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Building a Bridge to a More Robust and Secure Solar Energy Supply Chain

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Solar Energy Technologies Office

Authors

The authors of this report are:

Markus Beck, U.S. Department of Energy (DOE) - Solar Energy Technologies Office (SETO)

Andrew Dawson, DOE - Office of Clean Energy Demonstration (OCED)

Kyle Fricker, DOE – Office of Technology Transitions (OTT)

Daniel Inns, Boston Government Services, LLC, under contract to DOE-SETO

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Contributors:

Paul Basore, DOE-SETO

Jake Higdon, Office of the Under Secretary for Science and Innovation (S4)

Becca Jones-Albertus, DOE-SETO

Alejandro Moreno, DOE - Office of Energy Efficiency and Renewable Energy (EERE)

Susanna Murley, DOE-SETO

Garrett Nilsen, DOE-SETO

Executive Summary

To support the transition to a decarbonized power sector by 2035 and a decarbonized economy by 2050, the U.S. Department of Energy (DOE) Solar Energy Technologies Office (SETO) has identified potential pathways to a more sustainable, reliable, and resilient supply chain for solar photovoltaic technologies.

A resilient and reliable supply chain is diversified, both geographically and from a technology standpoint. It is not excessively concentrated and is financially sound and can adapt to changes in technology and demand. This report evaluates solar supply chain deficiencies and considers the composition, scale, and role of public and private entities in enabling a more secure energy future.

A robust domestic solar manufacturing sector increases supply chain resilience and brings other direct domestic benefits including job creation, economic development, acquisition and retention of critical know-how, and simplified shipping and logistics.

SETO has identified three exemplary scenarios that can achieve a more sustainable, reliable, and resilient supply chain for solar photovoltaic technologies:

1. Majority domestic production across all required supply chain segments for mature solar technologies (crystalline silicon and cadmium telluride).

2. A blend of domestic sourcing with diversified imports of mature technologies, including broader international production and collaboration for key supply segments.

3. Transition to new solar conversion technologies based on thin films and tandem structures.

During the transition from mostly imported solar components today to a larger market in the near future, the growing domestic manufacturing sector will likely rely on the first two scenarios. The third, new technology option will have limited impact by 2035—although it has significant potential to help achieve the 2050 decarbonization goals. Key considerations for each pathway scenario include: the scale of operations for every supply chain segment, the public and private sector support that the industry may need over time, and the relevant government policies that can reduce barriers to success.

A reliable, resilient supply chain is essential to meeting the Administration’s decarbonization goals. Growth of domestic manufacturing capacity is also a major opportunity to improve national energy security and provide a growing source of family-sustaining jobs.

About this Report

The U.S. Department of Energy (DOE) Solar Energy Technologies Office (SETO) works to accelerate the advancement and deployment of solar technology in support of an equitable transition to a decarbonized energy system by 2050, starting with a decarbonized power sector by 2035. To identify the most affordable, sustainable, and accessible path to decarbonization, SETO seeks to understand and mitigate risks and vulnerabilities that may threaten the success of the energy transition. This report reviews the type and scale of solar supply chain disruption risk, potential options for a domestic supply chain, and key considerations to enable a resilient and reliable supply chain.

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Introduction

In September 2021, SETO released the Solar Futures Study,[1] an analysis of the least-cost path to achieve a decarbonized electrical grid by 2035 and energy system by 2050. The study showed that these transitions are possible—without increasing energy costs to consumers—by utilizing known technologies supported by continuing research, development, demonstration, and commercialization (RDD&C) activities to further reduce their cost and improve performance. However, this transition would necessitate an enormous increase in rate of deployment required for key clean energy technologies, notably solar photovoltaics (PV).

Based on this study, the United States needs to deploy an average of 40 gigawatts direct current (GW_{dc}) of solar generation per year through 2025 and ramp up to 100 GW_{dc} per year by 2030.[1] By comparison, the highest domestic annual deployment on record is 24 GW_{dc} in 2021,[2] with most of the system components manufactured outside the country. The Solar Futures Study did not perform a detailed supply chain analysis and assumed that hardware availability would not limit deployment.

In February 2022, DOE's solar PV supply chain assessment[3] mapped the global crystalline silicon (c-Si) and cadmium telluride (CdTe) supply chains and identified significant disruption risk, especially due to the high concentration of companies with close ties to China in the c-Si supply chain. In addition, domestic production of solar components is far below the current demand and could not supply the necessary components for increased deployment without significant new investment. To decarbonize the electric grid by 2035,[4] the United States will need a secure solar supply chain.

With the recent passage of the Inflation Reduction Act (IRA)[5] and the President's invocation of the Defense Production Act[6] for solar manufacturing, there are new policy tools available to support the growth of manufacturing across the solar supply chain. Tax credits included in IRA are also expected to increase the rate of deployment.

