Cadmium Telluride Photovoltaics Perspective Paper

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Disclaimer

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List of Acronyms

CdTe	cadmium telluride
CTAC	Cadmium Telluride Accelerator Consortium
c-Si	crystalline silicon
EOL	end of life
FOA	funding opportunity announcement
GW_{dc}	gigawatts direct current
IRA	Inflation Reduction Act
LCOE	levelized cost of energy
MORE PV	Materials, Operation, and Recycling of Photovoltaics
NREL	National Renewable Energy Laboratory
PV	photovoltaic
PCE	power conversion efficiency
SIPS	Small Innovative Projects in Solar
SETO	Solar Energy Technologies Office
Te	tellurium
TCO	transparent conductive oxide
DOE	U.S. Department of Energy
US-MAC	United States Manufacturing of Advanced Cadmium Telluride

Purpose

This document describes the state of cadmium telluride (CdTe) photovoltaic (PV) technology and then provides the perspective of the U.S. Department of Energy (DOE) Solar Energy Technologies Office (SETO). It describes SETO's priorities to advance CdTe technology through investments to reduce costs, address materials availability and supply chain costs, and support the ongoing scale-up of CdTe technology within the domestic utility-scale PV market.

Executive Summary

CdTe is a key U.S. PV technology that was developed in the United States, has a substantial and growing U.S. manufacturing base, and holds more than a 30% share of the U.S. utility-scale PV market. Due to favorable policies supporting U.S.-based manufacturers and its ability to be made in the United States at a competitive price, CdTe will likely continue to have a role in the expansion of the domestic PV market.

Over the past two decades, the levelized cost of energy (LCOE) has decreased rapidly as power conversion efficiency (PCE) has increased and manufacturing economies of scale have been realized. At present, CdTe provides inherent manufacturing advantages over its main competitor, crystalline silicon (c-Si), including lower energy consumption and lower capital intensity for scale-up. However, c-Si technologies are currently able to attain significantly higher PCE at both the cell and module level, indicating that continued improvement of the CdTe PV technology will be necessary for it to remain viable in the long term.

The competitive position of CdTe PV relative to c-Si PV can be improved by reducing LCOE of CdTe PV and improving end-of-life (EOL) management to retain value in the supply chain. This can be accomplished by accelerating CdTe PV technology innovation, especially module PCE (including bifacial modules that can harvest light from both sides and tandem architectures that contain multiple absorber layers), materials availability (i.e., tellurium), LCOE (e.g., module lifetime, embodied energy), and circularity (recycling), while ensuring there is a skilled workforce to realize this progress. This enhances the performance, reliability, and bankability of CdTe PV holistically. In addition, as CdTe represents a significant share of utility-scale deployment, it is important that general PV system characterization, monitoring, operations, and maintenance tools, which are often based on c-Si technology, accurately assess and represent the performance of CdTe technology. SETO has identified the areas described in this report as top priorities to support the present and future competitiveness of CdTe technology.

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1 Current Status of Cadmium Telluride Industry and Technology

At present, CdTe is the leading domestically fabricated PV technology (by volume) and plays a key role in the expansion of PV deployment and employment in the United States. In 2022, CdTe technology commanded about 34% of the U.S. utility-scale PV market and about 3% of the world PV market, and preliminary 2023 data is currently indicating flat CdTe module shipments year over year.[1, 2, 3, 4] The historical market share of the CdTe module technology in the U.S. utility-scale market segment over the past 10 years is shown in Figure 1. Effectively all CdTe modules are currently used in utility-scale PV systems, as rooftop PV systems have more constraints on system size and efficiency needs that make silicon modules more favorable.

Domestic production of CdTe PV modules supports the U.S. economy, creates jobs, and provides technological diversity to the PV industry. The supply chain relating to CdTe PV is fundamentally different from c-Si PV, with materials and tools within it often sourced from firms in the United States or our allied nations, in contrast to c-Si.[5] As manufacturing of CdTe PV continues to expand, this expansion also helps drive U.S. economic growth.

