Initial Heliostat Supply Chain Analysis

Parthiv Kurup, Sertaç Akar, Chad Augustine, and David Feldman

National Renewable Energy Laboratory

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Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-7A40-83569
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Suggested Citation
Kurup, Parthiv, Sertaç Akar, Chad Augustine, and David Feldman. 2022. *Initial Heliostat Supply Chain Analysis*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-7A40-83569. https://www.nrel.gov/docs/fy23osti/83569.pdf.

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303-275-3000 • www.nrel.gov

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Acknowledgments

Funding provided by the U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy's Solar Energy Technologies Office. The National Renewable Energy Laboratory does not endorse the companies specified in this paper, and any mention is strictly for research purposes.

List of Acronyms

AC	Alternating Current
ATB	Annual Technology Baseline
BLS	Bureau of Labor Statistics
BOM	Bill of Materials
CAPEX	Capital Expenditure
CO_2	Carbon Dioxide
c-Si	crystalline silicon
CSP	Concentrating Solar Power
CST	Concentrating Solar-Thermal
Decarb	Decarbonization
DC	Direct Current
DEWA	Dubai Electricity and Water Authority
DLR	German Aerospace Center
DOE	U.S. Department of Energy
DRC	Democratic Republic of Congo
DSG	Direct Steam Generation
EFS	Electrification Futures Study
EPC	Engineering Procurement and Construction
EV	Electric Vehicles
Gen3	Generation 3
GW	Gigawatts
HelioCon	Heliostat Consortium
HRC	Hot-Rolled-Coil
HTF	Heat Transfer Fluid
IASS	Institute for Advanced Sustainability Studies
IEA	International Energy Agency
IPH	Industrial Process Heat
JEDI	Jobs and Economic Development Impact
kW	Kilowatts
kW_e	Kilowatts Electric
kWh	Kilowatt Hour
LCA	Life Cycle Analysis
LCOE	Levelized Cost of Electricity
LED	Light-Emitting Diode
LPO	Loan Programs Office
MENA	Middle East and North Africa
MFI	Material Flow Through Industry
MT	Metric Tonne
MW_e	Megawatts Electric
MWh	Megawatt Hour
NREL	National Renewable Energy Laboratory
O&M	Operations and Maintenance
OCC	Overnight Cost of Capital
OSW	Onshore Wind
PNIEC	Spanish National Integrated Energy and Climate Plan

PPA	Purchase Price Agreement
PV	Photovoltaics
R&D	Research and Development
SAM	System Advisor Model
sbp	Schlaich Bergermann und Partner
sCO_2	Super Critical Carbon Dioxide
SEGS	Solar Energy Generation Systems
SOTA	State of the Art
TEA	Techno-Economic Analysis
TES	Thermal Energy Storage
TWhth	Terawatt Hours Thermal
UAE	United Arab Emirates
USGS	United States Geological Survey
ZAR	South African Rand

Executive Summary

Globally, the growing demand for concentrating solar power (CSP) technologies, primarily for electricity generation plants, has been met by supply chains composed mostly of plentiful commodity materials, such as steel, aluminum, and glass. The majority of the commodity materials are sourced within the domestic market where the generating plants are constructed. However, specialty components are required for CSP solar field components—including the mirror panels used for heliostat applications—and these specialty components constitute about 30%–50% of total system installed costs. Only a few companies and countries, including the United States, have developed the capacity to supply such specialty components.

CSP manufacturing faces challenges in the United States and globally. Compared to photovoltaics (PV), CSP systems are much more complex and require a much larger minimum effective scale, resulting in higher total capital expenditure (CAPEX) requirements for system construction, lengthier development cycles, and higher energy costs. These CSP characteristics favor large, well-funded manufacturers and can potentially inhibit new, disruptive startup companies. In addition, the lack of consistent CSP project development across the globe creates planning, scale-up, and operational challenges for companies that manufacture specialty CSP components. Finally, the lack of a near-term U.S. market is a formidable challenge to domestic CSP heliostat manufacturers. Challenging project economics have stalled or spurred the cancellation of many U.S. CSP projects, and declining PV costs have influenced the switch of some large solar projects from CSP to PV. The current lack of strong domestic CSP demand makes a near-term expansion of U.S.-based CSP production unlikely.

Several opportunities exist for U.S. CSP heliostat manufacturing in the domestic and global arenas. CSP deployment is expected to grow in regions like China, Africa, and the Middle East over the next 3–5 years. Combining CSP with thermal energy storage (TES) could enable the potential for more rapid CSP growth beyond 2022, when the increasing penetration of PV and other variable generation sources will place a greater emphasis and value on dispatchability. More conservative projects estimate a potential of 39 GW by 2050 (Augustine, Turchi, and Mehos 2022). The United States could also benefit from the same innovation advantages it possesses with regard to PV. Additional innovation, commercialization efforts, and market development are needed for CSP to become competitive with other generating technologies. Further, development of TES and industrial process heat (IPH) applications could enhance CSP's unique benefits. Established U.S. research and development centers contribute to a strong CSP-specific innovation capacity and knowledge base, which could confer an advantage to U.S.-based firms, should domestic demand markets recover.

By 2035, there could be 500,000–1,500,000 direct and indirect solar PV jobs in the areas of installation and development, manufacturing, and operations and maintenance (O&M). Based on the CSP capacity estimates from the "Solar Futures Study," the construction of 39 GW of CSP (assuming mainly power tower) in the United States could lead to approximately 195,000 manufacturing, construction, and O&M jobs. This does not include the longer-term jobs and economic impact (e.g., taxes from plant operations staff) that will arise from operating the plants once they are constructed. We recommend that the field undertake further CSP supply chain analysis as well as a heliostat-focused supply chain modeling effort.

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1 Introduction

Concentrating solar power (CSP) provides significant value for economies, offering baseload-like dispatch of electricity (even at night), grid services, and value (Mark Mehos et al. 2017; World Bank 2021). In addition to electricity generation, other key factors are also important in CSP deployment, including the value of the supply chain, materials and commodities, construction and direct jobs, and workforce development. The United States is a leader in the development and deployment of new clean energy technologies, advancing global climate change goals. However, U.S.-based manufacturers of CSP components and systems have lost market share over the past two decades as systems and technologies such as solar photovoltaics (PV) and onshore wind have become fully commercial, dominating both in the U.S. and globally.

Local manufacturing of renewable energy technologies—and the associated supply chains—help increase a region's ability to adopt and develop industries that support both the domestic and global renewable energy markets (World Bank 2011). For example, for the Middle East and North Africa (MENA) to increase the deployment of an important renewable energy technology like CSP that utilizes the region's excellent solar resource conditions, local manufacturing, supply chains, and investment are identified as key factors in reducing costs and increasing regional strength (World Bank 2011). This investment then drives innovation, significant local job creation (during both construction and CSP plant operation), and value creation along the supply chains. The supply chain for CSP is primarily composed of plentiful commodity materials, such as steel, aluminum, and glass (Chung, Horowitz, and Kurup 2016; Stone & Associates 2011), that are produced in relative abundance in domestic markets like the United States. Even with local supply capabilities, CSP projects tend to use Mexican or Chinese steel unless there are local content requirements. This is unlike the key components of the crystalline silicon (c-Si) PV supply chain, which are more complex in nature (Carey 2021). With further growth and development, the CSP supply chain could provide significant economic benefits in the United States, as it has done in other regions such as Spain, which is globally dominant when it comes to CSP technology developers, expertise, and deployments (Pacific Green Technologies Group 2021).

This report will look briefly at the domestic heliostat supply chain and its implications. Power tower plants have large arrays of mirrors, called heliostats, that focus sunlight onto a receiver at the top of a tower. Heliostats are a critical component of CSP and concentrating solar-thermal (CST) power tower technologies. A utility-scale heliostat field (100 MW_e, for example) might include more than 10,000 heliostats (NREL and SolarPACES 2021). Heliostats represent 30%–50% of the cost of power tower system construction (Augustine, Turchi, and Mehos 2022; NREL 2021c), and are a primary driver of O&M costs. For parabolic trough technology, the solar field can be nearly 40% of the total system construction cost (IRENA 2016).

