Financing the Energy Transition

A Tale of Two Solar Technologies

October 2024

Contents

1. Executive Summary

*This report is the third in a series from JFI's **Financing the Energy Transition** initiative, pairing market analysis with levelized-cost-of-energy modeling to evaluate how trade and industrial policy are interacting with market forces to shape the transition to a low-carbon economy.*

Tariff policies intended to protect the US solar industry are unlikely to change the global picture. A lack of upstream solar capacity and new tariffs will likely translate into profits for more vertically integrated domestic producers and additional cost pressures for developers located further down the value chain, risking a slow-down in solar deployment in the shorter term. Using utility-scale data, we show that 2018 marked an inflection point for the experience effects of crystalline and thin-film project costs, which, we argue, can be attributed to tariff policy partially meant to catalyze the adoption of domestic solar technology like thin film. We conclude with a brief overview of recent literature studying the simulated distributional impacts of industrial tariff policy and contrast them with those found in subsidy regimes like the IRA.

Key points:

- *The US solar market has seen increased adoption of domestically produced thin-film technology.*

> Lawrence Berkeley National Lab (LBNL) 2023 Utility-Scale Solar Report, for instance, has reported a growing proportion of thin-film deployments that accounted for 38% of deployments in 2022. NREL's Winter 2024 Winter Solar Industry Report observes that thin-film technology represents around 4% of global PV deployments, but 27% of domestic utility-scale deployments, noting that 34% of systems built in 2022 used cadmium-telluride (CdTe), a leading thin-film technology.

- *This increased adoption is a result of tariff policy intended to catalyze domestic technology and value capture by encouraging substitution away from crystalline technologies produced in Asia.*

> Thin-film technology is notably exempt from tariff restrictions that came into effect in 2018. This, of course, is by design. NREL identifies domestic value capture for different US PV systems in their Fall 2023 Solar Industry Report. Domestic value capture for utility-scale systems averaged **50%** for CdTe vs **20%** for crystalline.

- *While the IRA has resulted in substantial announced investment in domestic manufacturing capacity, these announcements are unlikely to meaningfully change the global balance of solar manufacturing.*

> …93% of polysilicon, 92% of solar cells, and 84% of solar modules were produced by companies headquartered in mainland China in 2023. In addition, the solar manufacturing sector faces an overcapacity problem unlikely to resolve soon: just over 600 GW of modules were produced with 50% of capacity in 2023, with global PV additions totaling 400 GW. To drive home this overcapacity even further, the IEA estimates global capacity with 85% utilization is *already* nearly adequate to meet 2030 NZE and APS demand, and Asia continues to lead the way in solar and battery investment, making dramatic changes in the spatial distribution of solar manufacture even more unlikely…

- *Estimates of experience effects, which account for a substantial amount of variation in levelized cost reductions over time, suggest the policy has been successful at the national level.*

> Compared to the 2010-2018 period, we observe a near **tripling** of thin-film experience effects (15% to 38%) compared to a **doubling** of crystalline (18% to 34%) for the post-tariff 2019–2022 period. Read one way, this could be taken as evidence of the efficacy of the Section 201 tariff regime in accelerating thin-film deployment and experience effects.

- *The existing literature suggests that the increased domestic costs incurred by tariff policy introduces price distortions that, given the structure of the domestic solar industry, hamper more rapid adoption and result in substantial environmental externalities.*

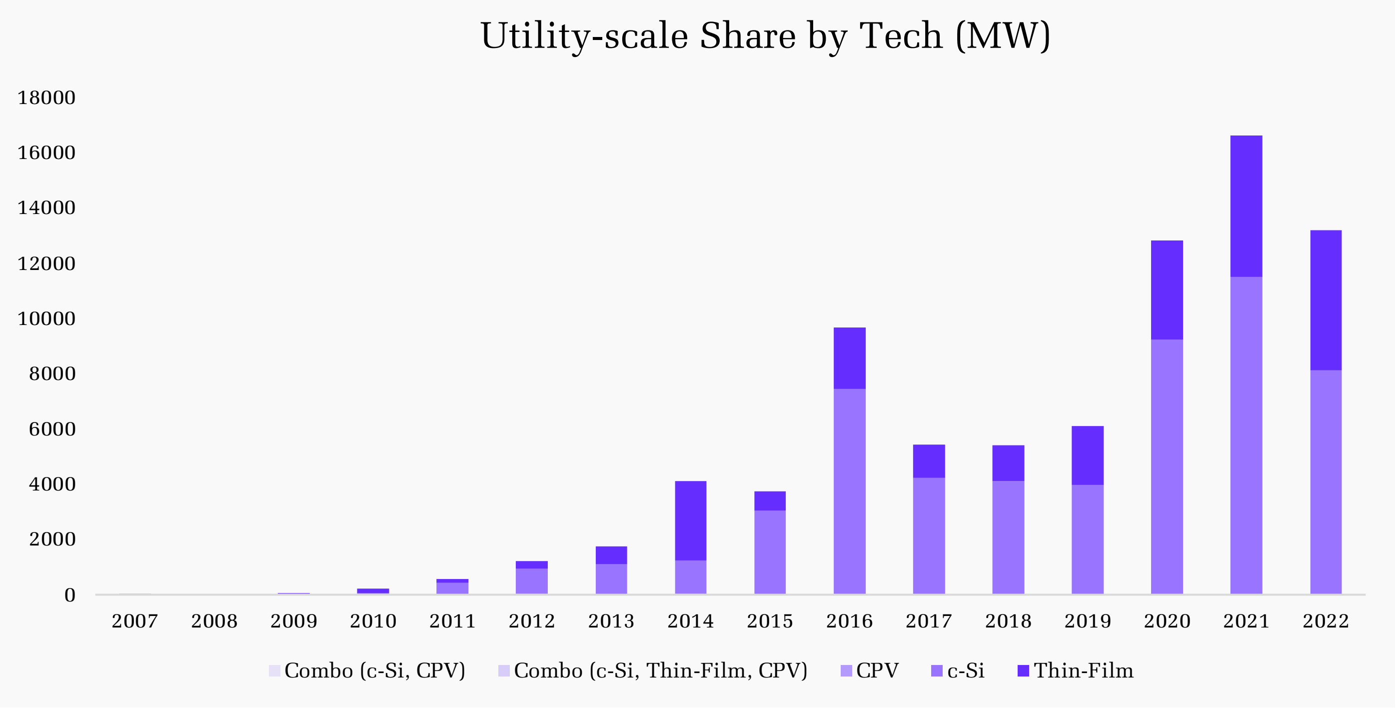
> A more recent Yale study on the effects of solar tariffs from Bollinger *et. al* found much of the same: reduced consumer surplus, large environmental externalities, and a large reduction in US solar employment due to the downstream exposure and market structure of American industry. Their model found much larger benefits from domestic production subsidies like those found in the IRA, "...which would have increased the domestic production share to over 25 percent, and in some periods closer to 50 percent."

- Decoupling solar production from Asia requires a balancing act that meets the urgency of the transition and needs of supply chain security.

Protective tariffs enacted to insulate domestic manufacturers from market forces will inevitably come at a cost to downstream solar developers, installers, and consumers in the short term while capacity continues to scale up and the domestic industry structure adjusts.

2. Thin film & tariffs

There are two main types of solar cell technologies used in utility-scale PV projects: thin film and crystalline. To date, crystalline technology has comprised the lion's share of solar deployments globally and domestically. However, these trends are changing; Lawrence Berkeley National Lab (LBNL) 2023 Utility-Scale Solar Report, for instance, has reported a growing proportion of thin-film deployments that accounted for 38% of deployments in 2022. NREL's Winter 2024 Winter Solar Industry Report observes that thin-film technology represents around 4% of global PV deployments, but 27% of domestic utility-scale deployments, noting that 34% of systems built in 2022 used cadmium-telluride (CdTe), a leading thin-film technology. Despite thin film's lower efficiencies relative to crystalline tech, the technology has several desirable features that make it particularly well-suited for utility-scale projects, including lower levelized costs and a smaller environmental footprint.



