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The capital intensity of photovoltaics manufacturing: barrier to scale and opportunity for innovation†

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Using a bottom-up cost model, we assess the impact of initial factory capital expenditure (capex) on photovoltaic (PV) module minimum sustainable price (MSP) and industry-wide trends. We find capex to have two important impacts on PV manufacturing. First, capex strongly influences the per-unit MSP of a c-Si module: we calculate that the capex-related elements sum to 22% of MSP for an integrated wafer, cell, and module manufacturer. This fraction provides a significant opportunity to reduce MSP toward the U.S. DOE SunShot module price target through capex innovation. Second, a combination of high capex and low margins leads to a poor financial rate of return, which limits the growth rate of PV module manufacturing capacity. We quantify the capex of Czochralski-based crystalline silicon (c-Si) PV manufacturing, summing to 0.68 \$/W_{aCap} (\$ per annual production capacity in watts, \$year/W) from wafer to module and 1.01 \$/W_{aCap} from polysilicon to module. At a sustainable operating margin determined by the MSP methodology for our bottom-up scenario, we calculate the sustainable growth rate of PV manufacturing capacity to be ~19% annually – below the historical trend of ~50% annually. We conclude with a discussion of innovation opportunities to reduce the capex of PV manufacturing through both incremental and disruptive process innovation with c-Si, platform innovations, and financial approaches.

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Broader context

For solar photovoltaic (PV) technologies, “cost per watt” and “minimum sustainable price” (MSP, in units of \$/W) are ubiquitous techno-economic evaluation metrics. Herein, an MIT-NREL collaboration team highlights the importance of an additional techno-economic metric: “capex,” an abbreviation of “capital expenditure,” or the upfront factory cost. The team quantifies end-to-end capex for single-crystalline silicon (c-Si) technology, from polycrystalline feedstock manufacturing to module assembly. The combination of high capex and low margins in the c-Si PV industry is found to contribute to many industry trends that cannot be explained by \$/W alone, notably: (i) high capex and low margins limit the maximum sustainable growth rate for manufacturing capacity to <20%, limiting how fast the industry can scale up without external support. (ii) Large capital investments for new manufacturing facilities present a barrier to innovation and promotes “technology lock.” (iii) High capex increases the margins required to satisfy investors (minimum sustainable price), reducing manufacturers’ profitability. Regarding solutions, the authors quantify the benefits of capex reduction to MSP and maximum sustainable growth rate of manufacturing capacity, highlight a range of potential technology and business solutions to promote capex reduction, and highlight successful examples of capex reduction in other industries.

1. Introduction and motivation for capex

The traditional metric of “dollars per rated watt” (henceforth abbreviated \$/W) is often used to evaluate photovoltaic (PV)

technologies and economics: the difference between per-watt “cost” and “price” dictates a PV manufacturer’s profitability, and the per-watt system price affects a consumer’s levelized cost of electricity. Competing PV technologies are compared on the basis of their per-watt manufacturing costs.^{1,2} Consequently, the \$/W metric features prominently in experience learning curves,^{3,4} technology roadmaps,^{2,5,6} and cost analyses.^{1,2,7,8}

Herein, we describe the crystalline silicon (c-Si) PV industry through the optic of a variable that influences both sustainable module prices and sustainable manufacturing capacity growth rates: “capital expenditure” (abbreviated “capex”), which is the upfront cost to build a factory and fill it with equipment. First, we examine how capex affects per-unit module prices (\$/W),

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linking with our previous analyses in ref. 2 and 8. Calculations indicate that halving capex could reduce module minimum sustainable prices by 0.13 \$/W (15% relative), providing significant progress toward achieving the U.S. DOE SunShot module price target.⁹ Second, we examine how capex helps to explain certain industry-wide trends related to scale and innovation including: a company's sustainable growth rate, the interdependence of rate of return on margin and capex, and barriers faced by companies seeking to scale up innovative technologies into commercial production. Third, we highlight innovation opportunities to reduce capex including: incremental process innovation, disruptive process innovation, platform innovations, and financial approaches.

2. Capex definition and calculation methodology

In the first part of this section, we provide PV-relevant definitions of capex and other financial terms for readers with a technical background. In the second part, we summarize the bottom-up cost modeling methodology employed in this study. Scientists and technologists with little prior accounting or financial experience are encouraged to peruse the "capex tutorial" in the ESI.†

2.1 PV-relevant definitions of financial terms used in this study

The upfront financial investment normalized by annual manufacturing capacity in watts ($\$/W_{\text{aCap}}$, with units of $\$/(\text{W}/\text{year})$ which simplifies to $\$/\text{year}/\text{W}$) is defined in eqn (1) as the initial investment. This is a sum of capex and the money that a

manufacturer must set aside to run its operations (working capital).^{8,10,11}

$$\text{Initial investment} \left(\frac{\$}{W_{\text{aCap}}} \right) = \text{capital expenditure} \left(\text{capex}, \frac{\$}{W_{\text{aCap}}} \right) + \text{working capital} \left(\frac{\$}{W_{\text{aCap}}} \right) \quad (1)$$

For consistency with best accounting practices,¹⁰ we define capital expenditure (capex) as the sum of physical property, plant, and equipment, as well as the engineering, procurement, and construction expenses of the manufacturing facility itself. Capex does not change with utilization rate (*i.e.*, the ratio of actual production to nameplate capacity). Thus, capex is a fixed cost. Working capital (WC) also contributes to the initial investment by the manufacturer, and is money that must be set aside to fund ongoing operations, such as buying materials and paying workers, when revenues are delayed relative to costs. Capex is the dominant contribution to the initial investment in the plant, accounting for approximately 80% of the total when a three-month duration of working capital is assumed. We note however that we have taken a conservative approach in our working capital calculation, and that a delay in revenues relative to costs does not always occur.

As an example, we examine the cost structure of a c-Si PV module, shown in Fig. 1. We define variable cost as the incremental costs to manufacture a PV module in $\$/\text{W}$, and is shown in blue in Fig. 1(a). Variable cost includes: materials, labor, electricity, and maintenance. Unlike capex, variable cost scales with production volume. Note that we approximate maintenance costs as a fixed percentage per year of the value

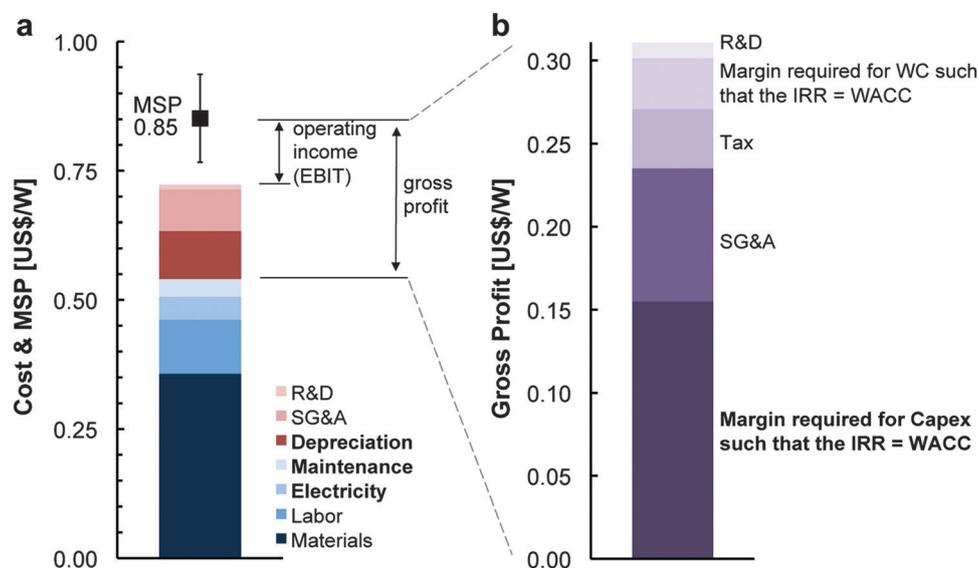


Fig. 1 (a) Breakdown of U.S. standard monocrystalline silicon cost components and minimum sustainable price that factor into gross profit and operating income (earnings before interest and taxes, EBIT). (b) Breakdown of gross profit, equal to the MSP minus variable costs. Capex-related items are bolded. The profit required to generate the required return for capex in (b) is approximately double the straight-line depreciation expense in (a) due to the required rate of return on the initial capital investment. If the WACC is increased (from 14% in this example), the disparity between these factors increases.



of the initial capex under the assumption that more expensive tools are more expensive to maintain. Therefore, in our model, maintenance cost does scale with the initial capex even though it is a variable cost.

The operating margin of a company is used to compare the profitability of companies and is equal to operating income divided by revenue. Operating income (earnings before interest and taxes (EBIT), highlighted in Fig. 1(a)), is the difference between selling price and the summation of: variable costs, sales general and administrative expenses (SG&A, overhead expenses of running a business), research & development expenses (R&D), and depreciation expenses. Depreciation expenses are defined as the capex allocated over time to account for the recovery of the funds used on the initial investment in capex. Some countries permit accelerated depreciation cycles in order to reduce tax burdens and encourage fixed-asset investment,¹² but for simplification straight-line depreciation is used to calculate the depreciation expense in Fig. 1(a). However, accelerated depreciation is considered in the detailed calculation of MSP. We will later use operating margin to benchmark PV manufacturers against other industries.

