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Photovoltaic Deployment Scenarios toward Global Decarbonization: Role of Disruptive Technologies

*Billy J. Stanbery, Michael Woodhouse, and Jao van de Lagemaat**

To totally decarbonize global electrical systems using photovoltaics (PVs) in the 2050–2060 decade, the world would need to install 63.4 TW of PV. This article models and explores how a PV manufacturing ramp-up trajectory toward this goal can be achieved while assuming that investors continue to make financially rational decisions avoiding stranded production assets and therefore protecting their return on investment. The model effectively exploits experience curve benefits in both the scaling of the manufacturing process and continued progress in product design technologies. The scale-up challenge is amplified because trajectories that achieve this goal require an unprecedented ramp-up of production capacity over just two decades, followed by relatively modest demand to maintain the installed base and support continued population growth. It is demonstrated that sustainable ramp-up of manufacturing is indeed possible and shown that the deployment of the requisite manufacturing capacity can be accelerated and accomplished at lower total capital cost by the introduction of disruptive technologies that have lower capital intensity, embedded energy, or higher efficiency.

1. Introduction

To avoid climate catastrophe, the world needs to decarbonize the energy system between 2050 and 2060, and photovoltaics (PVs) are expected to play a major role. PV installations have recently reached 1 TW across the world, and the amount of PV installed will certainly continue to grow to 10's of terawatt levels.[1] Coupling PV into other sectors of the energy economy such as manufacturing and transportation will allow the amount of PV installed to grow even further.[2,3] Coupling can be achieved by simultaneously utilizing grid-scale storage using batteries and mechanical storage such as pumped hydro as well as by producing energy carriers such as hydrogen using electrolysis. Hydrogen, for example, can be used to couple the electricity system into energy intensive industries such as steel production and the chemical industry. Several studies have assessed the growth of PV module manufacturing capacity needed to meet the goal of decarbonizing the global economy within the target decade of 2050–2060.[3,4] Assuming that all presently significant electrical applications would be provided by PV, the total installed PV generation capacity has been estimated to be 63.4 TW,[4] a more than 60-fold increase of currently installed capacity. This number represents an upper bound, as wind, geothermal, hydropower, and others would also be expected to contribute. A recent article[4] assumed that the necessary factories would be immediately built and produce the required PV over time, predicting up to 80 TW could be required to electrify the chemical industry and adequately scale direct carbon air capture. While worthwhile as a thought experiment, it does not leverage "learning by doing", as all industries do when scaling production, and thus does not capture the lowest cost solution.

This article explores how a ramp-up trajectory toward the 63.4 TW goal could be achieved assuming that investors make financially rational decisions avoiding stranded production assets while also effectively exploiting experience curve benefits in both manufacturing process and product design technologies. Any trajectory achieving the goal requires an unprecedented ramp-up of production capacity, followed by relatively modest demand after full decarbonization to support continued population growth. We explore whether such trajectories can be aided by the adoption of disruptive technologies providing lower capital intensity and embedded energy, or higher efficiency.

The rapid deployment and requisite scaling of manufacturing capacity place major constraints on financially viable scenarios. Within 30–40 years there are only about two typical 15 year factory lifetimes, while deployed module lifetimes are still climbing. Capital investment rates during this period must be sufficient to ramp up production capacity to hit the deployment goals. Once the 2050–2060 capacity target is achieved, PV demand is driven only by population growth, the need to replace power generation capacity losses from modules degrading and reaching their end-of-life (EOL). The rapid and sudden loss of the market growth driver will impact manufacturers' willingness to invest in capital expansion as the goal nears within the assumed 15 year

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factory lifetime. Therefore, we assume that new factories will only be built if they are projected to sustain full output throughout their lifetime. In this article, we do not address potential supply chain limitations, or changes needed to the overall energy system, as there are other analyses focused on those questions.

