PUBLISHED: 11 JANUARY 2016 | ARTICLE NUMBER: 15015 | DOI: 10.1038/NENERGY.2015.15

comment

Commercial progress and challenges for photovoltaics

Martin A. Green

The past five years have seen substantial cost reductions and greatly increased uptake of photovoltaics. Growth is being driven by ongoing improvements in both silicon solar cell costs and performance, making the commercialization of new technologies increasingly difficult.

Although exciting developments continue to be reported for several alternative photovoltaic materials — including CdTe (ref. 1), $CuIn_xGa_{1-x}Se_2$ (ref. 2), organic[3], dye-sensitized[4] and, most recently, organic–inorganic perovskites[5] — silicon (Fig. 1a) remains the dominant commercial photovoltaic technology with its stranglehold on the industry strengthening over recent years[6–9] (Fig. 1b). Continually falling prices[10,11] (Fig. 1c) are stimulating increasing awareness that solar photovoltaics will soon provide one of the lowest-cost options for future electricity supply. A recent report[12] suggests that photovoltaics will account for 35% of the additional electricity generation capacity installed globally by 2040, at a value of US$3.7 trillion. In the past, each doubling of accumulated production volume resulted in a 20% reduction in the price of modules[13]; if such rates hold, the forecasted increased production would reduce the average selling price (ASP) of modules from US$0.57 per watt (peak rating) for 2015 (http://pvinsights.com/index.php) to US$0.20 per watt (in 2015 dollars). Many anticipate a restructuring of the electricity supply industry to accommodate the reality posed by these low costs[14,15], with future photovoltaic markets more dependent on removing barriers to growth than on subsidies.

Continuing, incremental improvements to silicon cell technology can — and probably will — carry the industry through to such low prices. However, it is inconceivable, to this author at least, that standard silicon modules, even when developed to their full potential, represent the ultimate photovoltaic solution and that 'next-generation' technology will not at least be positioned for market entry over the next 25 years.

Silicon has obvious advantages for photovoltaics including abundance (it is the second most abundant element in the Earth's crust), ruggedness and non-toxicity, although it involves more complex and energy-intensive manufacturing steps (Fig. 1a) than the alternatives mentioned. What has been surprising is how both monetary and energy costs of these apparently complicated processes continue to decrease, largely driven by increased manufacturing volume, so that the largest contributor to silicon module price now comes from cell encapsulation (Fig. 1c). Similarly, at the system level, balance of system (BOS) costs — such as costs of installing modules — now exceed module costs[10,13]. This is mainly due to module price reductions, now entrenched by reductions in manufacturing costs (Fig. 2a). In parallel to cost reductions, the energy investment in manufacturing modules also continues to fall, with energy payback times for silicon systems in sunny Mediterranean locations now below one year[6,16] (and just over two years even above the Arctic Circle[6]). An increasingly large contributor in relative terms is the energy investment in encapsulating and deploying modules[16].

Beyond silicon

What type of photovoltaic technologies could displace silicon from its increasingly entrenched position? If judged by the research output published in high-impact academic journals, a low-deposition-cost, solution-processed approach would seem to be a key contender. Low deposition costs are certainly desirable provided that the energy conversion efficiency is not compromised. A crucial point sometimes not fully appreciated is that, for their main applications on rooftops or in large solar fields, for example, photovoltaic modules not only have to be durable but also, importantly, must not present safety or system hazards over their operating life. These requirements and the corresponding need to conform to assorted codes and standards (http://www.solarabcs.org) impose severe demands on the required quality for both encapsulation and installation, with similar constraints expected to apply to emerging technologies. Some relaxation is possible for low-voltage, low-power consumer and throwaway products, but the associated markets are relatively small and already addressed by hydrogenated amorphous silicon (a-Si:H). This environmentally benign (albeit low conversion efficiency) technology provides low-temperature, low-cost depositions suitable for flexible substrates, and has captured the solar calculator market (100 million units shipped per year as early as 1985[17]). Even a large increase in efficiency for such products would not seem guaranteed to open up previously inaccessible markets.

The encapsulation and installation costs associated with meeting commercial standards are higher for technologies with lower energy-conversion efficiencies because larger device areas are required to achieve the same power output. Moreover, non-silicon cells have generally a lower ruggedness, thus requiring more expensive encapsulation for comparable durability. These considerations tend to decrease the importance of deposition costs in determining the overall cost of the electricity that is generated. For thin-film CdTe modules, encapsulation and module testing accounts for 60% of the total calculated manufacturing cost, whereas deposition of front and rear contacts accounts for another 20% (refs 18,19). Thus, any opportunities to reduce costs by simplifying the deposition of the light absorber are minimal, although methods such as blade coating[19,20] are sometimes suggested as a path to revolutionizing photovoltaic costs[3].