[1] Solar Futures Study, www.energy.gov/eere/solar/solar-futures-study
[2] Solar Market Insight Report 2021 Year in Review, www.seia.org/research-resources/solar-market-insight-report-2021-year-review
[3] Solar Photovoltaics: Supply Chain Deep Dive Assessment, www.energy.gov/eere/solar/solar-photovoltaics-supply-chain-review-report
[4] White House Fact Sheet, www.whitehouse.gov/briefing-room/statements-releases/2021/04/22/fact-sheet-president-biden-sets-2030-greenhouse-gas-pollution-reduction-target-aimed-at-creating-good-paying-union-jobs-and-securing-u-s-leadership-on-clean-energy-technologies/
[5] H.R.5376 - 117th Congress (2021-2022): Inflation Reduction Act of 2022. www.congress.gov/bill/117th-congress/house-bill/5376
[6] www.energy.gov/articles/president-biden-invokes-defense-production-act-accelerate-domestic-manufacturing-clean

This report reviews potential scenarios and associated risks and considerations to bridge the gap toward a resilient and reliable supply chain for solar module technologies, including activities that the RDD&C community can pursue to support these goals.

Current Status of the U.S. Solar Module Supply Chain

More than 85% of modules installed in the United States from 2018 through 2020 were imported.[7] The majority of domestically installed solar modules are c-Si, with most of the supply chain sourced through China as shown in Figure 1. CdTe solar modules, a thin-film technology predominantly from a single U.S.-headquartered company, First Solar, represents the remainder of domestic deployment.

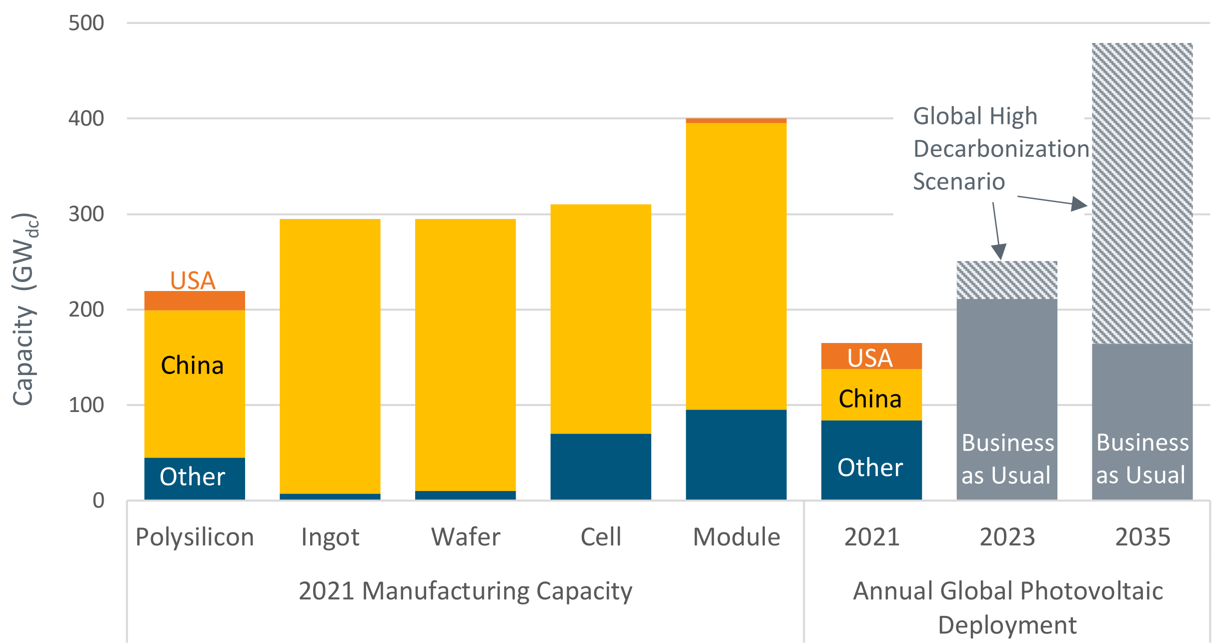

Figure 1: Global PV manufacturing capacity by country, and NREL deployment estimates.[8] Module capacity values include CdTe and c-Si.

For historical context, the first solid-state solar cells based on c-Si and CdTe were developed in the United States in the 1950s, and the U.S. together with Japan dominated the early manufacturing decades (albeit in a market less than 1% the size of today's). The introduction of the German renewable energy incentive scheme in 1999, and subsequent PV deployment policies in other European countries, saw European PV manufacturing increase to over 30% by 2005, as shown in Figure 2. At the same time, U.S. manufacturing dropped to only 10% and China implemented incentives for solar energy to grow manufacturing and deployment. By 2015 China

[7] U.S. International Trade Commission. Public Report: *Crystalline Silicon Photovoltaic Cells, Whether or Not Partially or Fully Assembled Into Other Products*. December 2021. pg. V-36

[8] Solar Photovoltaics: Supply Chain Deep Dive Assessment, Fig. 8. USA 2021 deployment data from NREL Quarterly Solar Industry Update, www.energy.gov/eere/solar/quarterly-solar-industry-update

had overtaken Germany's 40GW$_{dc}$ deployed PV to be the global leader in solar energy production, and the PV module manufacturing capacity expanded with growing local and international demand. The capacity build in China in the module sector was supplemented with upstream supply chain capacity expansions into cells, wafers, and polysilicon to arrive at the 2021 status as shown in Figure 1.