As with any financial investment, a manufacturer must generate sufficient income for their initial investment for it to be beneficial. The company's weighted average cost of capital (WACC) defines the cost of money (in percentage terms) for a company. The internal rate of return (IRR) is the rate of return generated by a series of cash flows, such as an initial cash outflow (eqn (1)) required to construct a manufacturing facility, followed by subsequent cash inflows generated by modules sales. IRR is expressed in percentage terms, like interest on a savings account. The company's goal is to complete projects that have an IRR that is greater than their cost of money (WACC). In this work, we apply a WACC of 14%, representative of a PV company.¹³ The minimum sustainable price (MSP) of a PV module, detailed in ref. 2 and 8, is defined as the minimum selling price (\$/W) at which the rate of return for the manufacturer equals their weighted average cost of capital. The MSP of a c-Si PV module is indicated in Fig. 1(a) by the black square. The required gross profit of a manufacturer is dependent on the MSP calculation, and is expanded in Fig. 1(b). Operating expenses, including SG&A and R&D, taxes, and the profit required to generate the required return on the initial capex and working capital investment consume a portion of the gross profit.

2.2 Model description: calculation of capex and minimum sustainable price

Using the general financial parameters introduced above, we calculate capex and MSP with the bottom-up cost model described in ref. 8 with updated inputs reflecting second half of 2014 (2H-2014) market conditions and technology. A version of this cost model is found in the ESI† and can be downloaded from.¹⁴ We model a U.S.-based greenfield c-Si PV factory that is vertically integrated from ingots to modules, as detailed in a previous study.⁸ For capex, we extend the model to include

polysilicon production.¹³ “Standard” c-Si technology is considered, whereby solar-grade polysilicon chunk is purchased at a cost of 23 \$/kg.¹³ Czochralski-grown monocrystalline silicon wafers are then fabricated into diffused-junction cells with full-area aluminum back-surface fields, and then assembled into modules. The module efficiency is 16%, resulting in a 260 W, 60-cell module. We believe our calculation of ingot-to-module manufacturing represents a reasonable scope for calculation that includes critical supply-chain components that are specific to PV. However, we do detail the capex of polysilicon production below and note that some input materials to PV manufacturing could provide scalability challenges in the future if PV demands begin to rapidly eclipse incumbent uses in other sectors. Silver metallization pastes may face this impeding challenge.¹⁵ For wafer, cell, and module assembly equipment, we assume 7 years useful life for equipment and longer for the manufacturing facility. These assumptions are in accordance with the general recommendations provided by industry collaborators and the U.S. tax code, although it is worth noting that equipment may also be rendered obsolete by innovation during their lifetimes.⁵

To estimate capex of the PV industry, we rely on market data from tool vendors and manufacturers. The total capex can be described as the sum of all process steps as in eqn (2),

$$\text{Total capex} = \sum_i \text{capex of process step } i. \quad (2)$$

The capex of a process step includes the cost of the equipment itself and the facility needed to house it.

Capex constitutes a significant fraction of the module MSP (\$/W).‡ As shown in Fig. 1, we calculate a MSP of 0.85 \$/W for a U.S.-based monocrystalline silicon PV factory, including variable costs totaling 0.54 \$/W. The resulting sustainable gross margin is 37% and operating margin is 15%. Fig. 1(a) shows the capex-related contribution of maintenance to the variable cost of the module. Fig. 1(b) shows the gross profit required for an adequate return on the capex investment. The dominant share of the gross profit is required to create an adequate IRR on the initial investment defined in eqn (1). The profit required for capex sums to 0.16 \$/W, while the profit required for working capital is 0.03 \$/W.§ We underscore that the profit required for capex is approximately double the simplified straight-line depreciation expense at the assumed WACC of 14%. This disparity increases with increasing WACC, and *vice versa*. Because of the time value of money in the IRR calculation for the manufacturer, a “full cost” methodology that includes

‡ The bottom-line impact of capex on MSP is expected to flow through to levelized cost of electricity (LCOE) calculations. While LCOE is more relevant to end customers with production incentives, its calculation involves many local technoeconomic assumptions including abundance and spectral quality of solar resource, module operating temperature, system discount rate, and local incentive structures. We do not extend our analysis from MSP to LCOE in this study, because no direct secondary LCOE benefits are expected from capex reduction other than MSP reductions.

§ Less margin is required by working capital because (a) it has a lower initial value than capex, and (b) at the end of a project, the working capital can be reinvested back into the company.



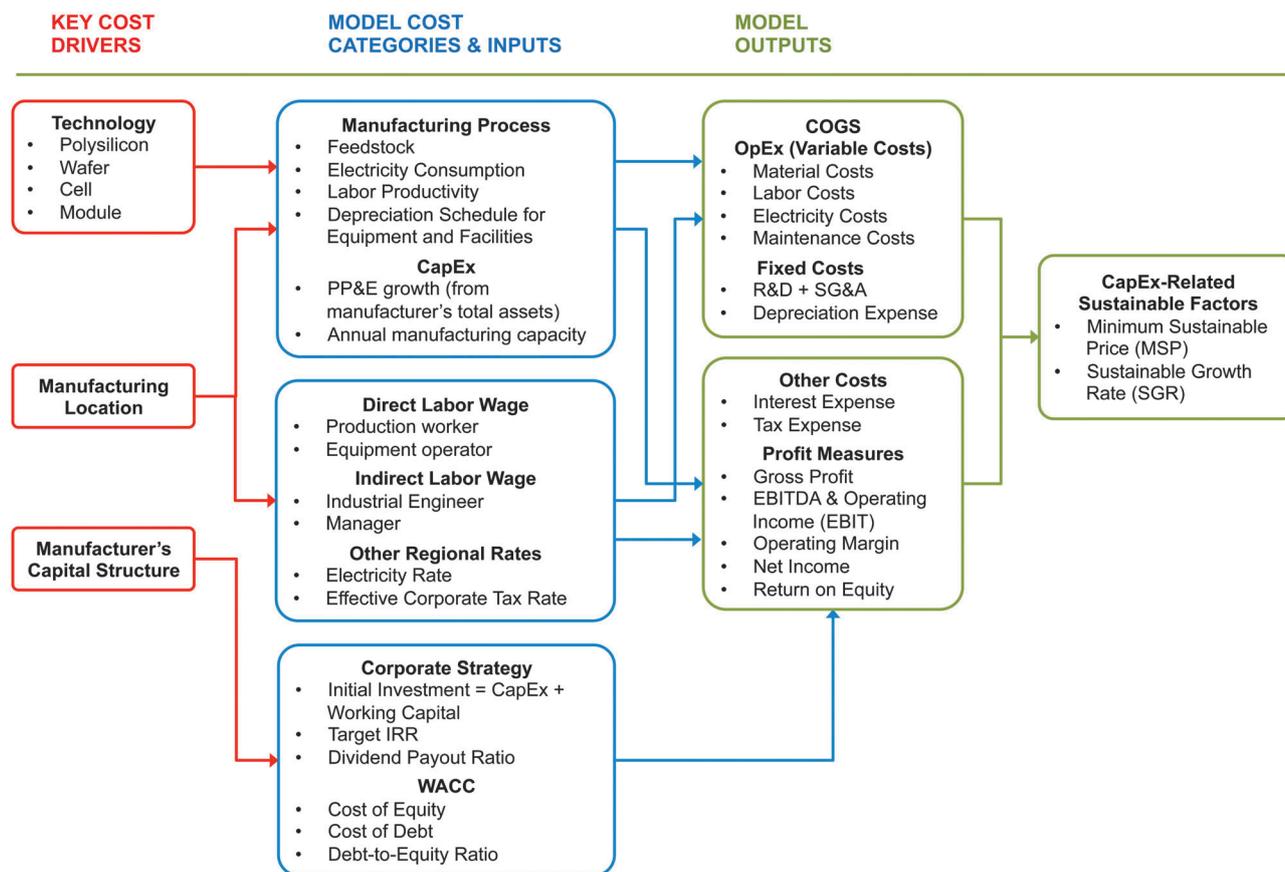


Fig. 2 Schematic representation of inputs and outputs of our model, which is also available in spreadsheet format in ESI.[†]

adding depreciation to variable cost is not sufficient to capture the impact of capex.[¶] In sum, the capex-related factors comprise approximately 22% of the module MSP, or 0.19 \$/W. This includes the margin required for capex (0.16 \$/W) and maintenance costs (0.03 \$/W) in the variable cost category.

In practice, a government agency could subsidize initial capex, or a portion of a capex-related loan. Both of these mechanisms, which reduce the realized capex to the manufacturer,^{16–18} have been observed in recent years. For such a factory, the module MSP (\$/W) will be lower than our calculations, which include the full contribution of capex. However, this “subsidized” scenario does not represent a self-financed growth model for the industry, thus we account for the full value of capex in our calculations.