Improvements to heliostat cost, performance, and reliability are necessary to achieve the U.S. Department of Energy (DOE) 2030 SunShot target for CSP of $0.05/kWh with 12 hours of thermal energy storage (TES) in the Southwest (DOE SETO 2021b). Low-cost, high-performance Generation 3 (Gen3) CSP technologies are expected to integrate with high-temperature tower receivers and TES with advanced supercritical carbon dioxide (sCO_2) cycles. DOE recently down-selected the solid-particle pathway as the most likely to meet the 2030

SunShot target (Sandia National Laboratories 2021). The National Renewable Energy Laboratory (NREL) led the liquid pathway (C. Turchi et al. 2021), and Brayton Energy led the gas pathway (DOE SETO 2021a). To help meet these SETO goals, heliostats between \$50–\$70/m^2 are likely needed, depending on the scenario and the performance of the CSP systems (DOE SETO 2021b).

The \$0.05/kWh 2030 target represents nearly a 50% reduction in the levelized cost of electricity (LCOE) for CSP power towers from 2018 estimates (DOE SETO 2021b). If a low-cost heliostat solar field of \$50/m^2 could be realized by 2030, the system effect would be nearly a 20% drop in the LCOE, helping achieve this type of LCOE reduction (Shultz 2020).

Recent research has found that the installed cost of a representative commercial heliostat deployed in the United States today is approximately \$127/m^2, whereas the installed cost of a next-generation advanced heliostat could be \$96/m^2 (Kurup et al. 2022). Both representative heliostats are highlighted in this report. As shown in Figure 1, although heliostat system costs have decreased considerably, and at present could be \$93–\$97/m^2 for a state-of-the-art (SOTA) heliostat, a \$50/m^2 heliostat cost is necessary to achieve aggressive targets for 100% decarbonization of the U.S. grid (Augustine, Turchi, and Mehos 2022). As shown in Figure 1, the mirrors, drives, pedestal, and foundations make up nearly 84% of the \$50/m^2 installed heliostat cost target. Although research and development (R&D) and increased deployment could lead to innovations in next-generation heliostats, a key aspect of future cost reductions will be to improve the supply chain of locally manufactured components.

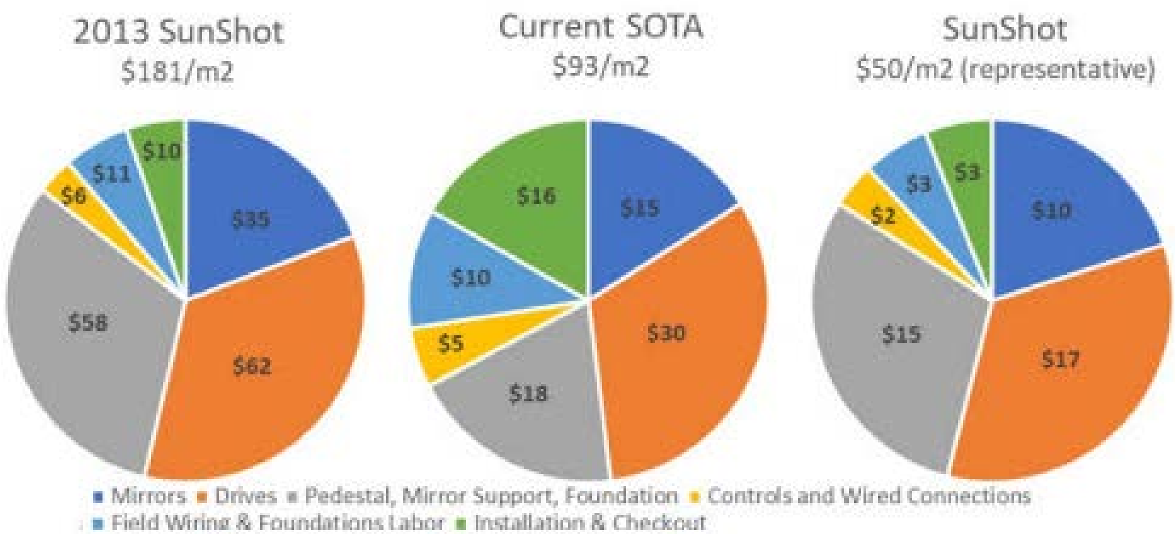

Figure 1. Cost reductions needed to get to the DOE SunShot 2030 target.

The Heliostat Consortium (HelioCon) for CST Power is focused on improving heliostat field cost and performance for the CST power industry. The consortium supports research, development, validation, commercialization, and deployment of low-cost and high-performance heliostats with optimized O&M for CSP and CST applications. The work in this report fits into the Advanced Manufacturing key research area. To advance U.S. heliostat technologies, HelioCon engages subject matter experts and general stakeholders for direct project-level collaboration, external consulting, mission-specific panels and workshops (NREL 2021c).

HelioCon also serves as a hub to integrate all DOE-funded projects that directly advance heliostat technologies. The HelioCon objective related to heliostat manufacturing and supply chain (NREL 2021c) is to:

> "Develop strategic core capabilities and infrastructure to support high-performance heliostat manufacturing, validation, and optimization and facilitate industry's ability to design, manufacture, install, and operate central receiver heliostat fields with higher technical and economic performance."

This report will cover aspects of the initial work for analyzing the existing heliostat supply chain. The remainder of the report covers the global CSP market and trends (Section 2), representative heliostat costs (Section 3), and the heliostat and material supply chain (Section 4). Section 5 covers key challenges; Section 6 covers opportunities; and Section 7 discusses recommendations from this work.

2 Global CSP Market and Players

2.1 Growth, Status, and Trends

The CSP industry has its roots in the LUZ parabolic trough plants that were established in California in the 1980s. LUZ built nine plants, Solar Energy Generation Systems (SEGS) 1–IX, that demonstrated the early commercial implementation of CSP trough technology, providing an important source of knowledge for future CSP system development (Mark Mehos et al. 2020). Over the last 20 years, the CSP industry has evolved into a global industry and supply chain. Standalone and hybrid CSP plants for electricity have been built in 12 different countries, and as of 2021, the industry is approaching 100 plants in commercial operation (World Bank 2021).

At present, the most widely deployed CSP technology for power generation uses parabolic trough collectors. As of 2021, 6,246 megawatts electric (MW_e) of worldwide operating CSP capacity has been installed (SolarPACES 2021). Of this, more than 4,000 MW_e utilizes parabolic trough collectors (SolarPACES 2021; C. S. Turchi, Stekli, and Bueno 2017). Power towers, the second-most deployed CSP technology, are approaching 2 gigawatts (GW) of global capacity that is either operational or under construction (SolarPACES 2021). Of the 1,110 MW_e of CSP construction worldwide in 2021, 260 MW, or 23%, was for power towers with molten salt (World Bank 2021).

As seen in Figure 2, Spain leads the world in installed CSP operating capacity at approximately 2.3 GW, and the United States comes in second at ~1.7 GW. As of 2021, 392 MW_e of power tower CSP capacity was operating at the Ivanpah Solar Electric Generating System in California (NREL 2021a). This capacity represents approximately 23% of the U.S. operating CSP capacity (SolarPACES 2021), and it comes from direct steam generation towers rather than molten salt power towers. The Crescent Dunes 110-MW_e molten salt power tower plant in Nevada has operated intermittently due to the failure of key components, including the hot salt tank and the steam generating system (Wesoff 2020). Notably, the availability of the heliostat field has not been a key issue impacting the annual performance of the plant.

The largest CSP plant being constructed in the world is the 950-MW_e system located in Dubai, United Arab Emirates (UAE), which consists of a combined parabolic trough, power tower with molten salt, and PV system (World Bank 2021). The complex, overseen by the Dubai Electricity and Water Authority (DEWA), is a 950-MW_e site composed of 600 MW_e of parabolic troughs (i.e., 3 x 200-MW_e trough plants) and a 100-MW_e molten salt tower site, with each plant having 12–15 hours of TES for the CSP portion (World Bank 2021). The 250-MW_e PV portion is also key, as the hybrid CSP-PV complex, along with a 35-year purchase price agreement (PPA), has led to the world record for the current lowest LCOE. The complex PPA is \$0.073/kWh (Lilliestam and Pitz-Paal 2018; World Bank 2021).