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[1] Smith, B. L., A. Sekar, H. Mirletz, G. Heath, and R. Margolis. 2024. *An Updated Life Cycle Assessment of Utility-Scale Solar Photovoltaic Systems Installed in the United States*. NREL. www.nrel.gov/docs/fy24osti/87372.pdf.
[2] Feldman, D., K. Dummit, J. Zuboy, and R. Margolis. 2023. *Summer 2023 Solar Industry Update*. NREL. www.nrel.gov/docs/fy23osti/87189.pdf.
[3] Feldman, D., J. Zuboy, K. Dummit, D. Stright, M. Heine, S. Grossman, and R. Margolis. 2024. *Spring 2024 Solar Industry Update*. NREL. www.nrel.gov/docs/fy24osti/90042.pdf.
[4] Feldman, D., K. Dummit, J. Zuboy, and R. Margolis. 2023 *Spring 2023 Solar Industry Update*. NREL. www.nrel.gov/docs/fy23osti/86215.pdf.
[5] See, for example, 5N Plus Inc. 2024. "5N Plus Inc. Renews and Increases Semiconductor Supply Agreement with First Solar." www.5nplus.com/en/news/5n-plus-inc-renews-and-increases-semiconductor-sup/; Department of Defense. 2024. "DOD Awards $14.4 Million to Sustain and Enhance the Space-Qualified Solar Cell Supply Chain." www.defense.gov/News/Releases/Release/Article/3743467/dod-awards-144-million-to-sustain-and-enhance-the-space-qualified-solar-cell-su/; Lasley, S. 2022. "First Solar Powers New Tellurium Demand." *Metal Tech News*. www.metaltechnews.com/story/2022/09/12/critical-minerals-alliances-2022/first-solar-powers-new-tellurium-demand/1082.html.

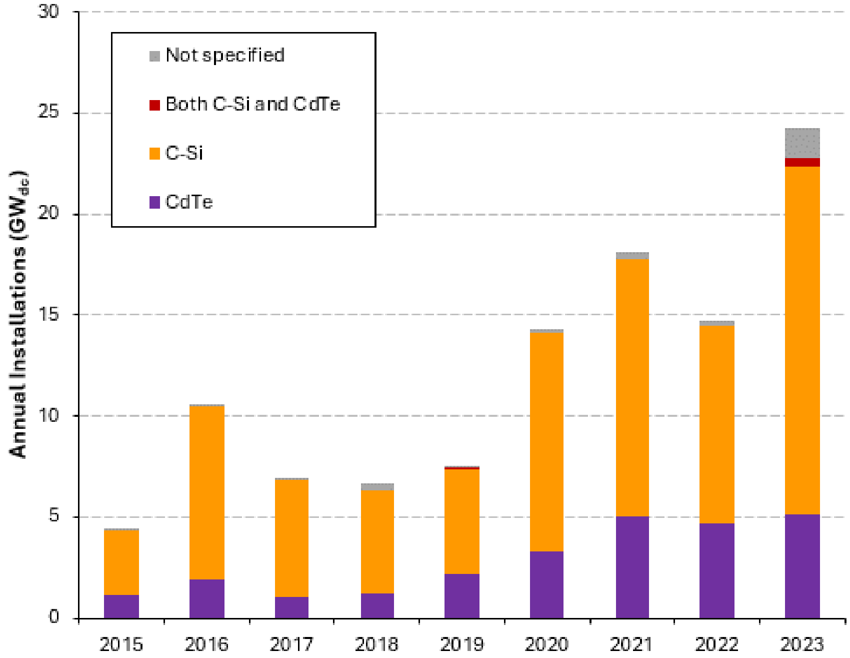

Figure 1. Market share of CdTe and c-Si PV modules in utility-scale PV systems installed in the United States. Figure credit: National Renewable Energy Laboratory (NREL)

Domestic CdTe production is set to exceed 10 gigawatts direct current (GW_{dc}) by the end of 2024 and reach 14 GW_{dc} by 2026.[6] The acceleration in recent CdTe production forecasts has been heavily influenced by the 2022 Inflation Reduction Act (IRA), which incentivizes domestic PV manufacturing. A key challenge for CdTe PV is to remain cost competitive with silicon PV, which is undergoing rapid technology improvement and is also currently poised to increase its U.S. manufacturing capacity.

1.1 Advantages of CdTe Technology

CdTe has many desirable attributes, including high durability, low embodied energy (the sum of all energy used in its production), a fast production process, and established bankability. In contrast to silicon solar modules, which comprise discrete solar cells arranged in strings, CdTe modules are monolithically integrated and directly deposited on single flat sheets of glass. The streamlined manufacturing process of CdTe photovoltaics can offer certain advantages over that of silicon: an 18.5% efficient CdTe module has about 35% the embodied energy compared to a single-crystal silicon module of the same power rating (144 half-cell bifacial silicon passivated emitter and rear contact module with 21% efficiency). One recent paper indicated that the additional embodied energy associated with manufacturing a silicon PV module would take roughly four additional months of module operation to pay back as compared to a CdTe module. [7]

1.2 Competition From Silicon Photovoltaics

Performance of the best R&D CdTe PV cells is currently lower than that of the best silicon cells. The highest-certified CdTe cell efficiency currently stands at 23.1% and was set using a 0.45 cm^2 cell area. The highest-certified silicon cell efficiency is currently 27.3%, set using a 243 cm^2 cell area.[8] The ability to make industrially relevant cells with high-power conversion efficiency is vital in order to provide headroom for commercial module