While our detailed model is available in ESI,[†] a schematic is presented in Fig. 2. This figure summarizes the linkages between the key model elements, including capex, working capital, variable costs, operating income (EBIT) and margin, depreciation, WACC, IRR, and MSP. This figure also shows linkages between terminology used in the following sections,

[¶] Depreciation is only considered in the MSP calculation because it has the effect of reducing taxable income, and thus has a cash flow impact. Depreciation itself is a non-cash expense (*i.e.*, no cash is consumed by depreciation).

including PP&E ratio, operating margin, debt-to-equity ratio, and sustainable growth rate.

3. Snapshot of c-Si PV capex

3.1 Quantifying c-Si PV capex

Based on market data from tool vendors and manufacturers, the capex breakdown of each process step for c-Si PV manufacturing in the 2H-2014 is shown in Fig. 3 for a hypothetical facility based in the United States. The capex for equipment is shown with a bright bar, while the capex for the facility is shown with a dark bar and the two are stacked for each process step. For ingot, wafer, cell and module, facility capex is allocated *via* the floor space required for each process step. For polysilicon, facility capex comprises a much higher proportion of the total capex and includes engineering and construction expenses of the plant itself. For wafer, cell, and module manufacturing, an existing facility could be more easily re-purposed than a polysilicon factory.

In this paragraph, we describe sources of uncertainty and variation in our capex calculations. First, given uncertainty in our market assessment, we can expect at most a $\pm 15\%$ variation in each capex category. Consistent with our expectations, updated capex data obtained in 1H-2015, presented in the ESI,[†] do not represent a significant change from the 2H-2014 values



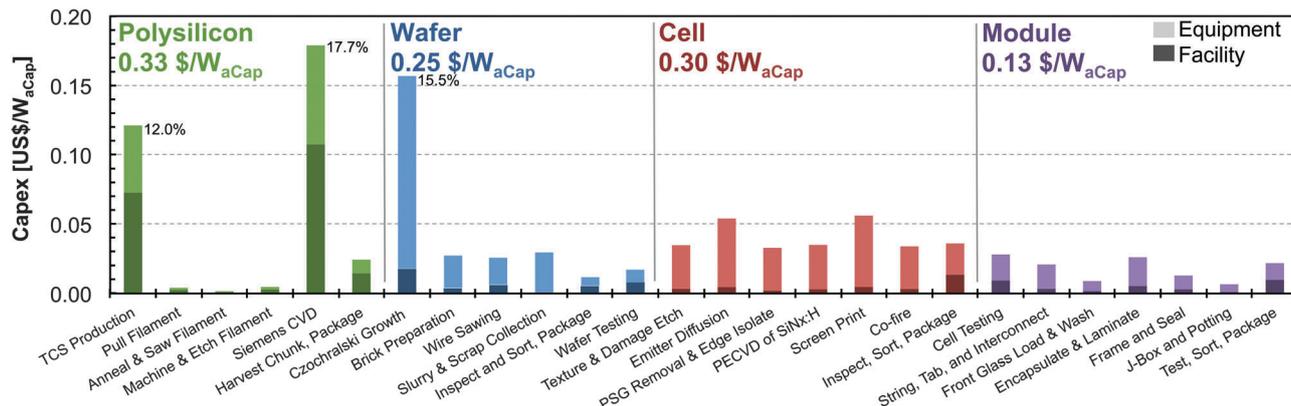


Fig. 3 Initial capex for 2H-2014 c-Si PV manufacturing, normalized by annual production capacity. Each step includes the cost of equipment (light bar) and the facility that houses it (dark bar). Polysilicon and cell production comprise the majority of capex, with the three process steps of Siemens CVD, Czochralski growth, and TCS production comprising 45% of total capex.

shown in Fig. 3, despite significant downward pricing pressure on equipment suppliers because of the recent manufacturing oversupply condition. Second, we note that polysilicon is one of the capex categories most significantly affected by downstream innovation and regional manufacturing. Improvements in both conversion efficiency and silicon usage directly affect the grams of silicon per watt, proportionately reducing the contribution of polysilicon capex when calculated using units of $\$/W_{aCap}$. Additionally, because the physical plant represents a large percentage of polysilicon capex, regional variations in labor, materials, and construction permitting will affect polysilicon capex; in China, polysilicon capex is estimated to be a quarter less than in the United States and Europe. Third, technology variations significantly affect capex, as described in Section 7. For instance, changing from Czochralski single-crystalline silicon to directionally solidified multicrystalline silicon reduces capex by approximately $\$0.1/W_{aCap}$, a $\sim 10\%$ relative reduction, because of the latter's higher throughput.

For a 2 GW_{aCap} factory of competitive scale⁷ using the baseline technology scenario, capex totals approximately US \$2 billion for a complete polysilicon-to-module factory. Alternatively, a total capex of approximately US \$1.4 billion is estimated for a factory that purchases polysilicon, as is modeled in Fig. 1. Fig. 3 shows that equipment for three manufacturing steps in polysilicon and wafering contributes around 45% of the total capex investment: Siemens chemical vapor deposition reactors for forming silicon rods, Czochralski crystal pullers, and trichlorosilane refining. Although no single step of cell manufacturing dominates to a similar degree, several moderately capex-intensive steps contribute 30% of the polysilicon-to-module capex. For the hypothetical manufacturer modeled in Fig. 1, the sum of capex for wafer, cell, and module manufacturing is $\$0.68/W_{aCap}$ and $\$1.01/W_{aCap}$ including polysilicon.

3.2 Comparing capital intensity of industries

We define capital intensity as the total capex required to produce a product divided by its sales price. Financial statements of publicly traded companies in the U.S. report the value

of certain capex components. This includes property, plant, and equipment (denoted "PP&E") over specified reporting periods. It is instructive to compare the book value of PP&E in a previous year to the revenue in a current year; we employ this "PP&E ratio" as a proxy for capital intensity. The one-year delay included in the comparison of PP&E to subsequent revenues assumes that PP&E additions are installed one year ahead of production to be ready for operation. A higher PP&E ratio implies higher capital intensity. This metric is impacted by the entire portfolio of company products, so a diversified company comprising divisions with a low PP&E ratio will lower the company's overall PP&E ratio. For example, a manufacturing company that diversifies downstream into "energy services" will lower its PP&E ratio.

To compare to our bottom-up model, we also define a modified ratio, $PP\&E_0$, which compares the year-zero initial investment required for a manufacturing facility over the first-year sales. Using the MSP of 0.85 $\$/W$, we calculate a $PP\&E_0$ ratio of 0.79 for the modeled manufacturer in Fig. 1 using a capex of 0.68 $\$/W_{aCap}$. The related $PP\&E_0$ ratio would be 1.19 (or higher capital intensity), assuming the same module price, if the company produced its own polysilicon with a total capex of 1.01 $\$/W_{aCap}$.

4. Capex limits the PV industry's sustainable self-financed growth rate

In this section, we quantify the sustainable growth rate (SGR) of a manufacturer. The SGR is of interest for several reasons. For example, one can compare the SGR with aspirational PV growth targets, including those determined by science and policy considerations (e.g., target emission reduction rates for stabilizing atmospheric CO_2 concentrations by increased renewable-energy deployment^{19–21}). One can also compare SGR with the historical cumulative annual growth rates (CAGR) of PV manufacturing capacity equal to approximately 51% over 2003–2013 (from 1.0 GW_{aCap} to 60.5 GW_{aCap}),²² in order to estimate the role of debt and equity in financing recent expansions of PV



manufacturing capacity. We note however, that manufacturing capacity growth does not have to maintain this rapid-growth trajectory to make meaningful contributions to global energy generation.²³ SGR can also be used to estimate the potential for an innovative technology that is able to scale faster than the incumbent.

We use the SGR model of Higgins^{24,25} as formulated by Ashta.²⁶ The SGR is defined as the growth rate achievable without modifying the existing financial policy of the company. This model fixes the amount of returns that are reinvested into company growth (*versus* dividends) and the debt-to-equity ratio. The SGR is dependent on capital intensity (PP&E₀ ratio, defined in Section 2.1) and operating margin (EBIT, defined in Fig. 1). Our model assumes all profits are reinvested into the company (*i.e.*, additional equity value is created from retained earnings without disbursements of dividends), an initial debt-to-equity ratio of 1 : 1, a nominal cost of debt of 4.6%,⁷ seven year straight line depreciation, three months of working capital, and a tax rate of 28%.²⁷ In Fig. 4, we calculate SGR as a function of these variables with (a) a constant debt-to-equity ratio, and (b) no additional debt. A company can grow more quickly with additional debt financing (done sustainably with a constant debt-to-equity ratio) instead of only relying on retained earnings, as may be required in a situation of frozen debt markets. If available, a company can obtain additional debt financing and maintain a constant debt-to-equity ratio when the value of equity in a company increases from earnings that are reinvested into the company.

For the example PP&E₀ ratio of 0.79 and operating margin of 15% for the hypothetical manufacturer in Fig. 1 selling at their MSP, a SGR of 19% results if new debt is available to maintain the debt-to-equity ratio. A SGR of 9% results if no new debt is available. These points are highlighted in Fig. 4 with open boxes. However, due to supply-demand dynamics, the actual pricing of PV modules may differ from the calculated MSP. We note that prices lower than the MSP will simultaneously increase the PP&E₀ ratio and decrease the operating margin,

leading to a further suppressed SGR relative to our calculation. Increasing prices will increase SGR. Because of these dynamics, our analysis is a snapshot, though our calculations of PP&E₀ and operating margin at prices equal to MSP attempt to approximate long-term trends.