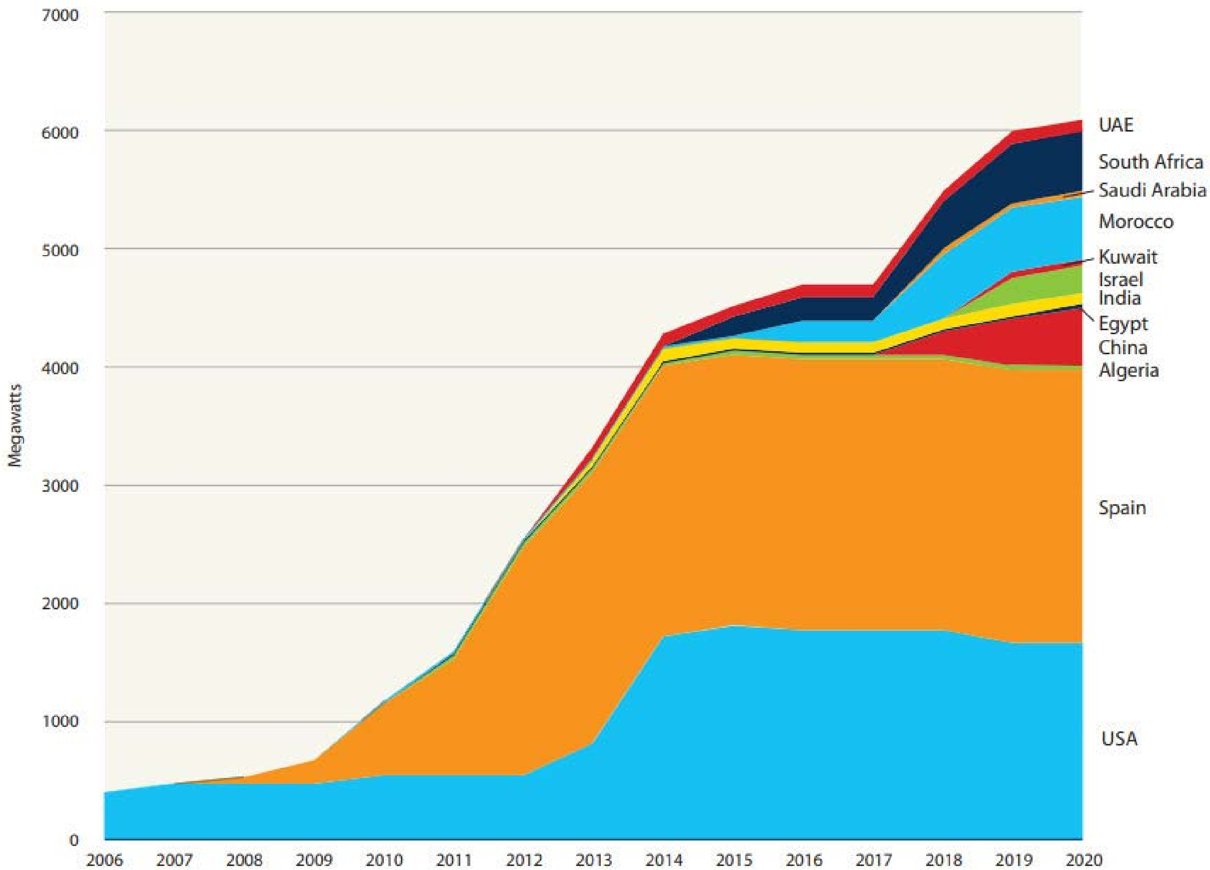

Figure 2. Global installed CSP capacity by country (2006–2020).

Illustration from World Bank

Today, the largest operating molten salt power tower plant is the Noor III 150-MW_e plant in Morocco, which includes 7.5 hours of TES (Chamberlain 2019). The 580-MW_e Noor Ouarzazate complex includes 360 MW_e of parabolic trough, 150 MW_e of power tower, and 70 MW_e of PV (Power Technology 2020). In 2021, a 110-MW_e molten salt power tower in Chile with 17.5 hours of TES was inaugurated and began syncing with the grid (Business Wire 2021; Renewables Now 2021). Another key developing market is China. In the last 4 years, approximately 350 MW has been built in China (150 MW_e of power towers), and 100 MW_e is in construction. Of the 100 MW_e in construction in China, 50% is for molten salt power towers (World Bank 2021).

A key aspect of CSP is that the deployment of trough and tower technologies in a country also leads to the development of an integrated supply chain and the utilization of domestic markets for products such as glass, concrete, and steel (Chung, Horowitz, and Kurup 2016). In all the markets in Figure 2, CSP can lead to the development of local supply chains and capacity development (World Bank 2013; 2021). This is an important motivator for markets like Morocco and UAE, which are seeing cost reductions through manufacturing and the development of local supply chains (Hasem 2017; World Bank 2021).

3 Representative Heliostat Costs

NREL has recently undertaken a detailed bottom-up costing for "commercial" and "advanced" heliostats. A summary of the bottom-up analysis is provided in this report, and some of the analysis has been extended. For further details, the full report can be found through the NREL publications database (Kurup et al. 2022). The "commercial" design was the Schlaich Bergermann und Partner (referred to as sbp) Stellio. The "advanced" design was the Solar Dynamics LLC SunRing.

3.1 Installed Cost for Commercial Heliostats

The sbp Stellio is a representative commercial heliostat. There are other commercial designs that exist, and future work will aim to undertake more bottom-up analysis of commercial heliostats. The NREL team performed a manufacturing, assembly, and construction analysis, leading to an installed cost of the Stellio heliostat with a production volume of 22,239 heliostats (this represents a solar field aperture area of 1,078,592 m^2, based on 48.5 m^2 Stellio heliostats) (Kurup et al. 2022). The analysis led to a total installed cost of the Stellio solar field of ~\$127/m^2, which includes manufacturing costs, tooling investments, and construction. The breakdown is shown in Figure 3.

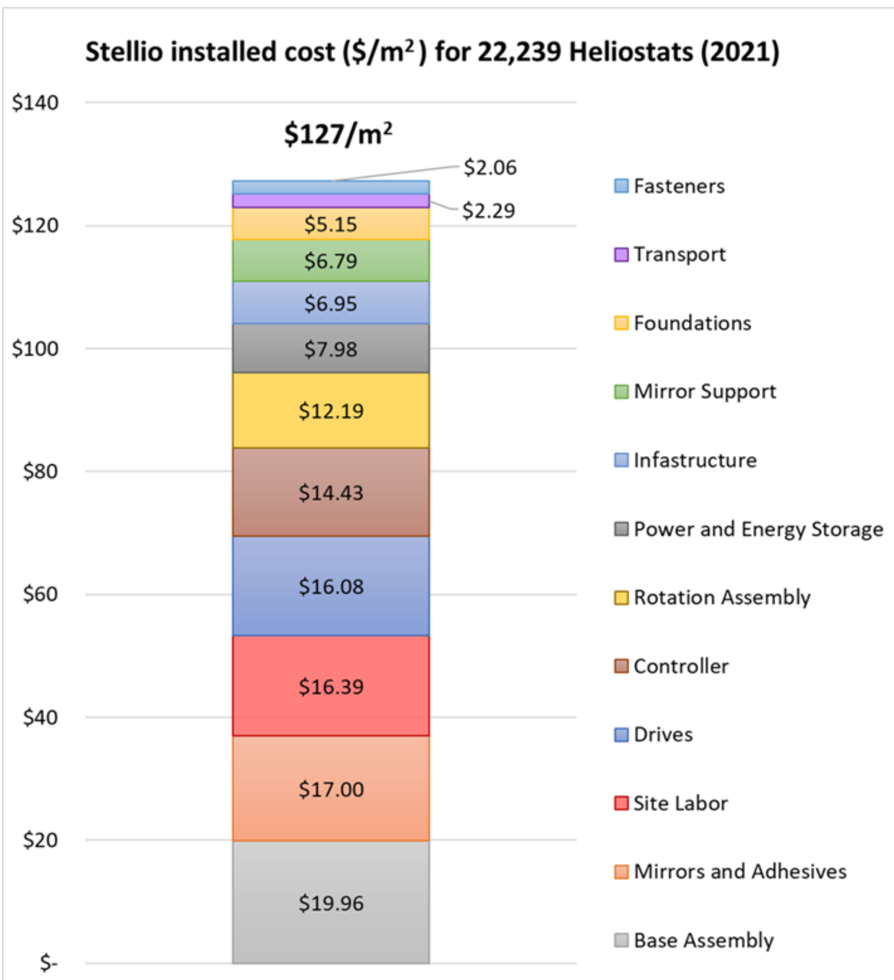

Figure 3. Installed cost for the Stellio assuming 22,239 heliostats (1,078,592 m^2 of aperture area).