LBNL

The more pertinent factor driving thin film's adoption, however, has been a consequence of policy. LBNL explicitly cites Section 201 tariffs introduced in 2018 as at least one reason that thin-film use has grown in their utility-scale sample. NREL, in an earlier 2019 study, used a combination of economic analysis and case study interviews to emphasize the influence tariff policy has on solar manufacturer planning decisions; indeed, the costs and benefits of different tariff policies were mixed for many producers. To quote from the report, "...most firms stated that the section 301 tariffs offset some—if not all—of the US manufacturing competitiveness provided by the Section 201 tariffs." While both types of tariffs derive their authority from the US Trade Act of 1974, Section 201 tariff investigations are conducted by the USITC and are designed to provide temporary relief from import competition. Section 301 investigations, on the other hand, are conducted by the USTR and remain in place on a more permanent basis to counter unfair trade practices. These Section 201 tariffs were put in place on a limited basis at a descending schedule set to expire in 2026, with an exemption on the first 5 GW of crystalline cell imports from a range of countries. Section 301 tariffs specifically target a wider range of imported products from China on a more permanent basis (recently increased for certain products), including cells and modules, lithium-ion batteries and other battery parts, steel and aluminum parts, and semiconductor components used in inverters. Given the concentration of manufacturing supply in China, the 5 GW in cell import exemptions (recently increased to 12.5 GW in response to industry pressure) that accompanied Section 201 module tariffs, the broader range of products targeted by Section 301, and the preponderance of module assembly without upstream capacity in the US, it's unsurprising that the benefits of these policies washed out for some domestic producers.

Tariff	Rate	Scope
Section 201	14.25%	Global, with exceptions, covers cells and modules
Section 301	50%	China, covers cells and modules (many other products included)
AD/CVD*	0.14%-292.61%*	Rates vary by cell and module producer from China, Cambodia*, Malaysia*, Thailand*, Vietnam*

** Pending, preliminary affirmative determinations have been released as of October 1, 2024, which differ from the alleged dumping margins in the initial petition. Rates from PV Magazine and the ITA.*

Another consequence of these Section 201 tariffs was the result of a special exemption granted in 2022, which incentivized most US importers to source crystalline bifacial modules. So pronounced was the use of this exemption that a recent petition by domestic manufacturers cited bifacial import shares as high as 98%.[1] The White House, responding to these complaints, announced on May 14th its plans to remove the exemption to protect US manufacturers from these "unfair imports," tacking on additional duties on SE Asia manufacturers found to be circumventing AD/CVD on Chinese manufacturers. Despite these complaints, as BNEF recently identified, some US-based proponents of these tariff policies enjoy foreign subsidies of their own, underscoring the competitive nature of these petitions. Analysts at Huatai Research, in a June 18 note titled *Positive Factors Benefitting US Homegrown PV Players,* opined on First Solar equity: "...we believe heightened US trade barriers and AI-driven power demand could boost module prices in the US." The market, writing as of October 8, initially priced in much of this good news, with subsequent earnings normalizing multiples.

Bloomberg

Leadership at First Solar further highlighted the role that tariff policy and the IRA have played in stabilizing their decision-making. In their 2023 annual report, they take note of the advantage "access to indirect or direct sovereign capital and support" provides producers in mainland China to compete at or below operating cost. This support includes, among other things: (i) tax breaks, (ii) free or subsidized land, (iii) cash grants, (iv) concessional loans and guarantees often mediated by the China Development Bank, and (v) state-backed equity investment. The benefits of tariff policy's balancing act are unevenly distributed among producers, often varying with the degree of vertical integration, particularly when Asia continues to dominate upstream

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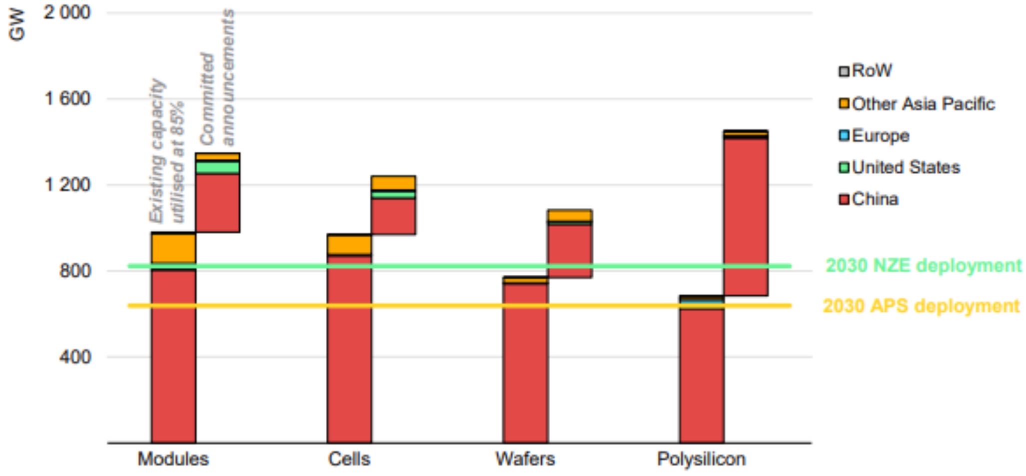
[1] The USTIC released a report in May 2023 with high-level estimates of the economic impacts of Section 301 tariffs on output and price levels between 2018 and 2021. They found domestic producer prices rose by around 3% and Chinese import prices rose by 25% because of the policy (p. 153).

crystalline production used as inputs by many domestic US producers further down the value chain.

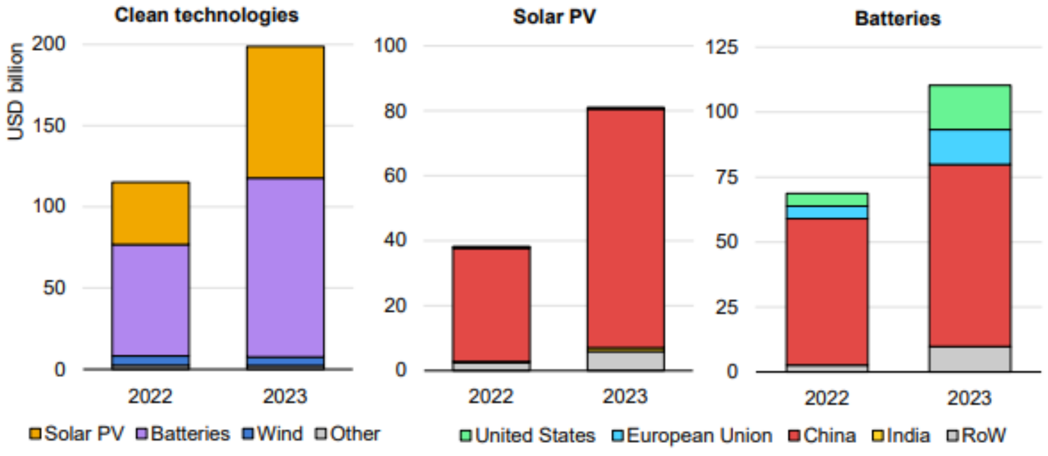
Despite the tailwinds recent tariff announcements would appear to present for a handful of integrated domestic producers, these actions seem unlikely to change the global balance of solar cell and module production, especially in a world where 93% of polysilicon, 92% of solar cells, and 84% of solar modules were produced by companies headquartered in mainland China in 2023. In addition, the solar manufacturing sector faces an overcapacity problem unlikely to resolve soon: just over 600 GW of modules were produced with 50% of capacity in 2023, with global PV additions totaling 400 GW. To drive home this overcapacity even further, the IEA estimates global capacity with 85% utilization is *already* nearly adequate to meet 2030 NZE and APS demand, and Asia continues to lead the way in solar and battery investment, making dramatic changes in the spatial distribution of solar manufacture even more unlikely. **Even if every US module manufacturing announcement** (138 GW) **materialized, existing capacity in mainland China would continue to dwarf that of the US** (over 1 TW in 2023, per Wood Mackenzie). Given these realities, such policy maneuvers are best interpreted as an attempt to decouple domestic clean energy manufacturing from China rather than an attempt to meaningfully shift the balance of global solar production in favor of the US. As the largest integrated US solar module manufacturer, First Solar's strategic behavior in this environment is paradigmatic of the current state of domestic solar manufacturing.