[6] Kennedy, R. 2023. "First Solar Announces Fifth US factory." *PV Magazine*. www.pv-magazine.com/2023/07/28/first-solar-announces-fifth-us-factory/.
[7] Wikoff, H. M., S. B. Reese, and M. O. Reese. 2022. "Embodied Carbon from the Manufacture of Cadmium Telluride and Silicon Photovoltaics." *Joule*. doi.org/10.1016/j.joule.2022.06.006.
[8] Green, M., Dunlop, E., Yoshita, M., Kopidakis, N., Bothe, K., Siefer, G., Hao, X. and Jiang, J. (2024), Solar Cell Efficiency Tables (Version 65). Prog Photovolt Res Appl. https://doi.org/10.1002/pip.3867.

power output to continue to grow and for the CdTe technology to remain competitive with a rapidly scaling silicon PV supply chain. Worldwide, while c-Si PV has over 1,000 GW_{dc} installed, this compares with around 30 GW_{dc} installed capacity for CdTe PV.[9, 10]

Fleetwide averages of CdTe module efficiency have historically remained within a reasonable margin of monocrystalline silicon modules, as shown in Figure 2. There is significant uncertainty in what will happen in the next few years as the silicon supply chain completes its transition to n-type tunnel oxide passivated contact and heterojunction modules, which could result in a dramatic increase in fleetwide module efficiency levels. The record efficiency of the highest-performing silicon module is 25.4%, while the record efficiency for CdTe modules is notably lower at 19.9%.[8] It will be necessary for CdTe module performance to continue rising for CdTe PV technology to remain competitive in the long term.

There is only one CdTe company manufacturing at gigawatt scale: as of September 2024, First Solar had a 9.4 GW_{dc}-per-year domestic manufacturing capacity accounting for all U.S. CdTe PV module production, and by 2025 over 20 GW_{dc} from factories in the United States, India, Malaysia, and Vietnam.[11, 12, 13] Regardless of their manufacturing location, the majority of all CdTe PV modules are currently deployed in the United States. Due to the low prices of silicon PV modules in the international market, it is currently unlikely that any planned increases in U.S. production will lead to significant CdTe PV module exports in the foreseeable future, although major advances in CdTe cell or module technology could alter this outcome.

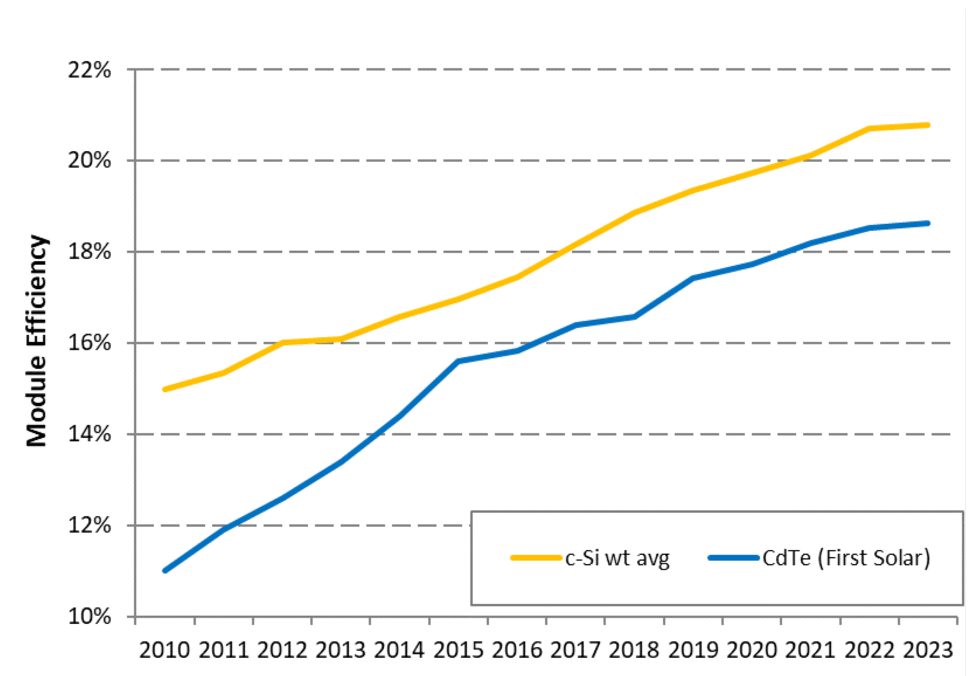

Figure 2. Fleet average efficiency values estimated from published information from the State of California (monocrystalline and multicrystalline silicon) and First Solar (CdTe).