The \$127/m^2 includes \$878,000 for tooling amortized over the production of the heliostat field volume, and a \$7.5 million heliostat assembly facility adjacent to the solar field. The total heliostat installed field capital expenditure (CAPEX) is approximately \$137 million. Table 1 shows the breakdown of the 22,239 heliostats for the Stellio solar field.

Table 1. Heliostat System Costs for 22,239 Stellio Heliostats (1,078,592 m^2 of aperture area)

Heliostat Subsystem	Installed Cost (\$/m^2) per Kurup et al. (2022)	Installed Cost Breakdown (%)	Estimated Installation Cost/Value (\$2021	Cost per Heliostat (\$2021)
Transport	2.29	2%	\$2,469,976	\$111
Site Installation Labor	16.39	13%	\$17,678,123	\$795
Infrastructure	6.95	6%	\$7,496,214	\$337
Foundations	5.15	4%	\$5,554,749	\$250
Purchased Parts		45%		
Fasteners	2.06	*(2%)*	\$2,221,900	\$100
Mirrors and Adhesives	16.08	*(13%)*	\$18,336,064	\$825
Controllers	14.43	*(11%)*	\$15,564,083	\$700
Linear Actuators	16.08	*(13%)*	\$17,343,759	\$780
Power and Energy Storage	7.98	*(6%)*	\$8,607,164	\$387
Manufactured Parts		30%		
Mirror Supports	6.79	*(5%)*	\$7,323,640	\$329
Rotation Assembly	12.19	*(10%)*	\$13,148,036	\$592
Base assembly	19.96	*(15%)*	\$21,528,696	\$968
Totals	\$127/m^2	100%	\$137.29M	\$6,174

As seen in Table 1, the largest contributors to the installed cost are the base assembly (~15%) and the mirrors and adhesives (~13%). The site labor costs (~13%) represent the total expected labor costs (based in Arizona) required to assemble and install the solar field. After mirrors, the linear actuators (~13%) and the control systems (~11%) are the second-most important cost contributors as purchased parts. The other manufactured parts, rotation assembly (~10%) and mirror support structure (~5%), constitute 15% of the total installed cost. The foundation costs (~4%) are variable because of site-specific considerations such as soil quality and expected wind loads. The transportation and shipping costs (~1.80%) are based on domestic shipping within the United States and are calculated based on vendor quotes provided by sbp.

All other categories, including site infrastructure and assembly, electrical cabling, interconnections, and fasteners, contribute ~15% to the total installed cost. The fasteners category alone is a relatively large contribution, even after switching from traditional bolting or welding to riveted construction to reduce assembly time and costs at this manufacturing scale.

This detail demonstrates the importance of each component and step in the manufacturing process. The Stellio heliostat uses a balance of purchased components and manufactured components, and a breakdown of the total cost by category is presented in Figure 4.

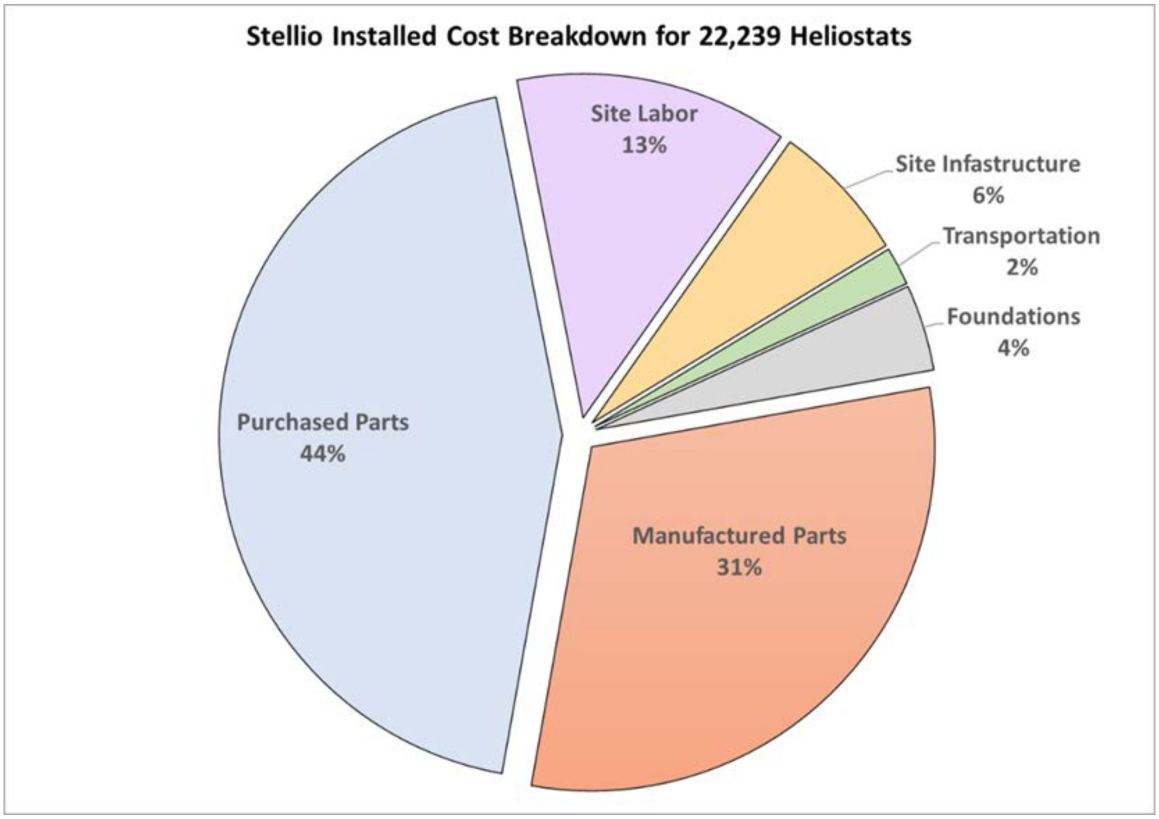

Figure 4. Total installed cost breakdown by category for sbp Stellio heliostat.

Purchased parts are the largest contributor to the total installed cost (44%). Manufactured parts and their fabrication into subassemblies that are shipped to the field are the second-largest cost contributor (31%). Site labor (13%) and site assembly and fixtures (6%) are the third. The cost of foundations is 4%, and the cost of transportation/shipping is 2%.

At present, in the released version of the System Advisor Model (SAM) (2021.12.02), the default heliostat installed cost is $140/m^2 (NREL 2021b; World Bank 2021). Based on the bottom-up heliostat work (Kurup et al. 2022), the estimated installed cost of an established commercial heliostat is $127/m^2. This value has been used in the Annual Technology Baseline (ATB) 2022 (NREL 2021a).

3.2 Installed Cost for Advanced Heliostats

The installed cost analysis of the Solar Dynamics SunRing heliostat was performed for a production volume of 40,000 heliostats, which represents a plant size of 80 MW_e with 12–16 hours of TES. Site assembly and construction costs were provided by Solar Dynamics. These costs include the equipment, infrastructure, and labor required to assemble and install all 40,000 heliostats. Arizona labor rates were used in this analysis, as labor rates in Arizona are lower than in California (e.g., 31% lower for construction laborers in 2021) (BLS 2021b) and the most recent CSP plants (e.g., Solana) have been built there.

With a total area of ~27 m^2 per heliostat, the analysis found the manufactured and installed cost to be approximately \$96/m^2. This includes a tooling investment (e.g., dies and stamping sections) of \$450,000 and an \$880,000 assembly facility. Both are amortized over the required production volume for 40,000 heliostats. The SunRing assembly facility consists of five stations that build the entire heliostat, without the foundation, in a common location. This allows for heliostats to be completed every 7 minutes (Kattke 2019). The heliostat is then transported to its final location using a single piece of heavy equipment. The total heliostat installed field CAPEX is approximately \$104 million. A breakdown of the total cost by category can be seen in Figure 5.