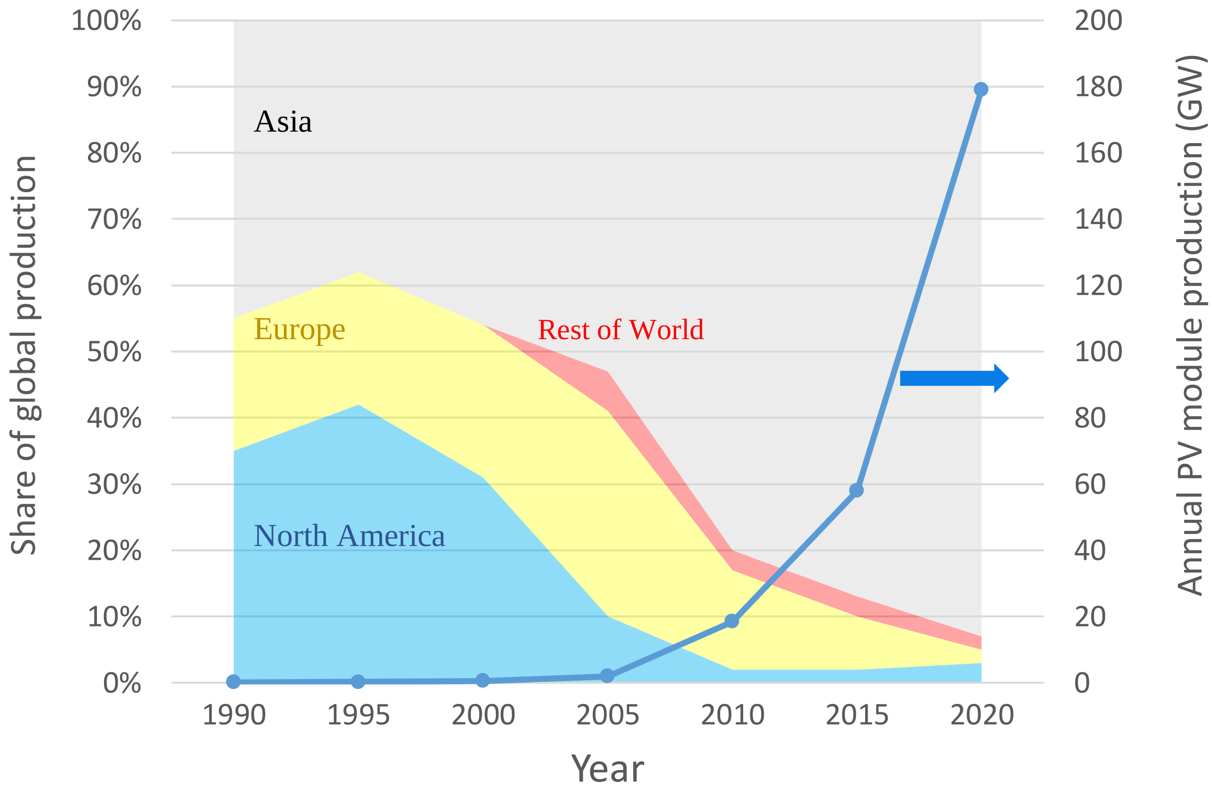

Figure 2: Global PV manufacturing capacity by region, and deployment estimates.[9] Module capacity values include CdTe and c-Si.

The supply chain for c-Si PV starts with silica (silicon dioxide) that is reduced in an electric arc furnace to metallurgical grade silicon, the feedstock to refining of high-purity polysilicon. Polysilicon is melted to grow monocrystalline silicon ingots, which are sliced into thin silicon wafers. Silicon wafers are processed to make solar cells, which are connected, sandwiched between glass and glass or polymeric backsheets using a polymeric adhesive, and typically framed with aluminum to make PV modules. The modules are mounted on racking or tracking structures and connected to the grid using a power electronics device called an inverter.

[9] Photovoltaics report, Fraunhofer ISE. www.ise.fraunhofer.de/en/publications/studies/photovoltaics-report.html
Volume data before 2010: Evolution of solar PV module cost by data source, IEA.
www.iea.org/data-and-statistics/charts/evolution-of-solar-pv-module-cost-by-data-source-1970-2020

The supply chain for CdTe PV starts with refining cadmium, tellurium, and selenium to high-purity compounded powders, which are then deposited directly onto a glass sheet. Another piece of glass and polymeric adhesive and sealant are applied, and a frame might be added to finish the module, which then can be mounted and connected to the grid in an identical fashion to c-Si modules.

As evaluated in detail in the PV supply chain review, the domestic c-Si solar manufacturing sector is composed primarily of established polysilicon production facilities and some c-Si module assembly plants relying predominantly on imported components. While the current domestic polysilicon capacity could supply 20 to 30 GW_{dc} of c-Si products, the United States currently lacks the ingot, wafer, and c-Si cell steps in the silicon PV supply chain. Further, many polysilicon facilities have been mothballed, producing below capacity, and/or serving other industries. The United States has about 5 GW_{dc} of c-Si module assembly capacity, yet annual production output has been below 3 GW_{dc}.[10] As a result, PV deployment in the United States remains dependent on imported c-Si cells and modules.

Due in part to the nature of thin-film manufacturing processes, the supply chain for CdTe modules is more complete in the United States, but globally, production is far less than c-Si modules. The primary producer, First Solar, has production facilities in the United States, Malaysia, and Vietnam, with plans to expand in both India and the United States.[11]

Elements of Reliable Solar Module Supply Chains

Supply chain risks for an industry can come from several issues, including excessive geographic concentration, trade friction, a small number of companies, lack of technological diversity, and poor financial health in one or more segments. Of these, geography, corporate diversity, and technology are key factors in creating a robust solar module supply chain for the United States.