Figure 10 Output from existing and announced solar PV component manufacturing capacity and 2030 deployment levels in the Announced Pledges Scenario and Net Zero Emissions by 2050 Scenario



IEA

Figure 5 **Clean technology manufacturing investment by technology and region, 2022-2023**

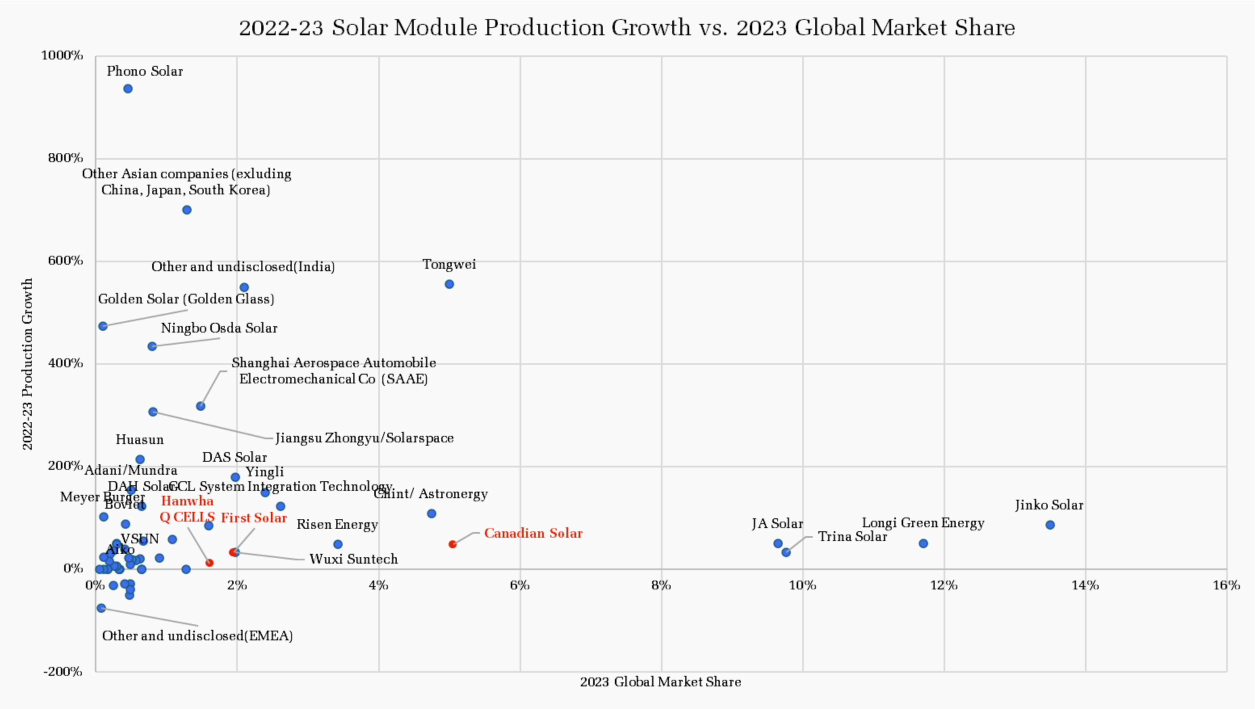


IEA. CC BY 4.0.

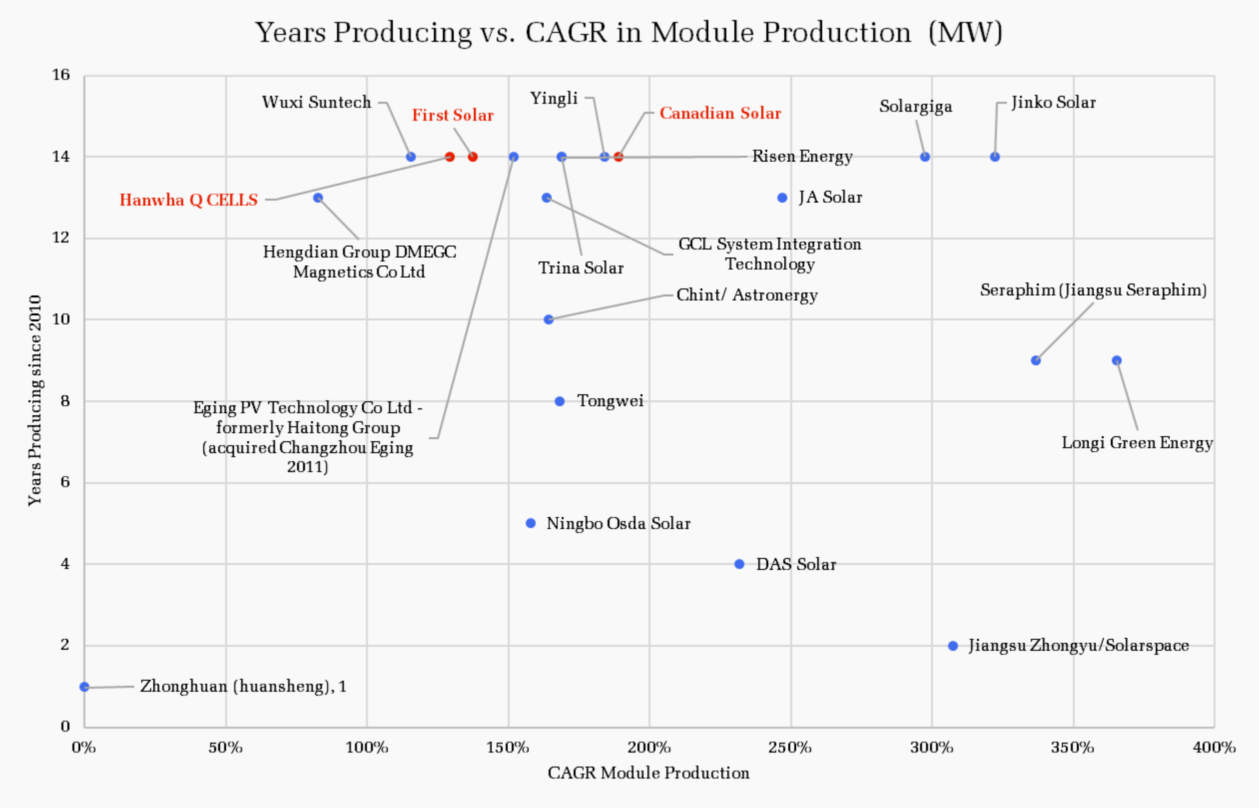
IEA

3. Firm data, scaling supply, & the IRA

We use firm production data from BNEF's solar analyst Youru Tan below to emphasize that module producers in China (in blue) retain dominant market share and continue to grow more quickly than producers based elsewhere (in red). First Solar's global market share is just shy of 2%, with a bevy of producers increasing module production at faster rates. While additional tariff measures may safeguard the domestic US market, the existing policies have done little to change the global picture.


2022-23 Solar Module Production Growth vs. 2023 Global Market Share
2022-23 Production Growth
1000%
800%
600%
400%
200%
0%
-200%
0%
2%
4%
6%
8%
10%
12%
14%
16%
2023 Global Market Share
Phono Solar
Other Asian companies (exluding China, Japan, South Korea)
Other and undisclosed(India)
Tongwei
Golden Solar (Golden Glass)
Ningbo Osda Solar
Shanghai Aerospace Automobile Electromechanical Co (SAAE)
Jiangsu Zhongyu/Solarspace
Huasun
DAS Solar
Adani/Mundra
Yingli
DAH Solar
GCL System Integration Technology
Chint/ Astronergy
Meyer Burger
Boviet
Hanwha Q CELLS
First Solar
Risen Energy
Canadian Solar
VSUN
Aiko
Wuxi Suntech
JA Solar
Trina Solar
Longi Green Energy
Jinko Solar
Other and undisclosed(EMEA)

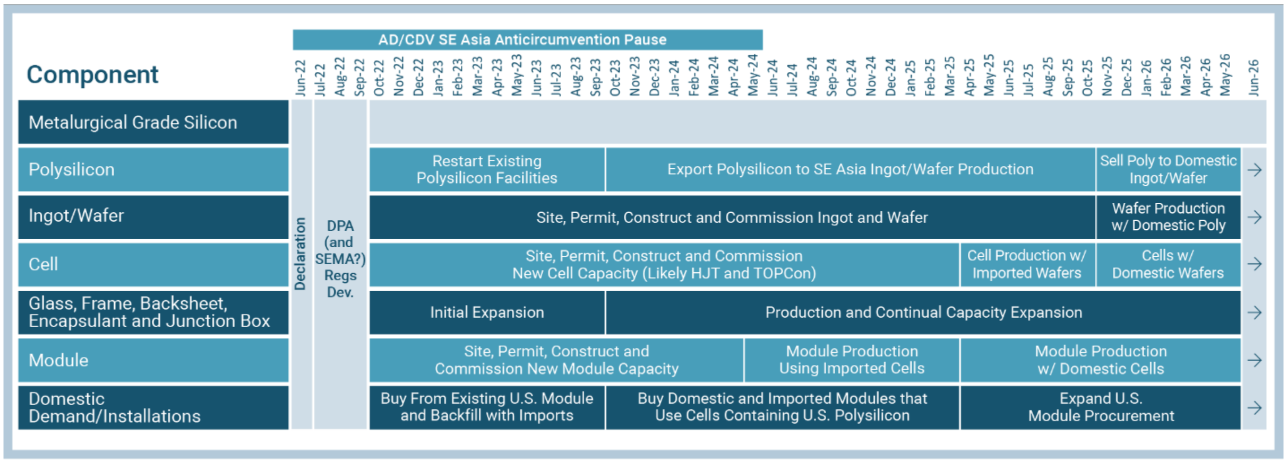
BNEF


Years Producing vs. CAGR in Module Production (MW)
Years Producing since 2010
16
14
12
10
8
6
4
2
0
0%
50%
100%
150%
200%
250%
300%
350%
400%
CAGR Module Production
Wuxi Suntech
First Solar
Yingli
Canadian Solar
Solargiga
Jinko Solar
Risen Energy
Hanwha Q CELLS
JA Solar
Hengdian Group DMEGC Magnetics Co Ltd
Trina Solar
GCL System Integration Technology
Chint/ Astronergy
Seraphim (Jiangsu Seraphim)
Eging PV Technology Co Ltd - formerly Haitong Group (acquired Changzhou Eging 2011)
Tongwei
Longi Green Energy
Ningbo Osda Solar
DAS Solar
Jiangsu Zhongyu/Solarspace
Zhonghuan (huansheng), 1

