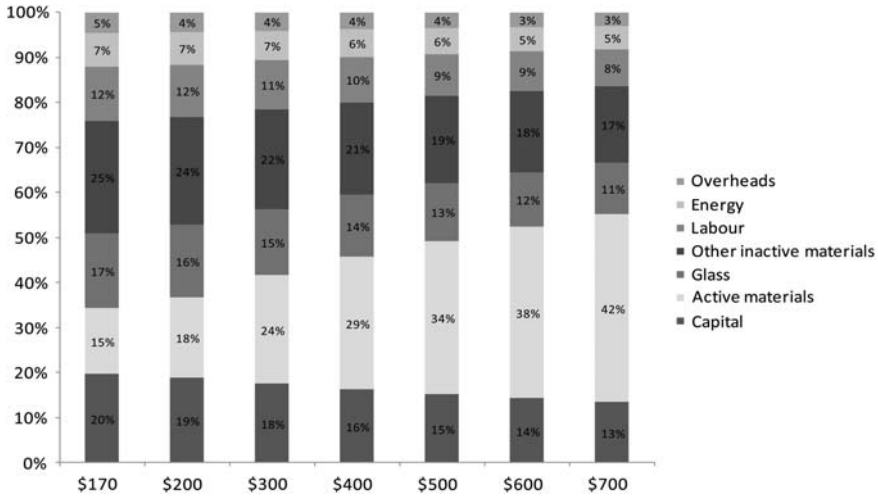


Figure 1.10 CdTe cost breakdown for increasing technical grade tellurium price (from 170 \$ per kg to 700 \$ per kg). Note changes over baseline case scenario of 0.75 \$ per W_p production cost, 170 \$ per kg tellurium price, 11.6% efficiency and large-scale production. Source: ref. 73.

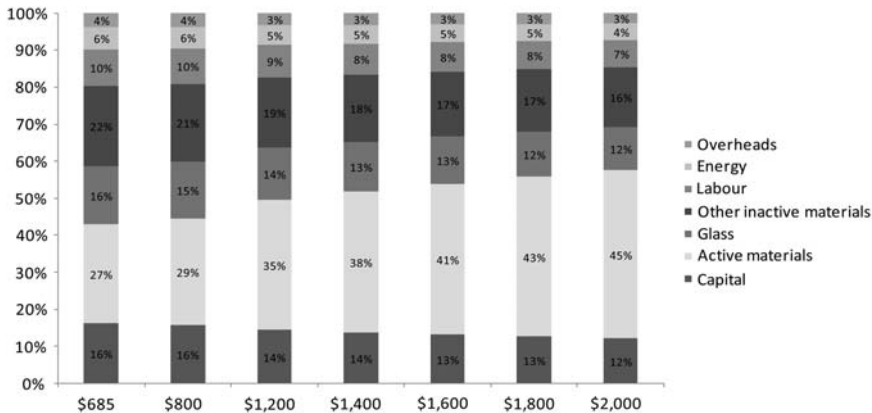


Figure 1.11 CIGS-planar cost breakdown for increasing technical grade indium price (from 685 \$ per kg to 2000 \$ per kg). Note changes over baseline case scenario of 0.97 \$ per W_p production cost, 685 \$ per kg indium price, 11% efficiency and large-scale production. Source: ref. 73.

Figures 1.10 and 1.11) with consequent impact on unit production costs (as shown in Figure 1.12 for CdTe—in this analysis 0.75 \$ per W_p has been assumed as the baseline unit production cost).⁷³ However, this impact can be eased by reducing the intensity of the cell's materials. This can be achieved by reducing the thickness of the active layer, by improving material

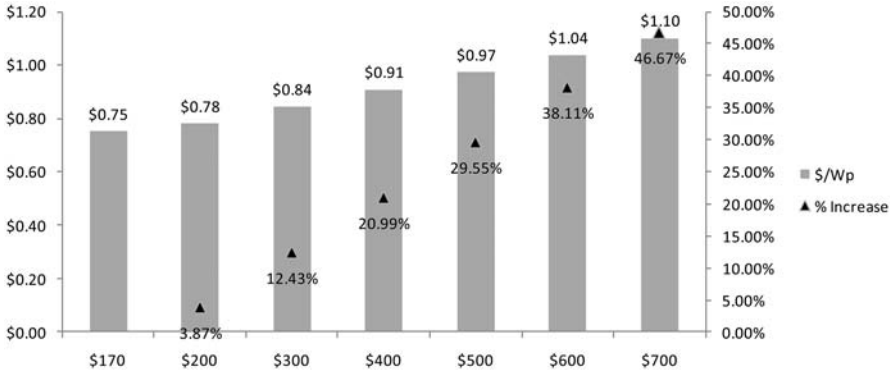


Figure 1.12 CdTe module production cost (\$ per W_p) for increasing technical grade tellurium price (from 170 \$ per kg to 700 \$ per kg). Note percentage production cost increase over baseline case scenario cost of 0.75 \$ per W_p, under tellurium price of 170 \$ per kg. Source: ref. 73.