Geographically Diverse Supply Chains

Geographic diversity in the supply chain can mitigate risks from political activities and from disruptions caused by natural disasters or other events that could impact shipping and logistics.

As shown in Figure 1, the global c-Si PV module supply chain is concentrated in China. The U.S. market relies on China for polysilicon, ingots, and wafers, but cell manufacturing and module assembly are typically located in southeast Asia. The majority of these cell and module suppliers in southeast Asia are Chinese-headquartered companies. This poses significant supply risk. Trade friction with China related to forced labor and unfair industrial subsidies, production slowdowns due to COVID-19 restrictions or electricity rationing, increased competition for

[10] Solar Photovoltaics: Supply Chain Deep Dive Assessment, Fig. 52. Note these values are increasing significantly as a result of the incentives in the Inflation Reduction Act.
[11] https://investor.firstsolar.com/news/press-release-details/2022/First-Solar-to-Invest-up-to-1.2-Billion-in-Scaling-Production-of-American-Made-Responsible-Solar-by-4.4-GW/default.aspx

shipping capacity, and other factors have impacted U.S. access to PV modules and components as a result of this concentration of the U.S. PV module supply in China and with Chinese-based companies.[12]

A geographically diverse but predominantly domestic supply chain would bring many benefits. Domestic manufacturing can be a source of tens of thousands of direct and indirect jobs, while ensuring adherence to environmental and labor standards and growing critical technology expertise. Further, if a larger portion of solar module inputs are domestically produced, then the industry would benefit from shorter shipping times and just-in-time manufacturing, which helps minimize working capital and adds financial stability in the system. International shipping costs and associated emissions would also be eliminated.

Another reason to increase domestic production is to mitigate international competition for modules and ensure U.S. access to them. Over 120 nations have set carbon neutrality targets for 2050.[13] To phase out dependence on Russian natural gas, the European Union recently increased and accelerated its cumulative PV deployment targets to 400 GW_{dc} by 2025 and 740 GW_{dc} by 2030. The annual global PV c-Si production capacity in 2021 was about 225 GW_{dc} for polysilicon and 300 GW_{dc} for cells.[14] As the urgency and rate of solar deployment increases, foreign competition for solar modules and other clean energy technologies will increase. This could either increase the cost that U.S. customers must pay for modules, or limit U.S. access if nations such as China or other major producers require domestic product to be used first for domestic projects or favor non-U.S. markets for other reasons.

The United States has the foundations for a robust PV-grade polysilicon supply chain, with multiple facilities in different states—Michigan, Tennessee, and Washington—which have access to reliable and low-cost electricity. Downstream, c-Si module assembly facilities of moderate size (i.e., up to 2 GW_{dc}) exist now[15] in several states and expansions announced to date[16] would nearly triple capacity from 5 to over 14 GW_{dc}. More announcements are expected.[17] While the existing domestic capabilities constitute a good base on which to build a full PV supply chain, the current capacity is far below the market demand. Furthermore, gaps in the supply chain impede innovation as do large geographic separations. A series of vertically integrated supply chain clusters in various regions would enable synergies to reduce cost and drive innovation. First Solar operates facilities that produce close to 3 GW_{dc} of thin-film module capacity in Ohio. They are expanding their Ohio campus to 6 GW_{dc} and recently announced 3.5

[12] June 2022 DOE Solar Market Update. www.energy.gov/eere/solar/quarterly-solar-industry-update
[13] National Public Utilities Council, https://www.motive-power.com/npuc-resource/carbon-neutral-goals-by-country/
[14] EU Solar Energy Strategy, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2022:221:FIN
[15] www.jaxdailyrecord.com/article/jinkosolars-only-u-s-factory-in-growth-mode-in-west-jacksonville
[16] www.georgia.org/press-release/solar-energy-giant-qcells-power-470-new-jobs-new-whitfield-county-facility
[17] www.pv-magazine-usa.com/2022/08/15/nine-gigawatt-solar-manufacturing-facility-being-scouted-for-qcell-module-manufacturing/

GW_{dc} capacity expansions in Alabama. Coupled with their overseas manufacturing operations,[18] First Solar qualifies as a geographically diverse supplier.

Corporate Diversity and Financial Health in Supply Chains

When a few large companies dominate majority market share in any segment of the supply chain, it creates risks of overpricing or having a huge gap in the supply chain. In contrast, multiple entities operating at scale enables the sustainable growth in support industries, supply chains, and the workforce. Companies in different segments of the supply chain must be financially sound, so that the entire ecosystem can expand or contract to address shifts in market dynamics and demand, and adopt next-generation technologies and other process improvements.

In the c-Si supply chain, there are multiple GW_{dc}-scale companies competing vigorously in all segments. However, while some solar cell and module companies are operating with healthy profit margins today, some are operating at low or negative margins, and most are relying on ingot and wafer makers that have historically operated at a loss.[19] While financing within China is available for these low- and negative-margin businesses, there is some longer-term risk around their financial stability. Within the United States, the largest single module producer is First Solar, which is not reliant on the silicon supply chain and historically has had positive profit margins. However, as First Solar represents over 90% of the global CdTe module supply, there is corporate concentration which entails supply chain risk.