Recent preliminary cost calculations more fully test this argument for perovskite

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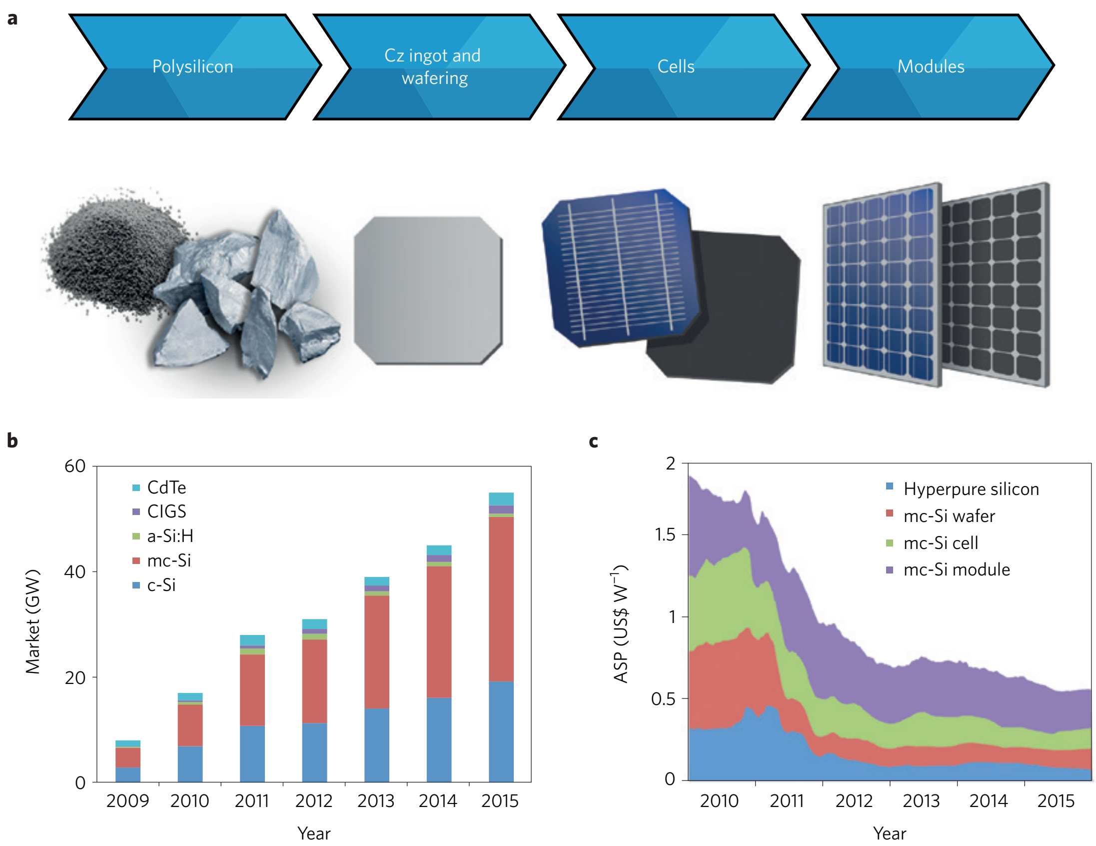

Figure 1 | Silicon photovoltaic technology, annual market composition and associated spot prices for silicon wafers, cells and modules. **a**, Silicon is first refined to high-purity polysilicon, then melted and resolidified to form crystalline or multicrystalline ingots that are sawn into wafers, then processed into cells and encapsulated into modules. **b**, Growth in annual photovoltaic market demand by technology, showing strong growth but a decline in thin-film market share (from 17% in 2009 to 8% in 2015; data compiled from multiple sources including refs 6–10). a-Si:H, amorphous silicon; mc-Si, multicrystalline silicon; c-Si, crystalline silicon. **c**, Average selling price (ASP) on the spot market for hyperpure silicon, multicrystalline silicon wafers, cells and modules, all converted to US$ per watt (pre-2015 data and conversion approach from ref. 10; 2015 data from http://pvinsights.com/index.php). The upper limit of each coloured region represents the ASP for the corresponding commodity, with the vertical extent of each colour indicating the price increment associated with each processing step in panel **a**. Panel **a** reproduced from ref. 31, Elsevier.

