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Perspective

Toward commercialization with lightweight, flexible perovskite solar cells for residential photovoltaics

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SUMMARY

Metal-halide perovskites have emerged as a promising class of next-generation solar cells. Here, we assess what lifetimes and efficiencies perovskite solar cells (PSCs) have to reach to lower the price of commercial residential photovoltaics (PVs) further. We find that using light and flexible substrates, as opposed to heavy and rigid ones, reduces the total installed system cost of PSCs, culminating in a lower balance of system (BOS) cost, as it is possible to use different mounting methods. Concretely, we analyze the scenario when the modules are directly placed onto a roof without requiring a racking system. This reduces both labor and material costs. Furthermore, it effectively lowers the necessary efficiency or lifetime of PSCs (T80 value) to achieve the same electricity cost as commercialized silicon. For 2021, we find that a rigid perovskite module with 17% efficiency would need at least 24 years to become competitive with residential-installed silicon. In comparison, a light, flexible module with the same efficiency would only need to last 19 years. In 2030, with the accordingly projected BOS costs, a 23% efficient perovskite module would need to last 24 years if rigid but only 17 years if flexible. Finally, we extend our analysis toward tandem structures with perovskite-silicon or all-perovskite tandem architectures. We find that flexible PSCs present a promising commercialization route because it can enable low manufacturing and BOS deployment costs, which opens up commercial viability at lower efficiencies or lifetimes.

CONTEXT & SCALE

Residential PV is an important sector for reaching net-zero emissions by 2050. Households will have to shift to electricity for heating, cooling, and electric mobility, which increases the need for local electricity production. The main cost drivers for residential PV come from the heavy weight and rigidity of the PV modules. A recently emerging new PV technology offers similar solar-to-energy conversion rates but at a significantly lower weight. It can also be employed on fully flexible PV substrates: such novel perovskite solar cells have attracted much attention in recent years. However, one major drawback is their operational stability trailing established silicon PV that has been stable for decades. In this article, we analyze how the technological advantages of lightweight perovskite solar cells may compensate for a lowered operational stability. We then calculate minimum lifetimes that perovskites would have to reach to stay competitive.

INTRODUCTION

Investment in renewable energy is one of the most effective mechanisms to combat climate change.[1–4] It is therefore imperative that we lower the price of renewable energy to attract consumers and to maximize its implementation in order to minimize the emission of greenhouse gases. One of the most accessible and clean renewable energy sources is photovoltaics (PVs).[5–7] A newly emerging material for PV is metal-halide perovskite, offering to lower the price of energy further while emitting even less CO_2 than other PV technologies.[8,9] In the following, we will assess what perovskites have to achieve to reach that target cost by comparing it with the prominent market leader for PVs: silicon solar cells.

Perovskite solar cells (PSCs) were discovered in 2009 with an initial power conversion efficiency (PCE) of 3.9%. They are now at certified efficiencies above 25%, rapidly reaching technologies such as silicon or GaAs.[10–12] Perovskites in a tandem stack with silicon even exceed the single-junction efficiency record of silicon of 26.8%, achieving a certified efficiency above 32%.[13] Hybrid organic-inorganic perovskites have exceptional material properties, including a sharp absorption edge,[14] solution processability,[15] and a tunable band gap of 1.2–3.0 eV[16–18] by interchanging the above cations, metals, or halides. PSCs have a broad spectrum of potential applications ranging from residential PV, large-area solar farms, flexible wearable devices, and low-sun-intensity applications for the internet of things to building-integrated systems.[19–21]

Despite this remarkable increase in efficiency, significant challenges remain concerning the long-term stability and toxicity of PSCs.[19,22–24] However, even if we were to overcome these challenges, a substantial hurdle for commercialization remains as the market-leading silicon underwent an enormous drop in production costs by more than two orders of magnitude in the last two decades—from 5 US $/$W_{DC}$ in 2000 to 0.23 US$/$W_{DC}$ in 2019 (DC refers to direct current).[25–27] Ongoing cost reductions with increasing scale are expected in the future. Competing with low-cost silicon, with long lifespans beyond 25 years and often less than 20 rel% efficiency loss, creates significant challenges for perovskites (or any other emerging PV technology at that).[28]

To gain a clearer understanding of what PSCs have to achieve to be an economically viable technology to compete with silicon, we calculate two scenarios based on 2021 values from the US Solar Photovoltaic System and Energy Storage Cost Benchmark: Q1 2021 report[29] and potential 2030 values (based on the SunShot 2030 target costs[30]) for residential PV. For each scenario, we assess the necessary lifetime (LT) of a perovskite module as a function of efficiencies to be competitive in the levelized cost of electricity (LCOE). We define LT in this report as the time until the module has 80% of its initial efficiency (T_{80}). For the 2021 scenario, we find that rigid perovskite modules need to last 19 years if they show a 20% module efficiency to be competitive with silicon at an LCOE of 11.9 US¢/W_{DC}. For the 2030 scenario, an LCOE of 5 US¢/kWh is calculated for silicon modules, which is the given target cost of the SunShot 2030 for residential PV. Such low electricity prices become possible because silicon solar cells are expected to reach higher module efficiencies of approximately 24% and longer LTs of up to 40 years.[27] To compete with silicon in, e.g., 2030, a 20% perovskites solar module would need to last 36 years, or a 25% efficient perovskite module would still need to last 21 years. This demonstrates that even with the significantly lower production costs of perovskites, it is challenging to become competitive with silicon, mainly because of the low LT of current PSCs and the limited experience with perovskite module stability.

Even if the cost of perovskite solar modules were reduced to zero, the total installed system cost reduction would be relatively small as the module cost is only one factor among many. For example, for residential PV in 2021, the module's manufacturing cost only accounts for 12% of the total installed system cost.[31] However, if perovskite solar modules could reduce other costs such as installation and structural BOS, the total potential savings could be up to 25%.