As discussed in the prior section, the United States has the makings of strong c-Si module assembly and polysilicon segments with companies independently operating at GW scale. As the supply chain expands into the ingot, wafer, and cell segments, a similar model would be optimal. The objective of a robust supply chain must be for multiple companies to establish operations to mitigate risk and strengthen the supporting network of suppliers and customers.

Technological Diversity in Supply Chains

An industry that is technically diversified can better avoid technology development risks and roadblocks that could limit the competitiveness of products and solutions in future decades. Differentiated technologies in the PV module supply chain can stem from different PV materials, such as c-Si, thin-film CdTe, and potentially emerging technologies like perovskites; while within the silicon supply chain, it could mean different ingot and wafer types, different wafering techniques and cell structures or module architectures, and new application areas. Globally, multiple new technology efforts are being pursued across the ingot, wafer, and cell segments. The future PV industry could look more technologically diverse than it has over the last decade, which was dominated by aluminum-alloyed p-type silicon cells. Encouraging this variety is a

[18] www.firstsolar.com/About-Us/Locations

[19] NREL spring report: www.nrel.gov/docs/fy22osti/82854.pdf

good hedge against the possible limits or failure of any single technology and limits the need for a whole industry to adapt to disruptions.

Thin-film CdTe technology is the most mature material alternative to silicon. The combined current annual CdTe production capacity is less than 11 GW_{dc} and the total capacity that the CdTe industry can reach is constrained. The primary limit is tellurium supply, which may cap annual production capacity to about 20 GW_{dc}.[20] If CdTe capacity could expand to 20 GW_{dc} per year by 2030, and if it exclusively served the U.S. market, it would be an important market player but still represent only 20% of the 100 GW_{dc} of yearly deployment the United States requires to achieve its decarbonization goals. In this decade at least, c-Si technologies will constitute the majority of U.S. deployment.

Amorphous silicon and CIGS thin-film solar cell technologies had measurable market share in prior decades, but ultimately failed to compete with the improving cost and performance of c-Si and CdTe. Similarly, while multicrystalline Si dominated the PV market for about a decade, the past decade saw a shift to monocrystalline Si. These developments demonstrate the need for multiple supply chains and technologies to ensure the industry can respond to such changes, even if single entities or technology types fail.

There are emerging technology alternatives to c-Si and CdTe PV technologies. If one of the emerging technologies were to enter the market, grow to multi-GW scale, and quickly establish bankability, it could potentially play a role in diversifying the established supply chain. However, it takes many years of deployment for markets to deem new technologies bankable. Given the capital at risk for installing systems at GW scale using new and unproven PV technologies, it will most likely take close to a decade before any new technology can compete with today’s proven c-Si and CdTe modules. A new technology like a tandem module concept or perovskite cell could add diversity to the supply chain in the following decades, and the supply chain must be able to adapt when these technological changes occur.

Key Elements for Success

Other key elements that reduce risk and improve long-term outcomes for supply chains are: sufficient scale, continued RDD&C, and expanded and consistent policy support. The solar PV supply chain deep dive[21] contains a more detailed assessment of policy elements.

Sufficient Scale

Factories in the c-Si and CdTe supply chain segments become more cost competitive as annual production capacity increases. For ingot, wafer, and cell manufacturing, the threshold of economic viability today appears to be about 2-5 GW_{dc} annual capacity per factory, with

[20] Solar Photovoltaics: Supply Chain Deep Dive Assessment: estimates 20 GW_{dc} annual capacity based on scale of copper mining
[21] Solar Photovoltaics: Supply Chain Deep Dive Assessment, Chapter 3

additional competitiveness as scale increases further. For polysilicon production, more than 10 GW_{dc} yearly capacity is required. These factory sizes enable economies of scale with equipment and component suppliers and allow companies to streamline operations for more complete plant optimization. Vertical integration across key segments of the PV manufacturing supply chain further enhances competitiveness. There is enough demand in the United States for multiple entities operating several large manufacturing plants across all segments.

To ensure robustness and economic viability, overall supply chain scale is also key. Roughly 20 GW_{dc} annual production across all segments of the c-Si supply chain would be needed to enable multiple entities per supply chain segment to be economically viable. To fully support domestic market needs when coupled with CdTe production, the sector would then need to grow 2-3 times by 2030. This would address two critical aspects of scale: facility size and industry competition.

Diversified Support to Industry

Rapid innovation has been central to the solar industry over the past two decades, driving substantial cost reductions and accelerating deployment. For the United States to reduce the supply chain risk and achieve its decarbonization goals, strong partnership between public and private sector funding will continue to be necessary. The needs for partnership span from R&D for next generation technologies, to manufacturing process and equipment development, to assistance in facility siting to workforce development. In addition, partnerships between government and the private sector can facilitate prioritization of diversity, equity, inclusion, and environmental justice considerations.

SETO's applied RDD&C funding works to advance new technologies and accelerate their move to market by strengthening innovative concepts; supporting partnerships with laboratories, facilities, and experts; and providing resources for technology validation. The office's funding programs seek to reduce the barriers to entry for small businesses and enable new technologies to enter the market and make meaningful impacts. This fosters technical maturation and the transition of solutions from academic and laboratory R&D programs to industry.

