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PERSPECTIVE

Photovoltaic technology and visions for the future

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Abstract

Due to rapidly reducing costs, photovoltaics has suddenly emerged as a previously underestimated new force in the race to control global warming. The technology now provides one of the lowest cost options for bulk electricity supply, as demonstrated by recently executed power purchase agreements for long-term electricity supply. However, the technology is still evolving with ongoing cost reductions likely to sustain the rapidly increasing uptake seen over the last 20 years. Present market conditions and the state of development of the technology are outlined, as are prospects for improvements and for significantly impacting carbon dioxide emissions.

1. Introduction

The price of photovoltaic modules has reduced rapidly over the past decade, decreasing by a factor of 15 over this period (figure 1(a)). These module cost reductions have contributed to an even more significant reduction in the levelized cost of photovoltaic generated electricity, as documented by the lowest price bids for international power purchase agreements (PPAs) for the long-term supply of electricity [1] (figure 1(b)).

Compared to Lazard's benchmark levelized cost [2] of US$60-142/MWh for electricity from a new coal-fired plant (US$36/MWh marginal cost for existing plant) and US$112-152/MWh for nuclear, bids for the long-term supply of photovoltaic electricity dropped below US$30/MWh in 2016 and $20/MWh and 2017. It seems only a matter of time before a bid below an incredible US$10/MWh (or 1 c/kWh) is received. Although these bids are for the supply of electricity 'when generated' rather than 'on demand', Snowy Hydro in Australia, by combining with existing pumped-hydro storage assets, recently announced the ability to supply 'firm' solar and wind generated electricity, on demand, at AUD$70/MWh (US$50/MWh). Competitive bids have also been received in the US for solar and wind supported by battery storage (US$36/MWh and $21/MWh respectively, although these prices are lowered by a 30% investment tax creditor, for wind, a production tax credit of up to US$24/MWh) [3].

The lowest bids of figure 1(b) have been forthcoming not solely due to the module cost reductions noted above, but also due to more favourable financing conditions [4]. Pre-2016, it was difficult to attract favourable interest rates for investments in photovoltaic systems due to their relative novelty, with lower rates for more established technology. As the confidence in the technology's ability to deliver has increased and fossil-intensive investments increasingly ran the risk of becoming stranded assets, the situation reversed. Financing for some of the more competitive photovoltaic bids has been through green bonds, fully subscribed by investors satisfied with low returns [5]. These changes nonetheless reflect real market forces in play that are likely to have an increasing impact on the ability to finance projects in the future.

Supported by the above cost reductions, the annual photovoltaic market has grown rapidly and consistently over the past two decades, increasing from 252 MW yr^{-1} installed in 2000 to 109 GW yr^{-1} in 2018 [6], an annually compounded increase of 40% yr^{-1} over this period. Since 2010, the compounded growth rate has relaxed to 25% yr^{-1} (figure 2(a)). If growth can be sustained in the 25%–40% yr^{-1} range for a little longer, annual installations will reach 1 TW yr^{-1} sometime over the next decade, between 2025–8.

The significance of this level of photovoltaic installation is suggested by figure 2(b), originally published in 2015 [7]. This figure dramatically illustrates the difficulties in relying on a political solution to global warming. Despite the best efforts of the four biggest emitters, the entire CO_2 emission budget allowable for constraining global temperature rise to 2 °C appears likely to be exhausted by these four alone towards the end of the next

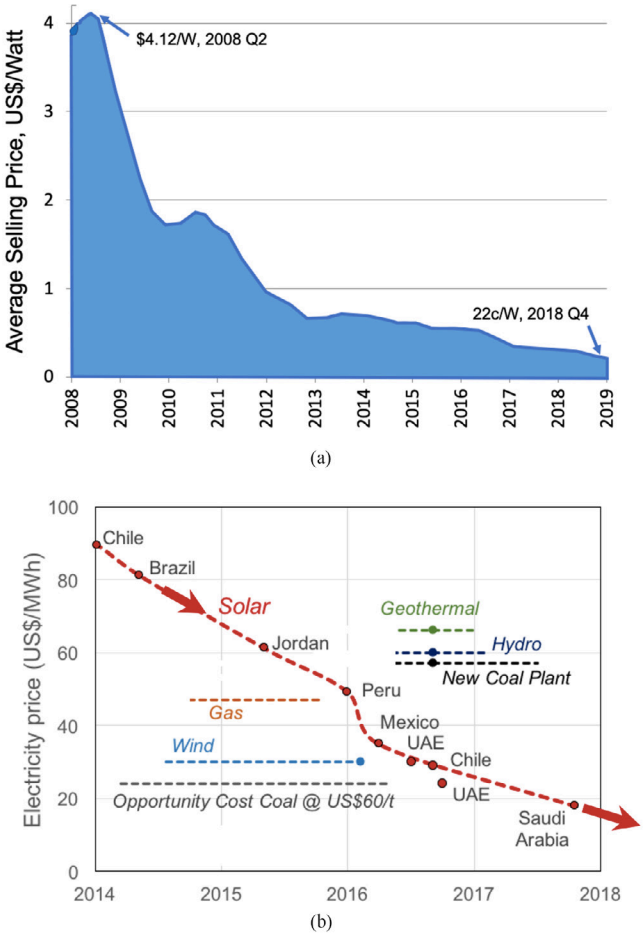


Figure 1. Photovoltaic module and levelized electricity supply cost reductions. (a) Reduction in average quarterly selling price of multicrystalline photovoltaic modules. (b) Timeline showing reduction in the lowest bids received for long term electricity supply under PPAs for both photovoltaic and other sources (Figures compiled from multiple sources including PVInsight, EnergyTrend, Greentech Media and IRENA).

decade. On the graph is indicated the approximate impact of installing 1 TW yr^{-1} of photovoltaics for three successive years, if displacing coal from electricity generation or oil from transport.

Given the poor prospects for political initiatives putting the world on required emission reduction trajectories such as shown in figure 2(b), the best outcome possible may be that these initiatives at least partly constrain emissions from other avenues, with photovoltaics (complemented by wind) taking on an increasing role in displacing coal from electricity generation and oil from transport.