One of the major costs for residential PV installations with silicon stems from the installation cost, comprising 10% of the total system cost.[31] Since the modules are rigid and relatively heavy (weighing around 10–15 kg m^{-2}), they need to be mounted onto a racking structure (3% of the total system cost) on the roof. With lightweight or flexible modules, the installation becomes significantly less arduous.[32,33] Materials costs could be reduced if simpler installation such as glueing could replace racking.[34] Further, the cost of storing and transporting the modules and supply parts

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(around 1.5% of the total system cost) can be lowered since flexible or lightweight modules can be transported and stored in larger volumes because they are thinner and weigh less and may be compatible with alternate transport concepts such as rolls for flexible modules. Therefore, we show that under such assumptions a 20% flexible module with a LT of 16 years could reach the same cost for electricity as silicon solar cells. In our future scenario for 2030, a flexible 20% perovskite module would need to last only 22 years. So the flexible PV module would need to last 3 or 14 years less, compared to the rigid perovskite modules at 20% efficiency for the 2021 and 2030 scenario, respectively. Finally, we extend our analysis toward perovskite-Si and all-perovskite tandem modules. We find that the necessary LT could be further lowered with a flexible all-perovskite tandem.

We note that we take a different approach from previously published cost analysis works for PSCs.[35–39] Those primarily focused on calculating the PSCs' potential manufacturing cost and often assumed the same total system cost as for silicon for the LCOE. To the best of our knowledge, this is one of the first studies to analyze the trade-off of module cost, efficiency, and LT combined with the benefit of low weight and flexibility of PSCs in a cost analysis. Further, many previous cost analyses assumed a specific long LT (sometimes up to 30 years) for their final LCOE. Notably, no perovskite solar module has yet passed the IEC 61215,[40] the standard stability test for PV modules, and so far, little research has been done on complete module stability. We believe, therefore, that it is currently best not to assume simplistic LTs. Instead, we take a different approach and estimate what LT perovskite solar module would need to reach to become competitive with silicon.

RESULTS

To compare energy technologies, it is necessary to calculate their total costs over their LTs to arrive at an estimated cost per unit of energy. This is referred to as the LCOE, here in US¢/kWh, for renewable energies.[41] The rationale behind the LCOE is to calculate the expenses each year after installing the harvested energy. The LCOE then is the sum of the cash flow (all costs) divided by the sum of all harvested energy. The LCOE formula used here is as follows:

$$LCOE = \frac{Man_0 + BOS_0 + \sum_{t=1}^{n} \frac{OPEX(t)}{(1+\delta_{nom})^t}}{\sum_{t=1}^{n} \frac{Yield_t(LT)}{(1+\delta_{real})^t}}$$

where Man_0 and BOS_0 are the costs for the module and the BOS, respectively, in the year of acquisition (t = 0), also called capital expenditure. A detailed breakdown of the cost distributions is shown in Figures 1A and 1B. The Man_0 and BOS_0 for 2021 are from the US Solar Photovoltaic System and Energy Storage Cost Benchmark: Q1 2021 report. We took the median of the installed residential PV systems in the US for 2021.[29] The 2030 Man_0 and BOS_0 are from the published estimated SunShot 2030 values.[42] Both Man_0 and BOS_0 are given in US\$/W_{DC}. PV modules produce DC power that has to be converted to AC (alternating current), which in general induces losses depending on the exact inverter and system. To be independent of those parameters, we use W_{DC}. Further, t is the time counted in years ranging from 1 to n = 25 for the 2021 and 1 to n = 40 for the 2030 scenarios, OPEX(t) is the operation and expenditure costs in year t in US¢/kWh, $Yield_t(LT)$ is the annual yield in year t, LT is the lifetime of the system, δ_{nom} is the nominal discount rate, and δ_{real} is the real discount rate. The expanded LCOE formula is shown and elaborated on in Note S1. Essentially, we model a residential PV system owned by a homeowner, financed through the homeowner's mortgage. We use the same parameters as in the latest