technology[19]. Using CdTe modules as a reference, an idealized sequence for manufacturing perovskite modules was costed. Major extrapolations from present realities were assumed in the analysis, highlighting areas that require large improvements before commercialization can be seriously contemplated. Perovskites were assumed to be capable of giving the same energy conversion efficiency for a ~1 m^2 module as the current standard for CdTe, which is now approaching 16% (Fig. 2b). However, as of the end of 2015, the highest confirmed efficiency for a 1 cm^2 perovskite cell is only 15.6%, and this value represents an initial efficiency that degrades with time. Other major extrapolations were that the costs of spiro-MeOTAD (which is used as hole transport layers in efficient perovskite cells[5]) were not "10 times that of gold"[21], as they currently are, but negligible, and that gold contacts[5] could be replaced by sputtered Al, an inexpensive rear-contact option. Additionally, it was assumed that standard CdTe module encapsulation (encapsulation between glass sheets with polybutyl rubber edge sealant) protected perovskite cells adequately from water vapour. These major extrapolations were deliberately introduced to determine the maximum module savings if deposition and contacting costs could be reduced to minimum levels. The resultant savings amounted to 25% per unit area at a 500 MW yr^{-1} manufacturing volume[19], with this percentage expected to decrease at higher volumes where depreciation and labour costs become less significant.

Barriers to entry

Do such potential cost savings from low deposition costs provide a compelling market advantage for emerging photovoltaic technologies, given the significant barriers to market entry they face[22]? On the supply side, existing industry players have large and expanding manufacturing capacities, reducing costs through economies of scale[22]. This not only presents a high and increasing capital-cost barrier to entry to enable competitive economies of scale, but significant additional costs accrue while throughput is built up to levels where these economies can be realized.

On the demand side, further barriers to building up market share are imposed by the exceptional durability of existing products[22]. Most manufacturers warrant power output of 90% rated after 10 years of field exposure and 80% after 25 years (one major manufacturer warrants 87% of rated output after 30 years[23]). Durability directly impacts the financing of large systems that provide a significant share of present and projected markets. A tiered system for manufacturers has emerged based on project bankability, that is the likelihood that projects using the manufacturer's products would be offered 'non-recourse' debt financing by banks (where claims are restricted to the collateral in event of default)[24]. Such financing is obviously less likely for products with limited field experience, inhibiting sales

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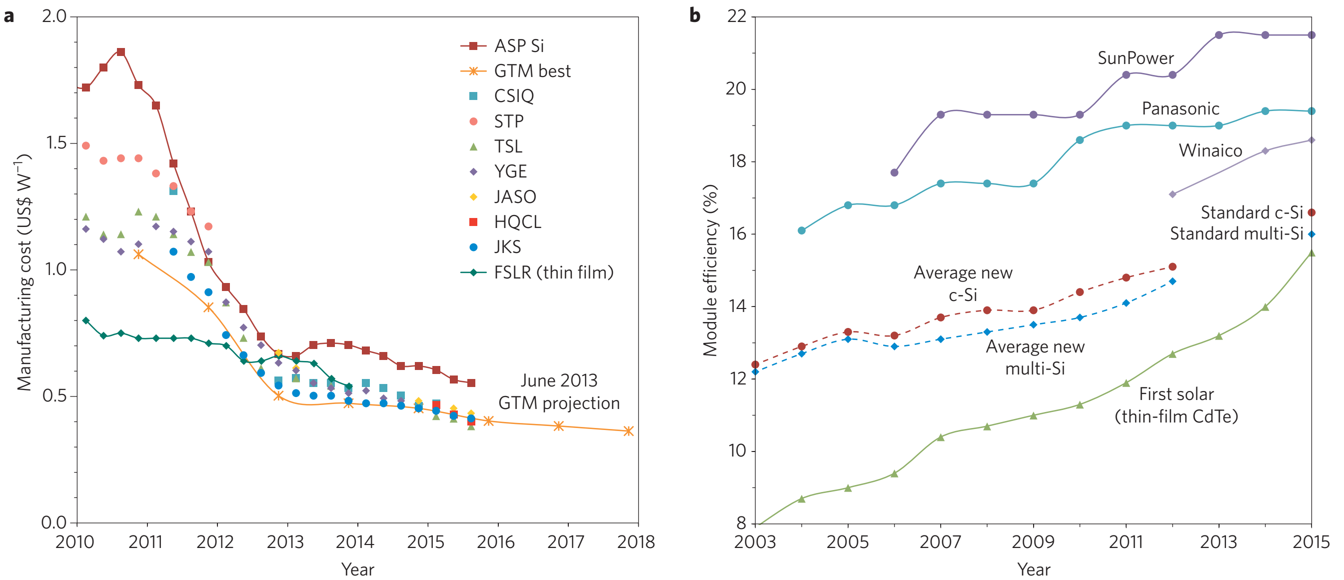