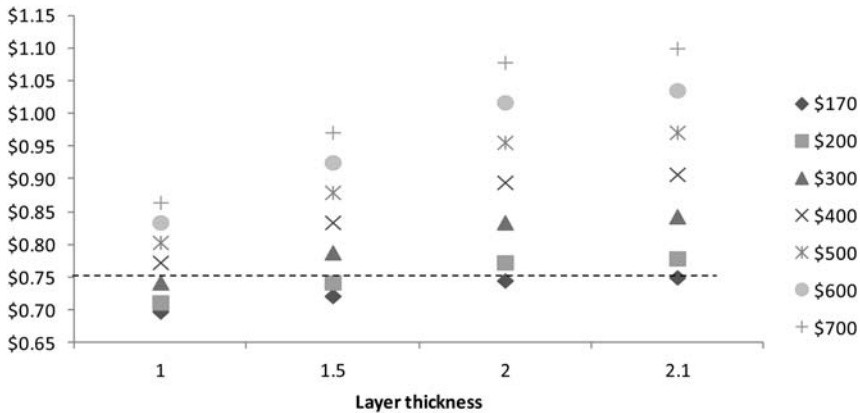


Figure 1.13 CdTe production cost (\$ per W_p) for varying layer thickness (from 1 to 2 μm) and tellurium price (from 170 \$ per kg to 700 \$ per kg). Source: ref. 73.

utilisation in the production process (improving both the effectiveness of deposition processes and the recovery and recycling of the material) and by increasing a cell's efficiency. For example, Figures 1.13–1.15 show how changes in these parameters can help ease the impact of increasing Te price on CdTe production costs (again, against a baseline production costs of

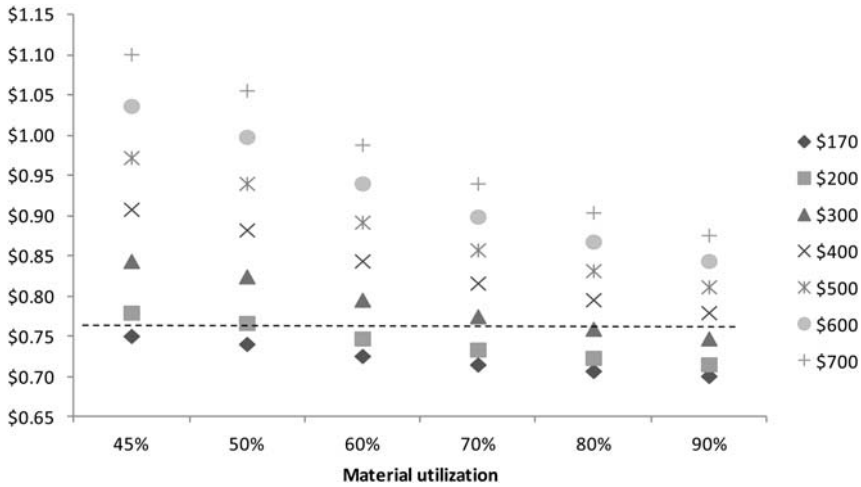


Figure 1.14 CdTe production cost (\$ per W_p) for varying material utilization (from 45% to 90%) and tellurium price (from 170 \$ per kg to 700 \$ per kg). Source: ref. 73.

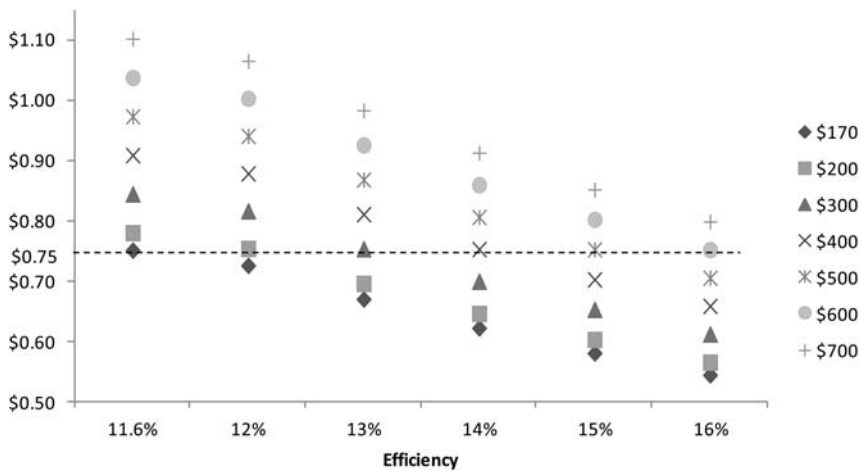


Figure 1.15 CdTe production cost (\$ per W_p) for varying module efficiency (up to 16%) and tellurium price (from \$170 per kg to \$700 per kg). Note changes over baseline case scenario of production cost 0.75 \$ per W_p , 170 \$ per kg tellurium price, 11.6% efficiency and large-scale production. Source: ref. 73.