[9] Scarpulla, M. A., et al. 2023. "CdTe-Based Thin Film Photovoltaics: Recent Advances, Current Challenges and Future Prospects." *Solar Energy Materials and Solar Cells*. www.sciencedirect.com/science/article/pii/S0927024823001101.
[10] Di Sabatino, M., R. Hendawi, and A. S. Garcia. 2024. "Silicon Solar Cells: Trends, Manufacturing Challenges, and AI Perspectives." *Sustainable Energy Technology*. www.mdpi.com/2073-4352/14/2/167.
[11] WTOL. 2024. "Toledo Solar to Close, Citing Challenges With Production and Lack of Cooperation From Other Companies." www.wtol.com/article/news/local/toledo-solar-to-close-challenges-production-lack-of-cooperation-from-companies/512-c73ac155-b479-4447-b2a5-28cbb4f5e8dd.
[12] First Solar. 2024. U.S. Securities and Exchange Commission Form 10-Q. https://s202.q4cdn.com/499595574/files/doc_financials/2024/q3/4aa851ff-d2b9-465c-9eae-20806ac61e81.pdf.
[13] First Solar. 2024. "First Solar Inaugurates $1.1 Billion Alabama Facility, Adds 3.5 GW of Vertically Integrated American Solar Manufacturing Capacity." https://investor.firstsolar.com/news/news-details/2024/First-Solar-Inaugurates-1.1-Billion-Alabama-Facility-Adds-3.5-GW-of-Vertically-Integrated-American-Solar-Manufacturing-Capacity/default.aspx.

1.3 CdTe Cost Analysis

The highest-performing CdTe modules are currently made by depositing CdTe onto low-iron float glass with a fluorinated tin oxide transparent conductive oxide (TCO) layer. The combined cost of the front and rear glass sheets can make up 15–20% of the total cost and a large fraction of the embodied energy of a completed CdTe module. Nippon Sheet Glass Group is the preeminent supplier of this commodity, with a large factory (inaugurated in 2020) located near both First Solar and Toledo Solar in Lucky, Ohio. Recently, Vitro Architectural Glass agreed to supply TCO-coated glass to First Solar, expanding and upgrading their Carlisle, Pennsylvania plant.[14]

Supporting the growth, diversity, and scale of the domestic CdTe supply chain could reduce the production cost and increase the cost competitiveness of CdTe modules. A breakdown of estimated CdTe PV production costs is provided in Figure 3, with material costs making up a majority of the final cost of goods sold. There is significant uncertainty in the cost modeling of CdTe module production since actual supply chain costs are proprietary to a single company. However, a useful takeaway from this analysis is that CdTe module production costs in the United States appear to be competitive with production in Southeast Asia, especially considering the impacts of the IRA and the additional shipping costs associated with delivering modules from Asia to the United States for deployment.

Dramatic cost reductions across the silicon supply chain have exerted intense downward price pressure to CdTe modules, which compete directly with silicon modules in the utility-scale PV market.[15] However, the cost competitiveness of domestic CdTe modules relative to imported silicon modules has been protected by trade policy, including tariffs on imported silicon solar cells and modules under section 201 of the Trade Act of 1974 (extended in 2022), anti-dumping and counter-vailing duties against silicon cells and modules from the People's Republic of China and Taiwan,[16] and tax credits for domestic PV manufacturing and domestic content through the IRA of 2022. In particular, the Advanced Manufacturing Tax Credits from the IRA have the potential to dramatically reduce the minimum sustainable selling price of U.S.-produced modules[17] and should provide a significant increase in competitiveness for domestic CdTe manufacturing. Additionally, U.S.-manufactured CdTe modules already have a domestic content of 60–90%, while U.S.-manufactured silicon modules often have a greater reliance on imported components. Given their relatively large domestic content and growing U.S. manufacturing base, CdTe modules are expected to be well positioned to contribute toward the domestic content bonus credit for the Investment Tax Credit and the Production Tax Credit for system developers and owners.

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[14] Vitro. 2023. "Vitro Enters Into Agreement With First Solar for the Manufacture of Glass for American-Made Solar Panels." www.vitroglazings.com/about/news/vitro-enters-into-agreement-with-first-solar-for-the-manufacture-of-glass-for-american-made-solar-panels/.
[15] Smith, B. L., M. Woodhouse, K. A. W. Horowitz, T. J. Silverman, J. Zuboy, and R. M. Margolis. 2021. *Photovoltaic (PV) Module Technologies: 2020 Benchmark Costs and Technology Evolution Framework Results*. NREL. www.nrel.gov/docs/fy22osti/78173.pdf.
[16] In addition, there is a case pending for four southeast Asian countries: International Trade Administration. "Commerce Initiates Antidumping and Countervailing Duty Investigations of Crystalline Silicon Photovoltaic Cells from Cambodia, Malaysia, Thailand, and the Socialist Republic of Vietnam." www.trade.gov/commerce-initiates-antidumping-and-countervailing-duty-investigations-crystalline-silicon.
[17] Internal Revenue Service. www.irs.gov/credits-and-deductions-under-the-inflation-reduction-act-of-2022.

