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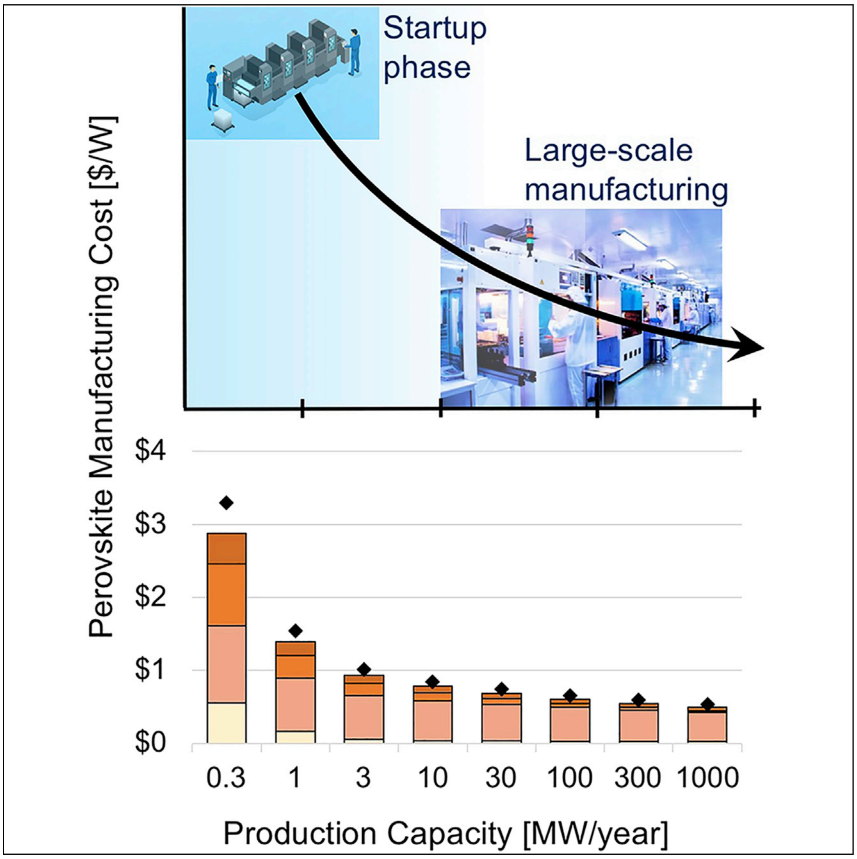
Economically Sustainable Growth of Perovskite Photovoltaics Manufacturing



The significant capex of photovoltaics manufacturing has made it difficult for new cell and module technologies to enter the solar power market. We show how technoeconomic modeling of cleantech products versus scale can be an important tool in assisting the commercialization of new energy technologies that often struggle to leave the lab with our analyses focusing on potential routes to market for perovskite photovoltaics.

Ian Mathews, Sarah Sofia, Erica Ma, ..., Sin Cheng Siah, Tonio Buonassisi, Ian Marius Peters

imathews@mit.edu

HIGHLIGHTS

Flexible perovskite modules manufactured for 3.3–0.53 $/W in a 0.3–1,000 MW/yr range

Minimum investment of >$1 billion required for profitability when selling at $0.40/W

Existing silicon manufacturer would grow at a faster rate by co-investing in tandems

Technoeconomic modeling of energy technology versus scale to establish route to market

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Economically Sustainable Growth of Perovskite Photovoltaics Manufacturing

Ian Mathews,[1,4,*] Sarah Sofia,[1] Erica Ma,[2] Joel Jean,[3] Hannu S. Laine,[1] Sin Cheng Siah,[1] Tonio Buonassisi,[1] and Ian Marius Peters[1]

SUMMARY

The significant capital expense of photovoltaics manufacturing has made it difficult for new cell and module technologies to enter the market. We present two technoeconomic models that analyze the sustainable growth of perovskite manufacturing for an R2R single-junction technology and a perovskite-silicon tandem module, focusing on the impacts of economies of scale and average selling price on profitability. We establish a cost range of \$3.30/W to \$0.53/W for flexible modules manufactured in factory sizes ranging from 0.3 MW/year to 1 GW/year. In addition, we model the cost to manufacture a tandem module consisting of a single-junction perovskite cell stacked in 4-terminal configuration onto a silicon cell and show how an existing manufacturer can grow at a faster rate by co-investing in tandems. Our analyses highlight potential routes to market for perovskite photovoltaics and the possibility to sustainably grow a photovoltaics manufacturing company even in markets with higher labor rates.

Context & Scale

We show how technoeconomic modeling of cleantech products versus scale can be an important tool in assisting a more rapid uptake of new energy technologies that often struggle to leave the lab. Our analyses highlight potential routes to market for perovskite photovoltaics and the possibility to sustainably grow a photovoltaics manufacturing company even in markets with higher labor rates. More generally, although technoeconomic modeling has proven to be a useful tool for assessing cleantech industries as they are and the long-term potential of new technologies once they reach scale—we encourage other cost modelers to quantify the impact of economies of scale during manufacturing growth to help in the search for viable and sustainable market on-ramps for their technologies.

INTRODUCTION

To mitigate the impacts of climate change, tens of terawatts of solar power must be deployed over the next decades.[1] With 500 GW of photovoltaics (PVs) installed globally to date, silicon photovoltaics remains the incumbent technology with its cost now at 0.25 \$/W and declining capex.[1] The rapid growth of installed photovoltaics continues to surprise even the experts, but for solar power to become the primary source of electricity globally, a large-scale and truly global manufacturing base is required that will not be able to rely on one region or technology. In light of this, perovskite photovoltaics offer a strong alternative photovoltaic technology with the potential for extremely low manufacturing costs through solution processing that could compete with silicon. However, new cleantech technologies have historically struggled to scale-up,[2,3] with their capital intensity resulting in long timelines for commercialization that are incompatible with traditional venture capital funding models,[4] that lead to lower success rates for cleantech startups compared to software and medical ventures.[5] In this paper, we use bottom-up cost modeling to explore economically sustainable strategies for one new cleantech innovation, solution-processed perovskite photovoltaics, to scale-up and enter the mature solar power market. Our goal is to help illuminate one or more pathways that could enable this groundbreaking technology to successfully scale-up and navigate the journey from lab bench to market.[6–8]

The path to market success is not clear—today's leading PV module manufacturers drive down prices by producing modules at the GW/year scale, largely in regions

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with low labor costs. As a result, it is difficult for new entrants to compete with established PV manufacturers on price. Thus many seek to commercialize their products in growing alternative markets such as the Internet of Things (IoT) applications, building-integrated photovoltaics (BIPV), telecommunications, vehicle integrated, and others where higher margins are possible.[9–12] Here, we show that such strategies can enable a sustainable route to scale, allowing perovskite manufacturing companies to leverage higher prices in alternative PV markets to overcome the capital intensity barrier for new cleantech products, and reach significant scale before entering the wider solar power market.[13] It is worth noting the growth of First Solar, where a number of years after its initial founding, the company scaled its manufacturing capacity from 6.5 MW/year to over 1 GW/year between 2004–2009 at a compound annual growth rate of 180%.[14,15] As outlined in Figure S1 in the Supplemental Information, this contributed to module manufacturing costs dropping from $2.94/W to $0.83/W, i.e., 22% per year, over the same period—although the influence of wider market conditions at the time cannot be ignored, where significant investments in photovoltaics manufacturing led to module price declines across the industry.