This framework can be applied to set a target capital intensity for sustainable growth. To reach a SGR of 51% at a constant operating margin of 15%, a PP&E₀ ratio of 0.19 is needed, which is approximately a 75% decrease. This may be achieved *via* technical or financial innovation (or a combination of the two). We explore the prospect of these innovations in Section 7.

It is apparent from the model that the manufacturing capacity growth spurt in the late 2000's (~60% annual growth from 2009 to 2011²²) required significant capital influx from debt sources for manufacturers to keep up. As in Fig. 4(a), even with high operating margin assumptions (25%) for the modeled manufacturer (PP&E₀ ratio of 0.79 after price is increased to 0.98 \$/W to support a 25% operating margin) and a constant debt-to-equity ratio, SGR is limited to 39% due to high capex. This is lower than the actual CAGR for manufacturing capacity. This situation is not indefinitely sustainable at a target debt-to-equity ratio of 1 : 1, but companies have good reason to attempt to grow quickly. Significant economies of scale are present in PV manufacturing,⁷ and companies are motivated to maintain market share in the growth phase of an industry to prevent facing other barriers to entry in the future. For our modeled manufacturer, this would necessitate a higher debt-to-equity ratio of 5.1 : 1 than the 1 : 1 assumed herein.

Excessive debt-to-equity ratios may prove problematic for companies. The Tradeoff Theory assumes that it is beneficial to leverage debt financing in a firm's capital structure until the optimal capital structure is reached.^{28,29} This is because if a firm has too much debt (namely, too high a debt-to-equity ratio), the cost of equity could increase because equity investors (*i.e.*, stock holders) are risk-averse and are concerned about the long-term solvency of the company. The cost of debt could also

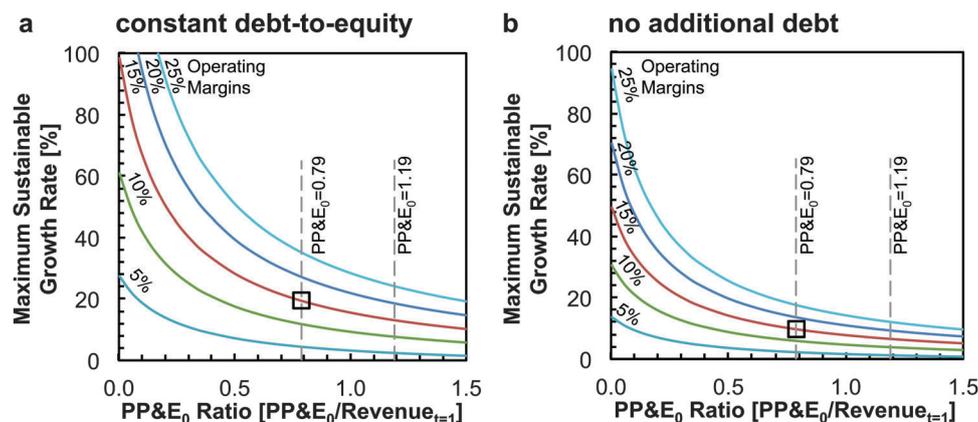


Fig. 4 The sustainable growth rate of a company with (a) a constant debt-to-equity ratio and (b) no additional debt are strong functions of capital intensity and operating margin. At the modeled capital intensities of ingot-to-module PP&E₀ = 0.79 and poly-to-module PP&E₀ = 1.19 manufacturing, the ability of PV manufacturers to scale in concert with historical trends at a 1 : 1 debt-to-equity ratio is poor. Reduced capital intensity, and increased operating margins, increase the PV industry's ability to scale.



increase in the higher leverage scenario due to an increased risk of the company not being able to make interest payments during periods of decreased profits. Therefore, a high debt level could eventually increase WACC when the optimal capital structure is passed, thereby causing financial distress and increasing the MSP. As noted above however, a company may have good reason to acquire more debt to grow quickly.

Increased interest payments from high debt leverage can also reduce the cash available for self-financed growth of a given company. In the PV industry, with volatile returns, this could prove especially problematic. For instance, Suntech used to be the largest module manufacturer in the world, with rapid capacity growth each year. Although Suntech successfully scaled up their capacity, their debt level also increased rapidly in their capital structure and subsequently aggravated the company operation. Financial distress gradually became a burden on Suntech and eventually bankrupted the company.³⁰ Therefore, although scaling up is an important factor to meet targets, the sustainable capital structure and growth rate for manufacturing companies may need additional attention.

5. Capex limits the internal rate of return of PV manufacturing

In this section, we present a framework to relate a manufacturer's profitability to its capital intensity and operating margin (*i.e.*, EBIT). In Fig. 5, we plot the yearly performance of operating margin and capital intensity (PP&E ratio defined in Section 2.1) of companies based on annual stockholder filings. The bubble area denotes yearly revenue as indicated on Fig. 5(a). The operating margin is calculated for the current year with the PP&E ratio given by $PP\&E_{t-1}/Revenue_t$. Internal rates of return (IRR) are also calculated as a function of operating margins and PP&E ratio. This framework allows for a direct comparison of the impacts of both operating margin (highly sensitive to module \$/W) and capex. A company enjoys the highest returns (IRR) in the upper left of the plot. We define success for the company when it operates above the line representing their WACC, as defined by the center of the revenue bubble. The IRR calculation assumes seven years of remaining life of the total book value of PP&E, along with no additional capex and constant operating margins. Additionally, three months of working capital is again assumed. IRR contours do not intersect the origin of the plot because of the requirements of working capital. A tax rate of 28% is also applied.²⁷ This framework, as well as the IRR calculation, assumes a traditional model in which products are sold after manufacturing. If a different model is applied, in which payments to the manufacturer may be delayed, the PP&E ratio may be inappropriate, as the yearly revenue is the denominator in the PP&E ratio.^{31,32}

A company's near-term strategy to improve their IRR is influenced by their current operating margin and capital intensity as reflected in Fig. 5. Thus, a manufacturer with high capex and low margins in the right of the plot faces a steeper gradient of IRR by increasing operating margin and may direct resources

to reduce \$/W-cost or increase \$/W-price. Over the long term, however, ignoring capex reduction opportunities may limit sustainable growth potential (see Fig. 4).

Different companies also have different WACCs, which dictate minimum IRRs using the MSP methodology. For a start-up company, a higher WACC (reflecting higher risk of failure) of approximately 45% is appropriate,³³ while a WACC of 14% was used for a representative incumbent PV manufacturer.¹³ For companies with a high WACC, Fig. 5 illustrates a narrow window for success. While a company with a low WACC may have an adequate IRR when its marker is in the upper-half of Fig. 5, a high WACC company may have an adequate IRR only in the upper-left, which places more significant constraints on capital intensity. Both types of company benefit from higher selling prices, as this moves the bubble toward the upper-left (affects both *x*- and *y*-axes).

In Fig. 5, nine firms are compared using this framework during the period of 2004 and 2013 based on data available in annual reports:³⁴⁻⁴³ First Solar, SunPower, Yingli, Trina, EnerSys (a battery manufacturing company; data for March end of fiscal year attributed to entire previous year), Intel, Apple Computers (data for September end of fiscal year attributed to entire year), Corning (glass and ceramics), and Alcoa (aluminum). We note that the ratio compares the book value of each company's property, plant, and equipment to revenue. Therefore the PP&E ratio is sensitive to whether a PV company owns installed capacity, as it may be recorded as PP&E, while revenues from the factory will be spread over time.

We observe several trends. First, PV firms do not have exceptionally high capital intensity relative to benchmark industries. However, they experienced higher volatility in operating margins than comparison industries from 2004 to 2013, implying that tomorrow's margins are less predictable. The PV companies also have an unfortunate combination of moderate to high capex and low margins. This is rare in steady-state comparison industries, where companies with high capex typically have high operating margins to sustain growth (Intel and Corning). The most attractive recipe for high IRR combines both high margins and low capex (*e.g.*, Apple Computer). Contract manufacturing, where factories are not owned, can help support this trend, and is discussed in Section 7.4. Alcoa provides an example of a comparison industry that was strongly affected by the recent global economic down-turn.⁴⁴

6. Discussion: influence of capex on PV industry trends

In this section, we discuss five higher-level implications of capex on PV industry trends.