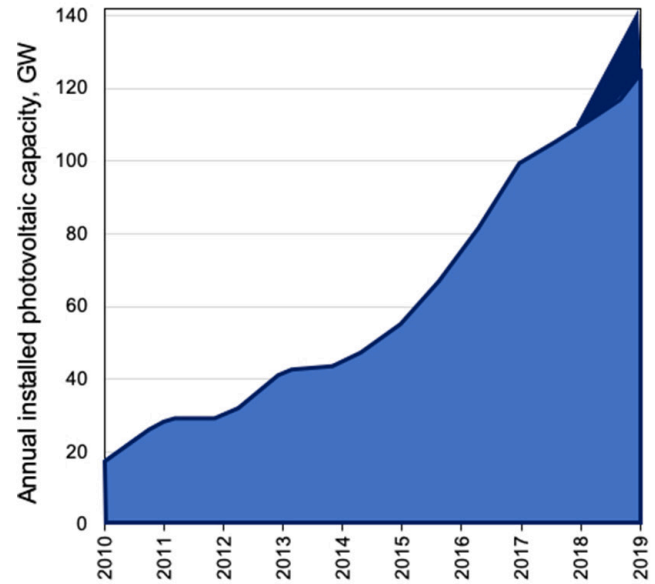
Photovoltaics technology is continually evolving with emphasis on improved energy conversion efficiency (ratio of output power to that in incident sunlight), with efficiency recently identified as having the largest impact on cost reductions seen to date [8]. There are paths to even higher efficiency with photovoltaics and hence to lower costs that will be outlined below.

Over recent years, silicon wafer-based technology has consolidated its role as the dominant solar technology accounting for over 95% of the market in 2018. This is despite earlier expectations silicon would eventually be displaced by less material intensive thin-film technology. As outlined below, the author's prognosis is that silicon cell technology will remain similarly dominant for at least the next decade, potentially, by then, starting to be augmented by combining within thin-film technology to produce silicon-based tandem cell stacks. This transition may ultimately lead to evolution away from dependence upon silicon by mid-century.

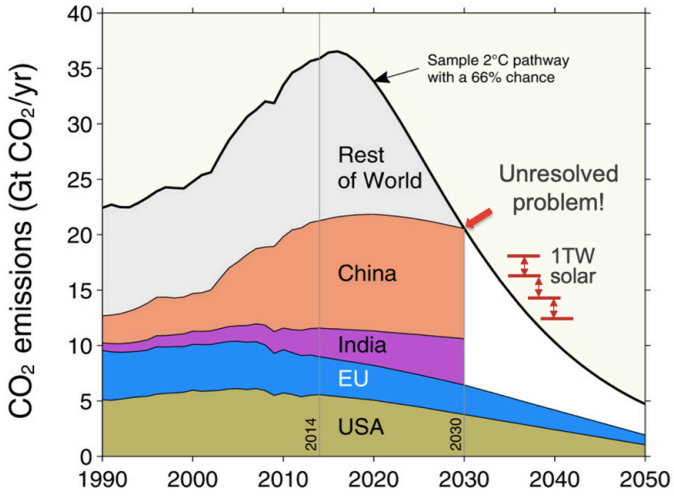
2. Cell technology

2.1. Silicon cells

Since the early 1980s and until very recently, the photovoltaics industry has exploited technology perfected in the historically important Low-Cost Solar Array Project led by the Jet Propulsion Laboratory (JPL) from 1975 to 1985 [9]. The cell design consolidated during this Project was similar to the 'black cell' developed for space use by Comsat Laboratories in 1974 [10], the highest efficiency cell of that era.



(a)



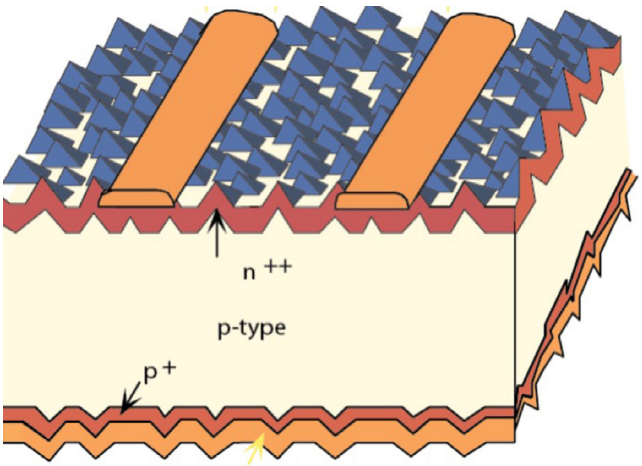
(b)

Figure 2. Market growth and global warming impact. (a) Market growth from 2008 to 2018 (preliminary) with projections for 2019 (data from Bloomberg New Energy Finance press release of 16 January 2019 [6]). (b) Global CO_2 emissions until 2014 with a subsequent emissions trajectory considered likely to limit global temperature rise to 2 °C. Added is the approximate impact of installing 1 TW yr^{-1} of photovoltaics for three successive years, if displacing coal from electricity generation or oil from transport (*Source: Peters et al 2015; Global Carbon Budget 2015*, modified by additional notation).

One improvement was replacement of thermally evaporated metal contacts by screen-printed contacts, a lower cost technique developed by Spectrolab [11] and first demonstrated at scale in modules supplied in the JPL Block II purchase of 1976/1977 [9]. This cell design (figure 3(a)) is now known as the 'Al BSF' cell due to the use of Al to produce the doped P^+ region at the rear historically described as providing a back surface field (BSF). Also introduced by Spectrolab at the same time was the first glass laminated module (figure 3(b)) with accelerated testing revealing these were 'the most resistant to the effects of the applied environmental tests' [12].

At this stage, Spectrolab withdrew from terrestrial activities to concentrate on the company's space business but the technology lived on, diffusing by several routes to multiple terrestrial cell manufactures. By the time of the Block V purchases from 1981 to 1985, almost all modern module features had been incorporated by most manufacturers, including the use of multi-crystalline silicon wafers and 'quasi- square' monocrystalline wafers, plus the use of EVA (ethylene vinyl acetate) encapsulants and multi-layered polymeric backsheets [9, 13].