2. Modeling of Manufacturing Scale-Up

Our analysis is intended to capture the scale and temporal dynamics of financing required to build the manufacturing capacity needed to manufacture enough PV modules as well as to manufacture these modules to provide the projected contribution of PV to decarbonize the global economy within the public policy "decarbonization decade," 2050–2060. It is intentionally a reductionist model making a minimal set of assumptions in order to demonstrate the significant scale and rapid acceleration of investment in PV module manufacturing capacity unavoidably required to achieve this goal. Those assumptions are as follows: 1) a 15 year factory/capital equipment lifetime irrespective of manufacturing value chain segment or product; 2) investors will not finance new factories/capital equipment unless they expect them to remain fully utilized throughout their 15 year lifetime; 3) module warranted lifetime will increase from a 2020 average of 30 to 50 years by 2040 and be decommissioned at their EOL, linearly degrading to 80% of their initial output and installed their year of manufacture; 4) the capital intensity learning curve for building new manufacturing capacity is the same for the disruptive technology as for the incumbent silicon technology; and 5) the experience curve learning rate for silicon modules' USD/W cost-of-goods-sold (COGS) metric will asymptote in 2030 to 12% annum^{-1}, but disruptive technologies will continue the historic learning rate of silicon thereafter.

Three historical datasets are utilized to build this model, including 1) the global annually installed module generation capacity growth from 2001 to 2020; 2) biannual global capital investment in segmented value-chain silicon manufacturing capacity 2014–2020; and 3) the module annual average sales price (ASP) from 2014 to 2020. The annual module manufacturing capacity is taken to be the difference between installed capacity each successive year. Inasmuch as 77% of the total installed generation capacity in 2020 had been installed since 2014 and the silicon manufacturing net operating income averaged about zero during this period,[5] we approximate the mean COGS as equal to the ASP in each of those years. Our model encompasses the above assumptions and data sets and is further explained below. The source code is available in Mathematica notebook format including detailed descriptions from the Supporting Information.

2.1. Continued Reduction of Manufacturing Costs by the PV Industry

In the last decade, the steadily increasing power conversion efficiency (PCE) of commercial modules as well as continued learning in the industry has relentlessly driven down the ASP in USD/W_p of PV modules. Improvements in PCE were the dominant factor from 1980 to 2012, contributing almost 25% to the decline in ASP from 1980 to 2001, but only 12% from 2001 to 2012, when scaling to larger factories and wafers along with wafer thickness reduction contributed more.[6] A recently published meta-analysis of the literature found that the ≈20% ASP learning rate is likely to decline to 12% in the long term.[7] In this modeling, we assume the ASP learning rate for silicon production will decrease to 12% after 2030, but that disruptive technologies will be able to sustain the ≈20% rate after that time.

Manufacturing cost reductions have been attributed in econometric analyses to "learning by doing" for mature, "learning by research" for reviving, "capital intensity" for evolving, and "market opportunity" for emerging technologies.[8] Silicon PV is relatively mature, whereas most alternatives are aptly categorized as emerging or evolving. Only evolving technologies show high rates of learning by doing, and high capital intensity and limited market opportunities can slow the pace of progress for both emerging and evolving technologies. Here, we analyze recent historical data (2005–2020) of manufacturing capital intensity to model the overall learning rate of silicon technology in terms of its constituent manufacturing steps. Note that this is distinct from the module ASP learning rate defined previously. The modeled learning rates are used to project the capital intensity of future manufacturing for both silicon and disruptive technologies in all scenarios. Disruptive technologies could potentially achieve lower capital expense intensity as their production scales, in which case the current model would underestimate their impact on global decarbonization.