Achieving an initial 30 GW_{dc} per year scale (i.e., 10 GW_{dc} CdTe and the 20 GW_{dc} c-Si needed for adequate scale) will require a substantial influx of capital to the sector—between $4 billion and $8 billion (see Appendix). The DOE Loan Programs Office has supported innovative technologies with $30 billion over the last 10 years and could assist solar manufacturing companies through debt financing. If appropriated by Congress, Defense Production Act funding could be another source of capital. Various grants and tax credits in the Infrastructure Investment and Jobs Act[22] and Inflation Reduction Act may also support facility builds, upgrades, and operation.

[22] Also known as the Bipartisan Infrastructure Law

Establishing a sustainable domestic and/or diversified supply chain is a complex, challenging process, and regular coordination among public and private sector actors will be essential to effect support of continued innovation across technologies. A portfolio approach will help ensure immediate robustness and sustained viability.

Expanded, Consistent, and Coordinated Policy Support

Consistent policy support is also critical to manufacturing competitiveness and growth. There are multiple types of policies that can support domestic solar manufacturing and coordination between multiple federal, state, and industry actors will be critical.

- **Manufacturing Production Support**: Tax credits tied to production volumes of different supply chain segments can directly offset higher costs of manufacturing in the U.S. until domestic producers reach sustainable scale.

- **Capital Expense and Factory Support**: Considering that the average selling price of modules and their components on the market today is very close to the manufacturing cost[23], an expected low return on investment in the PV supply chain will dampen private sector investment.[24] The high initial investment volume combined with time to build and ramp up production capacity for upstream materials, components, and modules (shown in the Appendix) makes cost of capital a critical hurdle. Removing this barrier by providing sufficient and rapidly deployable capital in the form of grants, loans or tax credits would encourage private-sector investment in domestic manufacturing, as the industry would be more competitive in a global marketplace.

- **Safeguard Tariffs and/or Anti-Dumping/Countervailing Duties**: Trade policy can improve the domestic competitiveness of specific segments of the supply chain by increasing the cost of competing imports. However, this can create higher costs for deployment. Trade policy should be coordinated so that protection for individual segment(s) of a supply chain do not negatively impact the competitiveness of domestic upstream or downstream supply chain segments.

- **Policies supporting consistent and growing deployment:** Policies such as the federal renewable electricity investment tax credit[25] can increase domestic demand, forming a strong and growing customer base for the local manufacturing sector. This will support greater utilization of any newly built supply chain capacity. As deployment increases in future decades, the supply chain can expand from the established base and take full advantage of the growing scale: to improve costs, increase geographic and corporate diversity, and therefore minimize risk for future investment across the supply chain.

[23] www.nrel.gov/solar/market-research-analysis/solar-manufacturing-cost.html
[24] Solar Photovoltaic (PV) Manufacturing Expansions in the United States, 2017–2019: Motives, Challenges, Opportunities, and Policy Context www.nrel.gov/docs/fy21osti/74807.pdf
[25] Homeowner's Guide to the Federal Tax Credit for Solar Photovoltaics, www.energy.gov/eere/solar/homeowners-guide-federal-tax-credit-solar-photovoltaics

- **Domestic and local content requirements:** Tax credits for solar deployment or state or federal procurements can be contingent on (or increased by) domestic content. This would generate additional demand for domestic products and act as an incentive for a local supply chain.

Policy uncertainty has a critical impact on domestic manufacturing. Because of the large capital expenditures for factories and associated return on investment periods of up to 15 years, the potential for changes in the specific values, durations, or existence of incentives can alter the viability of the project. There is also a lag time of 1 to 4 years between manufacturing support policies and the increased manufacturing capacity due to required time for siting, securing financing, construction, and commissioning of new facilities.

Supply Chain Scenarios

Reducing the U.S. solar industry's reliance on a concentrated foreign supply chain and improving domestic competitiveness would help to manage the risks associated with the current PV module supply chain. Three supply chain scenarios that could achieve these goals include:

1. **Majority domestic with mature technologies.** This scenario would focus on domestic production in all key segments of the module supply chain for both existing commercial technologies (c-Si and CdTe). It requires sufficiently large capacities at each production segment—polysilicon, ingots, wafers, cells, solar glass, encapsulants, and module assembly for c-Si —to make most of the modules needed to meet deployment targets. The domestic industry would need to produce modules at globally competitive prices to incentivize domestic consumption and maintain supply chain viability.[26] Establishing a full c-Si supply chain with several entities across all segments would take 2-3 years as outlined in the Appendix. Sufficient initial scale for competitiveness of the silicon supply chain would be approximately 20 GW_{dc} in annual capacity. With the additional announced and existing CdTe capacity of 10 GW_{dc}, the overall U.S. solar manufacturing capacity would be 30 GW_{dc}. From this base the supply chain would need to grow rapidly to match anticipated growth in market demand. Given the lack of domestic manufacturing expertise in key segments of the c-Si supply chain, the U.S. would initially depend on technology transfer—predominantly for equipment, process, and operational execution. Once approximately 20 GW_{dc} capacity exists, the future build-out can leverage technological improvements (e.g., direct or kerfless wafering, higher equipment throughput, thinner wafers etc.) to assure sustainable operations.
2. **Diverse, international supply chain.** In this case, domestic manufacturing is supplemented by an international supply chain located in friendly countries. The U.S. would rely on imports from reliable trade partners in some or all supply chain segments

[26] Currently it is about 30% more expensive to produce c-Si modules domestically, but the manufacturing production tax credits that are part of the Inflation Reduction Act provide incentives to offset the price difference.

to meet the full domestic demand. This is modeled as half of manufacturing capacity having domestic sources and half coming from imports. Given that timelines for building new capacity can be shorter in other countries, this may be faster to realize than building all capacity in the U.S.