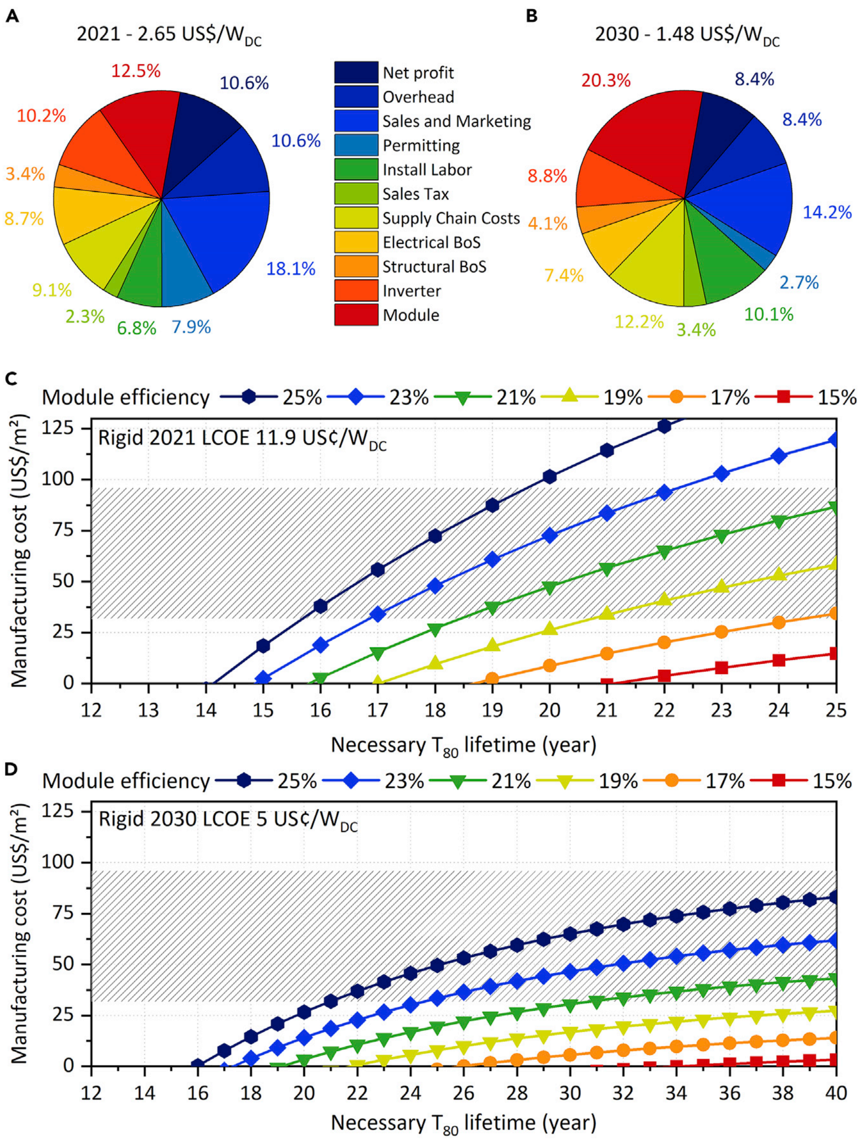

Figure 1. Cost parity analysis for rigid perovskite solar cells in 2021 and 2030

(A and B) Cost overview for the total installed system cost of a residential PV system (A) in 2021[29] and (B) in 2030 (according to the SunShot 2030 goals). The total cost for the 2021 and 2030 scenarios are 2.65 and 1.48 US$/$W_{DC}$, respectively.

(C) 2021 scenario for residential PV for an LCOE of 11.9 US¢/W_{DC} in Fredonia, Kansas. On the y axis are the manufacturing costs (US$/$m^2$) with the striped area marking the literature values[35–37] for different perovskite architectures. On the x axis is the T80 lifetime of the perovskite module. Plotted are $Man_0(t)$ for other module efficiencies, being the maximum manufacturing cost for LCOE parity with crystalline silicon (c-Si) modules.

(D) 2030 scenario for residential PV and an LCOE of 5 US¢/W_{DC} (note that the scale changed for the x axis to account for the different considered lifetimes in both scenarios).

US Solar Photovoltaic System and Energy Storage Cost Benchmark: Q1 2021 report from NREL.[31] We first calculate the LCOE for silicon solar cells. We then compare our LCOE range with existing calculations to check our model and input data.

The PV industry is a rapidly changing field where costs often decrease significantly over time.[26] Thus, our current assumptions for the installation price for PV modules in 2021 might be out of date in a few years.[26] We, therefore, calculate potential future values based on the SunShot 2030 initiative, which can be seen as a "best-case" solar scenario for 2030.[30] It aims for an LCOE of 5 US¢/kWh for residential PV. The SunShot2030 target costs are based on several pathways, which can be broadly differentiated into reducing degradation, reducing up-front costs, and increasing overall system LT (inverter included).[42] We assume here a relatively equal reduction in all three areas and adapt our overall system cost from the 2021 scenario according to the SunShot 2030 target costs. A detailed breakdown is shown in Figure 1B. We see the 2021 and 2030 scenarios as a likely corridor for the development of PV in the next decade. We note that even if this were not the case, our main conclusions for rigid PV would still be valid, as this parameter affects all considered PV technologies in similar ways, so any discrepancies will not affect the relative performance significantly.

We calculate for the 2021 scenario an LCOE of 11.9 US¢/kWh for residential PV in Fredonia, Kansas, as shown in Table 1 (medium solar irradiance). The 2021 NREL PV Benchmark report exhibits the same value.[29] For 2030, we calculated an LCOE of 5.5 US¢/kWh, as shown in Table 1.

It is essential for a newly emerging technology to be better than the already established technology. That means a new PV material needs to reach a lower electricity price than silicon. We see this as an essential step toward broad commercializing PSCs. Therefore, we take the calculated LCOE costs for the two scenarios as the target costs for our predictions below. We take the LCOE for Fredonia, Kansas, as it is a commonly used place for LCOE calculations. One of the main challenges in predicting what PSCs have to achieve is that they are still a newly emerging PV technology. This makes any prediction difficult due to rapid technology development. Below, we briefly outline what we consider significant difficulties in predicting LTs, efficiency, and manufacturing costs:

(1) Stability
Since the beginning of the field, significant progress toward more stable PSCs has been made[40]. However, already from the currently published stability data, it is evident that more progress is needed. Most stability data published are still in a time frame of months[43–45] and rarely go above a year,[46] compared with silicon where stability data extend toward several decades.[28] Another challenging factor is that most stability data are measured on single cells on a small area, and less is known about the stability of large-area perovskite modules.[40]

(2) Module efficiency
In the last few years, the perovskite module efficiency has been rapidly rising from the first certified module with 12.1% on 36.13 cm^2 in 2016 to 17.9% on 804 cm^2 in 2019.[47] However, currently, most published high efficiencies above 20% are still on small areas of below 1 cm^2, and even most larger area modules are still below

Table 1. LCOE for residential PV installations (USA)

	2021 (19.9% PCE, 25 years lifetime, 33 US¢/W_{DC} manufacturing cost (Man)	2030 (24% PCE, 40 years lifetime, 30 US¢/W_{DC} Man)
Fredonia, Kansas	11.9 US¢/kWh	5.5 US¢/kWh
Phoenix, Arizona	10.1 US¢/kWh	4.6 US¢/kWh
New York City	13.6 US¢/kWh	6.3 US¢/kWh

We calculate the LCOE for a current (2021) and a future range (2030 SunShot). All assumptions are given in Note S1 and the attached excel file. We calculate this for Phoenix (initial energy yield 1,706 kWh/kW_{DC}), New York City (1,259 kWh/kW_{DC}) and Fredonia, Kansas (1,445 kWh/kW_{DC}), the same location as the 2021 NREL PV Benchmark report.