0.75 \$ per W_p). Similarly, recent contributions show that thin film technologies have significant room to absorb potential critical materials price increases and expand their total potentially available supply base if improvements in their net material intensity are achieved.^{75,76} These are covered in Chapters 5 and 6.

1.6 Future Prospects for Cost Reduction and Thin Film PV

Estimates for future cost reductions in PV systems vary according to the source, market segment and country of reference, but they all indicate further decline over time. The European Photovoltaic Industry Association (EPIA) predicts European PV system prices will fall by 36–51% over the next 10 years (see Figure 1.6) and the PV generation cost (LCOE) to decline by around 20% by 2020.³⁴ Recent US estimates see the utility scale PV system price to decrease to between 1.71 and 1.91 \$ per W_p and that for residential systems to 2.29 \$ per W_p .⁷⁷ The average annual reduction of BOS costs has been estimated to be in the range of 8–9.5%.⁷⁸ Grid parity is expected to be achieved in southern Europe (and in high electricity price countries such as Italy) by the end of 2013 and spread across all Europe by 2020.³⁴ Similarly, PV LCOE is estimated to compete with residential electricity prices in a wide range of US regions by 2020 and grid parity to be achieved in high-cost regions by 2015.⁵⁰

In terms of PV modules both c-Si and thin film technologies are expected to experience further cost reductions. Crystalline silicon module production costs are expected to decrease thanks to increased efficiency and scale of manufacturing as well as process optimisation and reductions in input materials costs. Average production costs figures for c-Si are estimated to be in the 0.85 to 0.50 \$ per W_p range.^{49,50} Similarly, production costs of thin film PV technologies are also expected to go down further as shown in Table 1.1.

As also introduced in previous sections, increasing scale is crucial for PV technologies to reach lower unit production costs, particularly for thin film PV. This is, for example, clearly shown in Figure 1.16, where CIGS cost projections are presented for different levels of scale.

Increase in cell efficiency is also an important driver for future cost reductions, as it translates into a higher output per area, thus reducing the specific material consumption. As a rule of thumb, an increase in efficiency of 1% is able to reduce costs per W_p by 5–7%.³⁷ This challenge is particularly relevant to thin film PV, which needs to bridge the gap with c-Si module efficiency to improve its competitiveness in the flat plate modules global market. This would expand the range of applications that thin film PV would become suitable for (including rooftops) and reduce the BOS costs. As a rule of thumb it is estimated that a 1% increase in efficiency reduces BOS cost by between 0.07 and 0.1 \$ per W_p .⁷⁹ Cell and module efficiency

Table 1.1 Cost reduction potential of thin film PV (\$ per W_p)^a

	2010	2015
Single junction a-Si	0.99	0.55
Tandem junction Si	1.32	0.58
CIGS – co evaporation	1.31	0.63
CIGS – sputtering	1.31	0.69
CdTe	0.73	0.49

^aSource: ref. 50.

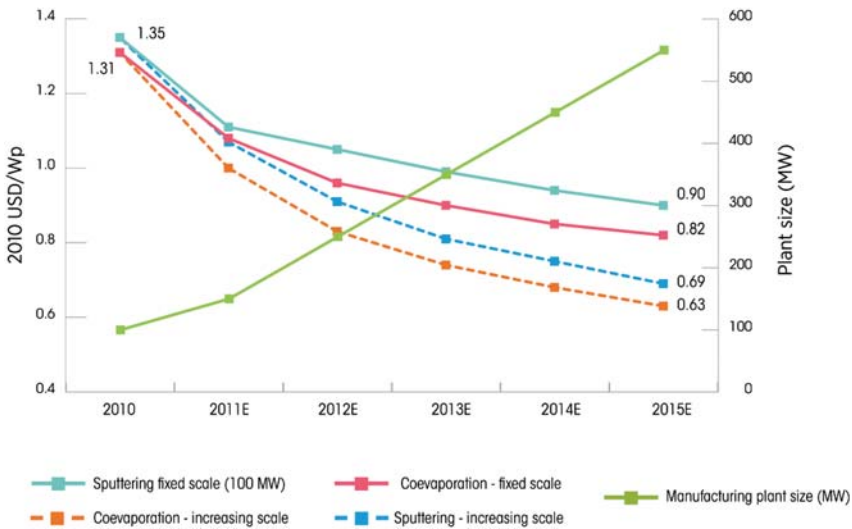


Figure 1.16 Projections of CIGS production costs as function of manufacturing scale, 2010–2015. Source: ref. 50.

increases are expected for both c-Si and thin film PV, with CIGS showing high potential to achieve efficiency levels comparable with c-Si, as discussed in Chapter 6.