As an alternative growth strategy, it may be possible to take advantage of the large silicon manufacturing base by manufacturing perovskite-silicon tandems presenting a distinct opportunity to leverage the sizable market share of silicon, while significantly boosting device efficiency relative to single-junction modules. The fabrication of perovskite-silicon tandems is well established with efficiencies exceeding 25% in the laboratory.[16,17] However, there are challenges to making a cost-effective perovskite-silicon tandem. Generally, sub-cells that have similar single-junction efficiencies and areal cell costs are most likely to produce a cost-effective tandem device.[18] This is a difficult balance for perovskite-silicon tandems since they feature two technologies with very different manufacturing approaches, with perovskite deposition being a solution-based process that potentially combines very low-cost materials with low capex, while silicon solar cells are potentially more capex-intensive to manufacture. We expand our analysis and explore the financial viability of perovskite-silicon solar cells, modeling the potential for perovskite-silicon tandems to lower the cost of PV and to enable faster manufacturing growth for existing manufacturers.

In the rest of this paper, we model how the module manufacturing cost for a perovskite startup decreases with increasing scale and the subsequent sustainable growth rates that can be achieved. We begin in Perovskite Manufacturing Costs versus Scale by developing a bottom-up technoeconomic model of solution-processed flexible perovskite photovoltaic modules and calculate the minimum sustainable price versus manufacturing scale. In Sustainable Growth of Perovskite Manufacturing, we use this cost model to analyze the potential growth rates for perovskite photovoltaic module manufacturing companies as a function of their size and the average price they obtain for their products, to understand how perovskites can gain traction and significant market share. We continue by estimating the capital investment levels required to establish profitable companies of different scales in various markets. In Sustainable Growth of Silicon-Perovskite Tandem Manufacturing, we model the cost to manufacture a tandem perovskite module consisting of a single-junction perovskite cell on glass stacked in 4-terminal configuration onto a passivated emitter and rear cell (PERC) silicon bottom cell using existing cost models available in the literature and analyze the prospective growth of an existing silicon manufacturing company that invests in tandems.

[1]Massachusetts Institute of Technology, Cambridge, MA 02139, USA
[2]Wellesley College, Wellesley, MA 02481, USA
[3]Swift Solar Inc., San Carlos, CA 94070, USA
[4]Lead Contact
*Correspondence: imathews@mit.edu
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Perovskite Manufacturing Costs versus Scale

While recent technoeconomic analyses established minimum sustainable prices for perovskite photovoltaic modules on glass of \$0.30/W–\$0.70/W, these studies limited their analysis to larger factory sizes of 100 MW and greater.[19,20] To address the question of the cost of small-scale manufacturing, we develop a cost model for a perovskite PV module factory versus scale, building on work by Chang et al.,[21] and assess the module manufacturing costs considering economies of scale. We evaluate the cost of producing perovskite modules in the U.S. using a single roll-to-roll printing line with a maximum production capacity of 3.6 MW/year, up to 1 GW/year and 278 printing lines, considering the realistic impact of scale on costs including material prices versus purchase volume, US labor costs, and facility costs. In this study, we focus on the manufacture of flexible single-junction modules as opposed to modules on glass or perovskite-on-silicon[22,23] or perovskite-perovskite tandems[24,25] given the lower expected influence of capex in solution processing as described in Figure S2 the Supplemental Information.

We develop a bottom-up cost model for a roll-to-roll solution processing perovskite photovoltaic module manufacturing facility, which is summarized here and outlined in detail in the Experimental Procedures section. Our modeled cell structure is based on structure D in[21] which is a combination of lower-cost active layer materials with a low-cost metallization scheme. We note that many other perovskite solar cell structures could be considered close to commercialization, but given our goal of evaluating the impact of capex on sustainable growth, we focus on this cell structure and use its comprehensive cost model description and leave it to others to assess their particular technology in a similar way. The manufacturing cost model includes the materials consumed and tool depreciation following a step-by-step process required to produce the module structure outlined in Figure 1A. The seven steps involved comprise: the purchase of indium-tin-oxide-coated polyethylene terephthalate (PET-ITO), laser pattering of the ITO layer, slot-die coating of (1) the perovskite absorber, (2) ZnO nanoparticles, and (3) the hole-conducting PEDOT:PSS layer, screen-printing of a Ag back contact, encapsulation in barrier foils using a laminator, cutting and contacting, and a final module testing step. Additional costs considered include the cost to purchase the buildings and facilities, labor for tool operations, tool maintenance including capital and labor expenses, facility and tool electricity usage, R&D expenses and selling, and general and administrative expenses (SG&A). Specific values are provided in the Experimental Procedures section.

To model the impact of increasing production scale, for all materials used, quotes for material costs versus purchasing volume were obtained. The purchase volumes used were the amount (kg, L, or m^2) of materials required for 3 months of manufacturing, i.e., it was assumed materials adequate for 3 months of manufacturing were purchased at once and stored on site before use. The economies of scale for purchasing the manufacturing tools of a 10% reduction in price for every doubling of purchase volume was assumed.[21,26] Our model considers manufacturing lines that are in use 24 h a day for 365 days per year and the minimum annual production for one printing tool is 3.6 MW/year. When modeling annual productions of less than this value, we use the capex value to purchase one printing line and the required facility size. Other costs we adjust for scale include the portion of revenues spent on R&D, which we assume reduce from 20% for small-scale manufacturing of 1 MW/year to 5% once a scale of 1 GW/year is reached. The SG&A is assumed to be reduced from 12% to 8% across the same range—we note the current percentage of revenues spent on R&D by today's top 12 PV companies is ~2%, and SG&A is ~11%.[27] The factory is