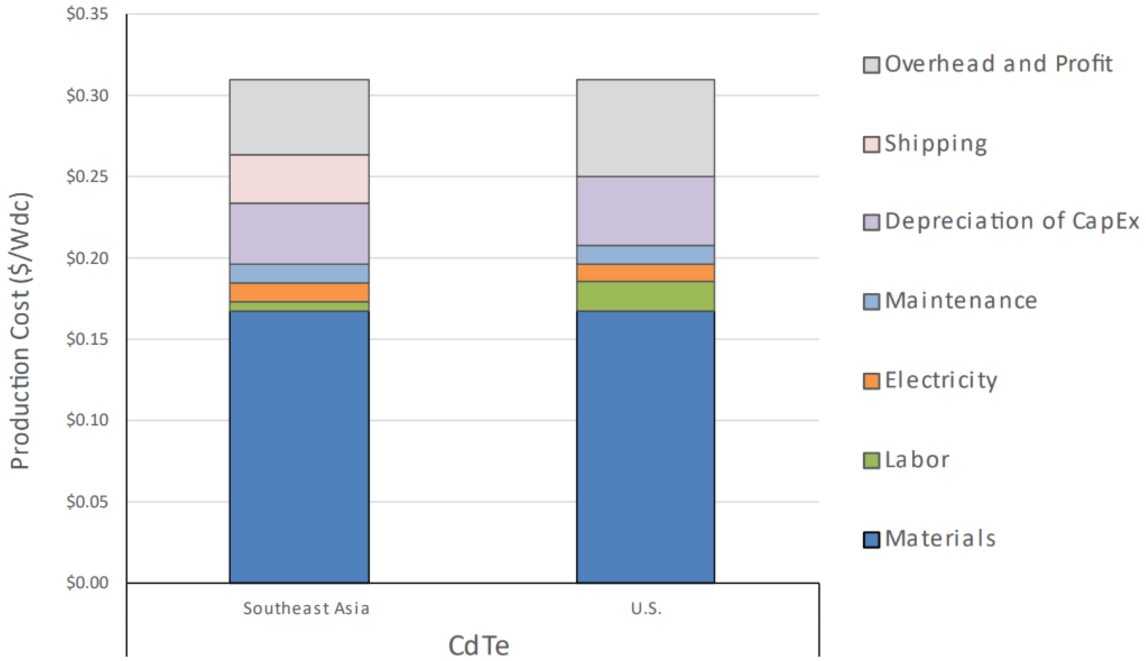

Figure 3. Modeled market price aggregated by cost category for CdTe PV modules produced in Southeast Asia and in the United States.

2 SETO CdTe Portfolio and Research Community

SETO has employed several programs to support the competitive position of CdTe PV.[18] This includes opportunities for cooperative funding agreements and grants for university and national laboratory research and development, as well as industry-focused research, development, and demonstration funding programs. Fiscal year 2020–2023 programming that supported CdTe innovation included multiple PV funding opportunity announcements (FOAs), Small Innovative Projects in Solar (SIPS) FOAs, Incubator FOAs, the Small Business Innovation Research/Small Business Technology Transfer Research funding program, the Technology Commercialization Fund funding program, and the American Made Solar Prize, as well as the CdTe Accelerator Consortium (CTAC) and National Renewable Energy Lab (NREL) core program for CdTe research.[19, 20, 21]

SETO's current and historical investments have supported CdTe PV innovation for LCOE reduction through improved PCE and manufacturing throughput, reduced module embedded energy, higher fielded module energy yields, and enhanced module recycling technology for the reclamation of valuable raw materials (and containment of their toxicity). Key research efforts that have been accelerated by federal support include the development of high-rate vapor transport deposition, Group V doping, and zinc telluride back contact technology. These innovations have ultimately helped enable high-volume high-throughput CdTe process capability with efficiencies

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[18] SETO. Cadmium Telluride. www.energy.gov/eere/solar/cadmium-telluride.

[19] SETO. Solar Research and Development Funding Programs. www.energy.gov/eere/solar/solar-research-and-development-funding-programs.

[20] NREL. 2023. "News Release: NREL Awards $2 Million in Contracts To Support Development of Cheaper, More Efficient Cadmium Telluride Solar Cells." www.nrel.gov/news/press/2023/news-release-nrel-awards-2-million-in-contracts-to-support-development-of-cheaper-efficient-cadmium-telluride-solar-cells.html.