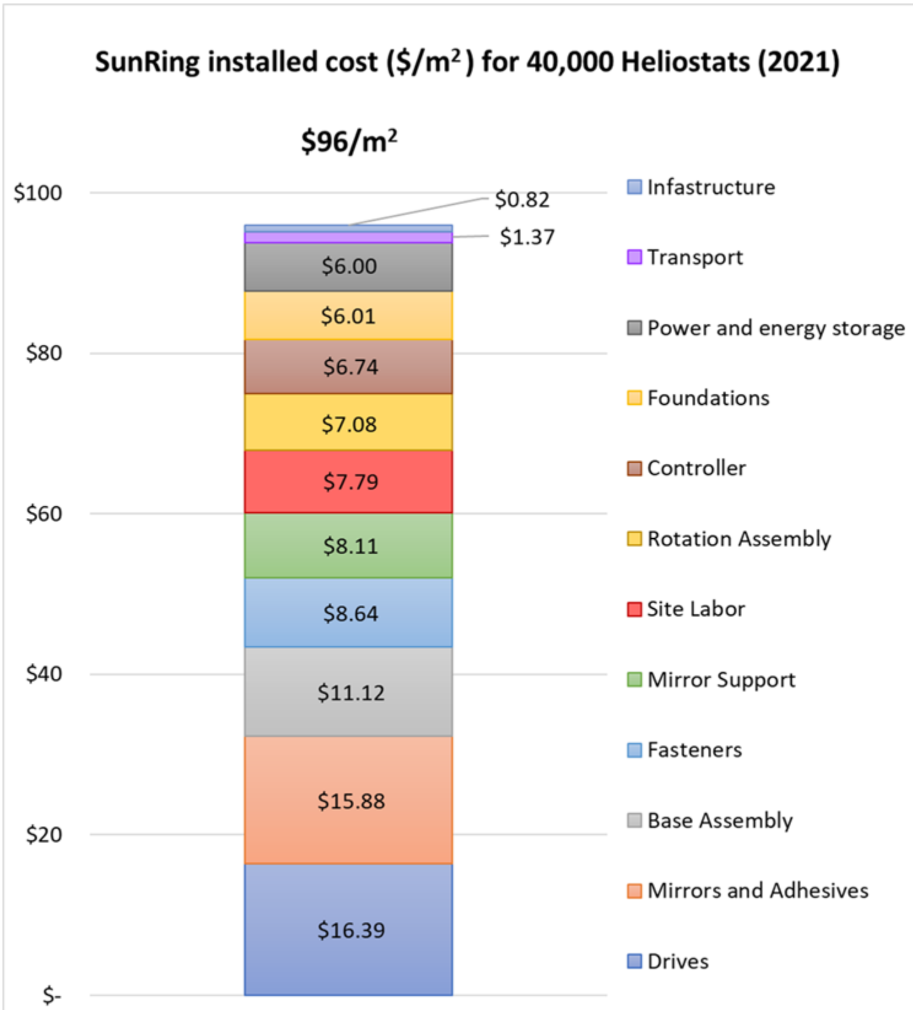

Figure 5. Installed cost for the SunRing assuming 40,000 heliostats yielding 1,078,560 m^2 of aperture area.

Table 2 shows the same breakdown of the solar field in terms of the total installed cost. It also shows the portion of the cost used for the installation of the equipment and solar field.

Table 2. Heliostat System Costs for 40,000 SunRing heliostats (1,078,560 m^2 of aperture area)

Heliostat Subsystem	Installed Cost (\$/m^2) per (Kurup et al. 2022)	Installed Cost Breakdown (%)	Estimated Installation Cost/Value (\$)	Cost per Heliostat (\$)
Transport	1.37	1.43%	$1,480,000	$37
Site Installation Labor	7.79	8.11%	$8,400,000	$210
Infrastructure	0.82	0.85%	$880,000	$22
Foundations	6.01	6.26%	$6,480,000	$162
Purchased Parts		56%		
Fasteners	8.64	*(9.00%)*	$9,320,000	$233
Mirrors and Adhesive	15.88	*(16.54%)*	$17,120,000	$428
Controllers	6.74	*(7.03%)*	$7,280,000	$182
Drives	16.39	*(17.08%)*	17,680,000	$442
Power and Energy Storage	6.00	*(6.26%)*	$6,480,000	$162
Manufactured Parts		27%		
Mirror Supports	8.11	*(8.46%)*	8,760,000	$219
Azimuth Track	5.26	*(5.49%)*	5,680,000	$142
Lower Support	1.82	*(1.89%)*	1,960,000	$49
Base Assembly	11.12	*(11.59%)*	12,000,000	$300
Totals	\$96/m^2	100%	$103.5 M	$2,588

Figure 6 illustrates that the major cost drivers in the SunRing heliostat design are purchased components. The purchased components make up 56% of the total cost. The drives and the mirrors account for almost one-third of the total cost. Manufactured components are 27% of the total cost. The base assembly is the largest cost of the manufactured subassemblies. This is because of both the large number of components within the base assembly and the mass and complexity of the hubs that ride on the azimuth track. The foundations can also be considered mostly purchased components, as the screw piles are 77% of the total cost. The fasteners, which include nuts, bolts, bushings, and rollers required for assembly, are also a significant contribution. The mirror support structure is the second-largest manufactured subassembly contribution because of its mass and number of parts. The site labor and infrastructure account for only 8% and 1% of the total cost, respectively.

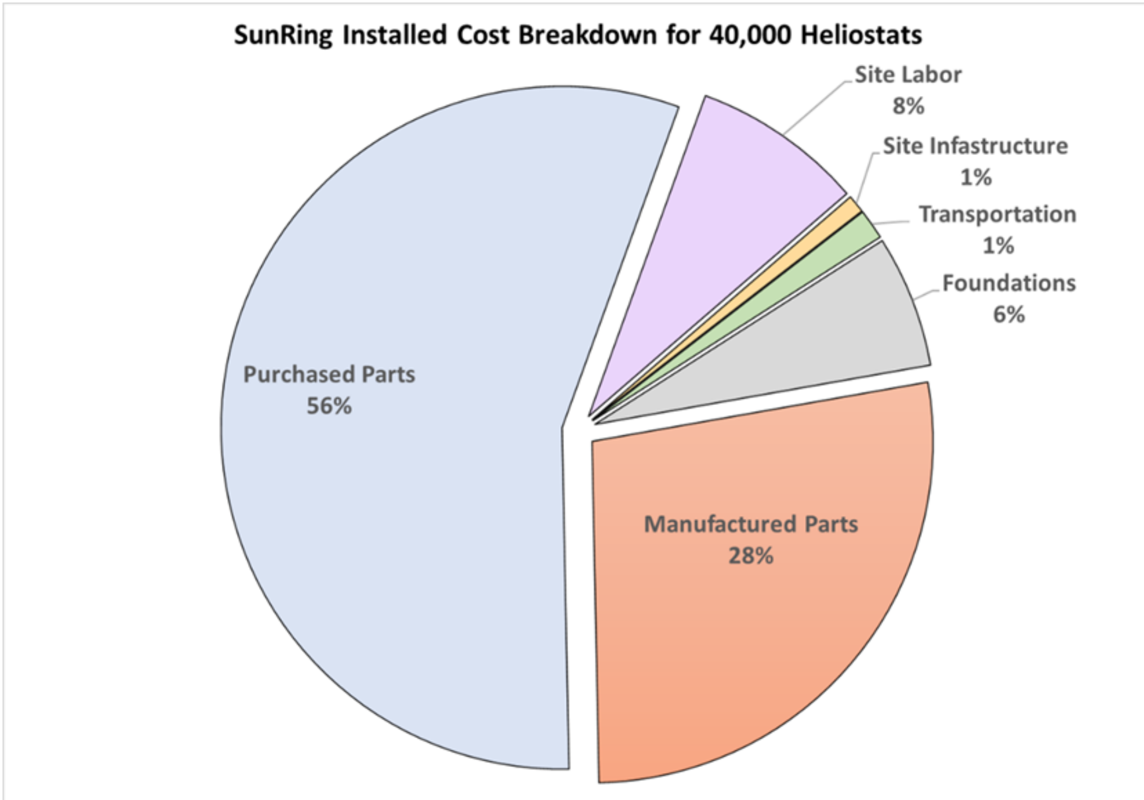

Figure 6. Total installed cost breakdown by category for Solar Dynamics SunRing heliostat.