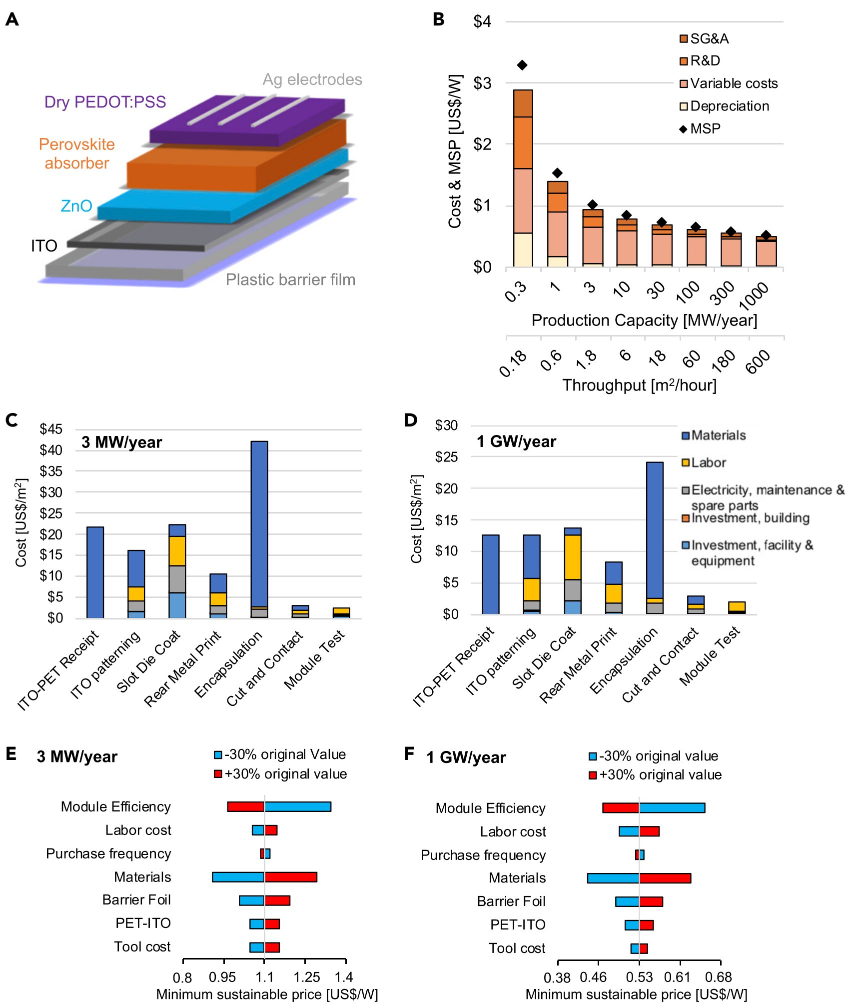

Figure 1. Flexible Perovskite Manufacturing Costs versus Scale

(A) Outline of the cell structure modeled. (B) The production cost and MSP for R2R perovskite modules versus scale.

(C) Breakdown of the costs per manufacturing step at 3 MW/year production capacity.

(D) Breakdown of the costs per manufacturing step at 1 GW/year production capacity.

(E) Sensitivity of the module MSP to various parameters at 3 MW/year production capacity.

(F) Sensitivity of the module MSP to various parameters at 1 GW/year production capacity.

assumed to suffer from 5% downtime for maintenance and repairs, while a final module efficiency of 18% and a PV industry standard weighted average cost of capital (WACC) of 14% was used to calculate the cost and minimum sustainable price (MSP) in $/W across all scales. We use a module efficiency of 18% to reflect the potential for this technology rather than the current state of the art where flexible single-junction perovskites have demonstrated efficiencies of over 19% but scaling such high efficiencies to module level is yet to be demonstrated.[28]

As summarized in Figure 1B, the modeled MSP for perovskite solar panels manufactured on plastic film range from $3.30/W for a small-scale annual production of 0.3 MW/year to $0.53/W for an annual production capacity of 1 GW/year (values are provided in Table S1 in Supplemental Information). At small scales of less than 3 MW/year, when one printing tool is purchased but underutilized, there is a

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relatively even distribution of cost contributions from capex, variable costs, R&D, and SG&A. As the scale of production increases to 10 MW/year, the cost of manufacturing decreases to $0.80/W and less, with material costs contributing most. The results show that for solution-processed photovoltaics, a relatively low manufacturing cost can be achieved at relatively small scales owing to the low capex contribution of R2R tools to the final module cost.

Given that at all scales, the variable or material costs make up the largest portion of the final module costs, it is worth considering these in more detail. Figures 1C and 1D show the step-by-step cost contributions from two ends of the manufacturing scale, 3 MW/year (1 printing line is utilized 80% of the year) and 1 GW/year. In both cases, a significant contribution to cost is the purchase of the three plastic foils used in the module manufacturing including the initial PET-ITO substrate and 2 layers of encapsulating barrier foil.

It should be noted than $0.53/W is not low enough to sell into the residential or utility-scale photovoltaic markets at a profit given recent module prices have been in a $0.20–$0.40/W range,[29] however, given our model is limited to one cell type and its associated cost of materials, we expect some advances in technology will reduce the projected costs for R2R perovskites before they reach GW-scale production. Our model outlines that research into these "advances" should focus on driving down the cost of materials including TCO-coated substrates, metal contact deposition, and barrier foils in combination with intrinsic perovskite materials stability. This section makes clear the importance of a combined optimization of the technical, manufacturing, and economic aspects of perovskite photovoltaics to enable scale-up.

Given the number of assumptions involved in an analysis like this, we conduct a sensitivity analysis on MSP for some key assumptions and costs and present the results in Figures 1E and 1F. Figure 1E presents results from a sensitivity analysis for a 3 MW/year annual production and Figure 1F presents the results from a sensitivity analysis for a 1 GW/year annual production considering a 30% decrease or increase in module efficiency, labor cost, and materials purchasing frequency with the price of each material scaled accordingly when they are purchased in larger or smaller volumes, prices for all materials used, prices for barrier foils only, prices for PET-ITO films only, and the costs to purchase all required tools. It is clear that, given the higher portion of the manufacturing costs attributed to variable costs as compared to capex depreciation, changes in the price of materials have a greater impact on module MSP than increases in tool costs. A 30% decrease in module efficiency also increases MSP significantly given that 30% less Watts are now produced per unit cost, re-emphasizing the importance of increasing the efficiency of currently demonstrated perovskite solar cells manufactured by high-throughput methods. In terms of reducing the MSP of this technology, it is clear that any technology that can reduce the cost of materials can have a significant impact with a 30% reduction in the cost of all materials reducing the MSP from $1.02/W to $0.83/W for the 3 MW/year production capacity and $0.534/W to $0.44/W for the 1 GW/year production capacity.

Sustainable Growth of Perovskite Manufacturing

Having established a range of costs for perovskite manufacturing versus scale, in this section, we calculate the sustainable growth rate of a perovskite PV company versus its scale and the average selling price (ASP) of its products. The growth rate calculation follows the method in[30] and outlined in the Experimental Procedures, where the portion of operating profits not used to pay for R&D and SG&A is assumed to be