6.1 High capital intensity impedes industry growth

First, as shown in Fig. 4, a high capex relative to revenue and cost of capital limits the sustainable growth rate of manufacturing capacity. As seen from Fig. 5, the capital intensity (PP&E to sales ratio) of pure-play PV companies is typically in the



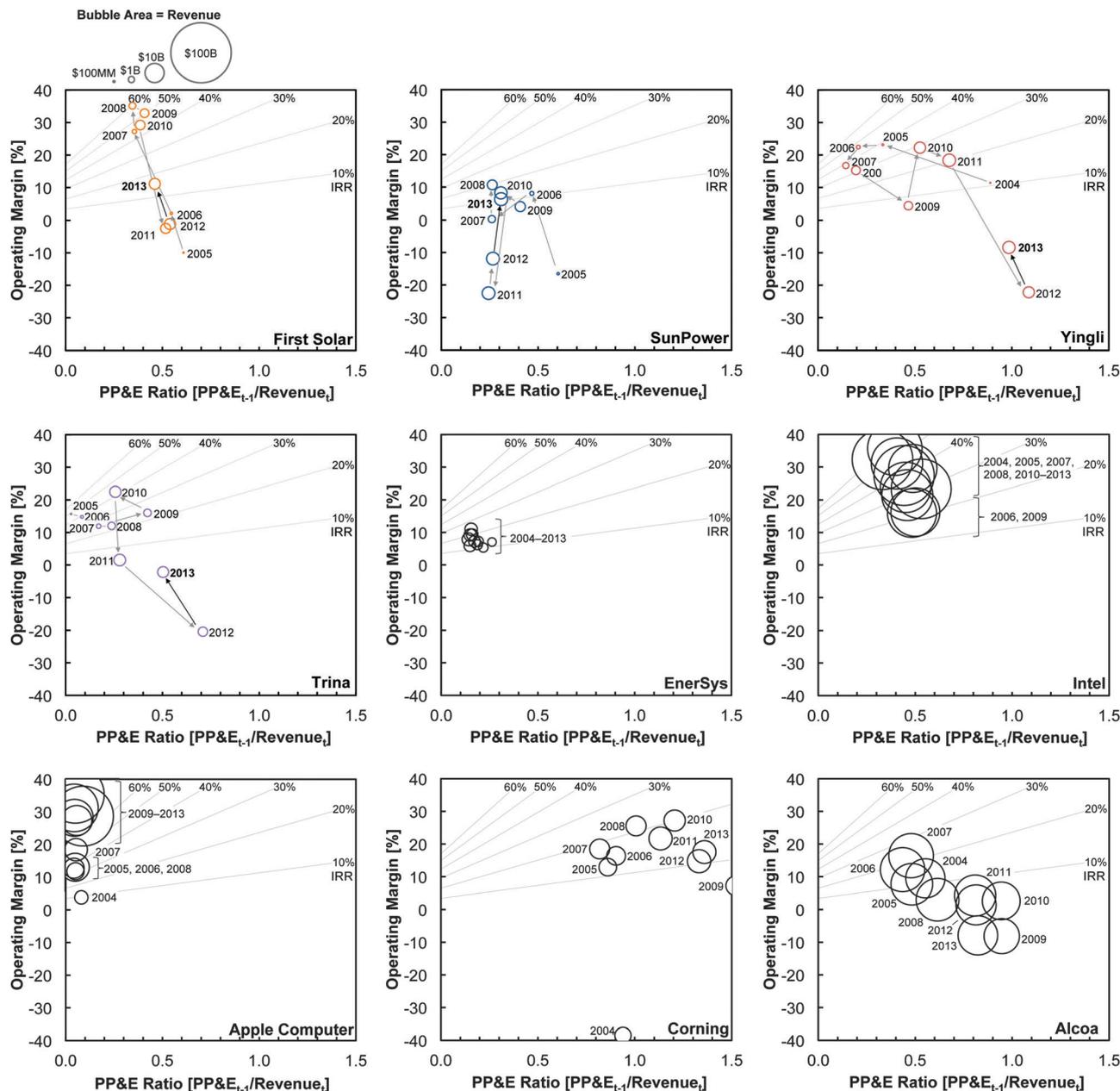


Fig. 5 The profitability of a company is directly related to capital intensity and operating margin. The internal rate of return (IRR, diagonal lines) is plotted as a function of operating margin and capital intensity (PP&E ratio, described in Section 2.1). Bubble area denotes annual revenue as shown top left. Four PV companies First Solar, SunPower, Yingli, and Trina are compared to a battery manufacturer, EnerSys, two differentiated technology companies Intel and Apple Computer, and two material companies Corning, and Alcoa.

range of 0.25–1.0. With a PP&E₀ ratio of 0.79 for the specific bottom-up case we modeled, the maximum self-financed growth rate is 19% for a 15% operating margin, and 39% at a high 25% operating margin. To maintain the historical cumulative annual growth rate of manufacturing capacity of 51% between 2003 and 2013,²² a reduction of capital intensity is needed (or additional debt burdens).

6.2 High capital intensity contributes to PV industry volatility

The market pressures associated with high volatility make long-term company strategy difficult to develop and execute. For instance,

deciding when to invest in an expansion of manufacturing capacity and how to finance it is challenging, in light of the combination of high capex, high margin volatility (Fig. 5), and many competitors that benefit from subsidies. If a company is too aggressive and expands manufacturing capacity before a down cycle (*i.e.*, oversupply condition), it risks bankruptcy. If a company is too conservative and does not expand capacity before an upward cycle (*i.e.*, undersupply condition), it risks not generating necessary revenue to grow (Fig. 4) and loses market share. Consequently, market leaders are inconsistent. Over the past decade, more than 15 companies have featured in the Top-5



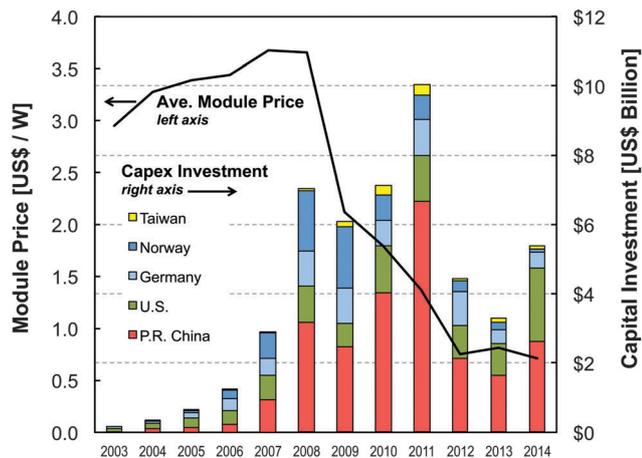


Fig. 6 Volatility of annual capital investment in the PV industry. Rapidly rising capital investment in the late 2000's contributed to an oversupply condition (augmenting demand-side factors), resulting in a rapid decrease of module price, which lowered capital investment.

PV module manufacturers list, including 6 that are no longer operating independently because they went bankrupt or were acquired.⁴⁵

The long lead time for new capex investment (*e.g.*, in extreme cases, 18–36 months for a polysilicon plant^{46,47}), implies that PV manufacturing cannot quickly react to changing demand (*e.g.*, market size, electricity prices, changes in government demand-side subsidies, and changes in international capital markets). Consequently, oversupply and under-supply conditions are amplified because of the long lead time associated with upstream capex expansion (Fig. 6), affecting downstream (module, installation) prices accordingly. This is manifest in the PV industry's experience learning curve,⁴⁸ as periods of oscillating prices.

6.3 High capital intensity promotes industry consolidation

Polysilicon, the segment of the supply chain with the highest capex, exhibits the largest degree of consolidation, evidenced by Fig. 7, which correlates the Herfindahl–Hirschman index (HHI, a measure of consolidation) with capital intensity, as a function of segment of value chain.^{49,50} Cell manufacturing does not align strongly with the trend of HHI and capex, though we note that factors beyond capex influence barriers to entry.^{13,51} Note that as consolidation advances (HHI increases), likewise the barrier to new entrants increases. Note that HHI increased during the recent oversupply condition, indicating industry consolidation.

6.4 High capital intensity represents a barrier for innovative technologies

Novel technologies with lower \$/W costs face additional barriers to adoption if they have high capex costs. If PV-industry consolidation leads to greater economy of scale advantages, the entry barrier (measured by total capex) to be an effective competitor increases. An example is fluidized bed reactor (FBR) silicon. Although the per-unit cost (\$/kg) is lower than standard Siemens,

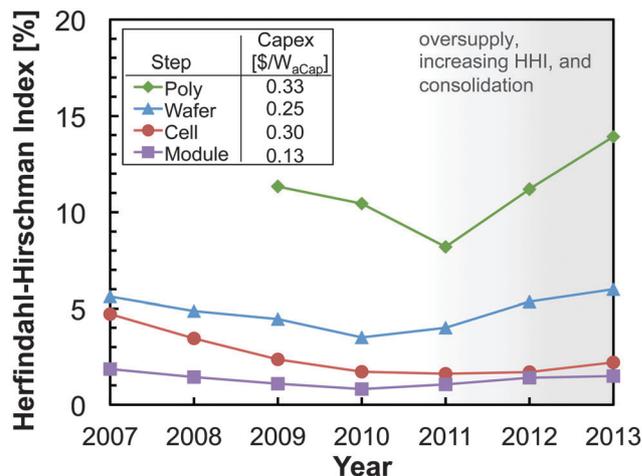


Fig. 7 The Herfindahl–Hirschman index (HHI) for four segments of c-Si PV manufacturing (polysilicon, wafer, cell, and module fabrication), as a function of year. A high HHI signals a concentrated industry. The HHI generally increases with capital intensity, though the less-consolidated positioning of cell manufacturing is noted. Furthermore, the HHI has been observed to increase in less profitable years of the PV industry.

the higher initial capex investment associated with FBR increases its MSP to above that of Siemens and increases the barrier to entry.¹³ This represents a “catch 22” for the PV industry technology roadmap: technological innovation is needed to lower per-unit costs and increase technology competitiveness, but high capex & low margins increase the degree of difficulty of executing an innovation-oriented business plan.