[21] NREL. Cadmium Telluride Solar Cells. www.nrel.gov/pv/cadmium-telluride-solar-cells.html#:~:text=Learn%20about%20NREL's%20expertise%20and%20projects%20on%20CdTe%20photovoltaic%20technology,.

over 19% and long projected lifespans (estimated >25 years).[22, 23, 24, 25, 26, 27] In addition to their direct impacts, these actions collectively have reduced the risk for large-scale investment in CdTe manufacturing technology and accelerated industrial growth.[28, 29]

There are two consortia that are active in CdTe technology development: CTAC, launched by DOE in 2022, is administered by NREL and funds work throughout the domestic CdTe R&D community. This consortium was created in response to specific congressional direction to accelerate domestic CdTe PV and includes key industrial and academic stakeholders. CTAC works toward the goals of CdTe cell efficiencies of > 24% by the end of 2025 and > 26% by the end of 2030, and it periodically releases solicitations for new research projects in areas that are important to the consortium's goals.

The United States Manufacturing of Advanced Cadmium Telluride (US-MAC) consortium was formed as a result of years of ongoing interaction and collaboration between members of the CdTe R&D community. US-MAC goals include enhancing and expanding the CdTe R&D ecosystem, supporting engagement between its members, and working to improve the overall competitiveness and market share of the CdTe PV technology.

3 SETO Priorities for CdTe Research, Development, and Demonstration

SETO accelerates the advancement and deployment of solar technology in support of an equitable transition to a decarbonized economy no later than 2050, starting with a decarbonized power sector by 2035. As a key part of this mission, SETO seeks to enable a sustainable, robust, and resilient solar supply chain that provides domestic value and job creation.[30] SETO accelerates the expansion of domestic manufacturing capacity and spurs private-sector investment by reducing technical and commercial risk of new technologies. The innovations and technologies that SETO funds increase value and domestic content of solar products across the entire supply chain and ensure U.S. technology leadership. Going forward, SETO will support CdTe PV through programs aimed at:

- Improving CdTe cell and module performance
- Increasing materials availability and strengthening the supply chain
- Enabling large-scale deployment and EOL reclamation.

3.1 Improving CdTe Cell and Module Performance

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22 NREL. 2013. "Rapid Deposition Technology Holds the Key for the World's Largest Manufacturer of Thin-Film Solar Modules." www.nrel.gov/docs/fy13osti/59010.pdf.
23 Burst, J. M., et al. 2016. "CdTe Solar Cells With Open-Circuit Voltage Breaking the 1 V Barrier." *Nature Energy*. www.nature.com/articles/nenergy201615.
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26 NREL. 1996. "Stability Testing of CdTe/CdS Thin-Film Photovoltaic Modules." research-hub.nrel.gov/en/publications/stability-testing-of-cdtecds-thin-film-photovoltaic-modules#:~:text=Industry-established%20protocols%20for%20testing%20efficiency%20and%20durability%20such%20as%20ASTM.
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30 SETO. Manufacturing and Competitiveness. www.energy.gov/eere/solar/manufacturing-and-competitiveness.

3.1.1 Increasing PCE

Achieving the highest possible module efficiency remains a major challenge for CdTe technology development, and with silicon PV manufacturers rapidly pivoting toward advanced bifacial and back contact cells that make use of tunnel oxide and heterojunction contact passivation, the race to maximize module performance is likely to become even more intense in the near future.

There are a variety of opportunities in CdTe PV cell and module manufacturing process that can increase PCE.[31] For example, improvements in window transparency, dopant activation, minority carrier lifetime, contact selectivity, and band edge defect states may improve PV performance, while thinner glass can reduce light absorption, cycle time, and total embodied energy.

SETO's support for activities in this area is currently provided through the FY24 Photovoltaics Research and Development FOA, the Advancing U.S. Thin-Film Solar Photovoltaics FOA, and the Materials, Operation, and Recycling of Photovoltaics (MORE PV) FOA. Recent support has also been provided through CTAC's 2023 Small Projects to Accelerate CdTe Technology Development and the SIPS funding program, as well as NREL core program funding for CdTe research.

3.1.2 Advanced Cell Concepts: Bifaciality and Tandem Integration

Modern CdTe PV modules are generally able to produce favorable energy yields per nameplate watt due in part to their temperature coefficient and blue-light spectral response as compared to silicon PV modules. The copper replacement module technology that is currently under development by First Solar represents one of the lowest warranted power loss rates for any PV cell technology and indicates a high degree of confidence in the expected degradation rates of this new technology.