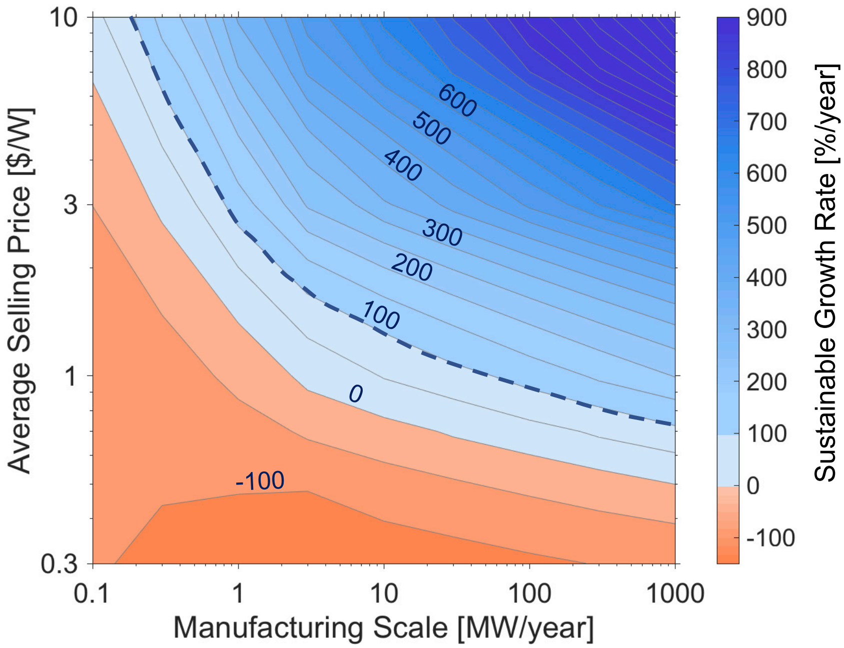

Figure 2. Potential Growth Rates for Flexible Perovskite Manufacturing

The annual growth rate of a perovskite photovoltaic manufacturing plant versus manufacturing scale and average selling price—the dashed blue line divides the regions above and below 100% year-on-year growth.

spent on purchasing new capex equipment and facilities to expand manufacturing capacity. We note this is one particular definition of sustainable growth where a company or industry relies on its level of profitability rather than the injection of additional equity to grow organically. Long-term expansion can also be sustained by raising capital through equity or debt or under certain market conditions, but we do not discuss these here.

For this analysis, average selling prices for photovoltaic products that range from 0.3–10 $/W were considered, representing the possible values across a wide range of PV markets from utility-scale systems to unmanned aerial vehicles.[9] It is assumed the additional benefits of perovskites beyond efficiency and cost such as flexibility and integrated manufacturing would enable the technology to compete with silicon and other incumbent technologies in high-value markets and obtain the ASPs described. Figure 2 outlines the sustainable growth rate of a perovskite manufacturing facility versus its scale and the average price products are sold for, assuming growth would not be constrained by demand (the size of each high-value market and the possible problem that these market sectors are not sufficiently large to absorb the output of the factory is an important consideration we discuss in the next section). For production capacities of under 1 MW/year where manufacturing costs are typically >1 $/W, larger average selling prices are required for profitability and growth—it should be noted, however, that these prices are available for products that can be adapted to niche PV markets for drones and IoT nodes. For the R2R process, we have modeled, the minimum sustainable price drops below 1 $/W as the factory scales up, reaching a minimum of 0.53 $/W at a scale of 1 GW/year. The growth rates for medium-sized companies of 10–100 MW/year are positive for average selling prices of >1 $/W. Growth rates of 100% and greater are readily achievable for average selling prices obtainable in alternative PV markets and

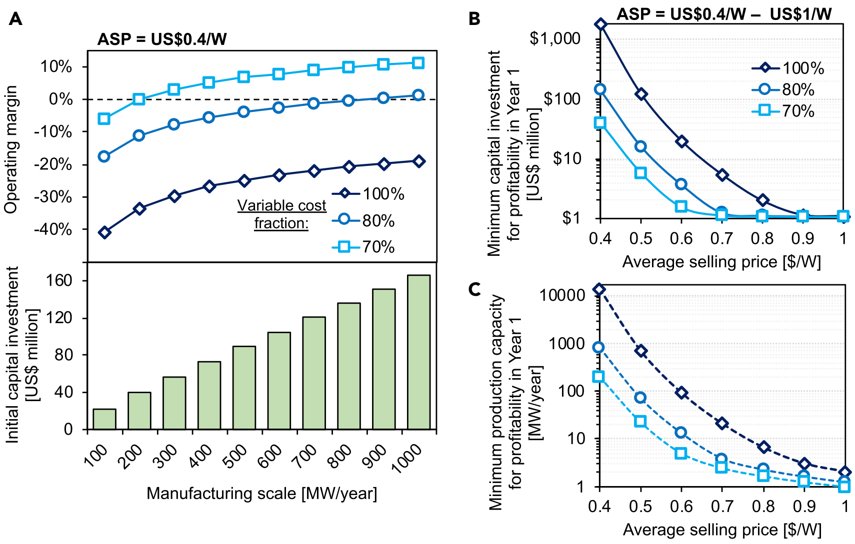

Figure 3. The Influence of Selling Price and Investment Size

(A) The operating margin versus initial capital investment for a roll-to-roll perovskite manufacturing facility and an average selling price of $0.40/W—considering multiple variable cost fractions as described in Sustainable Growth of Perovskite Manufacturing—and the break-even point in terms of (B) initial capital investment and (C) of production capacity required to establish a profitable roll-to-roll perovskite manufacturing facility over a range of higher selling prices representative of higher-margin niche markets.

show that perovskite manufacturing can be compatible with venture capital funds who typically look for growth opportunities with return on investments equivalent to ~100% year-on-year growth. We use growth in production capacity as a comparison for different R2R perovskite manufacturing facilities and highlight this 100% growth benchmark as a dashed line in Figure 2. We see that for perovskite manufacturers to reach >100% growth requires significantly different levels of ASP, as a function of production capacity. A small-scale (1–10 MW/year) factory must secure a minimum 1.5–3 $/W ASP for their products, while larger factories must sell for at least 1 $/W and the largest modeled (1 GW/year) must sell for 0.72 $/W. This value is around double the typical price currently obtained for photovoltaic modules in the grid-connected residential, commercial, and utility PV markets.

Capital-Intense Investment—Solar Power Market

Combining our bottom-up cost model versus manufacturing scale, and sustainable growth calculator, allows us to compare the different funding options for a perovskite photovoltaics manufacturing startup. As a first step, we analyze the level of equity investment required to build a company that sustainably sells mass market solar modules at $0.40/W. First, as we have shown that our particular module structure has an MSP of $0.53/W when manufactured at 1 GW/year, we also model a second case where, given the impact higher cost items such as the ITO-PET film and barrier foils have on the final module cost, we assume that new technologies will be sought to enable the cost of materials to reduce to 80% and 70% of their current costs—a requirement for the cost of roll-to-roll manufacturing of perovskite solar modules to be less than $0.4/W at all scales we investigate. With these additional cases for variable costs, we calculate the level of capital investment to establish a manufacturing facility versus its profitability or operating margin, as outlined in Figure 3A (note we exclude the initial startup R&D expenses used to develop the technology in the lab). Given current material costs, our results show that operating margins much less than 0% can be expected for a manufacturing facility with a capacity of 100 MW/year up to 1 GW/year. Considering cases where variable costs are lower, the operating margin of a 1 GW/year factory with variable material costs of 80% of current values is ~1% and requires an upfront capital investment of $165 million. If variable costs reduce to 70% of current values, the minimum scale required to operate with a positive operating margin is 202 MW/year, setting the minimum investment in capital items (tools, equipment, facilities, and buildings) to create a roll-to-roll perovskite manufacturing company that sells into the mass solar market of $40 million. This is a reasonable value for an existing large photovoltaics manufacturing company to raise and add a perovskite manufacturing line to their existing capacity, although consideration must be given to "bankability," i.e., the high risk of an unproven technology, especially one that faces a technology risk (stability) and a regulatory risk (lead content), could either dissuade investors or mandate a very large cost of capital. Given the additional costs a new entrant would also incur outside of the capital expense itself, this is a large sum to raise to establish a new company and manufacturing line, and entrepreneurs are likely better off starting a perovskite manufacturing company that targets alternative markets for the first years of operation.