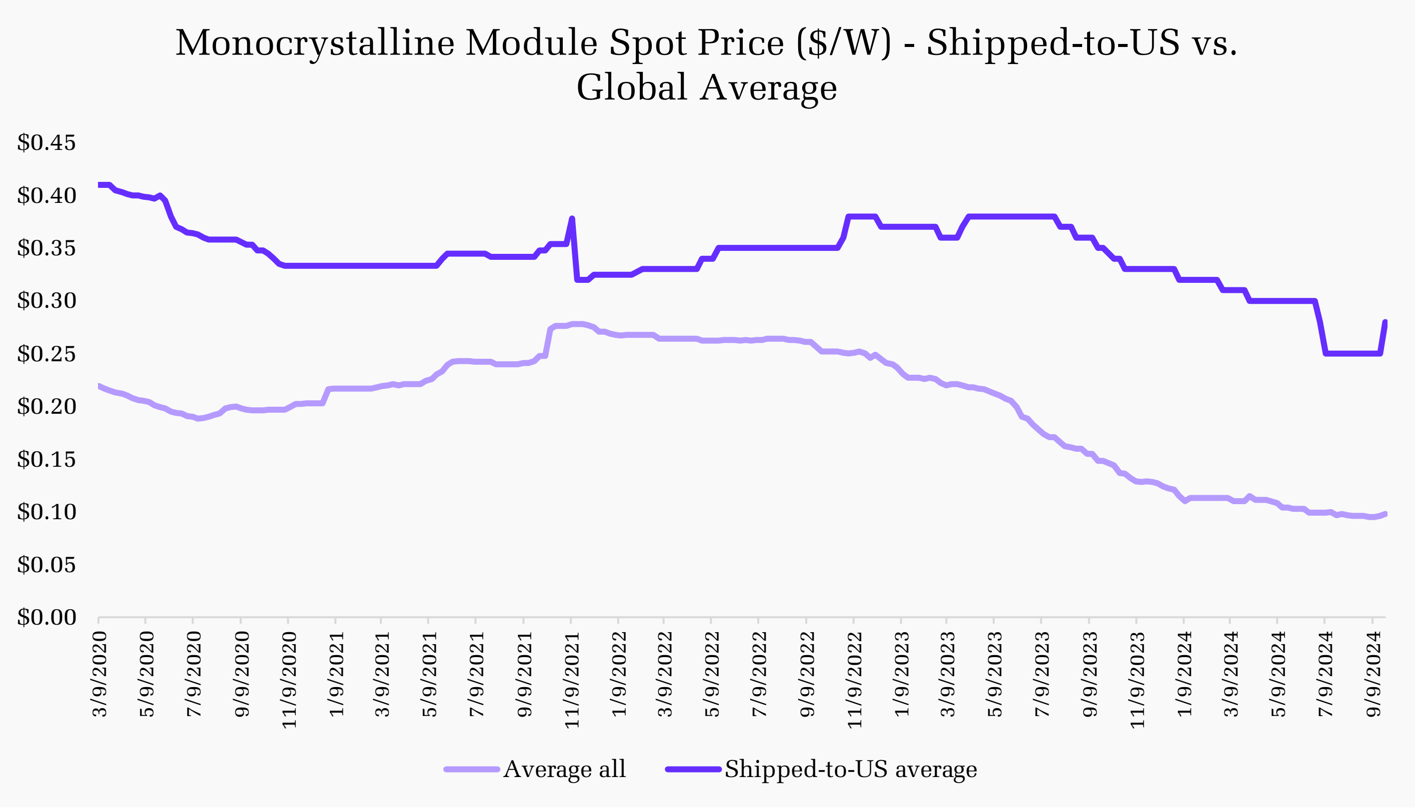
BNEF

This tension between protecting a growing domestic solar manufacturing base and the low costs needed to encourage a rapid deployment hinges on the extent to which domestic capacity can continue to ramp up and move down the experience curve. India's recent vacillation with its relaxation and reinstatement of its Approved List of Models and Manufacturers (ALMM) illustrates the difficulties that come with balancing these competing priorities starkly. In the US, industry groups like the SEIA have offered a glimpse into what this planning process might look like for different parts of the solar value chain, noting lead times of up to **two to three years** for nonexistent domestic crystalline ingot, wafer, and cell production capacity.

As upstream manufacturing capacity scales up in response to the buffer provided by tariff policy, tariffed crystalline wafers and cells from Chinese producers will translate into higher input costs for less vertically integrated domestic manufacturers, eroding margins for exposed producers and potentially forcing them to curtail expansion plans. A conservative estimate of US solar import dependence can be found in the Spring 2024 NREL Industry Update: 7.2 GW_{DC} of PV modules were produced in the US and 32 GW_{DC} of capacity was installed in 2023, which implies that at *least* 77% of installed modules were sourced from outside the US (and potentially even higher if we factor in exports and procurement timelines implied by the 55.6 GW_{DC} of imports in 2023). Given these time and supply chain constraints, it seems unlikely that domestic production can ramp up quickly enough to fully offset cost pressure from new tariff policy in the very short term (US module import spot prices and thin film are already 2–3X the global average, just compare $0.10/W globally and $0.25–30/W for US imports as of July 2024 for monocrystalline to $0.313/W for First Solar's thin film), but new procurement strategies and partnerships may buy domestic producers some breathing room.