the typical size of a commercial module.[48] Major challenges remain, and it is unclear how far perovskite modules can catch up to the efficiencies of small area PSCs.[49]

(3) Manufacturing cost

Most currently published PSCs use materials that are unlikely to be used in large-area devices due to their high prices or long-term instability. So far, it is not clear what alternative materials are suitable. For example, many of the currently published highest efficiencies[50,51] still use gold as electrode material, which is too expensive to be used on large-area modules. Commonly, screen-printed Ag is used for c-Si PV, but it is harder to adapt for PSCs as it reacts with the halides[52,53]. Another example is ZnO, often used in cost analyses for perovskites, as it has excellent material properties and is inexpensive. However, Schutt et al.[54] showed that it causes deprotonation of the organic cations and is thus not ideal for organic-inorganic perovskites. Similarly, the processing methods, such as spin coating, used for PSCs that achieve record efficiencies are often unsuitable for large-scale manufacturing. Thus, published cost analyses often assume the use of more cost-effective approaches that have not yet been shown to result in the same high efficiencies as small-area PSCs. Until low-cost materials and manufacturing processes are proven, it is difficult to predict manufacturing costs accurately.

It is very plausible that PSCs will continue improving their LT, large-area efficiency, and manufacturing cost. However, it is not precisely clear what values they will achieve in the foreseeable future (see above). Therefore, instead of making assumptions about these values, we analyze what values PSCs have to achieve in these areas to reach the same LCOE as silicon PV. We assess a range of different manufacturing costs as it is more representative of the potential cost of a commercial perovskite architecture instead of having a set value. In literature, the manufacturing cost of various architectures is already covered, which we adapt here. Coming to an estimated cost of perovskite solar modules on glass ranges from 32.69 to 96 US$/$m^2$.[35–37] For flexible PSCs, the published cost range varies from 35 to 74 US$/$m^2$.[55]

In the second step, we calculate the LT and efficiency that PSCs have to achieve to reach the lowest LCOE of silicon (back-calculation). Several terms contain the manufacturing cost in the previously shown formula for LCOE (Man_0). We solve this equation to find the manufacturing cost that delivers equivalent LCOE to c-Si PV, as a function of LT and efficiency. The formula is shown here:

$$Man_0(LT, PCE) = \left(LCOE * \sum_{t=1}^{n=LT} \frac{Yield_t(LT)}{(1+\delta_{real})^t} - \sum_{t=1}^{n} \frac{OPEX(LT, PCE)}{(1+\delta_{nom})^t} - BOS_0(PCE)(1 - debt_{frac}) \right) \Bigg/ A$$

The denominator A is shown in the supplemental information, a term which is necessary as the debt that are part of the OPEX cost, shown in the previous equation further above, contain Man_0. The PCE dependence, given through an assumed model, as well as the full equation are outlined in the supplemental information.

Analysis of rigid perovskite solar cells

In the following, we show Man_0(LT, PCE) for 2021 (current) and 2030 (future) scenarios (see Figures 1C and 1D). For the upper bound of efficiency, we take 25% PCE since the PSC records are within this range.[56] There are many combinations of PCE, LT, and manufacturing cost that would enable LCOE parity with c-Si modules. We explore some of these here.

First, we consider the 2021 scenario. Even if PSCs could reach 25% on a large area and the lowest manufacturing cost, they would still need to last at least for 16 years to match c-Si PV. With a more achievable lower efficiency of 21%, they would need to last for 4 more years. Interestingly, if PSCs are at the higher end of the manufacturing cost (96 US$/$m^2$), cost parity is more sensitive to LT since an efficiency of 21% (27 years) needs around a 7 more years in LT than a 25% efficiency PSC module—a much more challenging aim. Considering this parameter space, although many combinations would allow LCOE parity with c-Si modules, one of the most challenging requirements is the long LTs of at least 16 years.

In the 2030 scenario, it is more difficult for PSCs to reach the same LCOE as silicon. We observe some minimum requirements. The shortest LT requirement is 21 years (assuming record 25% efficiency and a lower bound manufacturing cost of 31.7 US$/$m^2$), much longer than the 16 years estimated for 2021. The maximum manufacturing cost is 83.1 US$/$m^2$, for a LT of 40 years and 25% efficiency. PSCs have to be at least 20% efficient (40-year LT and lowest manufacturing cost), compared with 17% in the 2021 scenario. Moreover, sensitivity to each input variable is increased. For example, at the lowest manufacturing cost, a drop from 25% to 21% efficiency would need to be compensated by an increase of 9 more years in LT (only 2 years longer for the 2021 scenario). Overall, if silicon continues its current development and reaches the SunShot 2030 target cost, it will become quite challenging for PSCs to compete with silicon.

Analysis of flexible perovskite solar cells

The total system cost contains various components of which the module manufacturing cost is only one part (Figures 1A and 1B). Until now, we have only considered the impact of PSCs regarding lower module manufacturing cost compared with silicon—everything else in the total system price we assumed so far to be the same. This assumed implicitly rigid perovskite modules, which would be expected to have similar size and weight to c-Si modules and, therefore, similar installation costs. However, when considering lightweight, flexible PSCs, there are potential cost advantages to account for. Metacarpa., for example, reported up to a 47% cost reduction in hardware installation labor through the change to flexible PV modules.[32] Further cost savings in the hardware installation were expected of up to 71%.[33] Additionally, light and flexible modules allow for alternative mounting methods that, for example, do not require additional racking but can be placed conformally to the roof.[34] In addition to installation cost reductions, further cost savings can be estimated for the transportation and storage of the modules. Regular solar modules are around 35 mm thick, whereas flexible solar cells are significantly thinner—comparable flexible organic solar modules are, for example, less than 5 mm thick.[57,58] This, combined with the lower weight, allows for reduced transportation costs due to tighter packing densities and lower weight per kW of the module. To account for these advantages, the upper bound of cost advantage for the BOS is shown in Figure 2A. We first discuss this ideal cost scenario (flexible scenario) for flexible modules and discuss potentially lower cost advantages afterward. We further discuss the BOS savings in Note S2. More BOS saving possibilities can be found for rigid solar modules in the Future of Solar Energy study.[59]