This technology has dominated the industry for more than 30 years, with improvements through increased cell size and reduced cell thickness, reducing from 300 μm to 180 μm, largely during the silicon supply crisis of 2006–2008. Although the basic cell structure remained unchanged over these three decades, other improvements originated from changes such as an increased number of busbars, the switch to silicon nitride antireflection



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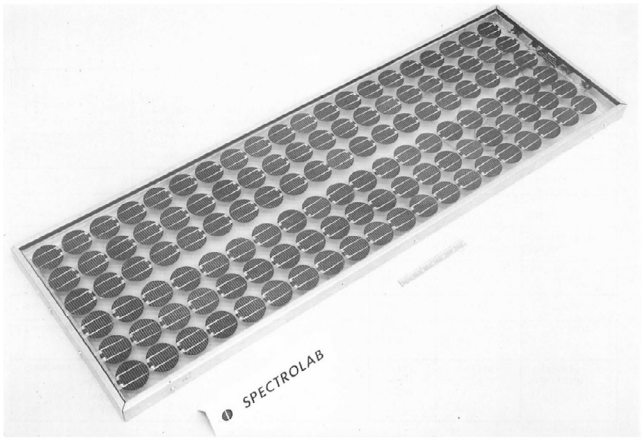


(b)

Figure 3. The Al BSF (back surface field) cell and first volume demonstration. (a) Schematic of the Al BSF Cell structure. (b) Spectrolab module supplied in US Government Block II purchases (1976/1977) incorporating both Al BSF cells and a laminated module design (1.2 m by 0.4 m, 30 W) [9].

coatings and most substantially, from progressive incremental improvements to screen-printing pastes. These developments improved cell efficiency from circa 11%–12% in 1980 to close to 20% by 2018.

The birth of the modern terrestrial solar industry can therefore be identified with the landmark Spectrolab Block II cells and modules supplied in 1976/1977. The highest silicon cell efficiency ever reported under terrestrial conditions at this stage appears to be 16.7% for a 'black cell' [14]. In 1983, the author's team made the first major improvement on this performance, demonstrating the first 18% efficient cell [15].

Also in 1983, the author first described the PERC cell of figure 4(a) (passivated emitter and rear cell) that has recently come to the fore, as subsequently described. The same team demonstrated the photovoltaic '4 min mile', the first 20% efficient cell, in 1985 with further incremental improvements in the following years. However, in 1989, a team led by Dick Swanson at Stanford University interrupted, albeit briefly, this run of records by demonstrating 22% efficiency with a highly innovative cell structure, now known as the IBC cell (interdigitated back contact), with both polarity contacts on the rear (figure 4(b)). This required careful attention to the electronic quality of both front and rear surfaces, as well as to that of the silicon wafer. This result increased our team's efforts to implement the PERC cell. PERC cells were successfully implemented and reported in 1989 and, with some help from Stanford, provided the vehicle to taking cell efficiency to 25% efficiency in 2008 [15].

Meanwhile, Sharp in Japan (now Panasonic) had been working on a novel heterojunction (HJ) cell using hydrogenated amorphous silicon (a-Si:H) as the HJ 'window layer' (figure 5(a)). The high hydrogen content (about 10%) changes material properties from those of pure silicon, increasing the bandgap, also resulting in much stronger optical absorption. The cell structure bears some similarities to the HJ technology used with Group III–V semiconductors. Although coming close, with 24.7% efficiency demonstrated in 2012 [16], ineffective photon absorption in the a-Si:H layer and overlying TCO (transparent conducting oxide) made it difficult surpass the 25% milestone. However, this difficulty was finally overcome by Panasonic, with 25.6% efficiency demonstrated in 2014 [17], by combining their HJ technology with the rear junction IBC approach first

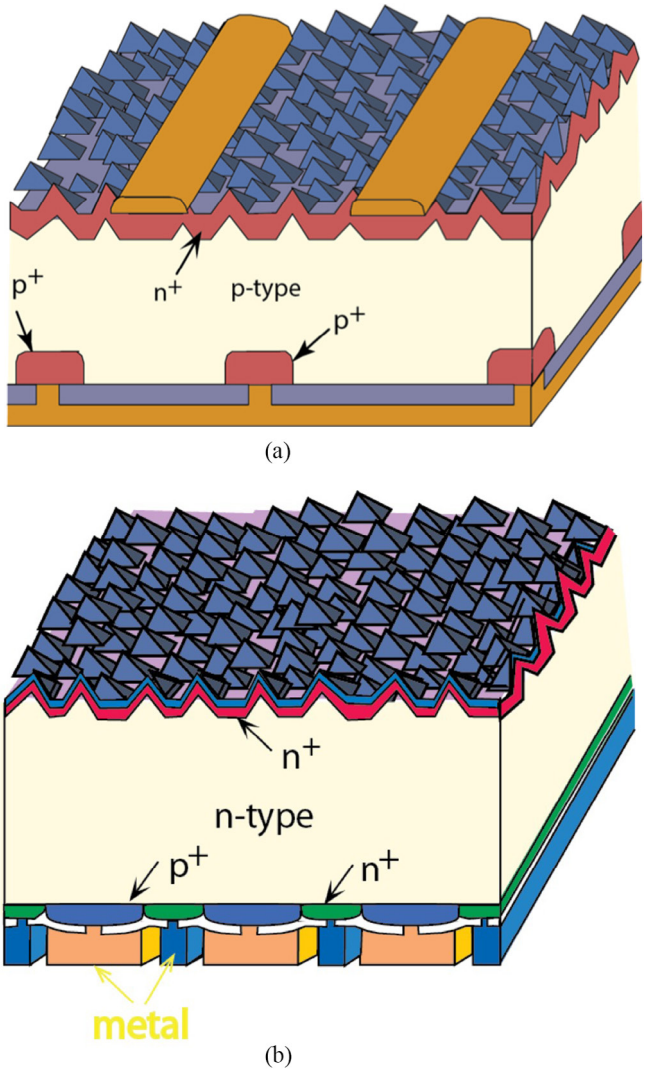


Figure 4. Schematics of high efficiency sells developed in the 1980s now used commercially. (a) The UNSW PERC cell (passivated emitter and rear cell). (b) The IBC cell (interdigitated back contact) with both contacts on the cell rear, first demonstrated by Stanford University.

demonstrated successfully by Stanford. This approach (HJ-IBC) has since been extended by Kaneka, another Japanese manufacturer, demonstrating 26.7% efficiency in 2017 [18].