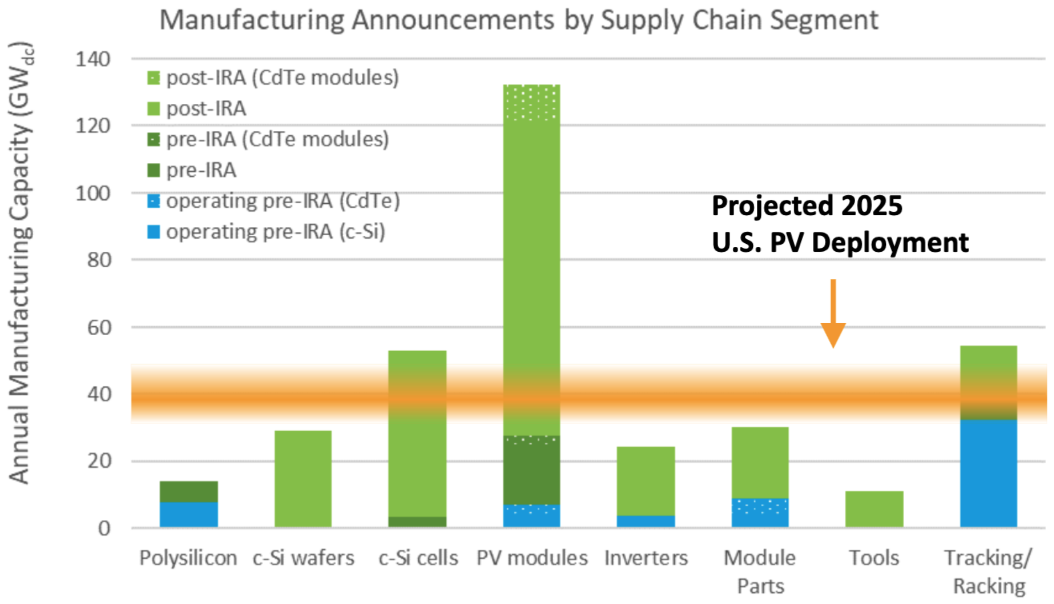


SEIA

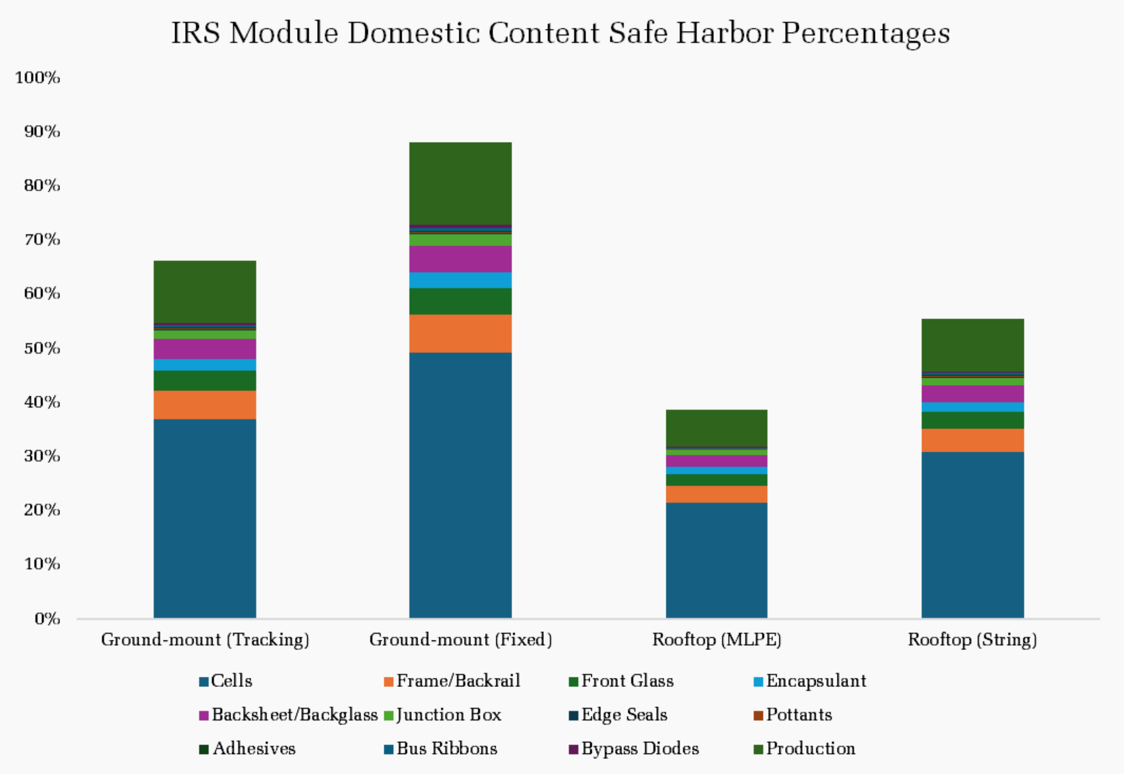


BNEF

The IRA has introduced substantial incentives to domestic manufacturers to support this industrialization process, amounting to $0.17/W according to BNEF estimates and leading to a flurry of manufacturing announcements. The Treasury acknowledges the realities of supply chain constraints in its ITC and PTC domestic content adder guidance: projects beginning construction prior to 2025 are required to source 40% of content domestically, ramping up to 45% in 2025, 50% in 2026, and 55% after 2026. These default “safe harbor” cost percentages for cells and modules are “disproportionately” higher than those found in other representative capital cost studies (compare the safe harbor percentages for modules to those found in the AEO’s cost estimates of ~30%), suggesting a buffer embedded in these incentives intended to stimulate upstream capacity.



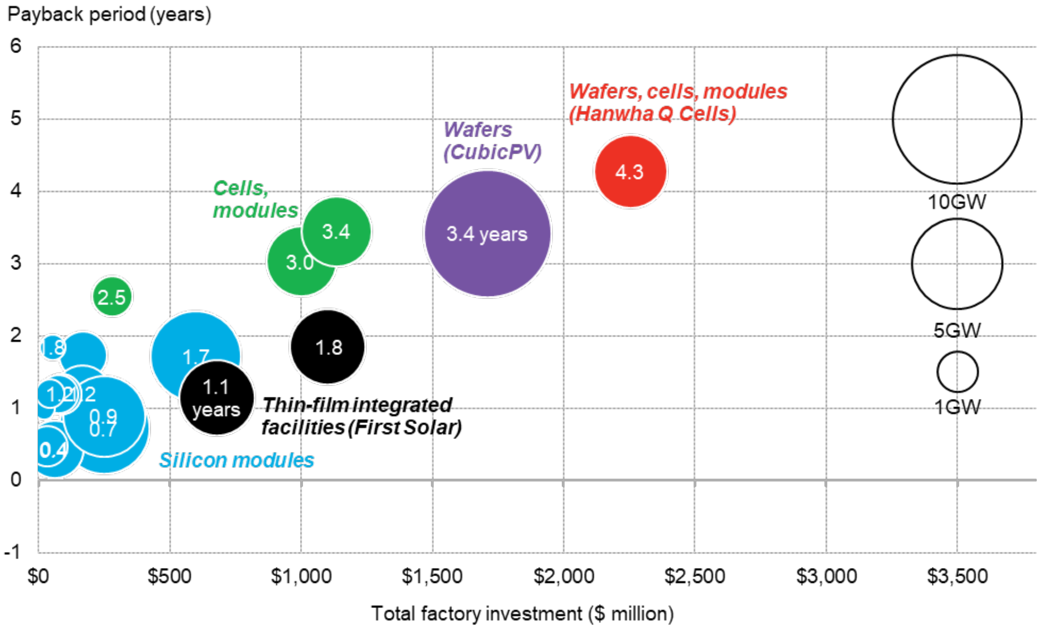
NREL



IRS

These benefits are material and incentivize the build-out of (i) silicon module and (ii) integrated factories relative to upstream components like cells and wafers at current capex and subsidy levels. A case in point: First Solar is projected by Marathon Capital equity research analysts to **support half of its**

gross profit margin through IRA incentives over the next few years, and expects to expand its operational capacity from 6 GW in 2023 to 14 GW by 2026. Analysts at Mizuho Securities, in a recent May 30 note anticipated tariff tailwinds: "...FSLR should be able to sell out all modules through 2029 at least, as competition from new US made solar cells is unlikely to materialize before 2026 (driving a three-year sold out backlog)." And yet, a closer look at LBNL data shows steady growth of First Solar's share since 2018 in the utility-scale PV sample that *precedes* the passage of the IRA, from 14% in 2018 to 19% in 2022, suggesting tariff effects.