In the following, we recalculated the previous Man_0(LT, PCE) for both scenarios with the flexible BOS. The total cost advantage in BOS in 2021 for the flexible scenario sums up to 0.22 US$/$W_{DC}$ (8.42% of the total system cost) for a 19.9% efficient module (the standard from the US Solar Photovoltaic System Benchmark: Q1 2021 report from NREL[31]). In 2030, the BOS cost advantage for a 24% module (the standard assumed future module

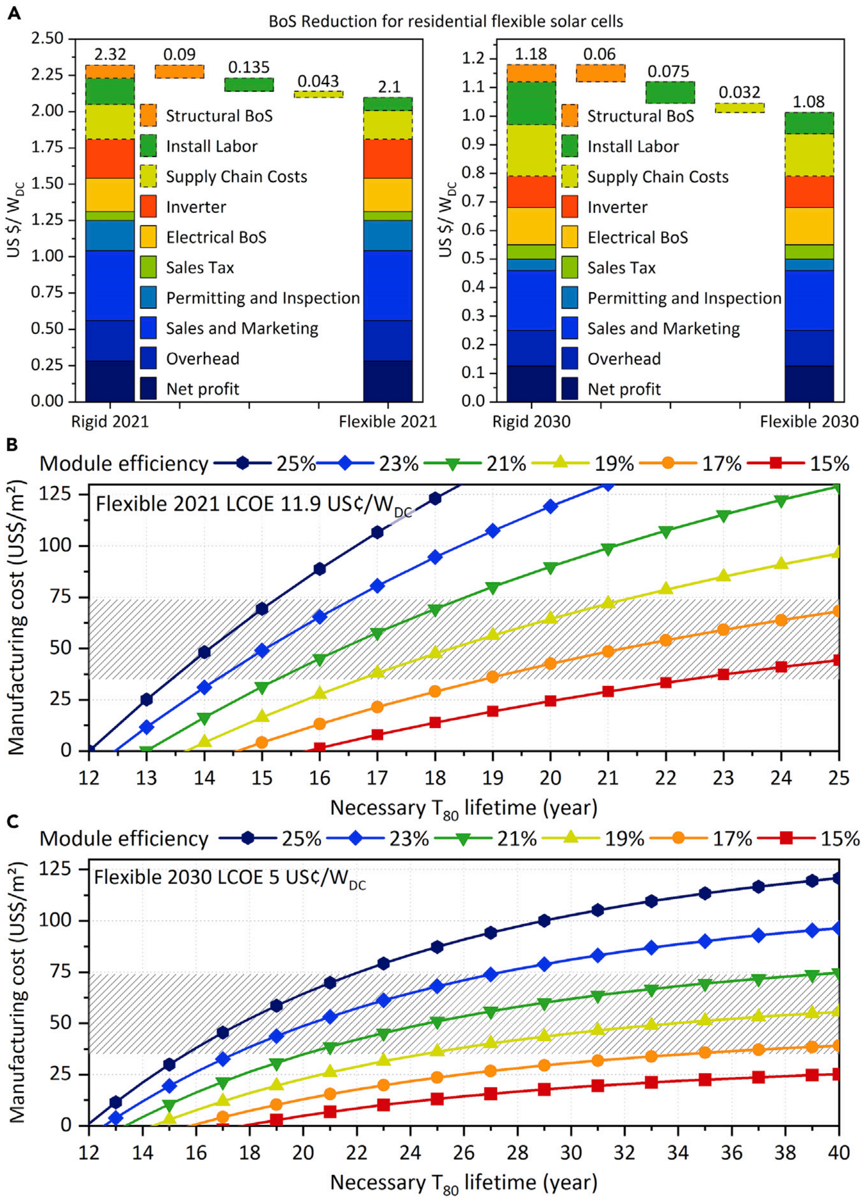

Figure 2. BOS reduction and cost parity analysis for flexible perovskite solar cells in 2021 and 2030

(A) Detailed breakdown of the assumed cost reduction for the flexible scenario for the 2021 and 2030 scenarios for a 19.9% and 24% efficient module, respectively. We note that because of our cost model, the absolute cost advantage for flexible substrates depends on the efficiency.

(B) 2021 scenario for flexible residential PV for an LCOE of 11.9 US¢/W_{DC}. On the y axis are the manufacturing costs (US$/$m^2$) with the striped area marking the literature values according to Chang et al.[55] for different used materials and processing steps. On the x axis is the T80 lifetime of the perovskite module. Plotted are $Man_0(t)$ for other module efficiencies meaning one constant PCE for each function.

(C) 2030 scenario for flexible residential PV and an LCOE of 5 US¢/W_{DC}.

efficiency here) is for flexibles 0.17 US$/$W_{DC}$ (11.3% of the total system cost). We first consider this flexible scenario and discuss potential lower BOS system advantages afterwards. The Man_0(LT, PCE) for 2021 and 2030 are shown in Figures 2B and 2C, respectively.

In 2021, flexible substrates would lower the minimum LT, which PSCs would have to achieve, to 13 years (25%, 35 US$/m^2), an advantage of 3 years, compared with rigid PSCs (25%, 31.7 US$/m^2). If flexible PSCs, for example, lasted 20 years, they would only need to achieve 16% at the lower bound of manufacturing cost. In comparison, rigid PSCs would need to be 5% more efficient to achieve the same LCOE (21%, 20 years, and 31.7 US$/m^2). Also, the minimum necessary efficiency for flexible PSCs is 14% (25 years, 35 US$/m^2). Rigid PSCs need at least 5% PCE more (19%, 25 years, 31.7 US$/m^2). A 17% flexible module could even have double the manufacturing cost of its rigid counterpart and still achieve the same LCOE. To summarize, the corridor of different scenarios under which flexible single-junction PSCs can reach a lower LCOE than silicon is wider in the 2021 scenario than for rigid PSCs.