A somewhat earlier but closely related approach is based on tunneling HJs. The author's team demonstrated record silicon cell open-circuit voltages in the 1976 to 1983 era using tunneling metal–insulator–semiconductor (MIS) structures [19]. The same team also describes the first cells, fabricated in 1981, where the metal was replaced by doped polysilicon in the tunnelling structure, demonstrating near record voltages for that era [19]. This idea has been more recently revived by the Fraunhofer Institute of Germany as their TOPCon scheme (tunnel oxide passivated contact) [20], which is actually a scheme for contacting the rear of the cell (figure 5(b)), despite the acronym suggesting otherwise. A similar approach has given even higher efficiency of 26.1% by applying the polysilicon tunnelling approach to both contacts in the IBC cell structure (both contacts on the rear), by ISFH (Institut für Solarenergieforschung) of Germany.

As the manufacturing industry also pushed to higher efficiency, replacing the entrenched Al BSF technology by one of the previous intrinsically more efficient designs became of increasing interest. Figure 6 shows a displacement timescale, as developed by a survey of industry participants [21]. Progress has been much more rapid than originally anticipated. PERC displaced BSF towards the end of 2018 as the cell with the largest share of production capacity, accounting for over 35% of cell production in 2018. The year 2019 will be historic in that it will be the first in the last 40 years where Al BSF is not the cell design produced in the highest volume, instead replaced by higher performing PERC.

The 2018 market share of IBC and HJ cells has been estimated as circa 1.5% and 0.7% respectively [22]. One hurdle for both has been the requirement for n-type, phosphorus doped wafers unlike the p-type, B doped wafers that dominate wafer supply.

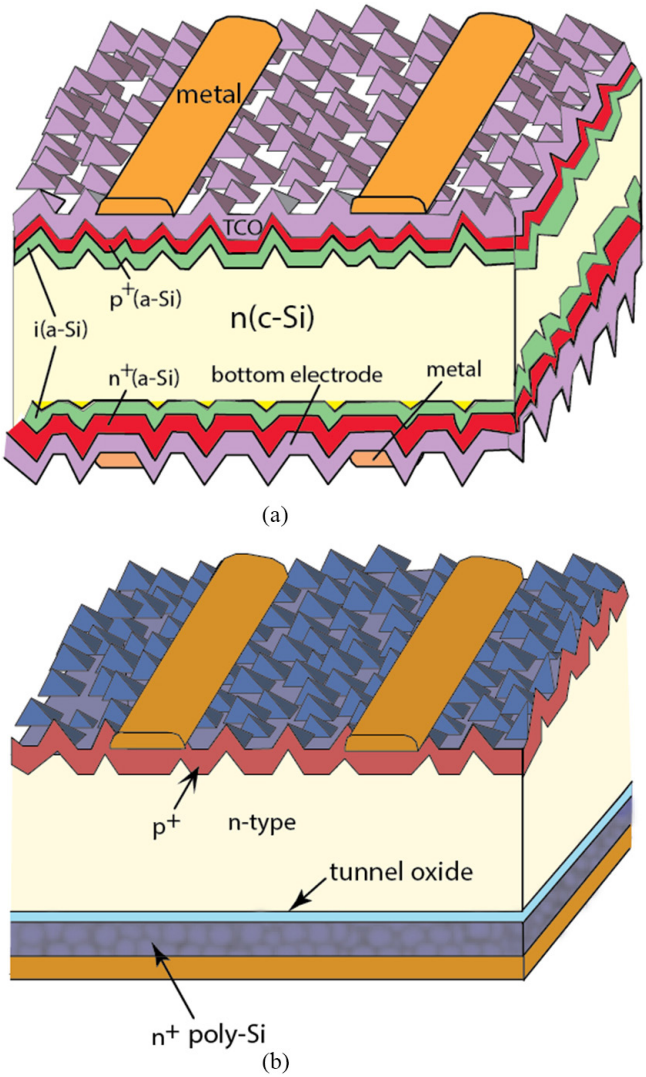


Figure 5. HJ and related tunneling oxide cell approaches. (a) HJ cell structure using wider-bandgap hydrogenated amorphous silicon layers as the HJ contacts. (b) The TOPCon (tunnel oxide passivated contact) cell using a tunneling structure for the rear contact.

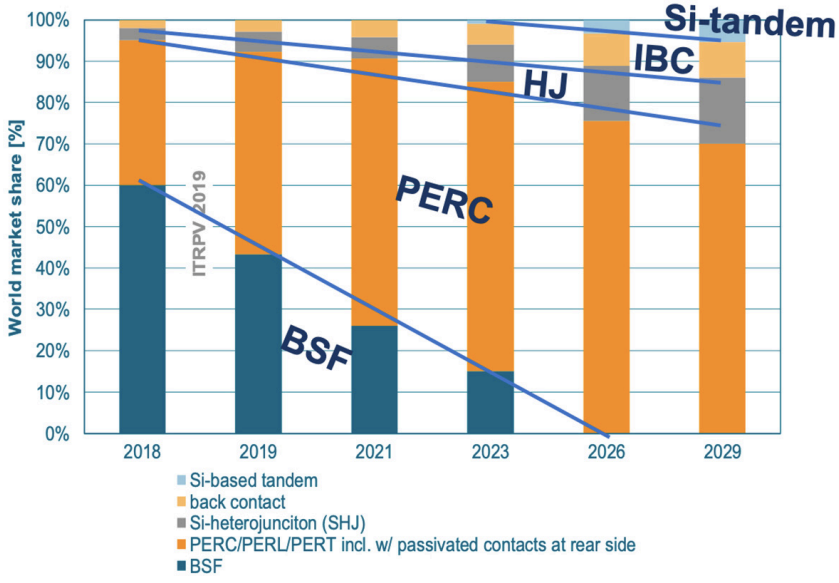


Figure 6. Projected manufacturing capacity share of different silicon-based cell technologies [21].