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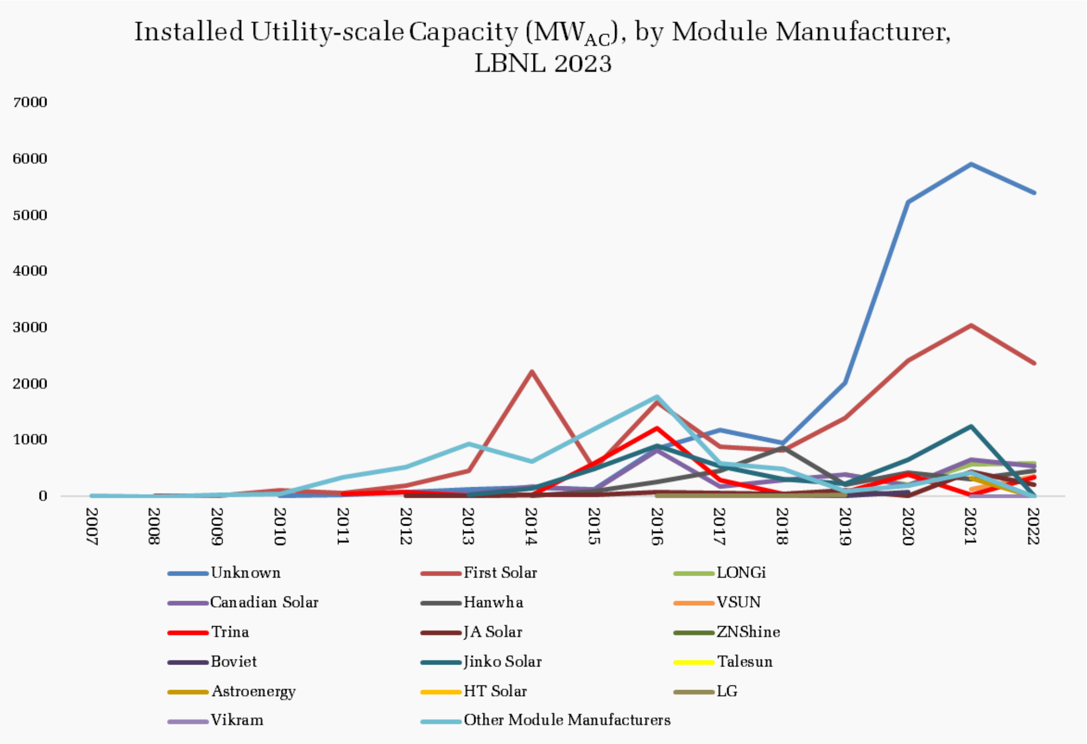
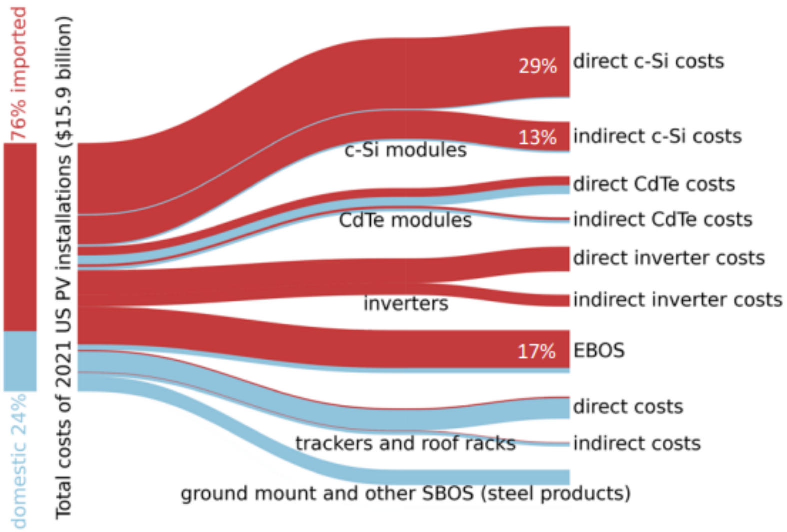
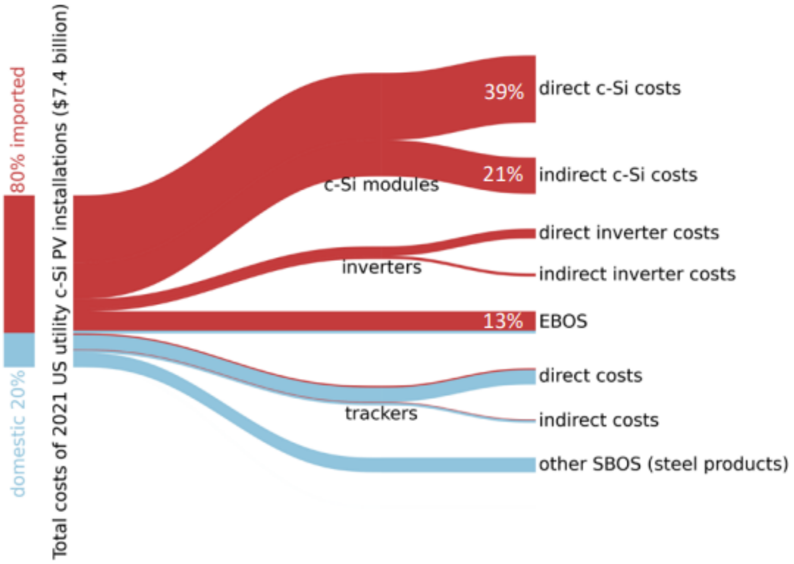


LBNL

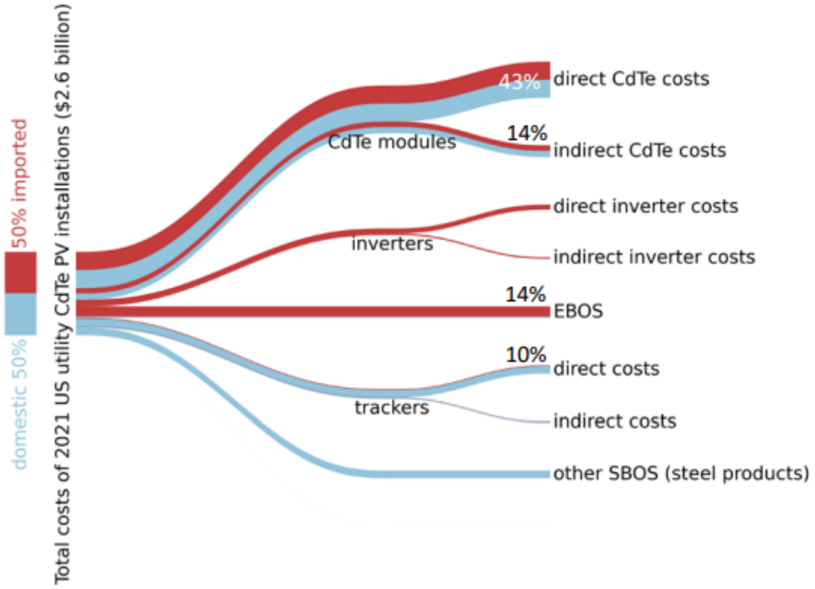
Thin-film technology is notably exempt from tariff restrictions that came into effect in 2018. This, of course, is by design. NREL identifies domestic value capture for different US PV systems in their [Fall 2023 Solar Industry Report](). Domestic value capture for utility-scale systems averaged **50%** for CdTe vs **20%** for crystalline (20%, they noted, was "significantly" below domestic content bonus thresholds).



NREL

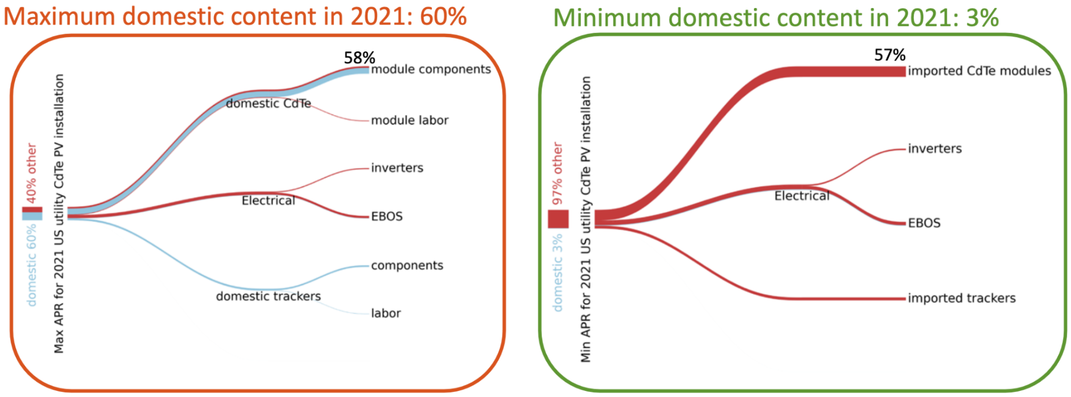


NREL



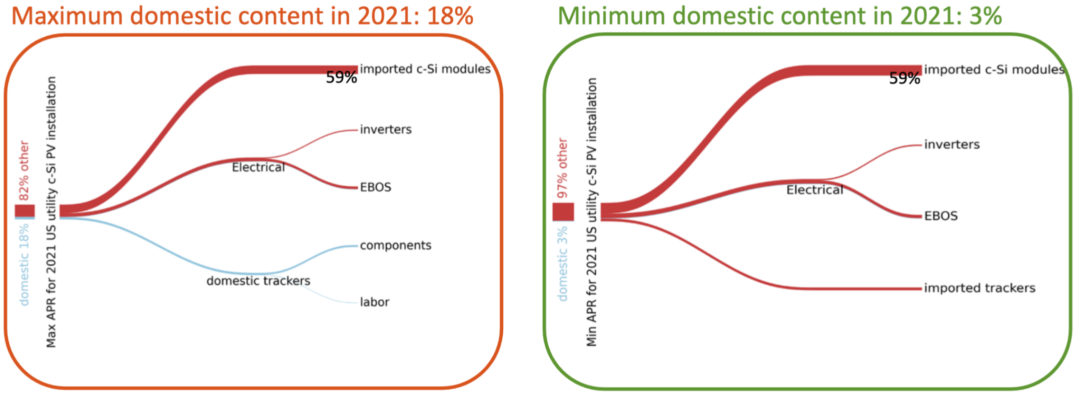
NREL

NREL continues this analysis by bounding domestic value capture ranges for CdTe (3–60%) and crystalline (3–18%) utility-scale systems. This higher potential for domestic value capture for CdTe systems explains, in part, tariff rationale and its hoped-for economic benefits.