3. **Long-term transition to new technologies.** This scenario considers the possibility of novel PV technologies that would augment, diversify, or replace mature technologies, reducing the need to expand the incumbent supply chains. Besides the ability to compete on energy conversion efficiency and long-term durability, these new technologies will need to demonstrate lower production cost and lower capital intensity to outcompete incumbent technologies for further PV manufacturing capacity expansions. Given the investment volume, time to de-risk a new technology, and lack of immediate availability, this scenario has potential for significant impact only after 2030.

Significant resources will need to be deployed to enable the scenarios outlined above—examples are shown in Figure 2 using domestic cost structures (Appendix). A 100 GW_{dc} per year wholly domestic supply chain would create more than 100,000 new manufacturing jobs and would require over $40 billion investment to build out that capacity. Training and educating such a large workforce would require additional dedicated resources.

Scenario 2 assumes that reliable international partners provide the equivalent of 50% of the U.S. deployment needs, while 50 GW_{dc} per year are produced domestically. Considering the existing 20 GW_{dc} polysilicon capacity, and Si and CdTe module capacity in place and announced[27] to be in place by 2025, this is a much smaller domestic expansion than Scenario 1. Consequently, the number of manufacturing jobs created, and capital resources required, are dramatically reduced.

Scenario 3 requires new technologies, for example perovskites, to be developed and scaled that have cost structures similar to current GW-scale CdTe,[28] which require lower capital and labor intensity than c-Si.[29] Given the uncertainty and approximately decade required to demonstrate bankability this scenario is not relevant to address the 2035 goals.

[27] https://investor.firstsolar.com/news/press-release-details/2022/First-Solar-to-Invest-up-to-1.2-Billion-in-Scaling-Production-of-American-Made-Responsible-Solar-by-4.4-GW/default.aspx

[28] $206 M / GW investment announced for CdTe: https://investor.firstsolar.com/news/press-release-details/2021/First-Solar-Breaks-Ground-on-new-680m-3.3-GW-Ohio-Manufacturing-Facility/default.aspx

[29] $175-200 M / GW investment required for large Perovskites factory > 0.5 GW in theory. I.Matthews et. al. (2020) "Economically sustainable growth of perovskite photovoltaics manufacturing". *Joule*, 4(4), pp. 822

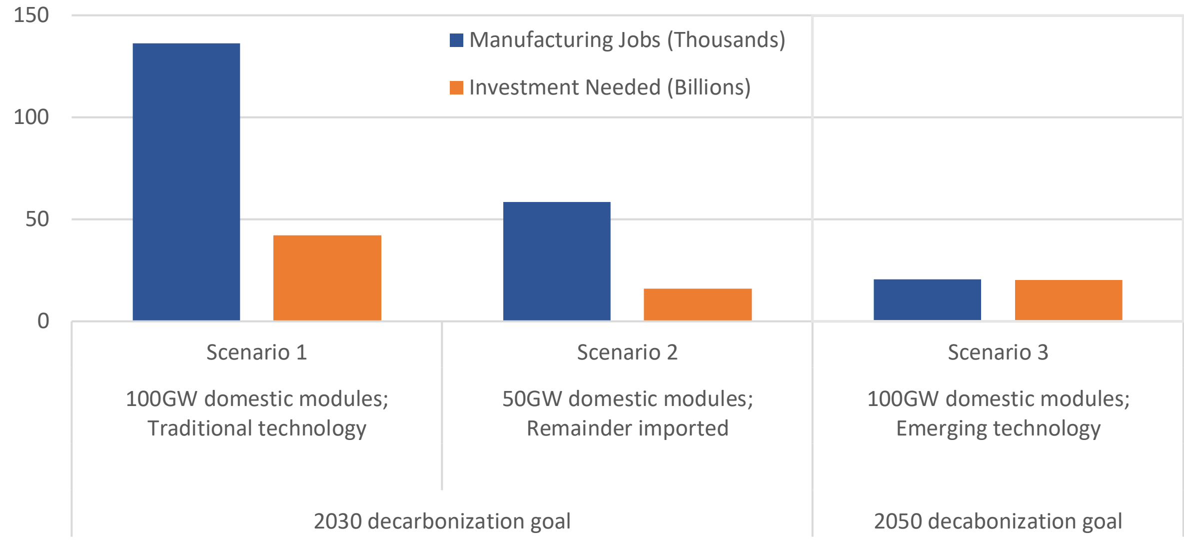

Figure 3: Manufacturing job creation and investment required for different example PV module supply chains.

Scenario 1: 100 GW_{dc} annual domestic module manufacturing by expanding CdTe and growing a complete c-Si supply chain.

Scenario 2: Domestic production of 50 GW_{dc}/year c-Si and CdTe, and reliance on imports for remaining 50 GW_{dc}.

Scenario 3: 100 GW_{dc}/year of domestic production using potential low-cost, less labor-intensive new technologies if they emerge as viable alternatives.