4 Heliostat and Material Supply Chain

4.1 Domestic Content

Unlike some other renewable energy technologies, CSP technologies generally do not rely on rare earth metals or other materials with potentially restricted supply (Chung, Horowitz, and Kurup 2016). For example, with light-duty electric vehicles (EVs), there are supply chain concerns about the current global expansion and demands for critical materials such as cobalt and lithium. Nearly 53% of globally mined cobalt—a key material in EV batteries—is from the Democratic Republic of Congo (DRC), and China refines nearly 47% the cobalt globally (Igogo et al. 2019). Similarly, nearly 80% of today's lithium production occurs in Australia, Chile, and Argentina (Igogo et al. 2019). This type of key material resource that is concentrated in certain regions of the world can lead to supply chain issues or a lack of supply in situations of adverse political pressure.

In contrast, CSP plants are constructed mainly from steel, aluminum, glass, and aggregate materials that are abundant, readily available, and frequently supplied by domestic sources for known uses. Key materials used in today's CSP plants are potassium and nitrate salts, which are sourced primarily from Chile (Chung, Horowitz, and Kurup 2016). Construction materials are available in most locations in the world where CSP plants might be deployed, which is an attractive attribute for local economies and supply chains. Domestic production of standard materials and the development of local supply chains are key enablers of CSP in locations such as Morocco and MENA (World Bank 2013; 2011). Turchi et al. found that in the United States, about 90% by mass and 79% by value of the commodity materials used in a 100-MW_e CSP plant could be locally supplied by domestic sources (C. Turchi et al. 2015). It is important to note that in this report, the material content analysis (Table 5) assumed that if a new CSP molten salt power tower plant was built in the United States, there was already significant capacity for commodity materials in United States and that the commodity material could be sourced in the United States. However, for a new CSP plant built in the United States, global commodities such as steel would be used, rather than only U.S. commodities and materials. The analysis shows the U.S. economic value with local sourcing.

The data from the Turchi et al. 2015 report, which highlights the material content for three different CSP configurations, is shown in Table 3. The three configurations were a nominal 103-MW_e CSP plant, with 6 hours of TES, for (i) a synthetic oil trough coupled to a two-tank molten salt TES; (ii) a salt trough directly coupled to a two-tank molten salt TES; and (iii) a molten salt power tower with direct two-tank TES.

Table 3. Materials Content (in Metric Tonnes (MT)) of Three Different Nominal 103 MW_e Configurations

Material	Oil Heat Transfer Fluid (HTF) Trough (MT)	Salt HTF Trough (MT)	Salt Power Tower (MT)
Carbon Steel, Iron, and Zinc	30,804	26,367	28,107
Stainless Steel	1,918	2,283	1,010
Alloy Steel	1	261	335
Copper	140	334	427
Silver	1	1	1
Ferronickel	11	10	-
Aluminum	441	333	287
Insulation	2,755	2,169	1,277
Glass	12,211	11,261	10,055
Plastics	508	400	617
Glue	12	11	-
Paint	233	215	-
Oils and Lubricants	4,600	95	95
Sodium Nitrate (Solar Salt)	40,100	16,301	10,451
Potassium Nitrate (Solar Salt)	26,700	10,867	6,967
Nitrogen	18	-	-
Concrete and Brick	66,661	59,088	78,829
Cement	49	-	-
Asphalt	7,960	7,347	3,879
Crushed Stone and Gravel	53,081	49,087	46,889
System Total	**248,204**	**186,431**	**189,226**

Most of the solar field is made up of standard materials such as carbon steel, glass, and copper. As seen in Figure 7 (data reproduced from C. Turchi et al. (2015)), of the estimated 189,227 MT of material associated with a nominal 103-MW_e molten salt power plant with 6 hours of TES, approximately 14% of the material content is in the solar field (26,832 MT). The MT of silvered low-iron glass depends on the specific heliostat design used. For the design highlighted, 10,055 MT of low-iron glass and 1 MT of silver were used (C. Turchi et al. 2015). As can also be seen in the figure, the steel content in the solar field is approximately 62% of the MT of the field (i.e., 16,584 MT compared to 26,832 MT).

Molten-Salt Power Tower Plant Material (metric tonnes) / System	Site Improvements	Tower	Receiver	Solar Field	Power Plant Systems	Steam Generator System	TES	Sum for Power Plant
Carbon Steel, Iron and Zinc	103	2,811	384	16,584	4,907	2,794	524	28,107
Stainless Steel	3	97	137	-	67	254	452	1,010
Alloy Steel	1	5	70	-	249	8	2	335
Copper	1	2	40	121	185	68	10	427
Silver	-	-	-	1.0	-	-	-	1
Ferronickel								
Aluminum	-	2	4	-	257	7	17	287
Insulation	-	40	88	-	53	27	1,069	1,277
Glass	-	-	-	10,055	-	-	-	10,055
Plastics	399	1	14	70	115	15	3	617
Glue								
Paint								
Oils and lubricants	-	-	-	-	95	-	-	95
Sodium nitrate (solar salt)	-	-	-	-	-	-	10,451	10,451
Potassium nitrate (solar salt)	-	-	-	-	-	-	6,967	6,967
Nitrogen								
Concrete and brick	624	53,033	-	-	12,213	10,080	2,879	78,829
Cement								
Asphalt	3,879	-	-	-	0	-	-	3,879
Crushed Stone and Gravel	46,609	-	-	-	280	-	-	46,889
System Total	51,619	55,991	737	26,832	18,421	13,253	22,374	189,227

Figure 7. System total material content for representative molten salt power tower plant.

The two biggest contributors to a heliostat field (based on the design used in C. Turchi et al. (2015)) are the carbon steel (which is then zinc galvanized) used for the heliostat support structures (16,584 MT) and the glass used for the heliostats (10,055 MT). Table 4 shows the estimated weight in MT of the glass and steel for the heliostat fields, based on the bill of materials (BOM) for the commercial and advanced designs. For the Stellio (commercial) design, we compared steel estimates against the NREL analysis, with estimates taken from the Kumul Dongfang (sbp 2022). For the SunRing (advanced) design, we used the manufactured components for the estimate. The MT of the glass for the heliostats is estimated from the number of heliostats and the density of low-iron glass (2,500 kg/m^3) (General Glass 2022; WGR 2011).

Table 4. Material Weight Estimates for Prior Analysis and Commercial/Advanced Designs

Material/Plant Area	Prior Analysis (MT)	Commercial Design (MT)	Advanced Design (MT)	References
Glass	10,055	10,786	10,800	(Kurup et al. 2022) (General Glass 2022; WGR 2011)
Steel	16,584	13,343	17,443	(Kurup et al. 2022) (sbp 2022)

4.2 Material Value and Embodied Domestic Jobs

Table 5 shows the Turchi et. al 2015 analysis updated to 2020 numbers, as well as the recent heliostat commercial and advanced field analyses. In Table 5, the estimated value is calculated based on the key materials for the heliostat field (such as the carbon steel, copper, silver, aluminum, and glass). The estimated value of the sector in Table 5 is determined by the overall annual production of the sector (MT) and the average price of the material in that year. The dollar value of the primary materials in the plants is estimated based on market prices for the different commodities, estimated annual production, and the percentage of the U.S. production of that material in 2020; the estimate also assumes that U.S. components are used for a CSP plant. These values are obtained from various sources, including the United States Geological Survey

(USGS) yearbook and reports, online commodity brokers (for cross-checking), and public reports. In addition, we estimate the fraction of the U.S. domestic supply represented by the mass required in each nominal 100-MW_e plant, and the commercial and advanced heliostat fields from the recent bottom-up analysis. For example, if a commercial heliostat field is built in the United States, based on the annual glass production, this could equal ~0.05% of the existing U.S. capacity in 2020. This is not meant to suggest that the heliostat manufacturing capacity for the 100-MW_e plant is ready and available in the United States, but that the material content and associated economic value could benefit the United States.