Although PV equipment vendors allocate a large percentage of revenue toward R&D, they are affected by the same multi-year “boom and bust” cycles. The recent down cycle in capex investment (Fig. 5) has forced some equipment vendors to delay or abandon efforts to introduce innovative silicon-based manufacturing equipment. Such an “innovation deficit” can impact technological development for years to come.

6.5 High capital intensity offers a window of opportunity for disruptive technologies

The scaling limitations highlighted in Fig. 4 imply that the long-term dominance of current silicon technology should not be taken for granted. If we consider what today may appear an *ad absurdum* scenario of a factory with an annual capacity of 1-terawatt of PV modules,⁵² two capex-related considerations raise concerns with today's technology: (1) the cost of the factory would be approximately \$1.01 trillion (roughly 30% of the 2014 U.S. Federal budget), and (2) the land area required to build the factory amounts to approximately 120 square miles (320 km²), which is roughly 10% of the area of the U.S. state of Rhode Island.⁵³ While none of these represent static

|| A 1 TW factory could maintain a worldwide installed PV capacity of 5 TW_{ave} (assuming 20% capacity factor, and 25 year module life). The current global electricity generation capacity is approximately 5 TW.

** This calculation assumes a factory area of 300 m²/MW_{aCap} updated from the reference for a 260 W, 60 cell, module.



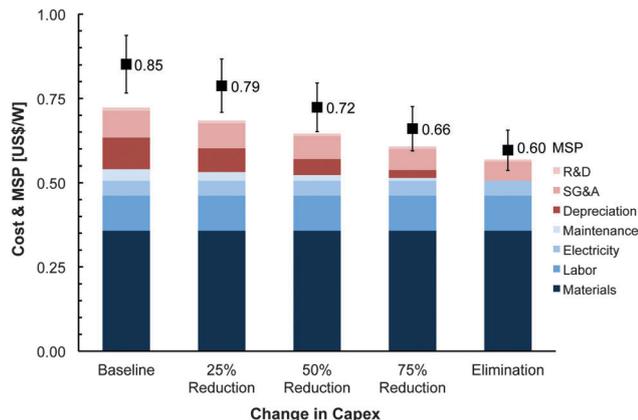


Fig. 8 Decreasing capex has a large impact on the MSP of module manufacturing, and provides the potential to reduce MSP by up to 0.25 \$/W in the modeled scenario. Halving capex provides a 15% reduction in MSP. The gross margin requirement drops significantly with reduced capex.

insurmountable barriers, they highlight the vast resources necessary to scale today's manufacturing processes to the terawatt scale. In the next section, we highlight opportunities for capex innovation, and provide quantifiable metrics.

7. Opportunities for capex innovation

Innovation targeting reduced capex could provide: (i) significant reductions in \$/W module, (ii) improvements in the sustainable growth rates achievable by the industry (Fig. 4), and (iii) modifications to the second-level implications presented in Section 6. A balanced approach could be applied between targeted reductions in per-unit cost and capex (which reduces margin requirements and maintenance costs). Capex innovation represents a viable pathway to reduce module MSP to achieve the U.S. DOE SunShot target⁹ and is one of the most influential variables, in line with the cost of silicon, that determine c-Si MSP.⁸

The calculations in Fig. 8 indicate that capex provides the opportunity to reduce MSP by up to 0.25 \$/W in our modeled scenario while significantly reducing the minimum sustainable gross margin.^{††} Halving capex reduces our calculated module MSP by 0.13 \$/W (15% relative), suggesting that capex innovation could play a significant role in sustainably reducing module prices. Reducing capital intensity would also improve the sustainable growth rate of the industry. Innovation opportunities broadly include incremental process innovations, disruptive process innovations, platform innovations, and financial approaches.

7.1 Incremental process innovation

A Pareto analysis of the current capex of PV manufacturing elucidates targeted areas of incremental improvement (Fig. 3). All potential capex innovations, however, must carefully weigh any impact on module efficiency, the most influential variable of module cost and price, as well as other cost factors.⁸ In short,

^{††} We note that maintenance costs are calculated as a fixed percentage of the capex.

we target innovations that do not sacrifice performance or reliability. Throughput provides a viable opportunity to improve capex (\$/W_{cap}) because of the inverse relationship between capex-per-unit and manufacturing throughput. This relationship highlights three foundational challenges: grow faster, process faster, and assemble faster. Growth-rate improvements of materials like multicrystalline silicon⁵⁴ may be realized,^{‡‡} but should consider accelerated defect generation. Process time improvements may be realized at other high temperature steps, such as phosphorus diffusion, by taking advantage of the exponential kinetics of the process.⁵⁵ Recently, the innovation of running a phosphorus diffusion furnace at a lower pressure not only nearly doubles throughput, it also obviates the dead-layer-removal step. Temperature cycling may also be sped by reducing tool thermal mass.⁵⁶ At the limit of this concept, relying on the local, rather than global, application of energy with laser processing may significantly reduce process time dedicated to global heating and cooling.⁶ Replacing batch processes with continuous processes may also provide throughput (and yield) improvements.⁵⁷

Widening process windows by increasing defect tolerance provides another opportunity for capex improvements. This could reduce constraints on equipment quality and cleanliness, and reduce expenditures on less-deleterious defects. Predictive simulation⁵⁸ and process monitoring can be employed to understand the most tightly constrained process variables and opportunities for improvement.

We note a pricing dynamic that can impact capex when innovations are applied to manufacturing equipment. A value-based pricing methodology, in which products are priced according to the value they produce,⁵⁹ suggests that equipment prices should rise when improvements in factors such as throughput, module efficiency, uptime, and material utilization are provided by new equipment. This 'splitting of the value pie created by the new innovation' provides a needed return on the equipment producer's efforts, while also providing benefits to the PV manufacturer. For innovations that directly address capex, such as throughput, the pricing change would still likely result in a net capex reduction to the manufacturer, reducing cost of tool ownership. For innovations that directly address variable costs however, such as material utilization, this pricing dynamic could have negative impacts on capex. Essentially, a value-based pricing methodology applied to an equipment innovation that improves a parameter like material utilization could reduce variable cost at the expense of increasing capex.

7.2 Disruptive process innovation

Process simplification provides another route to reducing capex. The disparate steps of the c-Si PV manufacturing process, as shown in Fig. 3, may be streamlined. An example to aspire to is provided by the float glass process, masterfully described by Utterback in ref. 60. Over 80 years of innovation (1880's–1950's) following Fig. 9, the disparate steps of glass manufacturing were streamlined into a single float-glass process.

^{‡‡} Changing from Czochralski to directionally solidified multicrystalline ingot growth reduces polysilicon-to-module capex by approximately 10%.



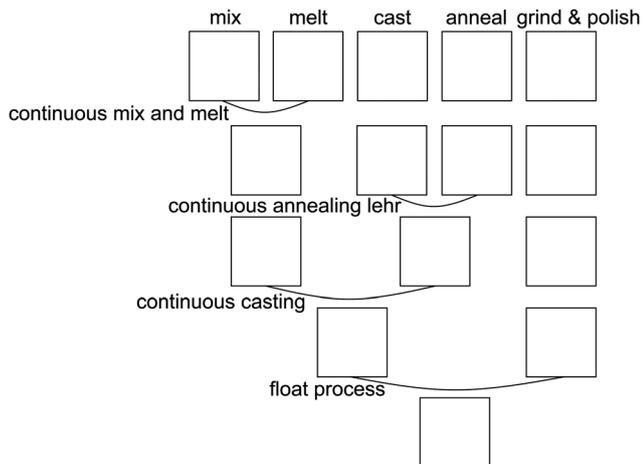


Fig. 9 The glass manufacturing industry consolidated disparate steps of manufacturing into the streamlined float glass process over the course of 80 years. The PV industry aspires to this example, yet, aims to accomplish similar streamlining over a much shorter time horizon. Figure adapted from Utterback.⁶⁰

Kerfless wafer growth techniques, including both vapor⁶¹ and melt⁶² approaches, take aim at the strong parallels between current silicon wafer manufacturing and 1880's glass manufacturing.

This general trend of disruptive process innovations that we observed for glass, seems to carry over for modern precision industries as well. Gillette razor blades in the 1990's provide another example. In the case of Gillette, the manufacturing throughput of Mach3 razors increased by $3\times$ relative to previous technology by replacing intermittent-motion with continuous-motion machines.^{63,64} This reduced factory footprint for manufacturing in one of the United States' most expensive cities – Boston.⁶⁵

A streamlined approach for c-Si could include epitaxial wafer growth⁶¹ direct from the gaseous silicon phase (avoiding polysilicon production and wire sawing) with an *in situ* emitter and back surface field (BSF).⁶⁶ For further downstream simplification, the wafer could also be grown pre-textured.⁶⁷ The implementation of a high-lifetime⁶⁸ wafer that is pre-diffused and pre-textured eliminates the majority of individual process steps of polysilicon and wafer manufacturing. Similarly, melt-based approaches for drop-in wafers provide significant simplification as well.⁶² These approaches might leverage streamlined silicon refining (*e.g.*, upgraded metallurgical-grade silicon, UMG-Si), where substantial R&D has been focused on closing the quality gap with Siemens-grade silicon. Taking the concept further, additional simplification could further streamline cell and module manufacturing by blurring the lines between the two currently disparate steps by attaching cells to partially laminated modules as a carrier.^{69–71} Modules could then be completed with pre-printed back-sheets to avoid tabbing and stringing that interconnect during the thermal process of lamination.^{72,73} In such a streamlined fabrication process, the partially assembled module could foreseeably progress down a conveyor through in-line processing equipment at the center of

various materials streams, as opposed to robot arms moving inertia-rich modules from one batch process to another.