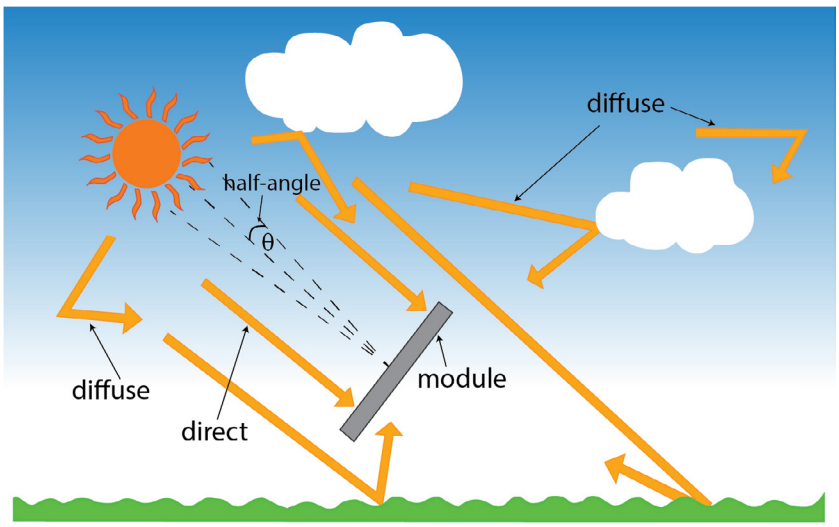


Figure 7. A bifacial module is able to respond to light scattered onto the rear module surface, enhancing output by 5%–20%.

Unlike the Al BSF approach, the PERC readily allows patterning of the rear contact, making it 'perfect for use in bifacial cells' [21], able to respond to light incident on both front and rear surfaces. This increases power generation by 5%–20% without any major additional costs, although a transparent back sheet is required for this use (figure 7).

2.2. Thin-film technologies

As noted, silicon dominated the photovoltaic market in 2018, with over 95% of the market. The remaining share is contested by a small number of thin-film technologies [23].

Of these, hydrogenated amorphous silicon (a-Si:H) was the early key contender, although this technology now has almost completely disappeared from the market. This approach, like wafer-based silicon, is environmentally benign and scalable, but was hampered by the low energy conversion efficiency of the manufactured product and the relatively expensive deposition approach. By using a tandem cell structure (section 2.3) by combining with microcrystalline silicon, with properties more similar to wafer-silicon than to a-Si:H, efficiency could be improved, although not to a competitive level, while further increasing depositions costs.

CdTe then emerged as the leading thin-film gaining 18% of the total photovoltaic market in 2007, during the era of a severe shortage of the refined silicon used to make wafers. This shortage was due to a transition as the market rapidly grew from reliance on companies traditionally supplying the microelectronics industry, to reliance on a new source of dedicated supply from companies servicing primarily photovoltaics. By 2018, CdTe market share had reduced to 2%–3%, although plans are to increase to 4%–5% in 2019. Although historically there have been some very extremely optimistic forecasts made for this technology [24], limitations of the availability of Te, as scarce in Nature as Au, intrinsically limits achievable market share to a minor role, as deduced by multiple independent studies [25–27]. The other 'elephant in the room' arises from the toxicity of Cd, with CdTe modules only saleable in Europe, for example, due to a periodically reviewed exemption from RoHS (restriction on hazardous substances) legislation.

The third commercial thin film technology is CIGS ($CuIn_{1-y}Ga_ySe_2$) with 1%–2% of the market, that avoids the issue of Cd in some implementations, but is similarly restrained to a small market share by its dependence on indium supply [25–27].

In academic circles, there has been much recent interest in another thin-film candidate, the Pb-halide perovskites [28]. Since 2012, these have made remarkable progress in laboratory efficiency, increasing recently to 23.7%, albeit for a tiny 0.1 cm^2 cell (compared to a record 26.6% for a 180 cm^2 silicon cell). However, while silicon is the most stable of the seven cell technologies now demonstrating efficiency over 20% (the other five are GaAs, InP, GaInP, CIGS, CdTe), these perovskites are by far the least stable being mechanically fragile and sensitive to oxygen, water, light, thermal shocks and electric fields [29]. They also incorporate one third Pb by weight with few prospects for its elimination, making them non-RoHS compliant, similarly to CdTe and some versions of CIGS. Moreover, the most efficient implementations require Au and Spiro-MeOTAD [28], several times more expensive than even Au.

Such difficulties notwithstanding, it is frequently asserted, usually without any credible supporting studies, that the Pb-halide cells offer a lower cost option than silicon and are about to displace it. The perceived advantage apparently lies in that the cells are processable from solution, although this would be of little cost advantage in a

technology already dominated by encapsulation and deployment costs [30], rather than those of cell processing. Although unlikely ever to match the durability of silicon modules, acceptable durability for less demanding consumer applications may well be attained, although consumer use may well be restricted by the high Pb content. The most promising application may be in tandem cells with silicon, discussed below, where an efficiency of 28% has already been demonstrated.

2.3. Future technology

A major driver for the industry has been the push to ever higher efficiency, as most recently reflected by the switch to PERC technology. This push arises because cell processing costs are subject to the same downward price pressure as in microelectronics, through increased manufacturing volume and processing sophistication. However, other costs, such as those of glass and polymer encapsulants, aluminium frames, junction boxes and cell interconnectors do not benefit to the same extent. Improved cell efficiency directly decreases all these less tractable costs, by reducing quantities required for a given output [30]. As noted, a recent analysis concludes that improved cell efficiency has been the most important factor in the module cost reduction seen over recent decades [8].

Efficiency becomes even more important at the system level. Higher efficiency reduces the number of modules that need to be transported to the installation site, the required area of mounting structures, the length of copper wire and cable trenches, the land area needing preparation as well as area-dependent O&M (operating and maintenance) costs. From the marketing perspective, companies able to offer the highest efficiency modules are also generally (and possibly correctly) perceived as having the highest level of technical prowess. These factors help explain the push to the higher efficiency technologies. Any company unable to keep up with the pace of technical development will struggle to survive.

Bifacial operation (figure 7), facilitated by the uptake of PERC, offers a near-term effective efficiency increase of 5%–20% relative by increasing the energy output from a given module area. What other options are available for further increasing efficiency?

Many approaches have been suggested, as recently reviewed by the author [31], although few are likely to give any practical advantage over the timescale needed for photovoltaics to make a timely impact upon global warming. One technology that has already demonstrated substantial efficiency advantage is the tandem cell approach, where cells of different bandgaps are stacked on top of one another (figure 8(a)).