Table 5. Molten Salt Power Tower Analysis and Recent Heliostat Analysis Estimated Values

Turchi et. al 2015 Analysis, Material	Modeled Salt Power Tower (MT)	Annual U.S. Production (MT) in 2020	Percent of U.S. Production (%) in 2020	Estimated Value of the Sector in 2020 ($B)	Estimated Value of Material in the Molten Salt Plant in 2020 ($)	Sources
Carbon Steel, Iron, and Zinc	28,107	72,700,000	0.03866%	91.0	$35,182,077	(USGS 2022)
Copper (Refinery Primary)	427	874,000	0.04886%	5.4	$2,635,820	(USGS 2022)
Silver (Refinery Primary)	1	1,420	0.07042%	1.0	$725,939	(USGS 2022)
Aluminum (Primary)*	287	1,012,000	0.02836%	2.0	$567,194	(USGS 2022)
Crushed Stone and Gravel	46,889	1,470,000,000	0.00319%	18.4	$588,396	(USGS 2022)
Recent Heliostat Analysis, Material	**Metric Tons (MT)**	**Annual U.S. Production (MT) in 2020**	**Percent of U.S. Production (%) in 2020**	**Estimated Value of Sector in 2020 ($B)**	**Estimated Value of Material in Heliostat Field in 2020 ($)**	**Sources**
Glass, in Turchi et al. 2015 Heliostat Field	10,055	20,000,000	0.05028%	25.0	$12,568,750	(Hasanbeigi et al. 2021)
Commercial Design, Glass	10,786	20,000,000	0.05028%	25.0	$13,482,500	(Hasanbeigi et al. 2021)
Advanced Design, Glass	10,800	20,000,000	0.05028%	25.0	$13,500,000	(Hasanbeigi et al. 2021)
Steel, in Turchi et al. 2015 Heliostat Field	16,584	72,700,000	0.02281%	91.0	$20,758,514	(USGS 2022)
Commercial Design, Steel	13,343	72,700,000	0.01835%	91.0	$16,701,692	(USGS 2022)
Advanced Design, Steel	17,443	72,700,000	0.02399%	91.0	$21,833,741	(USGS 2022)

For U.S. heliostat fields that were constructed in the United States, Table 6 shows the direct and indirect jobs related to the most common materials for the molten salt power tower plant, and the heliostat field based on the commercial and advanced designs. This assumes the sourcing and manufacture of the key commodity materials, such as carbon steel, copper, and aluminum, are from the United States. The estimated jobs per sector were taken from sources such as market reports and the Bureau of Labor Statistics (BLS). Then, direct and indirect jobs at the plant and component level can be estimated using labor multipliers, for example from C. Turchi et al. (2015).

Table 6. Jobs Associated With Key Materials in a Molten Salt Power Tower Plant and Recent Analysis

Turchi et. al 2015 Analysis, Material	Modeled Salt Power Tower (MT)	Estimated Jobs in Sector in 2020	Direct Jobs per Plant Based on the MT of Material Produced in 2020	Indirect Jobs per Plant in 2020	Sources
Carbon Steel, Iron and Zinc	28,107	72,230	28	114	(IBIS World 2022; BLS 2021c)
Copper (Mines and Mills)	427	11,000	5	20	(Statista 2022b)
Silver (Mines and Mills)	1	1,180	1	4	(Statista 2022a)
Aluminum (Primary)*	287	57,273	16	65	(IBIS World 2021a; BLS 2021c)
Crushed Stone and Gravel	46,889	86,586	3	3	(NSSGA 2021)
Recent Heliostat Analysis, Material	**Metric Tons (MT)**	**Estimated Jobs in Sector in 2020**	**Direct Jobs per Field Based on the MT of Material Produced in 2020**	**Indirect Jobs per Field in 2020**	**Sources**
Glass, in Turchi et al. 2015 Heliostat Field	10,055	87,850	44	47	(IBIS World 2021b; BLS 2021a)
Commercial Design, Glass	10,786	87,850	47	47	(IBIS World 2021b; BLS 2021a)
Advanced Design, Glass	10,800	87,850	47	47	(IBIS World 2021b; BLS 2021a)
Steel, in Turchi et al. 2015 Heliostat Field	16,584	72,230	16	68	(BLS 2021a; 2021c)
Commercial Design, Steel	13,343	72,230	13	54	(BLS 2021a; 2021c)
Advanced Design, Steel	17,443	72,230	17	71	(BLS 2021a; 2021c)

4.3 Heliostat Glass Suppliers

Relatively few comprehensive data sets exist regarding the CSP supply chain, especially with respect to producers of specialty CSP components (e.g., parabolic trough receiver tubes, mirrors, and reflective films). Similarly, there is no comprehensive heliostat database (e.g., flat glass producers, frame manufacturers, and drives) for the heliostat supply chain. Recent work by the World Bank has helped highlight some of the key heliostat manufactures and suppliers.

Key global suppliers of CSP mirror glass for heliostats are Flabeg Solar, Guardian Glass, Rioglass, and Cosin Solar. Table 7 shows the main heliostat suppliers today; Germany, Spain, and the United States are the biggest suppliers. Table 7 has been developed using key work from the World Bank (World Bank 2021) and NREL research. The table is not exhaustive, but it looks to understand the biggest heliostat mirror providers and the main references. We note that, for Siemens, the German company that has been a glass manufacturer for parabolic troughs (e.g., the Lebrija 1 plant (World Bank 2021)), we have not found the necessary data to add them the heliostat and mirror supplier table in Table 7. Saint-Gobain, a very large glass manufacturer, also has few current references for heliostat manufacture. At present, the German Aerospace Center's (DLR's) Jülich test site in Germany is the known reference for the use of Saint-Gobain Solar Glass (Saint-Gobain 2010).

Table 7. Key Mirror Glass Suppliers for Heliostats Globally

Component/ Industry	Key Suppliers	Country Where Manufacturing Is Located	Heliostat Project References	Power Tower Type	Sources
Mirror	AGC Glass Europe	Europe, e.g., Germany and Spain	Ashalim Plot B/ Megalim (Israel)	Direct steam	(SolarPACES and NREL 2021c; AGC Glass Europe 2022; Thor 2020)
	Cosin Solar/Damin Glass	China	Supcon Solar (China)	Molten salt	(CosinSolar 2018; SolarPACES and NREL 2021d)
			Gonghe (China)	Molten salt	(CosinSolar 2020; SolarPACES and NREL 2021b)
	Flabeg Solar	Germany (and U.S. prior*)	Crescent Dunes (U.S.)	Molten salt	(World Bank 2021)
			Sierra SunTower (U.S.)	Direct steam	(World Bank 2021)
			Hami (China)	Molten salt	(Keck et al. 2019)
			Redstone (South Africa)	Molten salt	(World Bank 2021; HelioCSP 2022)
	Guardian	Unites States	Gemasolar (Spain)	Molten salt	(World Bank 2021)
			Ivanpah (U.S.)	Direct steam	(World Bank 2021)
	Rioglass Solar	Belgium, Spain and South Africa (and U.S. prior*)	Noor III (Morocco)	Molten Salt	(World Bank 2021)
			Noor Energy 1 (UAE)	Molten salt	(Reve 2020)
			Khi Solar 1 (South Africa)	Direct steam	(Rioglass Solar 2021)
			Atacama 1 (Chile)	Molten salt	(Rioglass Solar 2021; SolarPACES and NREL 2021a)
	Saint-Gobain	Europe e.g., France and Germany	Jülich (Germany)	Air tower	(Saint-Gobain 2010; DLR 2020)

4.4 Global Heliostat Developers, EPCs, and Key Suppliers

U.S. heliostat developers include BrightSource Energy, Heliogen, 24/7 Solar, and Solar Dynamics (World Bank 2021; Kurup et al. 2022; Heliogen 2022). The key global heliostat developers include Sener (Spain), Abengoa Solar (Spain), sbp (Germany), Cosin Solar (formerly Supcon Solar, China), and Vast Solar (Australia) (World Bank 2021; Vast Solar 2014; SolarPACES 2020; Zhifeng 2019; Cosin Solar 2021).

Depending on the size of the heliostat developer, the step after manufacturing will be the installation, normally via an engineering procurement and construction (EPC) company. The main CSP EPC companies include Worley Parsons, Acciona, Abengoa Solar, Bechtel, Cosin Solar, and Shanghai Electric (World Bank 2021; PR Newswire 2018; SolarPACES and NREL 2021d).

Figure 8 shows the CSP heliostat supply chain. Table 8 shows some of the largest U.S. and foreign suppliers of heliostat raw materials through to integrators along the heliostat supply chain that are operating or potentially able to operate in the United States. Figure 8 and Table 8 are adapted from prior works (Chung, Horowitz, and Kurup 2016; C. Turchi et al. 2015), and are extended in this work.

Figure 8. CSP heliostat supply chain.