Figure 2 | Evolution of module manufacturing costs and energy conversion efficiencies. **a**, Quarterly module manufacturing cost data reported by a range of silicon module manufacturers (identified by stock exchange ticker code) compared with average selling price (ASP) and 2013 projections by GTM Research[32]. Data for one thin-film manufacturer with a contrasting cost trajectory are also shown. In June 2013, GTM Research projected module manufacturing cost for leading manufacturers of 36c/W by the fourth quarter of 2017, a figure now likely to be bettered. **b**, Upper curves show historical data for commercial module efficiency for several leading monocrystalline (c-Si) cell manufacturers. The dashed lines show the average efficiency values for new mono- and multicrystalline modules entering a large module database during the years indicated[33]. The lowermost curve shows the annual average production efficiency reported by a thin-film CdTe module manufacturer. The remaining two points represent module efficiency for mono- and multicrystalline silicon products regarded as standard in mid-2015 (http://pv.energytrend.com/pricequotes.html).

of newly introduced products into key market segments.

A further barrier is posed by ongoing improvements to existing technology and the size of the industry working to ensure that these improvements continue. In analogy with bicycle racing, this can be described as the 'peloton' effect. A 'breakaway' technology may have its moment in the sun but, in a race with no finish line, eventually it is likely to be overtaken by the pack, as has happened to some extent with thin-film CdTe technology. Although the sole successful CdTe manufacturer (FSLR) enjoyed by far the lowest manufacturing cost pre-2011 (Fig. 2a), the situation changed in 2012 (according to company reports of manufacturing costs, whose underpinning assumptions are not always clear), attributed to marked silicon cost reductions across the spectrum of polysilicon, wafers, cells and modules (Fig. 1c). One consequence of such ongoing improvements is that if a technology had a 25% cost advantage when investment decisions are made, by the time full production is reached this advantage might have disappeared altogether.

Efficiency is the key

If low deposition costs, particularly at the expense of efficiency, do not provide a compelling commercialization strategy, what other options might there be? One obvious answer is related to efficiency. Energy-conversion efficiency will directly impact the increasingly important encapsulation and BOS costs and hence is probably the key both to future photovoltaic electricity cost reduction and to commercialization of new technologies. A recent report on future photovoltaic costs[13] supports this assessment, suggesting that commercial module efficiency is likely to increase to 30% by 2050, potentially to 35%. The ability to reach such efficiencies may therefore be an important feature of next-generation technologies.

The need for ongoing efficiency improvements seems to be widely accepted by present manufacturers, with relative improvements in module efficiency of 2–3% per year in silicon and about 5% per year in CdTe modules (Fig. 2b). Such efficiency gains contribute increasingly significantly to ongoing cost reduction. Given the recent period of relative profitability (indicated by the increasing gap between ASP and manufacturing costs in Fig. 2a), large segments of the silicon industry are investing in upgrading to higher-efficiency passivated emitter and rear cell (PERC) technology[25], the first laboratory silicon cell demonstrating a 25% efficiency. PERCs are expected to provide the largest share of commercial cell production by 2020[9,10], with similar production efficiencies to laboratory values. Although other approaches have now reached 25% efficiency, one reason for PERC's wide adoption is its compatibility with previously standard technology, which minimizes the capital investments required to upgrade.

This switch to PERC will allow silicon's 2–3% per year relative efficiency improvement to continue for most of the coming decade, after which improvements are expected to saturate. At least some thin-film technologies may have bridged the efficiency gap to silicon by then (Fig. 2b). To take efficiency further, next-generation technology is required for both silicon and alternative technologies. Although several approaches theoretically give higher efficiency than standard single-junction cells[26], only one has demonstrated practical gains, namely the tandem approach (Fig. 3a), in which multiple cells with complementary light absorption properties are stacked on top of each other and usually connected in series. Tandem architectures are thus the leading contender for higher-efficiency next-generation technology.