7.3 Platform innovation

Platform innovation on material systems that could replace c-Si provide significant opportunities for capex reduction and process simplification by reducing the thermal budget, purity requirements, and process complexity of manufacturing. Module-based glass substrates provide the additional benefit of a uniform form-factor throughout the manufacturing process, avoiding the inherently disparate steps of the c-Si supply chain shown in Fig. 3. We estimate that the capex for CdTe module manufacturing is 0.80 to 0.85 $\$/W_{\text{aCap}}$ at a module efficiency of 12.8% to 14.2%, a 20% reduction from current c-Si. However, at 15% module efficiency, roll-to-roll approaches with printed ink absorbers provide a disruptively low estimated capex of 0.06 $\$/W_{\text{aCap}}$ for the cell process equipment. We note that this calculation is limited in scope, and that the capex constraints of other steps of the supply chain (*i.e.*, glass) could limit growth in this disruptive scenario. With these technologies, though, their ultimate MSP and field reliability are paramount to ultimate cost effectiveness.⁸

Shifting fixed costs to variable costs may also be achieved through optical concentration. For the same power rating, a concentrator reduces the capex-intensive solar-cell area while increasing commodity materials (optics, mechanics, racking, heat management) – thus potentially reducing the W_{aCap} required of traditional solar cell production per W_{module} . However, concentrator optics and mechanics still require assembly, which could reduce the capex advantage of concentrators. There are also non-capex considerations, including additional maintenance costs and location-dependent energy yield.

7.4 Financial approaches

Lastly, financial approaches such as equipment leases and contract manufacturing can reduce capital intensity and overcome barriers to entry for manufacturing. The one making the equipment available for lease must earn a suitable return, likely increasing the ultimate cost for the lessee, but a streamlined process and reduced upfront barriers could benefit some manufacturers, especially small innovators. Flexible production tools with common components may aid in the effectiveness of leasing by improving the capability to be repurposed. Additionally, manufacturing technologies that can repurpose existing infrastructure, such as leasing generic buildings rather than constructing custom facilities with cleanroom space, may benefit from a capex advantage. In Fig. 3, facility costs are allocated to process steps by the area of floor space required in a custom facility that is purchased. The facility capex accounts for approximately 16% of the total capex for a wafer, cell, and module manufacturer.

Contract manufacturing, or outsourcing, is another viable approach to reducing capital intensity. The semiconductor industry has implemented this approach were many “fabless” firms design and sell components that are manufactured by a third party. These firms, like Apple Computer, can enjoy



reduced capital intensity (Fig. 5). The equipment must be owned by someone however, though further consolidation may reduce investment risk by reducing the number of competitors that can potentially make bad investment decisions while also increasing barriers to entry through economies of scale. The relatively standardized process of c-Si PV production is ripe for this approach, and indeed many PV companies exist in a limited scope of the supply chain.

This approach opposes a vertically integrated company in which a manufacturer may own separate facilities for polysilicon, wafer, cell, and module manufacturing. Reasons to vertically integrate include if adjacent companies in the supply chain have more market power and if integration would raise barriers for other competitors.^{74,75} There has been a recent trend of PV manufacturers integrating downstream to come into closer contact with customers. We note however, that the stage of the supply chain with the most customer contact does not always have the largest economic surplus.⁷⁴ Integration will not necessarily hurt capital intensity if revenues increase proportionally to the additional capex required to expand. For example, downstream diversification into services (system integration, operation & maintenance) may provide an additional avenue for PV companies to reduce their capital intensity.

Lastly, steps to reduce the WACC for a PV manufacturer through technology and business-model innovations would also reduce the impact of capex on MSP. A focus on reliability is a technical goal that could support reduced WACC.

8. Conclusions

The current high capex of c-Si manufacturing has significant implications on both the per-unit profitability and scalability of the PV industry. Capex related components comprise approximately 22% of module MSP (0.19 \$/W); and halving capex provides a significant opportunity to reduce MSP by 15% (0.13 \$/W). We model a total capex for monocrystalline c-Si manufacturing of 1.01 \$/W_{acap} from poly to module, with three process steps contributing to 45% of the total capex: TCS, Siemens polysilicon CVD, and Czochralski growth.

Capex is high relative to the selling price of modules, which we define as the PP&E₀ ratio. With our simulated manufacturer, the sustainable growth rate of PV manufacturing is limited to less than 19% per year at 15% operating margins, and 39% per year at 25% operating margins. This is insufficient to keep pace with current industry trends, leading to increased debt burdens of manufacturers. The capital intensity of the PV industry is not unprecedented however. The integrated circuit and other specialty manufacturers maintain high capital intensities, but with lower volatility than the PV industry, and often higher margins.

Opportunities are available to reduce the capital intensity of c-Si manufacturing through both incremental process innovation, such as improving throughput (e.g., changing from Czochralski to directionally solidified multicrystalline silicon reduces capex by ~10%), and disruptive process innovation, such as epitaxially grown kerfless wafers directly from the gaseous phase with *in situ*

texturing and emitter formation, and monolithic module integration. Platform innovations, such as ink-based approaches have the potential to disruptively reduce capex for the PV manufacturer, but may expose capex constraints at other stages of the supply chain. With these approaches, material quality, module efficiency, and reliability are critical factors as well. Lastly, financial approaches such as equipment leasing and contract manufacturing can meaningfully reduce capital intensity.

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References

- 1 P. A. Basore, Understanding manufacturing cost influence on future trends in silicon photovoltaics, *IEEE J. Photovolt.*, 2014, **4**, 1477–1482.
- 2 A. Goodrich, *et al.*, A wafer-based monocrystalline silicon photovoltaics road map: utilizing known technology improvement opportunities for further reductions in manufacturing costs, *Sol. Energy Mater. Sol. Cells*, 2013, **114**, 110–135.
- 3 G. F. Nemet, Beyond the learning curve: factors influencing cost reductions in photovoltaics, *Energy Policy*, 2006, **34**, 3218–3232.
- 4 R. M. Swanson, A vision for crystalline silicon photovoltaics, *Prog. Photovoltaics*, 2006, **14**, 443–453.
- 5 H. Forstner, *et al.*, International technology roadmap for photovoltaic (ITRPV) 2013 results – revision 1, Semiconductor Equipment and Materials International, 2014.
- 6 D. M. Powell, *et al.*, Crystalline silicon photovoltaics: a cost analysis framework for determining technology pathways to reach baseload electricity costs, *Energy Environ. Sci.*, 2012, **5**, 5874–5883.
- 7 A. C. Goodrich, D. M. Powell, T. L. James, M. Woodhouse and T. Buonassisi, Assessing the drivers of regional trends in solar photovoltaic manufacturing, *Energy Environ. Sci.*, 2013, **6**, 2811–2821.
- 8 D. M. Powell, M. T. Winkler, A. Goodrich and T. Buonassisi, Modeling the cost and minimum sustainable price of crystalline silicon photovoltaic manufacturing in the united states, *IEEE J. Photovolt.*, 2013, **3**, 662–668.
- 9 U.S. Department of Energy, Sunshot vision study, 2012.
- 10 C. T. Horngren, G. L. Sundem and F. H. Selto, *Introduction to management accounting*, Prentice Hall, 1993.