Capitally Lighter Investment—Alternative PV Markets

In this section, we investigate what manufacturing scale is required to be profitable in year 1 if average selling prices higher than those available in the mass solar power market can be obtained. In Table 1, we outline the size of these alternative markets in 2018 to provide an idea of the limits of these markets to support photovoltaic manufacturing, and note the building-integrated PV market is currently a large opportunity while all others are expected to grow over the coming years.[31] Figures 3B and 3C shows the minimum scale of factory, and investment required, for a company to be profitable versus ASP—showing the scale that leads to an operating margin of 0% considering current material costs and the lower variable cost cases. For the current material costs, the minimum production capacity for profitability versus ASP ranges from 2.1 MW/year for an ASP of $1/W to >10 GW/year for an ASP of $0.4/W—the initial capital investment to establish manufacturing facilities ranges from $1.1 million to over $1 billion, respectively. These figures highlight why thin-film solar companies have struggled to establish themselves when set up to focus exclusively on selling into the mass solar power market, outlining the large sums required to establish a profitable PV manufacturing facility despite the use, in our case, of a low capex technology.

We also consider the cases where variable costs are reduced to 80% and 70% of their current values. Both cases require investments just over $1 million to enable profitability for selling prices over $0.70/W, while at the lowest $0.40/W price considered, there is a dramatic order-of-magnitude reduction in the initial investment required of $140 million and $40 million, respectively. It is clear that small decreases in material costs can significantly increase the product profitability, enabling much smaller sales volumes to cover the capex depreciation cost each year. The analysis outlines the holistic approach required to co-optimize the scientific, engineering, and economic parameters of a technology for successful commercialization.

Sustainable Growth of Silicon-Perovskite Tandem Manufacturing

Currently the PV industry produces approximately 100 GW of modules per year[32] while it is common for a new manufacturing facility to produce ~100 MW/year. In this section, we look to understand the attractiveness to current silicon

Table 1. Alternative PV Market Sizes in 2018

Market	Market Size (MW)
BIPV	700
Microscale	62.5
Portable-Charging	4
Vehicle Integrated	10
Aerospace	5

Data from Reese et al.[9]

manufacturers of investing in new perovskite-silicon tandem manufacturing lines. We aim to understand whether perovskite-silicon tandems could potentially provide a pathway to capacity expansion for these firms, by improving growth rates through the high efficiencies enabled by tandem architecture and the utilization of perovskite, a low cost, low capex material, while simultaneously avoiding the small-scale limitations of a new technology by leveraging their existing silicon know-how. Specifically, we explore the potential of growing 4T perovskite-silicon tandem capacity out of an existing manufacturing facility by utilizing the existing PERC silicon manufacturing lines as well as the revenue from silicon modules to grow the perovskite manufacturing capacity.

While high-efficiency monocrystalline silicon cells have been used to demonstrate high tandem efficiencies, the use of high-efficiency, high-cost bottom cells may not be the path to cost-effective tandems as this further exacerbates the cost discrepancy between the low-cost perovskite top cell and the more expensive, more capex-intensive silicon bottom cell. Furthermore, the bottom cell typically produces less than half of the total energy generated by a tandem, so the bottom cell quality has less impact on the overall tandem efficiency than the top cell. This argues for low-cost, lower-efficiency silicon, such as multi-crystalline silicon wafers, employing low-cost crystallization techniques such as ingot casting and kerfless or direct-wafering techniques, for use in tandem applications and that is what we investigate here. By leveraging the existing silicon cell and module facilities, tandem capacity can be added by only building the perovskite top cell manufacturing line, a significantly cheaper investment than building an entire tandem manufacturing line. The 4T configuration is ideal for this type of expansion since the top cell is fabricated entirely independently from the bottom cell, allowing the manufacturing lines to operate in parallel. Furthermore, the perovskite top cell is assumed to be fabricated in superstrate configuration onto the front glass, and then integrated as the front glass would be in a typical silicon module manufacturing process, allowing the silicon module fabrication process to remain almost entirely unchanged.

Therefore, we model the cost to manufacture a tandem perovskite module consisting of a single-junction perovskite cell on glass stacked in 4-terminal configuration onto a PERC silicon bottom cell using existing models in the literature for the top cell,[20] silicon cell,[27] 4T stacking[33] as summarized in.[34] The perovskite cell is assumed to be fabricated in superstrate configuration, as described in Song et al.,[20] onto low-iron, tempered, FTO-coated, anti-reflection front glass. For the semi-transparent top cell, the back contact is assumed to be replaced with indium-doped tin oxide (ITO), as ITO deposition is a commercialized process and is commonly used as a contact for perovskite cells in the literature.[16,22] To fabricate a 4T tandem, the manufacturing process is assumed to be the same as for a standard silicon module,[27] except the front glass typically added during lamination is now front glass with a

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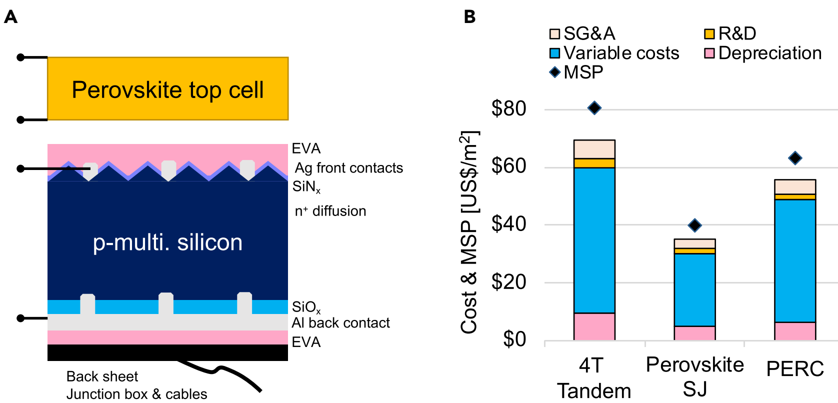

Figure 4. Tandem Cost Modeling

(A) Schematic outline of the modeled 4-terminal perovskite-silicon tandem module and (B) the manufacturing cost and MSP of the individual sub-cells and the tandem module.

single-junction perovskite cell deposited onto it. The two sub-cells are then laminated into a single module and separately wired into the junction box. For this tandem analysis, we do not model how the price of materials or other costs change with scale as all production capacities modeled are >100 MW/year and can be consider large-scale. Using the published manufacturing step costs and process flows, the manufacturing costs per area are 31.63 USD/m^2 and 50.64 USD/m^2 for the single-junction perovskite and silicon modules, respectively, while the 4-terminal tandem module is 63.07 USD/m^2. Given assumed single-junction module efficiencies of 18% and the tandem efficiency of 25.8%,[34] the MSP of the technologies is calculated and presented in Figure 4B with the tandem module value being 63.33 USD/m^2.