Maximum domestic content in 2021: 60%

Minimum domestic content in 2021: 3%

NREL

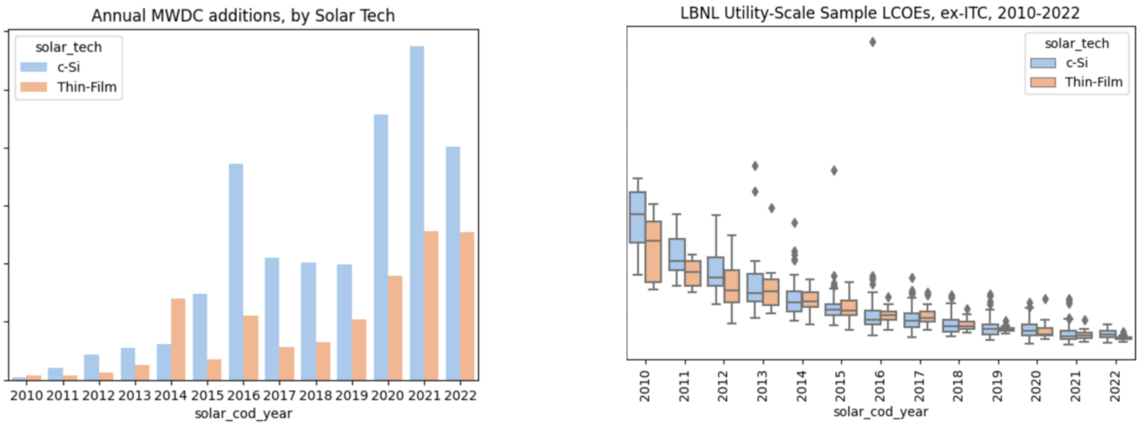

Maximum domestic content in 2021: 18%

Minimum domestic content in 2021: 3%

NREL

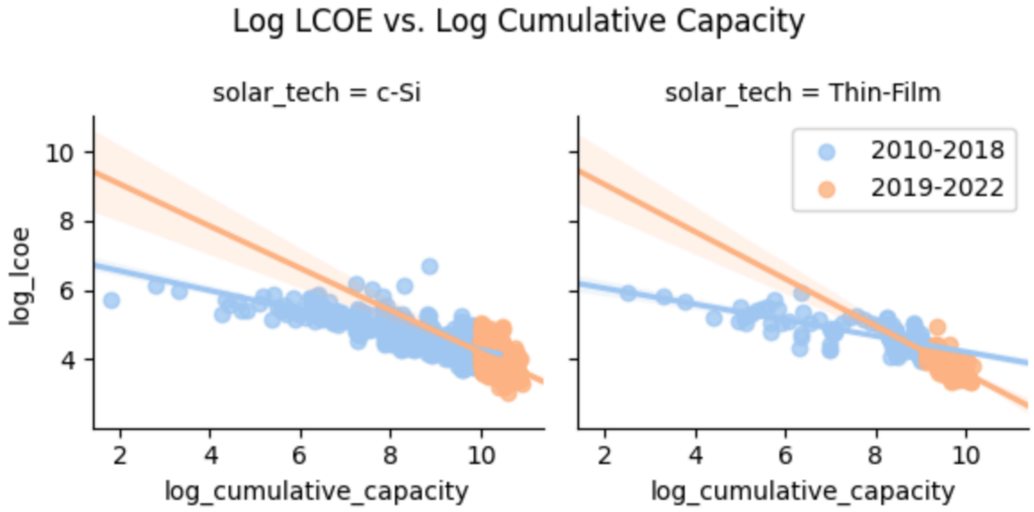
4. Tariff impacts in utility-scale data

These incentives to retain domestic value again prompt us to examine the influence tariff policy has had on domestic production and investment. Using LBNL’s utility-scale project data, we adjust levelized costs for degradation in capacity factor and look at non-hybrid projects that use specifically thin-film or crystalline modules (c-Si) put in commercial operation in or after 2010. We take declining levelized costs as evidence of experience effects for utility-scale projects. Of note is the period leading up to 2018, in which the center of mass of crystalline project costs fell below those of thin film, a trend that then flipped after 2018.

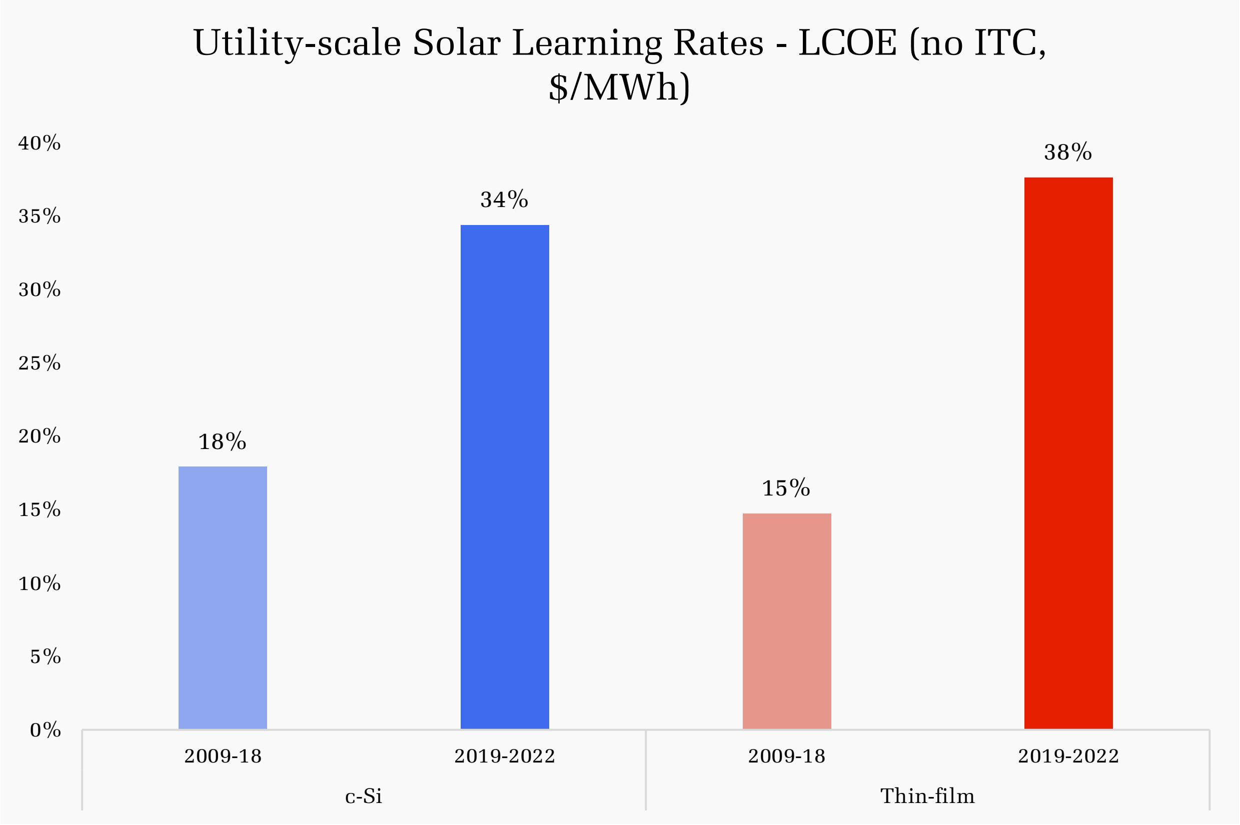


LBNL, Author's own calculations

We use log-log fits to emphasize a convergence between estimated experience effects between thin-film and crystalline technologies. Since Section 201 tariffs came into effect on February 7, 2018, we incorporate a buffer of several months to account for pass-through lags and include projects that came into commercial operation 2019 and after as part of our treatment group. Compared to the 2010-2018 period, we observe a near **tripling** of thin-film experience effects (15% to 38%) compared to a **doubling** of crystalline (18% to 34%) for the post-tariff 2019–2022 period. Read one way, this could be taken as evidence of the efficacy of the Section 201 tariff regime in accelerating thin-film deployment and experience effects.