The differences for a flexible substrate are more significant in the 2030 scenario. The minimum necessary LT is 16 years (25%, 35 US$/m^2), 5 years less than that of their rigid counterpart (25%, 21 years, 31.7 US$/m^2). The minimum necessary efficiency for a flexible module is 17% (34 years, 35 US$/m^2), 3% lower than for rigid modules (20%, 36 years, 31.7 US$/m^2). In 2030, the corridor of possible combinations for which flexible PSCs are competitive is significantly wider than for the rigid case.

Discussion of the cost advantage for light, flexible perovskite PV

The exact cost savings of flexible modules will likely depend on a variety of different factors, for example, the exact roof condition (tiles type, size, and angle of the roof). The estimated BOS cost advantage shown in Figure 2A may not always be achieved. The following discussion considers how a different, lower BOS cost advantage might impact the T80 LT necessary to reach the same LCOE as silicon.

The necessary T80 LT in our model depends on the efficiency, manufacturing cost, and flexible cost advantage, as all other cost factors are assumed equal between the rigid and flexible modules. There are many ways to visualize this 3D parameter space. First, we present a 2D map showing the necessary T80 LTs (for LCOE parity with c-Si) as a function of the manufacturing cost and flexible cost advantage while keeping the efficiency at 20% (Figure 3A). We also show the necessary LT as a function of efficiency and the flexible cost advantage for a constant manufacturing cost of 35US$/m^2 (Figure 3B). In Figures 3C and 3D, the same plots are shown for the 2030 scenario. Different possible values of the flexible cost advantage are shown with dotted lines by α, β, and χ, if we assume that particular BOS savings are (or are not) realized. For example, α indicates the scenario where there are only material cost savings from avoiding racking but no savings in installation labor or transport costs.

This allows us to understand the impact of lower BOS cost for flexible substrates at different efficiencies. For example, assuming that it is not feasible to achieve the same efficiency for a flexible module as on the rigid counterpart, we can examine Figure 3B. Here, a rigid 25% module and a 20% flexible module would need to last around 16 years, showing that a 5% lower efficiency is compensated for by the lower BOS cost. Alternatively, if we expect that it is only possible to save the cost of the racking (marked with α), but efficiency parity can be achieved, Figure 3D shows that a 20% flexible module would still offer a LT advantage of nearly 5 years, compared with the rigid module.

In the following, we will extend our analysis toward silicon-perovskite and perovskite-perovskite tandem architectures, as they are often considered an attractive pathway for perovskite commercialization.[60]