Figure 1 shows the manufacturing capital expense intensity for the dominant silicon PV technology. Its underlying analysis breaks the overall capital intensity down into four categorical constituent manufacturing steps. Capital intensity has units of dollars-per-Watt of annual nameplate manufacturing capacity USD/W_aCap/yr or [USD·yr/W]. We utilize the same categorical segmentation of the c-Si PV manufacturing value chain (polysilicon, wafer, cell, and module fabrication) as many previously published studies[9,10] and find learning rates of 0.535, 0.456, 0.570, and 0.566, respectively, for each of these categories. These results are used to project the capital intensity of future manufacturing for both silicon and disruptive technologies in all scenarios modeled herein as to not make any assumptions about future technologies as one such a technology could be perovskite on silicon tandems which obviously would have a capital intensity similar to silicon but the higher efficiency of such tandems could push the curves either up or down depending on the overall cost of adding the extra layers to the tandem. We chose to not make an assumption in either direction so as to not give any advantage or disadvantage to any particular disruptive technology.

2.2. Growing Manufacturing Capacity to Reach Decarbonization Goals

The cumulative module production required to meet the 63.4 TW capacity target is greater than the target value because of module retirement and output degradation. Simultaneously, the industry as well as the US DOE and other research funding agencies around the world are driving toward a 50 year module lifetime which is accounted for in our modeling. Global factors may also affect supply chains differently for different technologies, highlighting the importance of deploying diverse PV

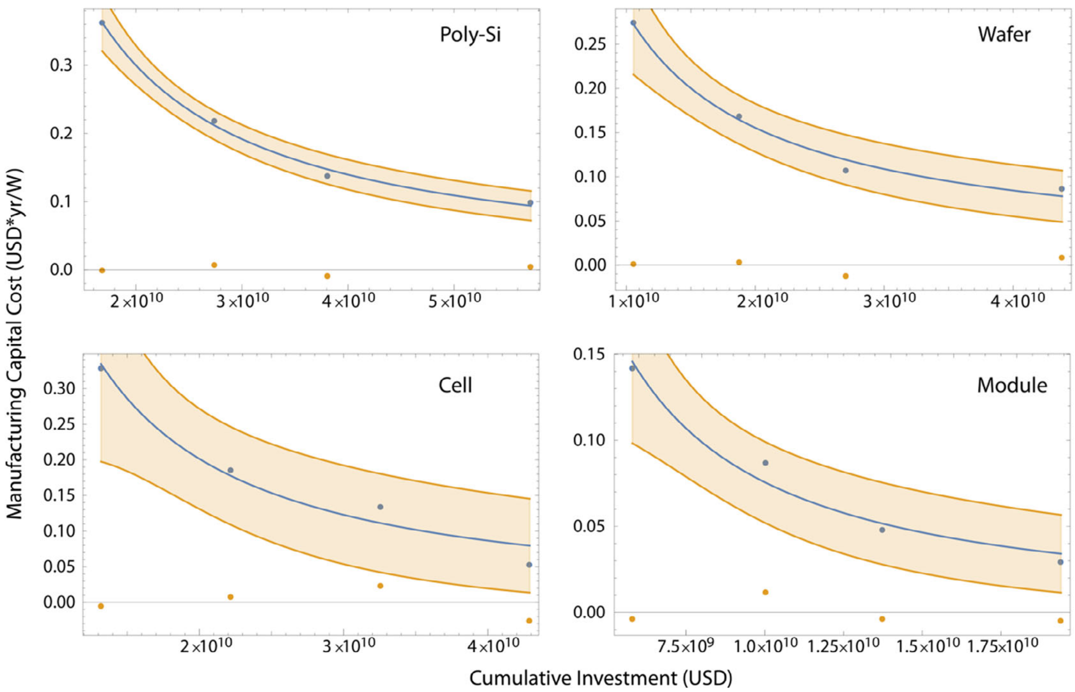

Figure 1. Learning rate analysis of segmented silicon PV module manufacturing supply chain capital investment history 2014–2020 in USD·yr/W versus cumulative investment in the production segment. The 95% confidence intervals of this analysis are bounded by orange lines and orange dots indicate best fit residuals as detailed in the Supporting Information.

technologies to mitigate supply chain vulnerability from dependence on critical resources only available in a limited number of nations. Furthermore, technologies offering lower capital intensity and embedded energy are more amenable to distributed manufacturing, which can reduce logistic supply and deployment costs, potentially providing more robust supply chains.