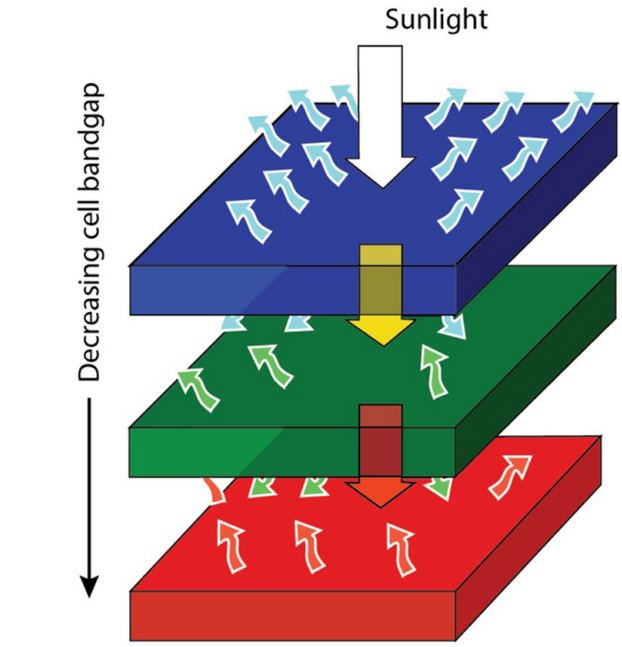
Solar cells are essentially photon conversion devices, ideally converting each incident photon with energy above the cell bandgap into an electron flowing in electrical loads connected between its terminals. Obviously, from energy conservation, this flow cannot continue if the voltage across the load builds up to the value equal to the cell's bandgap expressed in electron volts (eV). In fact, the highest conversion efficiency occurs when this voltage reaches about 60%–70% of the bandgap value.

The power output is determined by the product of the photons absorbed and this voltage. Low bandgap cells will give high current output but low voltage, while high bandgap cells will give low current but high voltage. The optimum occurs for an intermediate bandgap in the 1.0–1.6 eV range, with silicon and CIGS (1.1 eV) near the lower end of this range and GaAs and CdTe (1.4 eV) near the high end, with the range flattened by an atmospheric water vapour absorption band centred around the midpoint (1.3 eV) (see figure 8(b), lowermost curve labelled '1 J').

With two cells stacked, a better trade-off can be obtained. The higher bandgap cell is uppermost in the stack, acting similarly to a transparent glass sheet for photons of energy below its bandgap, allowing these photons to pass through to the cell underneath. If the two bandgaps are matched so that both cells absorb approximately the same number of protons, they can be simply connected in series, minimising associated costs. The top cell can convert at its full efficiency. Since the bottom cell has given up half its photon quota to the top cell, it will operate at about 50% of its standalone efficiency. If both bandgaps were in the 1.0–1.6 eV range, this would improve efficiency by approximately 50% compared to a single cell. However, the photon matching requirement pushes one or both out of this zone, limiting improvement to closer to 40%.

Efficiency increases further as more cells are stacked but with diminishing returns. In principle, efficiency can be approximately doubled by stacking a large number of cells. Figure 8(b) shows quantitative results for the maximum possible efficiency from a single cell (1 J) plus finite stacks up to 6 cells (6 J), as well as for an essentially infinite number. Note that silicon's bandgap is on the low side of optimum as a standalone cell (1 J), close to the optimum for the bottom cell in a two-cell stack (2 J) and too high for three cells or more. However, performance ideally increases as each extra cell is added to the stack and the departure from the optimum is never large.

Stacking cells on silicon is therefore a good strategy for improving efficiency, if stacks else can be deposited as thin films to minimise additional processing costs, but the problem is finding a suitable thin-film candidate. Initial interest was in a-Si:H, which is close to the perfect bandgap (1.7 eV) for matching the photon count as well as having sound environmental and material supply credentials. However, the highest efficiency a-Si:H cell is only 10% efficient so, according to the formula previously outlined, combining with a 25% efficient silicon PERC or HJ cell would *reduce* efficiency to a more modest 22.5%!



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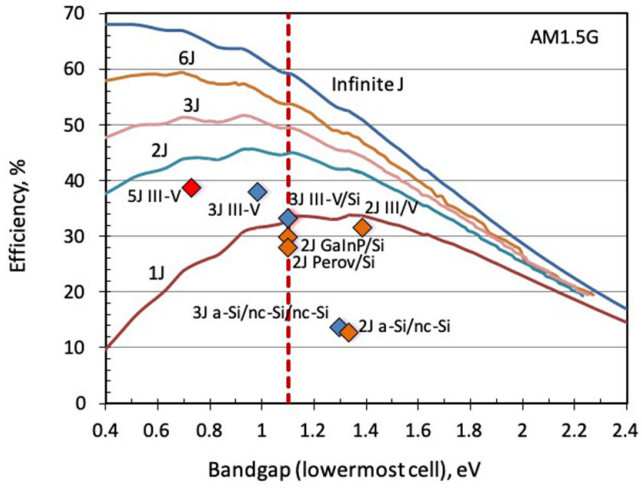


(b)

Figure 8. Tandem cell concept and corresponding efficiency limits for different numbers of stacked cells. (a) Cells of different bandgap shown stacked on top of one another, highest bandgap cell uppermost, showing the light emission processes during operation that fundamentally limit efficiency. (b) Limiting energy conversion efficiency for a single junction cell (1 J) and for stacks involving 2, 3 and 6 cells (2 J, 3 J, 6 J respectively) and an essentially infinite number of cells. The dashed line shows the limiting performance for cells stacked onto silicon. Also shown are assorted experimental results [31].

Combining a PERC or HJ cell with an overlying high-efficiency III–V cell would overcome this problem. However, III–V cells to date have needed to be of good crystalline quality for good performance and are normally deposited by expensive processes onto good-quality, but also expensive, Ge, GaAs or InP wafers. The problem is that silicon atoms are spaced too closely to act as a template for any viable 1.7 eV III–V semiconductor, necessitating costly buffer layers to provide the required match. Even with these, the best tandem cell result using this approach is 20.1%, well below that possible by silicon alone. The lattice spacing issue can be overcome by either wafer-bonding III–V and silicon wafers, an expensive option, or mechanically stacking the cells.