This evaluation has focused primarily on PV module production. However, power electronics (e.g., inverters, optimizers, rapid shut-down devices), other electronic balance of systems components (e.g., cabling, sensors, drives, etc.), and structural balance of systems components (e.g., racking, trackers) must be considered for all scenarios, where they could be leveraged to improve overall national position within the complete solar manufacturing ecosystem.

Note the scenarios are examples only, and the table in the Appendix shows a range of investment and time required to put domestic capacity in place. The detailed values depend on various factors such as equipment availability and cost, degree of automation, geographic location, greenfield vs. brownfield expansion options using pre-existing facilities, permitting, material/consumable suppliers, and infrastructure like railways and roads already in place.

These scenarios have differing levels of relevance to 2035 and 2050 targets. Perovskite and tandem technologies could enable Scenario 3, but even under the most aggressive predictions they will not be in the market at scale for years.[30] Thus, Scenario 3 is not likely to be the best option to support the 2035 decarbonization goals but may significantly supplement capacity by

[30] The Path to Perovskite Commercialization: A Perspective from the United States Solar Energy Technologies Office. ACS Energy Lett. 2022, 7, 5, 1728–1734, https://pubs.acs.org/doi/10.1021/acsenergylett.2c00698

2050. Both c-Si and CdTe represent proven, bankable technologies and Table 1 provides a relative rating of Scenario 1 and 2 versus the status quo (December 2022).

Table 1: Qualitative rating of key aspects associated with the first two scenarios

	Time to Scale	Capital Expenditure	Job Creation	Viability	Leveraging Knowledge Transfer	Supply Chain Diversity	Policy Uncertainty
Scenario 1	−	−	+	●	+	●	●
Scenario 2	●	●	●	+	+	+	+
Status Quo	+	+	−	−	−	−	−

Conclusions

Solar PV is a key enabling technology and a major commercial opportunity for the electricity and energy system decarbonization and energy security of the United States. However, reaching decarbonization goals requires a resilient and reliable supply chain for solar equipment. Today a major gap exists between required U.S. deployment rates and the manufacturing production capacity that the United States directly controls or upon which the nation can rely.

To manage this risk, the United States must quickly diversify solar supply chains and improve our domestic position. To be successful, a domestic sector with a minimum of 30 GW_{dc} annual production for most if not all components of the supply chain is likely needed within 2-3 years, with as much as 100 GW_{dc} needed by 2030. The RDD&C community and federal government will need to take a diversified approach to balance near- and long-term risks as well as providing agile support tailored to industry sector and technology needs. Well-aligned policies could have a strong positive impact, but policy uncertainty will delay or prevent the investment in, and growth of a domestic manufacturing sector. If successful, job growth would be substantial and multiple domestic industries outside of solar energy technologies would benefit, including semiconductor manufacturing and downstream industries such as electric vehicles and energy storage, further improving national security, competitiveness, and employment.

It is critical to act quickly—the 2035 decarbonization goals are aggressive yet achievable and affordable with today's proven solar technologies. Expansion takes time and execution will be risky and imperfect, but failure to act could severely limit the nation's ability to ensure climate and energy security.

Appendix

Investment volume and time to capacity associated with building each key PV supply chain segment for present c-Si and CdTe technologies in the United States.

		Investment Required per Gigawatt (GW) in Millions	Time to Build Capacity	Annual Plant Capacity	Investment for Minimal Viable Sector in Millions 20 GW c-Si and 10GW CdTe in 1-3 Years	Investment for Healthy Sector in Millions ~3X the Minimum ~50 GW Total
Crystalline Silicon (c-Si)	Polysilicon	$250-300	3-4 years (y)	15,000-40,000 Metric Tons (MT)	$0[31]	$6,250-7,000[32]
	Ingot & Wafer	$80-100	1-2 y	>2-5 GW/each	$1,200-2,000	$4,000-5,000
	Cell	$50-130	1-2 y	>2-5 GW/each	$750-2,600	$2,500-6,500
	Module	$50-80	9-15 months	1-20 GW/each	$750-1,600	$2,500-4,000
	Total				$2,700-6,200[33]	$15,250-22,500[34]
Cadmium Telluride (CdTe)		$200-270[35]	1 y	2-10 GW/each	$900-1,100	
Module Components	Solar Glass	$25-35[36]	12-18 months	4-6 GW/each	$375-700	$1,250-1,750

[31] 70,000-75,000 MT existing capacity (~26-28 GW @ 2.7g/W). Note: Solar Photovoltaics: Supply Chain Deep Dive Assessment, www.energy.gov/eere/solar/solar-photovoltaics-supply-chain-review-report states 76,500 MT total across plants sized 1,500-35,000 MT which includes semiconductor grade silicon capacity.
[32] additional 5-20 GW
[33] All in capital expenditures, not including module components or balance of system (BOS) components.
[34] Cumulative all in capital expenditures, not including module components or BOS
[35] Lower bound represents brownfield expansions: https://investor.firstsolar.com/news/press-release-details/2021/First-Solar-Breaks-Ground-on-new-680m-3.3-GW-Ohio-Manufacturing-Facility/default.aspx Greenfield costs more: https://investor.firstsolar.com/news/press-release-details/2022/First-Solar-to-Invest-up-to-1.2-Billion-in-Scaling-Production-of-American-Made-Responsible-Solar-by-4.4-GW/default.aspx
[36] Estimate from U.S. glass industry, depending on thickness and processing like tempering. Note that supply chain report quotes $150M / 2 GW

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