To model PV module demand (**Figure 2**a red curve) which is an input driver to our modeling, we use a second-order Verhulst equation, a generalization of the logistic distribution that includes an asymmetry parameter ξ allowing for either rapid initial deployment followed by a slower ramp down or a slower initial deployment followed by a rapid ramp down (Equation (1))

$$1-\left(1+(2^{\xi}-1)e^{\frac{t-\beta}{\tau}}\right)^{-1/\xi} \tag{1}$$

This mathematical distribution is widely used to model extraction and manufacturing industries as well as energy production accessible resources (and in this context market opportunities) are depleted.[11] In our model, the full factory utilization constraint slows investment into manufacturing capacity expansion as demand peaks and subsequently declines. For each decarbonization year within the target decade, we model the value of ξ for which the lowest total capital expense for the requisite

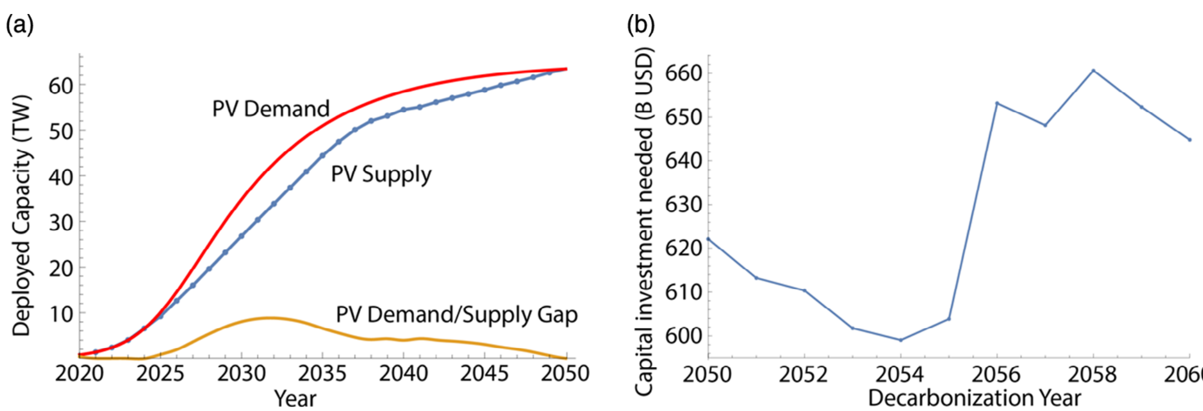

Figure 2. Silicon deployment. a) Cumulative market demand for PV given by a Verhulst distribution versus time (red) and modeled achieved deployment (blue dots) because of deferred investment in factories. The orange curve shows the gap between PV demand and supply. b) Total minimum CapEx investment (2020 USD without inflation) versus decarbonization year needed to create the manufacturing capacity for reaching 63.4 TW by the decarbonization year.

manufacturing capacity is achieved, which is provided by the most rapid production capacity ramp rate option.

As shown in Figure 2, the manufacturing industry will not fully meet the demand trajectories every year because of investors' unwillingness to finance incompletely utilized manufacturing capacity. By delaying build-out of manufacturing capacity, they can ensure full utilization. Yet even when imposing the full utilization requirement, silicon PV achieves the generation capacity deployment goal. That said, the required scale of PV module manufacturing capacity vastly exceeds the 2020 level of ≈137 GW yr^{-1}, multiplying 20- to 30-fold to reach 2.9–3.7 TW yr^{-1} within 10–15 years, and requiring 600–660 billion USD CapEx investment, consistent with another recently published assessment of requisite capacity expansion.[12] It is encouraging that our analysis shows this growth could be achieved when guided by rational investment decisions which do not generate underutilized production capacity, although recent data suggest that 2022 module production capacity only reached levels that this model predicts were needed by 2021.