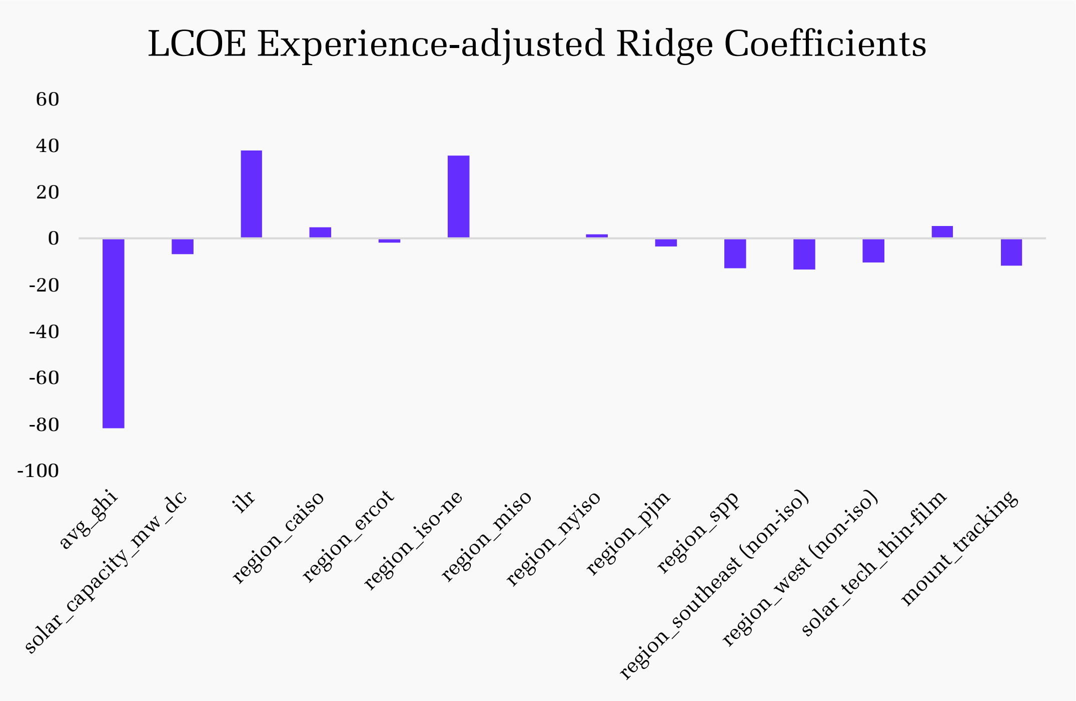


LBNL, Author's own calculations



LBNL, Author's own calculations

In our two-stage model, roughly **40%** of the variance in levelized costs is attributable to these experience effects. Controlling for experience effects, an additional **12%** of variance is explained by regional (irradiance, geographic market) and technical factors (e.g. scale, inverter load ratio, mount type, module technology type). Unsurprisingly, higher average irradiance, which varies substantially by region, translates into reduced levelized costs through increased capacity factors; greater inverter load ratios (presumably to guard against degradation and conversion losses) imply greater capital costs due to greater DC capacity buildout; tracking technology similarly increases capacity factors and thus reduces levelized costs. There is enough regional heterogeneity in thin-film deployment to not place too much weight on the thin-film factor's loadings (ERCOT and CAISO, for instance, had thin-film shares of 30%, while MISO and PJM had shares closer to 10%, and most thin-film projects were built to take advantage of relatively higher irradiance than their crystalline counterparts); the experience-adjusted LCOEs of the overall sample for thin film are ~30% lower than crystalline, suggesting differences between thin-film and crystalline technologies are captured by regional factors.



LBNL, Author's own calculations

Thus, if one accepts this crude proxy for tariff intervention in 2018, we can reframe tariff policy as an effective accelerant for domestic technologies like thin film, perhaps mediated through substitution effects away from more expensive tariffed crystalline.

5. Conclusion

At the national level, tariff policy has helped drive adoption of domestic solar technology. Limited global market penetration and broader solar deployment that meet the urgency of the energy transition, however, remain barriers that can only be overcome by efficient cost competition and coordination strategies that are not solely focused on retaining domestic value.[2] Indeed, studies have found large welfare losses from previous tariffs, with counterfactual estimates of US solar demand in the absence of tariffs 17.2% higher, a loss compounded by tariff pass-through rates as high as 134% (a $1 increase in tariffs results in an estimated $1.34 increase in final consumer prices that Houde and Wang explain is a consequence of manufacturer and installer market power). Distributional results of the study from the

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[2] Illustratively, using AEO 2025 capital cost estimates for utility-scale PV gives us ~30% module-related capital costs. If we take spot prices of $0.25/W and assume a counterfactual of the global average $0.1/W (a reduction of 60%, or 18% at the project level) then with the price elasticity of demand of –0.65 estimated in 2017 by Gillingham et. al for residential systems (which is admittedly quite different) gives us a very crude counterfactual demand estimate for solar PV systems that is 11.7% higher. Assuming a 12% margin over cost production brings this counterfactual demand closer to 10.45% higher.

counterfactual case indicate that (as expected) tariffs are markedly negative for Chinese manufacturers, US installers, consumers, and tariff revenue,[3] but surprisingly only mildly positive for US manufacturers, and this is all before accounting for the social cost of carbon.[4] To follow the logic of the Houde and Wang study to its conclusion, these policies may introduce a degree of price distortion in the solar market that lead to longer-term inefficiency and welfare loss.

Indeed, these losses are intuitive and well-described by traditional economic theory, found in studies evidenced by a broad range of literature cited by the Tax Foundation in relation to the broader 2018 tariff regime: " ... the tariffs have raised prices and lowered economic output and employment since the start of the trade war in 2018." A more recent Yale study on the effects of solar tariffs from Bollinger *et. al* found much of the same: reduced consumer surplus, large environmental externalities, and a large reduction in US solar employment due to the downstream exposure and market structure of American industry. Their model found much larger benefits from domestic production subsidies like those found in the IRA, "...which would have increased the domestic production share to over 25 percent, and in some periods closer to 50 percent."

Solar tariffs are not tech-agnostic or even distributionally neutral; they shift profits away from producers located further down the value chain (module assemblers, developers, installers, and consumers) to incumbent vertically-integrated competing technology manufacturers at the higher price levels needed to stabilize profits and investment, which reduces demand and mass deployment in the shorter term. A careful balance must be struck to avoid missing the forest for the trees; there are more potent, positive instruments at our disposal, like those enshrined in the IRA, to develop an independent solar manufacturing base that avoid missing deployment targets crucial to climate objectives.[5] Protective tariffs enacted to insulate domestic manufacturers from market forces will inevitably come at greater cost than explicit investment and subsidy policies in the shorter term as capacity continues to scale up and the domestic industry structure adjusts.

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[3] Of the close to $560 million of additional total welfare generated in the counterfactual tariff-free case, $295 million went to the US (consumers, installers, offset by a loss in tariff revenue and a minor $6.6 million loss for manufacturers) and $271 million to China (manufacturers).

[4] This same study, which studied US PV installations between 2012 and 2018, used Nordhaus' 2017 cost of $36/tCO$_2$ to arrive at a figure of $252.9 million in 2015 dollars for the social carbon savings in the tariff-free counterfactual case. The EPA's own estimate is $190/tCO$_2$, which would bump counterfactual carbon cost estimates to $1.33 billion. If we are to use even more recent estimates of $1056/tCO$_2$ we get close to $7.4 billion. These cost estimates may continue to increase given recent trends.

[5] For context, the US has produced close to 23% of cumulative historical carbon dioxide emissions between 1950–2018 while China has produced close to 15%. The US is now producing closer to 13%, which on a per capita basis is still among the highest in the world.

6. Appendix

Our two-stage model (i) fits a technology-specific experience curve and (ii) fits a ridge regression on the residuals from (i). By controlling for technology-specific experience effects over time in (i), we were able to increase the number of data points used in the second fit in (ii), eliminating confounders and increasing robustness of the narrative.

The first fit was run on the 2023 LBNL Utility-Scale Solar dataset, restricting the data to thin-film and crystalline projects that were put into commercial operation 2010 or later. Our estimation used cumulative capacity in $\mathrm{MW_{dc}}$ sorted by project commercial operation date, and took the form:

$$\text{(i) } \ln(LCOE_{tech})_i = \alpha_{tech} + \beta_{tech} \cdot \ln(cumulative\ tech\ capacity)_i + \varepsilon_i$$

This was followed by a second tech-agnostic fit of the residuals from (i), which we term $Adj\ LCOE$ (transforming back to non-log terms), using geographic indicators, irradiance, technical factors, and scale/capacity variables taking the form:

$$\text{(ii) } Adj\ LCOE_j = \Sigma_i \beta_i X_{i,j} + \varepsilon_j$$

Note we use continuous fits in (i) for the two technologies for simplicity. This is justified because the fits for 2010–2019 and 2019–22 are not as strong as the combined fits. One potential reason for this is the relative dearth of data and noise introduced by the pandemic for the 2019–2022 period. Separately, using 2018 rather than 2019 as the treatment cutoff emphasizes the degree of convergence even further but fails to account for tariff pass-through lags. We use discontinuous experience effect estimations in this brief solely for descriptive purposes.