The growth model in the previous section was based on self-funded growth. This section instead looks at the potential of coupling growth by using revenue from the sales of existing manufacturing capacity to invest in new technology, manufacturing capacity of perovskite top cells that can be integrated with the existing silicon manufacturing capacity. This models the scenario of a large, existing silicon manufacturing plant investing in perovskite-silicon 4T tandems by building top cell manufacturing capacity to combine with a portion of the silicon production as the bottom cell, thus producing both 4T tandems and silicon single-junctions as the tandem capacity is expanded. For clarity, this coupled growth model is referred to as co-dependent growth, as distinguished from the original, self-funded model assuming independent growth.

Using our cost models and an assumed tandem cell efficiency of 25.8%, the manufacturing capacity expansion for a hypothetical manufacturing plant is modeled over 15 years using the methods described in the Experimental Procedures using both an independent and co-dependent growth model as shown in Figure 5. For all scenarios, the facility is assumed to be a 2 GW silicon factory starting with a 100 MW perovskite-silicon 4T tandem capacity and uses a constant 1:1 debt-to-equity ratio. All co-dependent growth assumes f_{si} = 0.5. Two module pricing schemes are considered: fixed margin and efficiency-adjusted margin. For all modules in the fixed-margin scenario, a 15% margin is used,[27] where the margin is defined as the percent of the selling price that exceeds the manufacturing cost (materials, labor, depreciation, utilities, and operating expenses). For the efficiency-adjusted margin scenario, all single-junction modules use a 15% margin while the tandem module margin is increased to reflect the added value of

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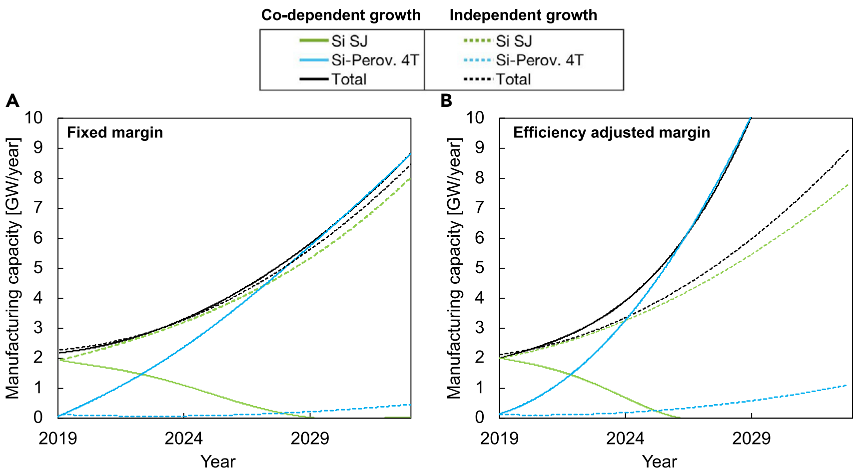

Figure 5. Tandem Manufacturing Growth Rates

The predicted growth in manufacturing capacity of a PERC silicon manufacturing facility that co-invests in perovskite-silicon tandem manufacturing using a (A) fixed margin or (B) efficiency-adjusted margin approach.

high-efficiency. The tandem module selling price is set such that the dollar-per-watt price is equal to the dollar-per-watt price of the silicon single-junction. This results in a margin of 24%.

For independent growth, Figure 5A shows that for a fixed 15% margin, investing in tandems slightly helps the overall capacity expansion, resulting in a 7.4% increase in capacity after 15 years relative to the baseline silicon. For co-dependent growth, tandem manufacturing expands at a faster rate than silicon initially as almost half of the available capital for growth is split between the technologies, with silicon eventually reducing to zero as the profits used to maintain silicon manufacturing are not adequate, and tandems become the dominant technology. Given the same margins and similar capex contribution of the technologies, however, this does not lead to a greater expansion.

Figure 5B outlines the results when we use an efficiency-adjusted margin to equate the tandem dollar-per-watt price to the single-junction price. In this case, the greater margin results in the tandem manufacturing capacity expanding at a greater rate than the fixed-margin case, reaching 1 GW/year within 15 years. The fastest growth, however, is achieved for a co-dependent model where the amount of capital available for expansion is a combination of profits from silicon modules and the now more profitable tandem modules. This co-dependent and efficiency-adjusted margin approach results in the largest predicted expansion of the total manufacturing capacity over the 15 years.

While co-investing in a low-cost tandem under an adjusted-margin scenario is a better method for expanding tandem manufacturing more quickly, the choice to set the fraction of investment spending on silicon, f_{si}, at 0.5 is a somewhat arbitrary choice. The optimum investment fraction is entirely dependent on the specific technology costs and efficiencies. More work could be done on the optimization of the year-to-year investment scheme to maximize overall growth, as this is a rather complex problem. Simply optimizing to maximize capacity for each subsequent year does not generally give the best overall growth as this method tends to heavily favor investing in silicon in the early years.

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Table 2. Price and Economies of Scale for the Materials Used in Our Photovoltaic Module Manufacturing Model

Materials	Unit	Usage (Unit/m^2)	Max. Quote Obtained by Volume (Unit)	Price per Unit at Max. Volume ($/Unit)	Min. Quote Obtained by Volume (Unit)	Price per Unit at Min. Volume ($/Unit)	% Price Decrease per 10X Volume Increase	10 MW/Year Price ($/Unit)	100 MW/Year Price ($/Unit)	Source
ITO-coated PET	m^2	1	10,000	$20	100	$31	19.7%	19.5	15.6	Mianyang Prochema Commercial Co., Ltd.[36]
ITO patterning materials	m^2	1	13,000	$8.20	120	$10	10%	8.2	7.5	Chang et al.;[21] Azzopardi et al.[37]
ZnO nanoparticles	g	0.055	1,000	$0.175	25	$1.56	74.5%	0.19	0.11	US Research Nanomaterials Inc.[38]
FAI	g	0.14	5,000	$1.338	5	$8.41	45.8%	1.7	0.95	GreatCell Solar [39]
PEDOT:PSS	mL	4.6	20,000	$0.228	250	$0.65	42.4%	0.18	0.1	Sigma-Aldrich[40]
IPA	mL	11	200,000	$0.003	1,000	$0.06	72.7%	0.003	0.002	Sigma-Aldrich [40]
PbI_2	g	0.95	1,300,000	$0.25	50	$1.08	17.9%	0.37	0.31	Chang et al.[21]
DMF	g	2.9	18,000	$0.047	100	$0.565	67%	0.03	0.01	Sigma-Aldrich [40]
MAI	g	0.14	1,000	$0.85	5	$3.38	45.25%	0.72	0.39	GreatCell Solar [39]
Paste	g	6	200,000	$0.66	5,000	$0.79	10.6%	0.69	0.62	Manufacturer communication
Barrier foils	m^2	2	5,000,000	$10	5,000	$20	20.6%	16.9	13.4	Manufacturer communication
Double-sided tape	g	3	1,000	$0.75	70	$1.83	53.8%	0.22	0.1	Machui et al.[41]
Costs Assumed to Not Vary with Scale										
Contact buttons	pair	13.1	–	–	–	–	–	$0.10	$0.10	Chang et al.[21]
Screens	use	13	–	–	–	–	–	$0.01	$0.01	Chang et al.[21]
Nitrogen	m^3	8.3	–	–	–	–	–	$0.033	$0.033	Chang et al.[21]