While Figure 2 shows that the growth of manufacturing capacity can be sustainably achieved despite the currently ongoing asymptote in silicon manufacturing technology learning rates, it also shows that there is a significant gap between demand and supply that reaches a full 10 TW in 2030. The scale of this gap varies with decarbonization year and is affected by the simplification made in this analysis of a 15 year lifetime for all production assets, whereas supply chain raw material extraction industries like the polysilicon supply chain typically require much longer term investments. Nevertheless, such a strong difference between demand and supply could attract investment into less capital-intensive and thus disruptive alternative PV technologies.

2.3. The Opportunity for Disruptive PV Technologies

Two viable disruptive pathways have been proposed with the potential to reduce both the numerator (i.e., manufacturing cost) and denominator (PCE × area) of the USD/W module cost metric. First, the materials cost per unit area for direct bandgap semiconductor alternatives including CdTe, CIGS, and perovskites is dramatically less than that of silicon; and solution-processed technologies such as perovskites also have the potential to dramatically lower manufacturing CapEx investment requirements. Second, several tandem PV technologies have demonstrably realized their higher efficiency potential, some incorporating silicon as their low-bandgap partner, and others CIGS. Single-junction and tandem alternatives have the potential to become cost-effective solutions once they can be sustainably sold at prices competitive with single-junction crystalline silicon. Owing to their higher efficiency and potentially revolutionary methods for installation, advanced solar technologies also carry value due to balance-of-systems costs savings.

To model the prospective market impact of alternative technologies, we assume that some alternatives will continue their cost reduction beyond the 2030 time frame when we anticipate silicon's ASP learning rate will have slowed to its predicted asymptotic rate consistent with other commodity manufacturing industries.[7] After that we assume that all new CapEx investment will be into those disruptive technologies because they deliver lower COGS and can be sold profitably for a lower ASP or provide manufacturers higher margins. **Figure 3** shows the prospective evolution of PV deployment transitioning from silicon to those disruptive technologies while providing the same combined manufacturing capacity each year as the previous scenario relying on silicon alone.

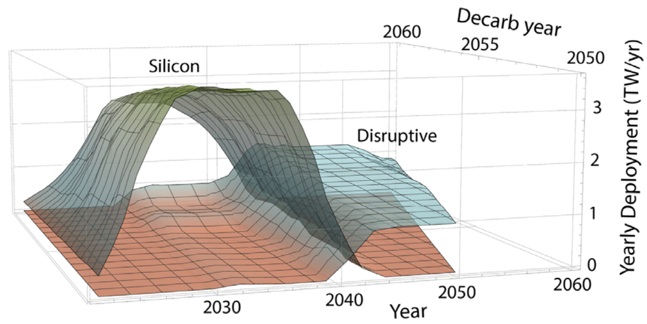

Figure 3. PV deployment rate for silicon and prospective disruptive technologies as a function of decarbonization year. Disruptive technologies dominate from 2040, producing about 1 TW yr^{-1}, but in many scenarios their capacity expansion ramps swiftly after 2030.

Figure 4 shows the overall cost of goods sold for decarbonization between 2050 and 2060 in these two alternative scenarios for two different amounts of total installed PV while maintaining the financially sustainable manufacturing capacity expansion constraints described above. Our analysis shows that the cost savings associated with the ascendence of disruptive technologies climbs steadily to hundreds of billions of USD. More importantly, the analysis shows that disruptive technologies have an overall manufacturing market opportunity between 1and 2 trillion USD even when the total amount of PV installed is substantially less than 63.4 TW.