Two areas where CdTe modules currently lag behind other absorbers are bifaciality and tandem integration. Advanced silicon cell technologies such as those using tunnel oxide and heterojunction architectures can exhibit rear-side efficiencies that are 85% or more of the front-side efficiency. CdTe cells are beginning to demonstrate bifaciality, but at significantly lower levels. Tandem cell architectures are becoming quite common in the long-term roadmaps of major PV manufacturers as cell fabrication costs are reduced and increasing efficiency becomes a larger and more potent lever for reducing the overall cost of PV systems. Silicon, perovskites, and copper indium gallium selenide absorbers have bandgaps that are very well suited for integration into tandem cells, but CdTe is caught in a middle ground that is difficult to optimize around. The incorporation of zinc or magnesium to form cadmium zine telluride (CdZnTe) and cadmium magnesium telluride (CdMgTe) represents a possible way to move the bandgap into a viable regime for tandem incorporation, but using these materials introduces processing challenges that have thus far prevented their use in high-throughput manufacturing. This area of research is open to new solutions and may become important in the medium to long term as tandem cell technologies attempt to enter the mainstream PV market.

SETO's support for activities in this area is currently provided through the Advancing U.S. Thin-Film Solar Photovoltaics FOA. Recent support has also been provided through the Fiscal Year 2022 Solar Manufacturing Incubator, CTAC's 2023 Small Projects to Accelerate CdTe Technology Development, and the SIPS funding program.

3.2 Increasing Materials Availability and Strengthening the Supply Chain

3.2.1 Enhancing Tellurium Availability

Tellurium (Te) is a chemical element that makes up 10 to 15% of the cost of a CdTe PV module. Though not seen to date, its constrained availability may place a practical limit on the maximum size of the CdTe PV supply chain. It is difficult to identify this ceiling due to uncertainty in global Te production, which is primarily harvested as a by-product of copper refining. The United States Geological Survey has reported that approximately 640 metric tons of Te were produced globally in 2022,[32] although anecdotal reports indicate that the amount of Te available on the international market may be significantly higher. Historically, copper refining processes have been optimized exclusively for copper production, and Te recovery capabilities have not yet been deployed in many relevant

[31] Scarpulla, M. A., et al. 2023. "CdTe-Based Thin Film Photovoltaics: Recent Advances, Current Challenges and Future Prospects." *Solar Energy Materials and Solar Cells*. www.sciencedirect.com/science/article/pii/S0927024823001101.
[32] U.S. Geological Survey. 2023. "Tellurium." pubs.usgs.gov/periodicals/mcs2023/mcs2023-tellurium.pdf.

copper processing facilities. As Te recovery capabilities are introduced and as global copper production changes in the coming years, the availability of Te will adjust accordingly.

Breakthroughs in the production, refining, or overall availability of Te represent important areas of work due to their ability to significantly increase the maximum possible market size for CdTe PV. More comprehensive implementation of Te recovery capabilities from currently available copper electrorefining residues has been estimated to be capable of substantially increasing global annual Te production, perhaps by a factor of 2–3x.[33] Further Te resources that have been identified include the Te that is currently lost during intermediate steps in the copper refining process, and as part of copper and other metal ore mine tailings, which are estimated as having an additional multiplier effect on potential Te availability. Increasing Te production can be challenging since commodity Te is only produced as a by-product of copper refining and is not mined directly.[34] New technologies that enable the efficient extraction of larger quantities of Te within the copper refining process are needed. Module EOL management through recycling preserves Te that has been extracted while minimizing the energy needed to reuse this critical mineral[35] refined and incorporated into fielded modules for reuse (*vide infra*).

SETO's support for activities in this area is currently provided through the Advancing U.S. Thin-Film Solar Photovoltaics FOA. Recent support has also been provided through CTAC's 2023 Small Projects to Accelerate CdTe Technology Development.

3.2.2 Reducing Supply Chain Costs and Advancing Domestic Manufacturing Methods

Improvements in manufacturing efficiency, including innovations in equipment, metrology, and automation, could increase manufacturing scale and deployment. Innovations to further reduce the embodied energy of module components and to enable larger-volume manufacturing of CdTe PV modules and their components across the supply chain will support increased deployment of this technology. The entire set of materials comprising CdTe PV and the process used to integrate them impacts the cost and lifetime performance of the technology. Improvements to the lifetime performance can decrease the LCOE; however, long-term field validation studies are needed to quantify the value.

Glass advances that can reduce weight or increase supply have the potential to reduce cost. One example is integration of thinner glass superstrates. A 33% reduction in glass thickness (3 millimeter to 2 millimeter) can yield 50% more modules with the same input energy and reduces the shipping weight of finished modules (and therefore embedded energy from glass) by nearly 15%. This also improves throughput and reduces the energy required in all unit processes where the glass is heated and cooled. The operational expenses as well as energy savings should translate to lower manufacturing cost.