Either option requires the use of one of the expensive substrates mentioned above as the III–V template. This substrate would have to be recycled hundreds or thousands of times to bring its effective cost anywhere close to that of silicon monocrystalline solar wafers (presently 0.16 US cents cm^{-2}). This seems an unlikely commercial route for terrestrial cells. Additionally, key III–V elements (Ga, In, As) are scarce or toxic.

The high efficiency obtained with thin-film Pb-halide perovskite cells previously mentioned combined with their relatively high and tuneable bandgap also makes this technology of interest for stacking onto silicon. Good results have recently been obtained with 28% efficiency demonstrated, higher than the best silicon cell, with further near-term improvements anticipated [32]. Commercialisation of perovskites in this tandem configura-

tion in conjunction with silicon is thought to be a more likely path than as a standalone thin- film cell in direct competition with silicon. Tandem cells could be cautiously introduced as a premium high-performance product by an established major silicon cell manufacturer [30], provided durability was not compromised compared to standard silicon product, although this is presently considered a very challenging requirement.

However, a more rugged, abundant thin-film material that did not involve toxic elements, such as Pb, would clearly be a better option if it could reach the same high performance levels as demonstrated by the perovskites. One candidate is CZTS (Cu_2ZnSnS_4), with efficiency steadily increasing although still only at 11%, too low for viable application. Finding other materials capable of the filling this role may be one of the most important challenges remaining to be solved to allow photovoltaics to reach its full potential, in terms of the incredibly low costs that would result (less than US$5/MWh electricity costs would seem likely).

If such a material system can be found, stacking two cells onto silicon will be a logical extension of the approach, since the increase in processing complexity and extra costs would be small. This would reduce the silicon cell contribution to a third of its standalone performance.

By this stage of commercialisation, there would be sufficient manufacturing and field experience with the thin-film technologies involved that these would be fully validated. Silicon may then exit from the field in further developments involving larger cell stacks. By mid-century, solar performance may approach the limits for tandem stacks as shown in figure 8(b).

3. Environmental Impact

3.1. Environmental credentials

Solar cells can provide one of the environmentally most benign approaches yet suggested for supplying the world's energy [33]. Moreover, most of the attributed environmental impact comes from the energy required during the manufacturing and installation of the solar panels, with this attributed impact arising largely from the poor environmental qualities of the presently incumbent energy technologies. Present energy payback time is now below one year for standard silicon modules deployed in reasonably sunny locations [34], with even shorter payback times calculated for thin-film modules.

Instead of following the standard convention of imagining cells are produced from electricity generated from the actual generator mix typical of the manufacturing region, one could alternatively imagine they are fabricated with the electricity that earlier cell production from the same or similar facilities is contributing to this mix, either locally or globally. For example, most cell manufacturing is now occurring in China which has more than enough solar installed to fully support the energy requirements of all stages of this manufacturing. Why should other more polluting technologies, such as coal, get the benefit in environmental calculations from the cleaner electricity mix that accelerated solar installation is creating, rather than it being attributed solely to the source?

The conventional analysis imparts two independent time dependencies, both often overlooked, that continually reduce the already small attributed impact. The first of these come from the same types of improvements that have resulted in the dramatic reductions in costs already noted, particularly in the energy requirements for wafer and cell fabrication. Some authors have ascribed a similar learning rate to the corresponding reduction in attributed environmental impact as is commonly used when describing cost reductions [35]. The second time dependency comes from steadily improving environmental quality of the energy generation mix, as discussed above, with photovoltaics expected to accelerate these improvements in the future.

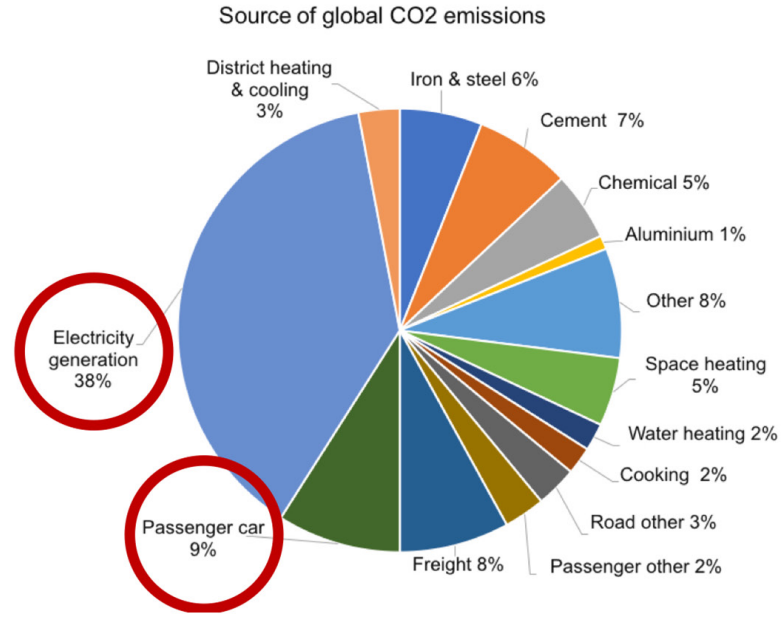
3.2. Impact on global carbon dioxide emissions

Figure 9(a) shows the sources of global CO_2 emissions [36], indicating the majority come from electricity generation with transport providing the next largest grouping. Together these account for 60% of emissions.