2.4. Disruptive Technology Candidates

The example of CdTe-based PV, which represents around 16% of the US PV market,[13] illustrates how a nontraditional technology can compete by having both a lower capital intensity and a high enough efficiency to compete on a USD/W basis. A newer candidate technology that is widely discussed in recent literature is perovskite PVs.[14] Perovskites can be printed with high-rate roll-to-roll processing leading to very low capital intensity manufacturing.[15] Challenges remain with long-term durability not yet proven;[16] however, several organizations such as the US-based PACT center are now providing objective testing and validating characterization protocols that can quantify module performance and accurately measure and predict power loss and degradation for perovskite-based modules. Other potentially disruptive technologies include tandems, which can lower the USD/W metric by increasing module efficiency. A perovskite on silicon tandem, for example, could enable the industry to transition from single-junction silicon modules to perovskite on Si tandems to full perovskite tandems in stages. Several companies are currently attempting to commercialize perovskite on silicon tandems such as TandemPV and CubicPV in the US as well as

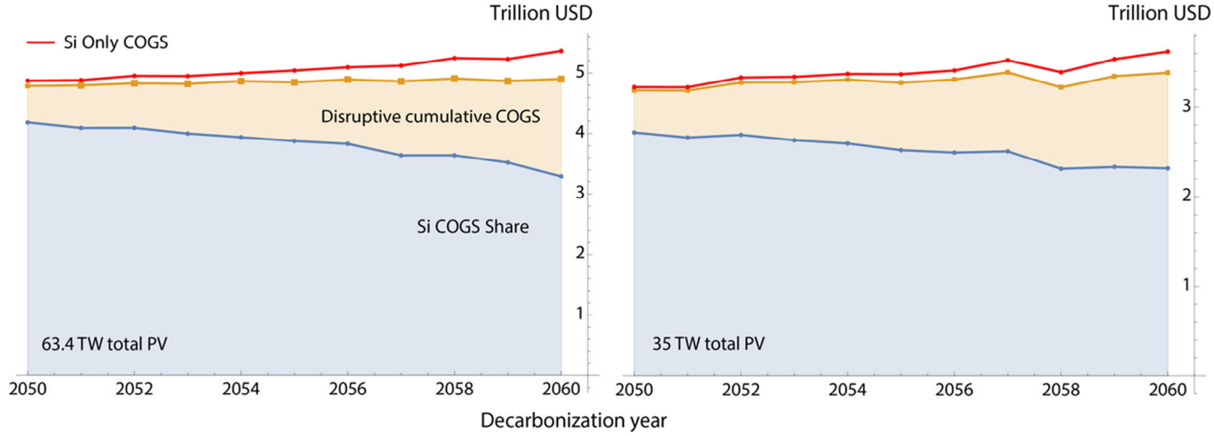

Figure 4. Cumulative cost of goods sold as a function of decarbonization year when a disruptive technology is included in the modeling for a total target of 63.4 and 35 TW total PV to account for contributions from other clean energy technologies to decarbonization. The overall raw cost of manufacturing the PV required is significantly lower when a disruptive technology is introduced and does not depend on the target decarbonization year. The disruptive technology represents a 1–2 trillion USD market opportunity measured as COGS in 2022 dollars.

OxfordPV in Europe, and devices and minimodules based on this technology continue to break records with the current record from CSEM and EPFL at 31.25%. Other possible tandems being developed for commercialization include perovskite on perovskite, CdTe on c-Si, and perovskite on CIGS. All of these technologies still need research and development with respect to scalability and manufacturability at terawatt levels, durability on par with silicon,[17] and circularity, to be viable market alternatives.

3. Conclusions

In this article, we present modeled viable trajectories to supply $>$ 60 TW installed PV capacity to meet the goal of global decarbonization and study the effect of a disruptive technology on deployment cost and market opportunity. The model accounts both for anticipated industry learning as its production volume increases and financiers' avoidance of investments in stranded manufacturing assets. We find that disruptive technologies provide a 1–2 trillion USD market opportunity and that the cost savings potential of such disruptive technologies could amount to hundreds of billions of dollars. Most importantly, disruptive technologies such as solution-processed PV and tandems that provide lower capital intensity than single-junction silicon technology can have a major influence on decarbonization.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available in the supplementary material of this article.

Keywords

decarbonization, disruptive technology, energy systems, energy transition, photovoltaics, renewable energy, solar energy

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