SETO's support for activities in this area is currently provided through the Advancing U.S. Thin-Film Solar Photovoltaics FOA. Recent support has also been provided through the Solar Manufacturing Incubator FOA and the American-Made Solar Prize.

3.3 Enabling Large-Scale Deployment and End-of-Life Reclamation

3.3.1 Optimizing CdTe PV Plant Monitoring and Operations

With increasing CdTe PV deployment, innovations in plant and fleet monitoring and diagnostic methods can improve the reliability and reduce the cost of this technology at scale. System operators and operations and maintenance firms that are accustomed to silicon PV modules may need additional information and resources to begin making use of CdTe PV modules. New system monitoring and maintenance approaches developed specifically for CdTe PV systems along with the adaptation to CdTe of best practices currently used on c-Si PV systems can help maximize value and enable even larger-scale deployment of the CdTe PV technology.

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33 Nassar, N. T., H. Kim, M. Frenzel, M. S. Moats, and S. M. Hayes. 2022. "Global Tellurium Supply Potential From Electrolytic Copper Refining." *Resources, Conservation and Recycling*. www.sciencedirect.com/science/article/pii/S0921344922002774.
34 McNulty, B. A., and S. M. Jowitt. 2022. "Byproduct Critical Metal Supply and Demand and Implications for the Energy Transition: A Case Study of Tellurium Supply and CdTe PV Demand. *Renewable and Sustainable Energy Reviews*. www.sciencedirect.com/science/article/abs/pii/S1364032122007213.
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SETO's support for activities in this area is currently provided through the Advancing U.S. Thin-Film Solar Photovoltaics FOA and through the MORE PV FOA.

3.3.2 Building the Solar Workforce

First Solar's planned manufacturing expansions will place significant demands on the local workforce in order to successfully build and staff the intended production facilities. A similar build-out of manufacturing capacity across the silicon supply chain will require similarly capable workers to produce the PV modules needed to drive the ongoing clean energy transition. SETO has an established priority to support the training and advancement of a skilled workforce that is representative of their local communities and of the larger national population. Historically these efforts have been focused on augmenting the downstream workforce that deploys and operates PV systems, but the recent explosion of manufacturing announcements that have followed the IRA and Creating Helpful Incentives to Produce Semiconductors Act has created uncertainty about whether there will be sufficient workers available to build and staff the intended production facilities.

SETO is currently developing its plans to assist in training the U.S. PV manufacturing workforce, and the Scaling the U.S. Solar Manufacturing Workforce Request for Information was previously released to determine the most effective ways to support work in this area. Recent support has also been provided through the Solar Manufacturing Incubator FOA and the American-Made Upskill Prize for the Solar Manufacturing Workforce.

3.3.3 End-of-Life Material Recovery

As the number of deployed CdTe systems grows and the fleet ages, EOL planning becomes increasingly important. As CdTe PV modules approach their eventual decommissioning, it is generally the responsibility of the system owners to ensure that modules are recycled or disposed of in compliance with any applicable regulations. SETO wants to help enable every CdTe PV module to be disposed of according to any applicable regulations, and to improve recycling technology so the component materials can be recaptured by the domestic supply chain. Given that millions of PV modules are deployed every year, it will be a significant challenge to successfully return them to recycling facilities for processing. New ideas or technologies that can assist with this goal are also of potential interest for future RD&D efforts.

Reclamation and recycling of CdTe PV materials that are eventually decommissioned from the field can also help extend the availability of Te, although this material stream will be delayed by the significant service lifetime of typical PV modules. Other materials used in modules, such as aluminum, steel, selenium, and glass, are also potentially recyclable. Innovations in CdTe PV recycling processes and their automation can further reduce waste and cost and improve materials availability. CdTe module recycling technology has already been demonstrated by First Solar at moderate scale and has the potential for further innovation. While manufacturing scrap is recycled on-site, EOL CdTe modules are currently primarily landfilled, as it is currently much cheaper than recycling.

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4 Conclusion

CdTe PV is playing an important role in the rapid domestic PV manufacturing expansion required to support our 2030 decarbonization goals. CdTe is a readily scalable thin-film PV technology for which manufacturing capacity can be rapidly increased, with lower capital expenditure and fewer unit processes compared to silicon. Domestic manufacturing capacity for CdTe is expected to grow more than fourfold by 2026, from 2.8 GW_{dc} in 2022 to 14 GW_{dc} per year. Strategic investments in reducing cost, improving performance, growing the supply chain, improving EOL handling, and managing the growing fleet of fielded CdTe modules will help maximize its future role alongside c-Si PV. SETO has identified the areas described in this report as valuable funding areas to support the present and future competitiveness of CdTe technology.