- 11 Capital budgeting cash flows, 2012, ch. 7, www.rdboehme.com/MBA_CF/Chapter07_emba.ppt.
- 12 C. T. Horngren, G. L. Sundem, W. O. Stratton, D. Burgstahler and J. Schatzberg, *Introduction to management accounting*, Pearson Prentice Hall, 2008, pp. 332–342.
- 13 R. Fu, T. James and M. Woodhouse, Economic Measurements of Polysilicon for the Photovoltaic Industry: Market Competition and Manufacturing Competitiveness, *IEEE J. Photovolt*, 2015, 5, 515–524.
- 14 Available at <http://pv.mit.edu/TMA/>.
- 15 M. A. Green, Ag requirements for silicon wafer-based solar cells, *Prog. Photovoltaics*, 2011, 19, 911–916.
- 16 S. Lacey, *How china dominates solar power*, 2014, <http://www.theguardian.com/environment/2011/sep/12/how-china-dominates-solar-power>.
- 17 Y. S. Zhang and S. Barnett, *Fiscal vulnerabilities and risks from local government finance in china*, IMF Working Paper, WP/14/4, 2014.
- 18 Y. Lu and T. Sun, *Local government financing platforms in china: a fortune or misfortune?*, IMF Working Paper, WP/13/243, 2013.
- 19 S. J. Hassol, Questions and answers: emissions reductions needed to stabilize climate, The Presidential Climate Action Project.
- 20 L. Bird, C. Chapman, J. Logan, J. Sumner and W. Short, *Evaluating renewable portfolio standards and carbon cap scenarios in the U.S. Electric sector*, NREL Report No. TP-6A2-48258, 2010.
- 21 K. S. Cory and B. G. Swezey, *Renewable portfolio standards in the states: balancing goals and implementation strategies*, NREL Report No. TP-670-41409, 2007.
- 22 International Energy Agency, Trends 2014 in photovoltaic applications – survey report of selected IEA countries between 1992 and 2013, Photovoltaic Power Systems Programme (PVPS), 2014.
- 23 P. A. Basore, D. Chung and T. Buonasissi, *Economics of future growth in photovoltaics manufacturing*, Proceedings of the 42nd IEEE PVSC, New Orleans, LA, 2015.
- 24 R. C. Higgins, How much growth can a firm afford?, *Fin. Manag.*, 1977, 6, 7–16.
- 25 M. M. Fonseka, C. G. Ramos and G.-l. Tian, The most appropriate sustainable growth rate model for managers and researchers, *J. Appl. Bus. Res.*, 2012, 28, 481–500.
- 26 A. Ashta, Sustainable growth rates: refining a measure, *Strategic Change*, 2008, 17, 207–214.
- 27 P. Dittmer, *U.S. Corporations suffer high effective tax rates by international standards*, Tax Foundation, 2011.
- 28 M. Z. Frank and V. K. Goyal, Trade-off and pecking order theories of debt, Social Science Research Network, 2007, available at SSRN: <http://ssrn.com/abstract=670543>.
- 29 H. Baker and G. Martin, *Capital structure and corporate financing decisions – theory, evidence, and practice*, John Wiley & Sons, Inc., 2011, ch. 10.
- 30 K. Bradsher, *Suntech unit declares bankruptcy*, 2014, <http://www.nytimes.com/2013/03/21/business/energy-environment/suntech-declares-bankruptcy-china-says.html>.
- 31 M. Urdanick, *A deeper look into yieldco*, 2015, <https://financere.nrel.gov/finance/content/deeper-look-yieldco-structuring>.
- 32 SunEdison, Capital markets day, 2014.
- 33 G. Festel, M. Wuermseher and G. Cattaneo, Valuation of early stage high-tech start-up companies, *Int. J. Bus.*, 2013, 18, 216.
- 34 First Solar Inc., Form 10-k, 2006–2013.
- 35 First Solar Inc., Financial statements, 2014, <http://investor.firstsolar.com/financials-statements.cfm>.
- 36 SunPower Corporation, Form 10-k, 2005–2013.
- 37 Yingli Green Energy Holdings Company Limited, Form 20-f, 2007–2013.
- 38 Trina Solar Limited, annual report, 2006–2013.
- 39 ENERSYS, Form 10-k, 2005–2014.
- 40 Intel Corporation, Form 10-k, 2007–2013.
- 41 Apple Inc., Form 10-k, 2004–2014.
- 42 Corning Inc., Form 10-k, 2004–2013.
- 43 Alcoa Inc., Form 10-k, 2004–2013.
- 44 Alcoa Inc., 2011 annual report.
- 45 P. Mints, *Top ten pv manufacturers from 2000 to present: a pictorial retrospective*, 2014, <http://www.renewableenergyworld.com/rea/news/article/2014/01/top-ten-pv-manufacturers-from-2000-to-present-a-pictorial-retrospective>.
- 46 C. Annis, *More polysilicon plants still under construction despite enormous pv overcapacity – why?*, 2014, <http://www.solarbuzz.com/resources/blog/2013/03/more-polysilicon-plants-still-under-construction-despite-enormous-pv-overcapacity-why>.
- 47 M. Osborne, *Rec silicon expanding polysilicon production and mulling 20 000 mt jv in saudi arabia*, 2014, http://www.pv-tech.org/news/rec_silicon_expanding_polysilicon_production_and_mulling_20000mt_jv_in_saud.
- 48 D. Feldman, *et al.*, Photovoltaic system pricing trends: Historical, recent, and near-term projections 2014 edition, NREL Report No. PR-6A20-62558, 2014.
- 49 M. A. Adelman, Comment on the “h” concentration measure as a numbers-equivalent, *Rev. Econ. Stat.*, 1969, 51, 99–101.
- 50 R. A. Arnold, *Microeconomics*, Cengage Learning, 2013.
- 51 M. Porter, *The five competitive forces that shape strategy*, Harvard Business Review, 2008.
- 52 U.S. Energy Information Administration, International energy statistics, 2014, <http://www.eia.gov/cfapps/ipdbproject/IEDIndex3.cfm?tid=2&pid=2&aid=7>.
- 53 A. Kreutzmann and M. Schmela, Emancipation from subsidy programs: centrotherm builds first grid-parity factory - while simultaneously underscoring the necessity of continued subsidies, *Photon Int.*, 2008, 12, 84–92.
- 54 D. Franke, T. Rettelbach, C. Häßler, W. Koch and A. Müller, Silicon ingot casting: process development by numerical simulations, *Sol. Energy Mater. Sol. Cells*, 2002, 72, 83–92.
- 55 D. P. Fenning, *et al.*, Improved iron gettering of contaminated multicrystalline silicon by high-temperature phosphorus diffusion, *J. Appl. Phys.*, 2013, 113, 214504.
- 56 P. A. Basore, *Personal communication*, 2014.
- 57 D. W. Jimenez, Cost of ownership and overall equipment efficiency: a photovoltaics perspective, *Photovoltaics Int.*, 2009, 6, 16–22.



- 58 D. P. Fenning, *et al.*, Darwin at high temperature: advancing solar cell material design using defect kinetics simulations and evolutionary optimization, *Adv. Energy Mater.*, 2014, **4**, 1400459.
- 59 T. T. Nagle and J. E. Hogan, *The strategy and tactics of pricing: a guide to growing more profitably*, Pearson Prentice Hall, 2006.
- 60 J. M. Utterback, *Mastering the dynamics of innovation*, Harvard Business School Press, 1996.
- 61 T. S. Ravi, *Technology development for high-efficiency solar cells and modules using thin (<80 μm) single-crystal silicon wafers produced by epitaxy*, NREL Subcontract Report: NREL/SR-5200-58593, 2013.
- 62 E. M. Sachs, *et al.*, Methods for efficiently making thin semiconductor bodies from molten material for solar cells and the like, *U.S. Pat.*, 8,293,009 B2, 2012.
- 63 J. Surowiecki, *UK: The billion dollar blade*, 2015, <http://www.managementtoday.co.uk/news/411367/UK-billion-dollar-blade>.
- 64 H. P. Schaefer, *High-speed, high-precision manufacturing*, MIT Laboratory for Manufacturing and Productivity Seminar Series, 2012.
- 65 S. Malone, *Manufacturing can thrive but struggles for respect*, 2015, <http://www.reuters.com/article/2011/12/14/us-usa-manufacturing-respect-idUSTRE7BD1WR20111214>.
- 66 K. Van Nieuwenhuysen, *et al.*, High-quality epitaxial foils, obtained by a layer transfer process, for integration in back-contacted solar cells processed on glass, Photovoltaic Specialists Conference (PVSC), 38th IEEE, Austin, TX, 2012, pp. 001833–001836.
- 67 R. Brendel, R. Auer and H. Artmann, Textured monocrystalline thin-film si cells from the porous silicon (psi) process, *Prog. Photovoltaics*, 2001, **9**, 217–221.
- 68 D. M. Powell, *et al.*, Effective lifetimes exceeding 300 μs in gettered p-type epitaxial kerfless silicon for photovoltaics, *Appl. Phys. Lett.*, 2013, **103**, 263902.
- 69 R. Brendel, Thin-film crystalline silicon mini-modules using porous si for layer transfer, *Sol. Energy*, 2004, **77**, 969–982.
- 70 J. H. Petermann, H. Schulte-Huxel, V. Steckenreiter, S. Kajari-Schroder and R. Brendel, Principle of module-level processing demonstrated at single a-si:H/c-si heterojunction solar cells, *IEEE J. Photovoltaics*, 2014, **4**, 1018–1024.
- 71 V. Steckenreiter, R. Horbelt, D. N. Wright, M. Nese and R. Brendel, Qualification of encapsulation materials for module-level-processing, *Sol. Energy Mater. Sol. Cells*, 2014, **120**(part A), 396–401.
- 72 M. Späth, P. C. d. Jong, I. J. Bennett, T. P. Visser and J. Bakker, *A novel module assembly line using back contact solar cells*, presented at the 33rd IEEE PVSC, San Diego, CA, 2008.
- 73 S. A. Mann, M. J. de Wild-Scholten, V. M. Fthenakis, W. G. J. H. M. van Sark and W. C. Sinke, The energy pay-back time of advanced crystalline silicon pv modules in 2020: a prospective study, *Prog. Photovoltaics*, 2014, **22**, 1180–1194.
- 74 J. Stuckey and D. White, *When and when not to vertically integrate*, 2015, http://www.mckinsey.com/insights/strategy/when_and_when_not_to_vertically_integrate.
- 75 S. Boyson and C. Han, Eras of enterprise globalisation: from vertical intergration to virtualisation and beyond, in *Multi-national corporations and the merging network economy in asia and the pacific*, ed. J. J. Palacios, Routledge, 2008, pp. 26–57.