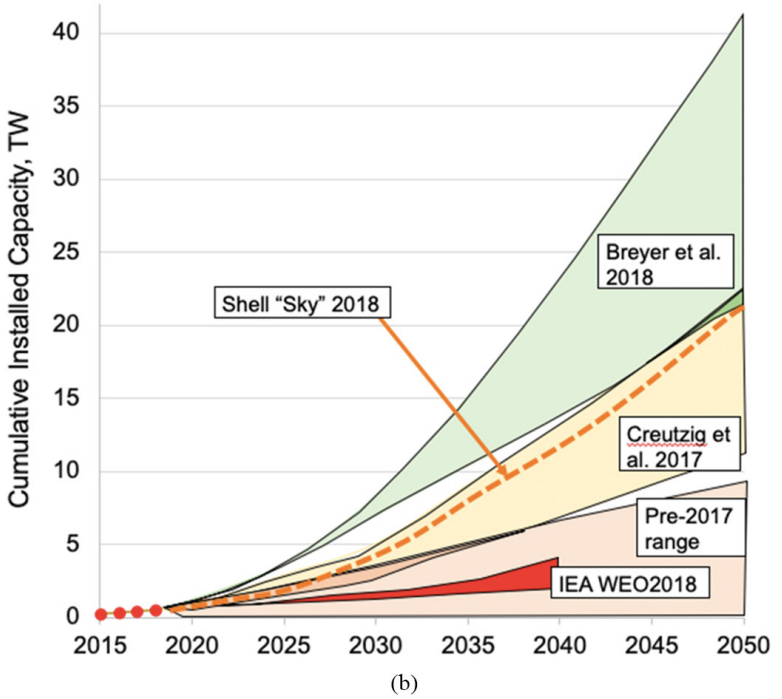
Photovoltaics has long been regarded favourably as a long-term option for sustainable energy supply, helping to at least partly reduced these emissions. However, studies of likely uptake and impact pre-dating the massive system cost reductions of 2016/2017 apparent in figure 1(b) have almost invariably been very conservative and can now be largely discounted. This conservatism is understandable given the then speculative nature of the anticipated photovoltaic cost reductions.

With this impediment now removed, studies that less reservedly address the impact of these low and reducing photovoltaic costs are beginning to emerge. Figure 9(b) summarises the results of several studies of the projected accumulated installed photovoltaic capacity over coming decades to 2050. Shown are the range of results for multiple pre-2017 studies [37], projecting up to 9 TW of installed photovoltaic capacity by 2050. Also shown are the results of five more recent studies [37–41], most projecting much higher volumes.

The International Energy Agency (IEA) claims to be 'the world's authority on energy' and is widely used as a source for policy makers around the world. However, the organisation appears to have an unfortunate, but deliberate, policy of understating the likely impact of renewables, consistently and systematically underestimating growth by completely unprofessional margins over the past two decades. The latest outlook [38], released



(a)



(b)

Figure 9. CO_2 emission sources and photovoltaic uptake projections. (a) Percentage of global CO_2 emissions from different sources (IRENA data for 2015 [36]). (b) Pre-2017 projections for cumulative photovoltaic installation compared to several more recent projections [37–41].

only in November 2018, assumes the exponential annual market growth apparent from figure 2(a) will suddenly stop and the market drop back to 100 GW yr^{-1} for the next two decades! The IEA results [38] from all studied "scenarios" are included in figure 9(b), but should be regarded as unreliable in the extreme, based on the organisation's past extremely poor performance in this area in anticipating actual outcomes.

By contrast, in a 2017 study, Creutzig *et al* [37] project cumulative installations between 11–22 GW by 2050 with an annual installation rate of 0.4–0.9 TW yr^{-1} after 2030. Volumes depend on whether or not photovoltaic installed system costs decrease below US$450/kW.

In March 2018, Shell, a major oil company, released the results of their 'Sky' scenario with photovoltaic capacity projections for 2050 also in the 22 TW range, increasing to 69 TW by the end of the century [39] (values are deduced by assuming average generation of 1600 kWh per installed kW).

Also in 2018, Breyer *et al* [40] report the results of a comprehensive study of a transition scenario to a low carbon future, driven largely by the improved economics of solar. These authors also project circa 22 TW installed

photovoltaics capacity by 2050, complemented by 3 TW of wind capacity, with this meeting the traditional electricity demand, appropriately increased. Their scenario involves a more rapid initial uptake than the previous two, displacing a very significant 10 Gt yr^{-1} of CO_2 emissions by 2030.

In subsequent work [41], the study was extended to transport, with strong photovoltaic uptake for this application anticipated post-2030. This is via direct electrification of vehicles as well as indirectly through the generation of synthetic fuels, such as hydrogen, methanol and Fischer-Tropsch fuels. An additional 19 TW is projected by 2050 for these transport applications. The authors have more recently also systematically explored a wider range of applications including in the chemical industry, where all basic feedstock chemicals were investigated, in desalination, in CO_2 direct removal, in the heat sector, and in the steel and other industries, including the refining of Al and Cu. The results of this extremely comprehensive study suggest these applications could well push the total combined photovoltaic capacity to over 63 TW by 2050 [42].

This would allow photovoltaics to contribute to decarbonisation even more rapidly than suggested by figure 2(b). These volumes may sound high but, going back only a few years, there is almost no observer, informed or otherwise, who would have projected that over 100 GW of photovoltaics would be installed in 2018 alone at average module wholesale prices below 30 c/Watt. As the authors of the above work note [41]: '*Not many have yet understood what USD$10/MWh for photovoltaic generation really means*'.

There have been many discussions, often heated, regarding the feasibility of achieving the high levels of renewable energy penetration implied by the more recent studies of figure 9(b). A succinct but comprehensive overview can be found elsewhere [43], suggesting such outcomes are not only feasible, but economically viable, even attractive [40, 42], given recent solar and wind cost reductions.

4. Conclusion

The more rapid than anticipated increase in photovoltaic production volume and associated cost reduction have greatly increased prospects for a rapid transition to a sustainable, low carbon future. There is no longer a need for concern regarding the costs of such a transition, but rather an expectation of cost savings.

Cell technology continues to evolve with the industry transitioning in 2018 from technology entrenched for over 40 years to higher efficiency PERC cell technology. Additional cost reduction and effective efficiency improvement is anticipated from the concurrent switch to bifacially responsive cell designs, allowing light scattered onto the module rear to be collected.

A switch to low-cost tandem stacked cell designs would allow these ongoing cost reductions to be sustained for several more decades. These tandem cells would most likely first be introduced in the form of thin-film cells stacked on top of an otherwise standard silicon cell, given the clear path to market introduction of such a product. The challenge is to find materials as efficient, stable, benign and abundant as silicon to allow this pairing. If such materials can be found, silicon could then potentially be displaced by mid-century, likely by a four cell, all thin-film tandem stack.

Even without such transformational developments, photovoltaics will provide the lowest cost source of electricity over coming decades, continuing its rapid uptake. Several recent studies project that over 20 TW of photovoltaics will be installed by 2050, with one suggesting this may increase to over 63 TW, when applications apart from traditional electricity supply are taken into account. Such a strong uptake would provide a benign and low-cost technical solution to the challenge posed by global warming.

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