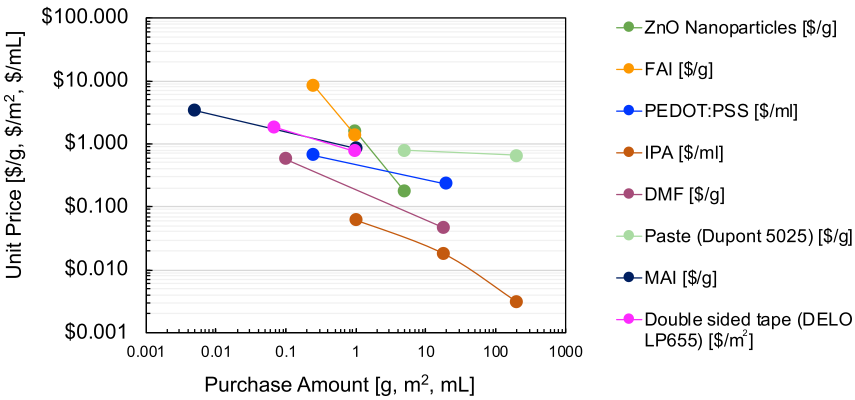

Figure 6. Plot of the Maximum and Minimum Unit Prices versus Order Volume for the Materials Used in Our Mode

Conclusions

We presented two technoeconomic models that analyzed the sustainable growth of perovskite manufacturing for an R2R single-junction technology and a perovskite-silicon tandem module. A cost model for a roll-to-roll perovskite photovoltaic manufacturing facility versus scale was presented and used to establish a cost range of $3.30/W to $0.53/W for flexible modules manufactured in factory sizes ranging from 0.3 MW/year to 1 GW/year for a baseline scenario. We used these numbers to show the economically sustainable annual growth rates for a company selling photovoltaic modules in different markets, obtaining a wide range of possible values, depending on selling price and scale of manufacturing. Selling into the mainstream utility market requires a prohibitively large upfront investment for a technology with reliability and regulatory (Pb toxicity) risks; we determined minimum levels of investment over $1 billion to establish a profitable manufacturing facility selling into the mass solar power market with an average selling price of $0.40/W. This large initial investment and barrier to market entry for perovskites can be reduced in two ways: (1) the initial investment reduces to $40 million for a 1 GW/year scale, if lower-cost materials, specifically barrier foils and TCO-coated plastics, can be found, highlighting the role of disruptive innovations in related industries, or (2) selling into niche markets for $1/W or greater, representative of IoT, BIPV, and vehicle-integrated markets, reduces the initial capital investment required to ~$1 million.

In addition, we modeled the cost to manufacture a tandem perovskite module consisting of a single-junction perovskite cell on glass stacked in 4-terminal configuration onto a PERC silicon bottom cell and showed how an existing silicon manufacturer can expand at a faster rate by co-investing in tandems. These conclusions assume that perovskite manufacturing technology can be scaled-up successfully to obtain high efficiency with low materials costs, and that issues of degradation and toxicity do not significantly impact commercialization.

Our analyses highlight potential routes to market for perovskite photovoltaics, and the possibility to sustainably grow a photovoltaics manufacturing company even in markets with higher labor rates. They also reinforce the need to co-optimize the scientific, engineering, and economic parameters of a technology to significantly improve the likelihood of its mass market adoption. Overall, we presented a technoeconomic methodology that can be used to accelerate the commercialization and scale-up of perovskite photovoltaics, finding that the achievable growth rates are compatible with venture capital funding given certain conditions. We show how technoeconomic

Table 3. Facility Costs for Our Models that We Assume Do Not Vary with Scale

Category	Item	Units	Assumed Value
Location	factory location	–	USA
Module performance	efficiency	–	18%
Utilities	electricity cost	\$/kWh	0.07
	electricity for services	kWh / tool kWh	1
Building related	building cost	\$/m^2	1,000
	floor ratio	total / footprint	3
	building and facility maintenance rate	% of capex per year	4
Labor	operator cost	\$/h	20
	indirect labor cost ratio	–	0.1
	maintenance technician cost	\$/h	25
Depreciation	facility and equipment	years	7
	building		25

modeling of cleantech products versus scale can be an important tool in assisting a more rapid uptake of new energy technologies that often struggle to leave the lab. We encourage other technologists to adjust their technoeconomic models to consider scale and search for viable and sustainable market on-ramps for their technologies. Technoeconomic modeling has proven to be a useful tool for assessing cleantech industries as they are and the long-term potential of new technologies once they reach scale. Perhaps their greatest capability can be to help technologies cross the "valley-of-death," and navigate the path from invention to impact.

EXPERIMENTAL PROCEDURES

Our bottom-up cost modeling approach combines our previous work[33,35] with perovskite cost models from other authors.[21] Our primary contribution to this field is to adapt these existing models to assess manufacturing costs for low-volume production—an excel spreadsheet version of this model is provided in the Supplemental Information ("R2R Cost Model.xlsm"). For this, we assume our perovskite solar panels will be manufactured by roll-to-roll printing on plastic films as in[21] with a PCE of 18%.

Materials Costs versus Scale

The cell architecture we use is sequence D in Chang et al.[21] and includes ITO-coated PET, a printed ZnO nanoparticle electron contact, two-step deposition of FAI + PbI_2 ink and MAI ink, a printed "dry PEDOT:PSS" hole contact, and a final encapsulation barrier. We established material costs through multiple sources including Sigma Aldrich, Alibaba, and individual suppliers. Table 2; Figure 6 show the costs of materials used in our model, with order-of-magnitude price increases observed for many materials (e.g., MAI, IPA, and Ag paste) when reducing annual production volumes from 1 GW/year to 1 MW/year. We assume the factory owner purchases all materials required for 3 months of manufacturing and stores the materials on site. The maximum costs and % price decline with volume are given in Table 2 with the full range for each material plotted in Figure 6.

$$\textit{Price change}\ (\%) = 1 - 10^{\frac{\log\left(\frac{P_1}{P_2}\right)}{\log\left(\frac{V_1}{V_2}\right)}}$$

Table 4. Model Assumptions for Small-Scale and Large-Scale R&D and SG&A Spending

Cost Assumptions	1 MW/Year	1 GW/Year
R&D [% of Module Cost]	20%	5%
Sales general and admin. [% of module cost]	12%	8%

$$Price\left(\frac{\$}{unit}\right) = P_1 * (1 - Price\ change)^{\log\left(\frac{V_n}{V_1}\right)}$$

Facility Costs

We establish a cost of manufacturing at small scale by assuming some costs (depreciation periods, labor rates…) do not vary with scale. Table 3 summarizes the costs we assume do not vary significantly with scale and we keep constant in our models while Table 4 summarizes the costs we assume do vary with scale.