Overall, despite the significant technological improvements, production capacity investments and cost reductions that have been achieved, thin film PV has not yet fully harnessed its potential to capture a relevant PV market share. Challenges still lie ahead for thin film PV to improve its competitiveness with respect to c-Si for flat plate applications. Moreover, the potential of thin film PV to deliver innovative devices and systems (such as flexible modules or PV glass), and thus product differentiation, still needs to be fully harnessed. It remains unclear what will be the future prospects for such niche (and more costly, at least initially) PV products, in particular given the consolidation the global PV industry is currently experiencing. However, niche applications such as building integrated photovoltaics are promising emerging market segments where thin film PV is likely to be better placed to deliver.

1.7 Outline of Book and Context of Topics in Terms of Techno-economic Background

This chapter sets the scene for thin film PV in a world dominated still by crystalline silicon PV modules and many new emerging PV technologies. The challenge for any of these PV technologies is to have the potential for:

- high efficiency;
- low materials costs;

- low production costs;
- low embodied energy and low equivalent greenhouse gas emissions;
- good long-term stability.

These are the challenges that form the basis for this book and are addressed for each of the materials systems considered for thin film PV production. In Chapter 2 the fundamentals of thin film PV are discussed and their relevance for achieving high absorption of solar radiation, high efficiency and thin film structures explained. Chapter 3 covers the range of thin film silicon PV cells and expands on the themes of absorption of solar radiation, improving cell efficiency and the challenges of achieving stable performance over a period of many years.

Transparent conducting oxides (TCOs) are common to all thin film PV device structures and in some respects are the most important part of the device, performing the dual role of high transparency and high electrical conductivity. Without this the PV device efficiency would be severely limited. Chapter 4 on this topic is set in the context of the developments at NREL in the USA, which has been a leader in the science and technology of TCOs, and provides insights to the choices that need to be made in selecting and developing TCO thin films for different PV structures.

The leading commercial thin film PV material, CdTe, is described in detail in Chapter 5. This chapter covers some of the historical developments in CdTe solar cells and goes on to look at some of the advanced techniques that can give a greater flexibility in performance and PV module design.

Chapter 6 looks at alternative chalcogenide materials such as the kesterites which replace the high cost In and Ga with lower cost Sn and Zn. In this chapter some techniques are described on how to explore a large number of different phases in discovering new thin film absorber materials.

III-V solar cells, the topic of Chapter 7, are not strictly thin film PV devices though they are fabricated from very high quality thin film materials and represent the pinnacle of achievement not only for compound semiconductors but also for any solar cell material. Recent progress has seen multi-junction cells achieve conversion efficiency under solar concentration of over 40% and this chapter explores the path to achieving over 50% conversion of solar energy. There is a lot to learn in improving PV cell efficiency in the lower cost thin film PV technologies from these very high performance cells.

Chapter 8 makes a comprehensive analysis of the role of light capture in thin film PV and is a key part of the materials challenges as this affects the whole thin film PV structure and the surfaces. The microstructuring and passivation of surfaces is discussed before the chapter moves on to more advanced surface structures involving nano-materials and nano-structures.

The theme of light capture is continued in Chapter 9 where the topic of photon management is covered. Again, the objective is to capture more of the solar radiation into the thin film structure than would be achieved in

a conventional thin film PV device. The approaches covered here include fluorescent materials to achieve photon energy conversion either from short wavelengths to longer wavelengths or from the infrared to the visible. The objective is to capture the solar radiation at wavelengths not normally captured by the thin film PV device. Thus a wider range of the solar spectrum can be captured leading to higher efficiency, one of the challenges set in the techno-economic analysis in this chapter.

This book brings together some of the exciting innovations in thin film PV materials and presents challenges for future generations of high efficiency, low cost and highly stable PV module technology. Much of the background to this book and the contributing authors come from the UK research programme on thin film PV, PV21, which has established new approaches and fertile areas of research to enable thin film PV to make a major contribution to future global renewable energy demand.

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