United we stand

Tandem cells have been used commercially for around two decades in two contrasting applications. At the low-efficiency end of the

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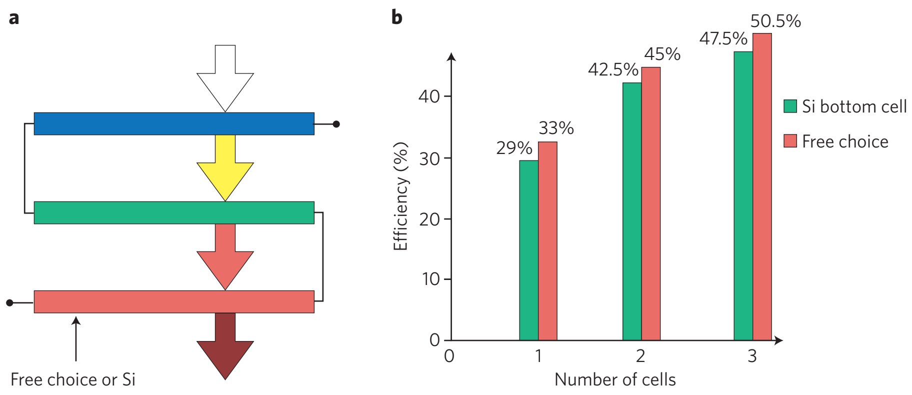

Figure 3 | Tandem solar cells and their limiting efficiencies. **a**, Three-cell, series-connected tandem cell stack. Cells with the highest photon energy response threshold are placed uppermost, allowing lower energy photons to filter through to underlying cells. The arrows show the passage of sunlight through the cell stack, with its colour successively modified as its highest energy component is absorbed. **b**, Limiting efficiency under the standard Air Mass 1.5 global spectrum as a function of the number of cells in the stack, comparing the case where the bottom cell is restricted to silicon with the unconstrained case.

spectrum, tandems have boosted efficiency and improved stability of a-Si:H cells[27] and, at the high-efficiency end, provided high-efficiency (but high-cost) group III–V cells for space and concentrating photovoltaics[28].

There are other appealing aspects to a tandem cell next-generation scenario, apart from improved efficiency. One is that tandems may offer evolutionary paths to increased efficiency. Provided that the tandem approach represented an extension of a company's established manufacturing process, modules incorporating tandem cells could be introduced initially as a premium product by an existing silicon or thin-film manufacturer. This would be a lower-risk strategy than if a new market entrant developed and offered next-generation modules as its sole product, competing directly against established manufacturers. Further evolution is then possible by successively increasing the number of cells in the tandem stack. Another appealing feature is that tandem cells may be able to take full advantage of the complementary strengths of multiple photovoltaic technologies.

A monolithic tandem structure, in which cells are deposited sequentially onto a single substrate, is likely to be the most practical (Fig. 3). Efficiency limits for the silicon case are lower for two reasons. One is that the (fixed) silicon bandgap is slightly below the optimal one for a single-junction cell, but increasingly above the value that would be optimal as more cells are added to the stack. The second is that unavoidable non-radiative recombination in silicon is strong relative to the radiative component due to silicon's indirect bandgap, restricting its limiting efficiency to below radiative limits[29,30]. This becomes less important as the number of cells increases and, correspondingly, internal carrier concentrations in operation decrease.

Going ahead

To conclude, recent progress has ensured a bright future for photovoltaics. As in microelectronics, silicon technology remains strongly entrenched and is likely to drive the industry to the next stage of its development, becoming one of the lowest-cost options for large-scale electricity generation. To progress further, what seems to be needed is not necessarily a lower-cost way of depositing cells, as deposition and related costs become increasingly less significant contributors to total costs as manufacturing volumes increase, but higher conversion efficiency than is possible with standard single-junction cells. Tandem cell stacks seem to be the most practical path forward, with additional potential benefits from building on the growing photovoltaic industrial infrastructure, rather than attempting its replacement. Considering other relevant issues — such as resource availability, the probable increase in restrictions on the use of hazardous substances and market introduction strategies for new technologies — silicon may be the leading candidate for the substrate for such cell stacks. The challenge is to find thin-film material systems that allow one or preferably more cells to be deposited on silicon to boost efficiency, without compromising the durability of the silicon module. This may be the most important challenge facing the photovoltaic research community and one that warrants increased effort. ❐

Martin A. Green is at the Australian Centre for Advanced Photovoltaics, School of Photovoltaic and Renewable Energy Engineering, University of New South Wales, Sydney, New South Wales 2052, Australia.
e-mail: m.green@unsw.edu.au

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