Tools and Steps

Krebs et al. previously provided numbers for the cost of purchasing the tools required to build an R2R organic PV manufacturing line, including guidance on the price versus scale. The total reported costs were USD 678,000 for the ITO patterning tool, slot-die coater, screen printer, laminator, equipment for sheeting and pinning, and a module tester—all R2R tools—with a production capacity of 3.6 MW/year.[42] We adjust the cost of the tools for inflation for a new total tool cost of 797,000 USD with the individual tools outlined in Table 5. We assume the combined factory yield and tool uptime is 95%.

Perovskite-Silicon Tandem Sustainable Growth Model

For the purpose of this work, only the sustainable growth rate is considered, which is defined as the maximum growth rate that can be achieved while maintaining a constant debt-to-equity ratio of 1. Consistently growing faster than the sustainable growth rate results in a company continuously deepening their state of debt. The model for sustainable growth rate is based on the model presented in Powell et al.,[35] based on the models in Higgins,[43] Fonseka et al.,[44] and Ashta.[45] The sustainable growth rate (SGR) is defined as the ratio of net income to capex scaled by the debt-to-equity ratio, thus limiting the annual expenditure on capacity expansion to match the annual income, plus the allowed new debt:

$$SGR = \frac{I_{net}}{capex}\ x\ \frac{1}{debt\ to\ equity\ ratio}$$

where I_{net} is the net income [$\$/W_{aCap}$], defined as the remaining proceeds after deducting all associated costs, per watt annual capacity (W_{aCap}):

$$I_{net} = m_{op}ASP - interest - taxes$$

where m_{op} is the fractional operating margin and ASP is the selling price of the module ($/W). The operating margin is defined as:

$$m_{op} = \frac{P - COGS - OPEX - depreciation}{ASP}$$

where COGS is the total variable costs of fabrication (materials, labor, etc.) and OPEX are the operating expenses including R&D and SG&A.

The growth model has previously been used to model self-funded growth. Our analysis also looks at the potential of coupling growth by using revenue from the sales of existing manufacturing capacity to invest in new technology. This models the

Table 5. Equipment Input Cost Assumptions for a Single Production Tool

Equipment	Tool Cost (USD, in thousands)	Facility Cost (% of Tool Cost)	Floor Space (m^2)	Spare Parts (% capex/year)	Electricity Usage (kW)
ITO patterning tool	118	30	15	10	15
Slot die coater	465	30	12	10	25
Screen printer	79	30	10	10	15
Laminator	33	5	10	4	25
Sheet and pin	34	2	5	4	10
Module tester	68	3	5	4	2

scenario of a large, existing silicon manufacturing plant investing in perovskite-silicon 4T tandems by building top cell manufacturing capacity to combine with a portion of the silicon production as the bottom cell, thus producing both 4T tandems and silicon single-junctions as the tandem capacity is expanded. By leveraging the existing silicon cell and module facilities, tandem capacity can be added by only building the perovskite top cell manufacturing line, a significantly cheaper investment than building an entire tandem manufacturing line. The 4T configuration is ideal for this type of expansion since the top cell is fabricated entirely independently from the bottom cell, allowing the manufacturing lines to operate in parallel. Furthermore, the perovskite top cell is assumed to be fabricated in superstrate configuration onto the front glass, allowing the module formation process used for the silicon modules to remain almost entirely unchanged as the top cell is integrated into the module like the front glass for a silicon module. To model the co-dependent growth, a fixed fraction of the net income, f_{si}, is set to be re-invested into silicon manufacturing, while 1 - f_{si} is invested into expanding the perovskite top cell manufacturing. Given, f_{si}, the sustainable growth rate for the silicon capacity and for the perovskite top cell capacity is found. The silicon growth is given by:

$$SGR_{Si} = f_{si}\frac{\left(I_{Si}\left(\frac{A_{Si}}{A_{Si}+A_{4T}}\right)+I_{4T}\left(\frac{A_{4T}\left(\frac{\eta_{4T}}{\eta_{Si}}\right)}{A_{Si}+A_{4T}}\right)\right)}{capex_{Si}} x \frac{1}{debt\ to\ equity\ ratio}$$

where η_{Si} and η_{4T} are the silicon single-junction and 4T tandem module efficiencies, respectively, and A_{Si} and A_{4T} are the annual areal capacity for silicon single-junction and 4T tandems, respectively. Note that the total silicon areal capacity is the sum of these two areas since a portion of the silicon capacity is employed as the tandem bottom cell, and that this is the growth rate for the total silicon capacity, including the portion used in the 4T tandems. As this equation shows, net income from the sale of both the silicon SJ and 4T tandem modules.

Similarly, the co-dependent sustainable growth rate for the 4T tandem is given by:

$$SGR_{4T} = (1-f_{si})\frac{\left(I_{Si}\left(\frac{\eta_{Si}A_{Si}}{\eta_{4T}A_{4T}}\right)+I_{4T}\right)}{capex_{\Delta 4T}} x \frac{1}{debt\ to\ equity\ ratio}$$

$Capex_{\Delta 4T}$ refers to the capex associated with only building the additional facilities required to convert a silicon SJ production line to a tandem production, i.e., the perovskite top cell production through the back contact and interconnection step when it would be integrated into a module. In both equations given above, the net income, I, for the different devices are scaled to account for difference in the production capacity providing that income and the capacity of the technology being scaled-up.

From these two co-dependent growth rates, the equivalent sustainable growth rate for the manufacturer overall is:

$$SGR_{total} = \left(\frac{A_{4T}\Delta\eta_{4T}}{A_{4T}\Delta\eta_{4T} + A_{Si}\eta_{Si}}\right)SGR_{4T} + \left(\frac{A_{Si}\eta_{Si}}{A_{4T}\Delta\eta_{4T} + A_{Si}\eta_{Si}}\right)SGR_{Si}$$

Using this growth model, the capacity expansion for a few scenarios of perovskite-silicon 4T tandems are modeled over 15 years. In these calculations, once the top cell areal capacity has grown to equal the total silicon area such that all module production is converted to 4T tandem modules and no silicon single-junction module production remains, the growth reverts to the independent growth model but for the 4T tandem parameters.

SUPPLEMENTAL INFORMATION

Supplemental Information can be found online at https://doi.org/10.1016/j.joule.2020.01.006.

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AUTHOR CONTRIBUTIONS

Conceptualization, I.M., S.S., T.B., and I.M.P.; Methodology, S.C.-S., S.S., I.M., and J.J.; Investigation, E.M., H.L., I.M., S.S., and S.C.-S.; Writing – Original Draft, I.M. and J.J.; Writing – Review & Editing, I.M., T.B., and I.M.P.; Supervision, T.B. and I.M.P.

DECLARATION OF INTERESTS

J.J. is the co-founder and CEO of Swift Solar, a US company developing perovskite photovoltaics.

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