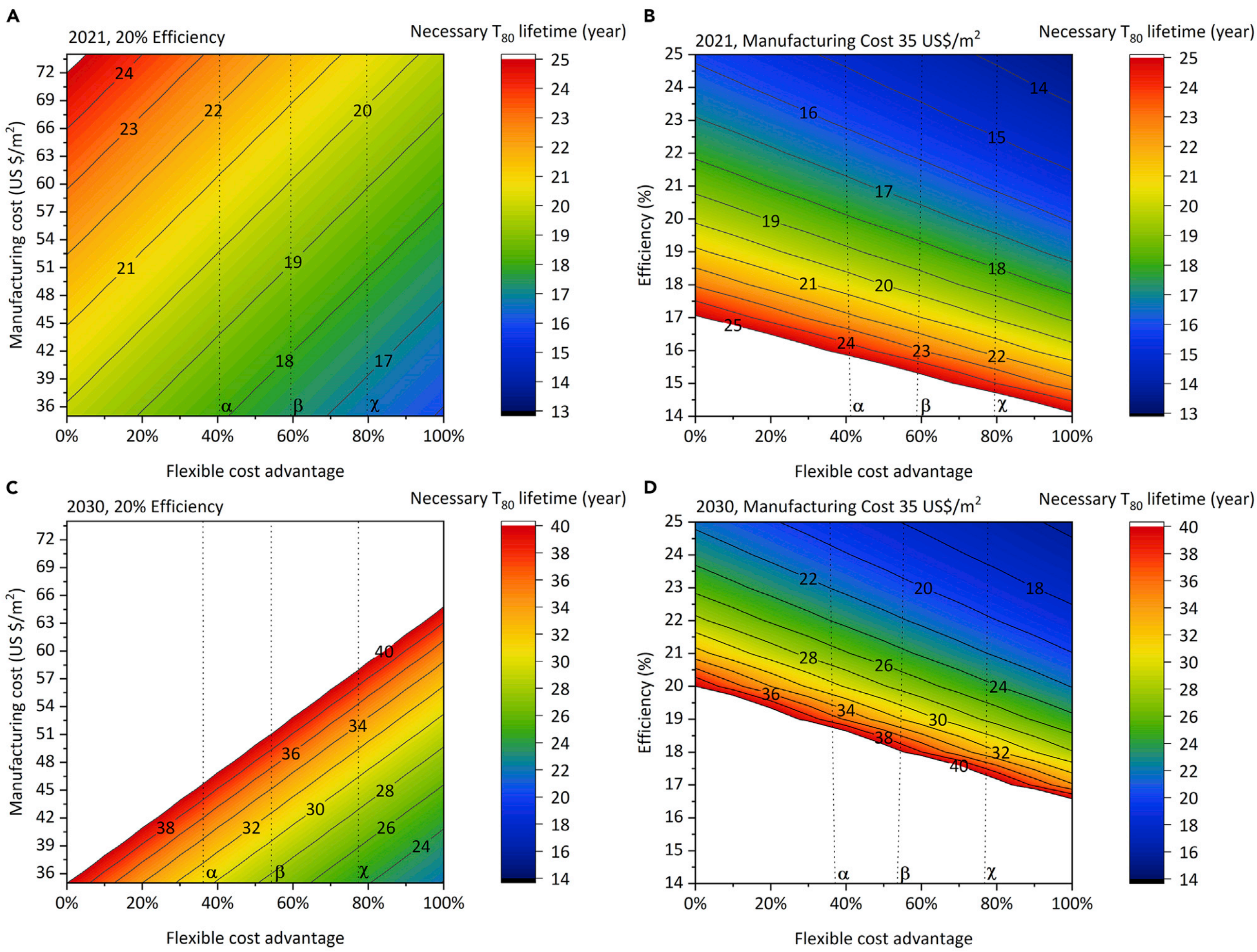

Figure 3. Impact of different flexible cost advantages on the necessary parameters for cost parity

(A–D) 0% and 100% flexible cost advantage represent the rigid and flexible scenario calculations shown in Figure 2A. 2021 and 2030 scenarios for the (A and C) manufacturing and (B and D) efficiency vs. the flexible cost advantage, respectively. Note the different color scales between the 2021 and 2030 scenarios. The manufacturing vs. flexible cost advantage plots are calculated for a 20% efficient module. The efficiency vs. flexible cost advantage plots are calculated for the lower bound manufacturing cost of flexible substrates of 35 US$/m^2. The dotted lines indicate different parts of the flexible cost advantage: (α) no cost for the racking, (β) adds a drop in supply chain costs (e.g., lower transport and storage costs), and (χ) adds a drop of one quarter in the installation labor. The 100% flexible advantage scenario is no cost for the racking, a drop in supply chain costs, and half the installation labor.

Analysis of silicon-perovskite and all-perovskite tandem solar cells

One of the main strengths of PSCs is their ability to change the band gap by changing the I/Br halide or the Pb/Sn metal ratio.[61,62] This makes them especially attractive for tandem solar cells, which increases the potential efficiency above 30% PCE.[63] Just recently, a silicon-perovskite tandem with 32.5%[64] and an all-perovskite tandem with 28%[65] were reported. That offers another technological advantage over single-junction silicon solar cells. We therefore extend our previous analysis of the 2021 and 2030 scenarios toward tandems to assess this advantage. However, we also want to highlight that Sn-based perovskites—necessary for all-perovskite tandems—face additional stability challenges, due to the oxidation of Sn^{2+}, that might make it more challenging to reach the outlined LTs.[66,67]

To account for higher efficiency potential, Figures 1C and 1D (rigid) and Figures 2B and 2D (flexible) can be extended to consider higher efficiency values and higher module manufacturing cost. This is shown in Figures S1–S4, with the efficiency range increased to 30% and the manufacturing cost range increased beyond 300 US$/m^2. In these adapted figures, as an alternate way to view the data, the x axis is changed from the T80 LT to the module efficiency, and the required LT for equivalent LCOE to c-Si is shown with a color scale.

We then use these figures to compare alternate rigid and flexible single-junction and tandem configurations and the required efficiency and LT targets for each. Since there are multiple cost estimates for each module type, for this analysis, we consider a set of cost data based on recent publications, the lowest published cost estimates of each module type.[37,55,68,69] We note that to the best of our knowledge, there is no published estimated manufacturing cost for flexible all-perovskite tandem solar modules. Therefore, we use the difference between perovskite-perovskite tandem and perovskite cells and added this to the flexible perovskite cost.[55,69] These cost estimates are shown in Figures S1–S4 and are used to determine the efficiency and LT requirements for each module configuration in Figures 4A and 4B.

Next, we discuss the results from Figures 4A and 4B. At equivalent T80 LT, a rigid all-perovskite tandem needs around 1% to 1.5% higher PCE, compared with its rigid single-junction counterpart, whereas a flexible all-perovskite tandem needs to show a 1.2% to 1.8% higher PCE than its single-junction flexible counterpart. These higher efficiency requirements seem feasible considering the analysis of Hörantner et al. that indicates practically achievable efficiencies of even above 30% PCE.[63] Reaching this efficiency would mean that the flexible all-perovskite tandems offer the lowest necessary LTs of around 12 and 14 years in 2021 and 2030, respectively. We show how different manufacturing cost would impact these results in Figures S1–S4.

In literature, the silicon-perovskite tandem configuration is seen as an attractive pathway to commercialization.[70] Kamaraki et al.[71] argue that they can easily be integrated into an existing silicon production line. However, since the silicon bottom cell is generally expected to be more expensive than a perovskite bottom cell, it would need a longer LT here to reach the same cost of electricity (assuming equivalent PCE).

To the best of our knowledge, it has not been outlined how a potential lower BOS cost from flexible modules would impact the cost of electricity. We have outlined the advantage and how it would affect the resulting necessary LTs for flexible PSCs. We believe it is essential to know how much of an advantage a flexible substrate would offer, compared with a rigid substrate, before embarking on the pathway to developing commercial products. Here, we outlined which technology seems to be the most promising from the standpoint of necessary LTs. We discuss the current status of flexible PSCs in terms of efficiency and stability further in Note S3. We also outline potential further technological advantages of PSCs in Note S4. Finally, we especially highlight that, so far, there are few reports measuring the operational stability of flexible PSCs in realistic conditions e.g., with an encapsulation suitable for a flexible solar cell in air.

Conclusion

Energy systems producing minimal CO_2 during their production and LT are needed for a sustainable energy future. PSCs offer to lower this for PVs even further. However, their current low LTs are the biggest hindrance toward commercialization. We outlined how those necessary LTs can be further lowered for residential PV by considering flexible substrates.

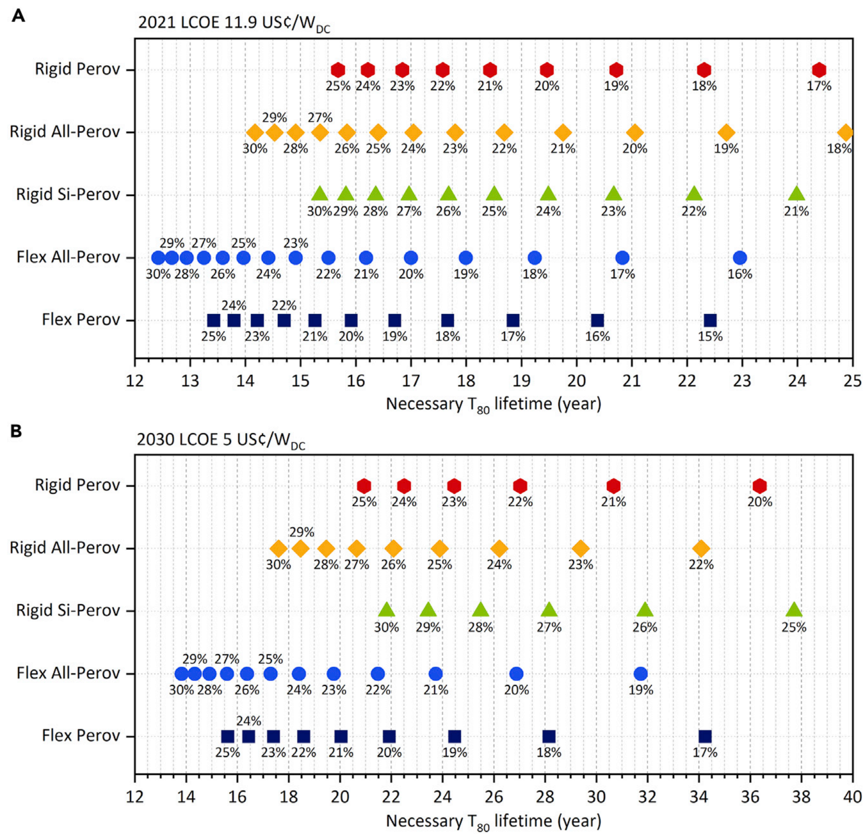

Figure 4. Direct comparison of different perovskite PV architectures and their necessary lifetimes for a given efficiency to achieve the same cost as c-Si

(A) Comparison of the results for various architectures in the 2021 scenario for residential PV (LCOE of 11.9 US¢/W$_{DC}$) for a selection of estimated manufacturing costs. 31.7 US\$/m^2 for a rigid perovskite solar module,[37] 80 US\$/m^2 for silicon-perovskite tandem,[68] 45.2 US\$/m^2 for a rigid all-perovskite tandem,[69] 35 US\$/m^2 for a flexible perovskite module,[55] and 47.5 US\$/m^2 for a flexible all-perovskite tandem module.[55,69] The respective indices are the module PCEs. All analysis plots are shown in Figures S1–S4.

(B) Comparison for the 2030 scenario (LCOE of 5 US¢/W$_{DC}$).

Based on what is necessary to reach the same price of electricity as silicon solar cells, we calculated what LTs, efficiencies, and manufacturing cost perovskite solar modules would need to reach. We assessed two scenarios for residential PV: the 2021 scenario (11.9 US¢/W$_{DC}$) based on the 2021 NREL PV benchmark report[31] and a 2030 scenario (5 US¢/W$_{DC}$) based on the SunShot 2030 target costs. For 2021, rigid PSCs would need efficiencies of 17% PCE or higher and LTs of 16–24 years could achieve the same electricity price as silicon. For 2030, rigid PSCs would need to reach at least 20% PCE and 21–36 years of LT. With the current status of reported LTs for PSCs (typically in the range of months to 1 year), we believe this will be challenging to achieve. However, it is still necessary for rigid modules to be mounted using expensive racking. Considering flexible substrates could reduce BOS costs. This would lower the burden on the necessary module LTs, efficiencies, and manufacturing costs. In 2021, flexible PSCs would need to achieve lower target efficiencies of 15% PCE and LTs of 13–22 years. In 2030, flexible PSCs have to be at least 17% efficient and last for 16–34 years. This offers a wider corridor of possible combinations in which perovskites could reach the same electricity cost as silicon.

We extended our analysis toward tandem solar cells and found that the necessary LT could be further lowered with a flexible all-perovskite tandem.

So far, flexible PSCs are lacking in efficiency, compared with rigid ones, and there is not much operational stability data. Most reports focus on bending tests, which are important, but they should not replace the need for thorough stability testing under operational conditions. While it can be expected that the efficiency gap between rigid and flexible devices can be closed or at least lowered, it is not a given that a flexible encapsulation can be as robust as the glass-to-glass encapsulation used for rigid devices. Rigorous stability testing simulating operational conditions, e.g., with encapsulation in air, will be necessary to assess if flexible PSCs are ready for the market. However, early reports from companies seem to be promising.

If these challenges especially regarding operational stability can be addressed, flexible or lightweight PSCs offer to lower the cost of residential PV further by easing the installation on-site. Moreover, further opportunities may arise from previously unsuitable sites, given the lower weight and easier installation of the flexible devices, such as lightweight roofs and walls. Also, integration into roof tiles seems easier than for rigid ones. We believe that overal our cost analysis highlights a highly attractive way to commercialize perovskites with flexible or light substrates.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.joule.2022.12.012.

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AUTHOR CONTRIBUTIONS

Conceptualization, P.H., M.P., and M.S.; methodology, P.H. and M.P.; investigation, P.H., M.P., S.C., N.L.C., and M.S.; writing – original draft, P.H.; writing – review & editing, P.H., N.L.C., and M.S.; funding acquisition, M.S.; resources, P.H. and M.S.; visualization P.H.; supervision, M.S.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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