Table 8. Key Suppliers and Developers in the U.S. Heliostat Supply Chain

Primary Raw Materials	Sample Raw Material Suppliers	CSP Heliostat Components	CSP Component Suppliers	CSP Integrators/ Developers	References
Steel and Stainless Steel	• Nucor • U.S. Steel • AK Steel • Commercial Metals	• Solar field frame and heliostat structures • Drives • Pipes • Structures	• Various local manufacturers could fabricate steel heliostat components • Titan Trackers	• Heliogen (U.S.) • BrightSource Energy (U.S.) • Worley Parsons (U.S.) • Bechtel (U.S) • Acciona (Spain) • Abengoa Solar (Spain) • Sener (Spain)	(World Bank 2021) (Kurup et al. 2022) (Thomas Publishing Company 2022b)
Aluminum	• Alcoa • Century Aluminum • Kaiser Aluminum	• Cladding and solar field components	• Alcoa • Century Aluminum • Kaiser Aluminum		(Thomas Publishing Company 2022a)

Primary Raw Materials	Sample Raw Material Suppliers	CSP Heliostat Components	CSP Component Suppliers	CSP Integrators/ Developers	References
	• Arconic				
Glass	• Guardian • Flabeg Solar • Saint-Gobain • Rioglass	• Mirrors and facets	• Guardian • Flabeg Solar • Saint-Gobain • Rioglass • AGC Europe	• 3M (U.S.) • Guardian (U.S.) • Flabeg (Germany) • Rioglass Solar (Spain) • sbp (Germany)	(Industry Select 2020; IBIS World 2021b)
Silver	• Glencore • Newmont • Southern Copper Corp.	• Backing of heliostat facets • Reflectors		• 3M (U.S.) • Guardian (U.S.) • Flabeg (Germany) • Rioglass Solar (Spain) • sbp (Germany)	(Kay 2018)
Copper	• Rio Tinto • Glencore • BHP • Freeport McMoRan	• Wiring • Cables • Reflectors • Power systems		• 3M (U.S.) • Guardian (U.S.) • Flabeg (Germany) • Rioglass Solar (Spain) • sbp (Germany)	(Mining Technology 2022)
Concrete, Crushed Gravel, Rock	• Suppliers nationwide	• Foundations			

This list is an attempt to show some of the key potential suppliers for commodity materials needed for heliostat component production. Until further detailed investigations are conducted, including extensive collaboration with CSP developers, it is unlikely that a more exact list of material and component suppliers—and their manufacturing capacities—can be determined for U.S. heliostats. At the time of this writing, the United States has no local content requirements for CSP components, plants, or heliostat fields. Although many CSP components and raw materials are readily available from U.S. sources, discussions with industry and heliostat developers such as sbp and Solar Dynamics indicate that importing certain items may prove more cost effective. For example, Solar Dynamics expects to use Chinese glass transported to the United States via shipping containers for heliostat facets for U.S. projects. Still, many materials are likely sourced domestically. For example, in developing the CSP parabolic trough Solana project (250 MW), Abengoa Solar estimated that 73% of the equipment supplied was of U.S. origin (Chung, Horowitz, and Kurup 2016).

5 CSP and Heliostat Challenges

CSP for electricity and heat faces many challenges in the United States and globally. In this section, we look at the main heliostat challenges along with broader CSP challenges. These challenges include the technology's large effective scale, high complexity and cost, inconsistent annual manufacturing for CSP components and systems, and uncertain near-term growth prospects. Heliostat manufacturing and deployment follows the annual demand and build-out of CSP power towers in the United States and globally.

5.1 Large Scale, Complexity, and Cost

The most critical challenges to CSP deployment (both trough and tower technology) revolve around CSP's competition with conventional and other renewable generation technologies, and the implications for all-in system development and installation costs. Particularly compared with PV, CSP trough and power tower electricity systems are much more complex to develop, gain land permits for, design, construct, and operate. They also require a much larger minimum effective scale, generally 50–100 MW_e (Xavier Lara 2021), than cost-effective residential PV systems, which can be as small as 3 kilowatts electric (kW_e) for the residential benchmark (Ramasamy et al. 2021). This large scale and high complexity typically result in lengthier development cycles. Three years is the average construction time for power tower systems. For example, the Redstone 100-MW power tower plant in South Africa with 12 hours of TES is expected to be constructed in 31–36 months (Energy Trend 2022; SolarPACES 2022). Along with long development and construction timelines, CSP plants have much higher total CAPEX requirements for the project and system construction, and the energy they produce is higher cost

Global competition within the CSP power tower industry is characterized by a few very well-funded companies or large parent companies that have created CSP firms focused on project development. Most CSP developers and EPCs (e.g., ACWA Power, BrightSource, Abengoa Solar, and Sener) are vertically integrated companies with capabilities ranging from R&D to EPC. The large capital requirements to develop and deploy power tower and heliostat technologies at commercial scale can bar new, disruptive energy startup companies. For example, the Redstone power tower project, which is in construction, is estimated to have a CAPEX of 11.6 billion South African rand (ZAR) (SolarPACES 2022); in U.S. dollars as of March 2022, this is approximately $767M (XE 2022). By comparison, PV plants in the United States at the 100-MW_e utility scale with single-axis tracking (for example) have an estimated installed cost of $0.89 per watt, or approximately $89M (Ramasamy et al. 2021).

Today's main specialty CSP and heliostat component manufacturers have developed expertise by leveraging existing core competencies of a parent company. For example, Schott has a long history in the glass industry, and with R&D support from the German government, has developed a leading position in CSP receiver tube manufacture. Flabeg was spun out of Flabeg GmbH, one of the biggest mirror and glass producers in Germany. These specialty manufacturers have typically developed processing and tooling in-house, and they generally do not purchase "turnkey" manufacturing lines from capital equipment suppliers, as is observed in the PV industry. As a result, knowledge flows in CSP component manufacturing are more restricted, potentially enhancing firms' ability to retain and fully capitalize on proprietary knowledge stocks, but also potentially restricting manufacturing capacity growth and scale-up.

5.2 Volume and Precision Manufacturing for Heliostats

Heliostat manufacturing and assembly demands high precision of the components and high production volumes, which is a unique challenge compared to other high-volume tracking systems, such as utility-scale PV. For example, recent analysis assumed that for the commercial and advanced designs, a heliostat field of approximately 1.1 Mm^2 would be needed for a large CSP power tower plant (Kurup et al. 2022). Although CSP power tower systems, which include heliostat costs, have been decreasing (World Bank 2021), high manufacturing capacities and greater expertise are needed in different countries for cost reductions to continue. For a sufficiently large project—such as the 450-MW_e Likana CSP project in Chile, which put a bid into the auction at $0.04/kWh—high-volume manufacturing can be one mechanism for cost reduction (Kraemer 2021). Through high-volume manufacturing and quality controls, commodity production of goods (such as automotive glass) can decrease costs due to amortization of equipment, standardization of parts, and improvements in the manufacturing process. Heliostat manufacturers and developers (e.g., sbp for the Stellio heliostat) have yet to repeatedly manufacture and deploy millions of heliostats. As such, the high-volume manufacturing needed for heliostats is still in its infancy.

In the United States, there is no specific heliostat manufacturing capacity from dedicated heliostat manufacturing facilities. Heliostats can be manufactured in the United States—such as for the Ivanpah project, where CSP developers contracted with existing metal and glass suppliers in the United States—but companies still need to build permanent or temporary manufacturing facilities where heliostat facets, structures, and components can be produced. It is important to note that a Flabeg glass facility in Naugatuck, Connecticut, was shut down in 2021 (Branch 2021; Klein 2021).

5.3 Inconsistent Annual Demand and Pipeline

For specialty manufacturers serving the sector, the high minimum scale for generating systems creates particular challenges. Demand can be volatile due to the small size of the CSP industry, the lengthy development cycles, and the large project sizes relative to the total market size. This volatility is reflected in the year-on-year total industry growth rates shown in Figure 9. As seen in Figure 9, the annual year-on-year global installed capacity growth from 2009 to 2017 decreased significantly, with a large resurgence of installations in 2018 and a subsequent drop in 2019 and 2020. The industry installs small numbers of large-capacity projects on an inconsistent basis, making manufacturing capacity planning, scale-up, and efficient operation difficult.

Looking ahead to 2030, the International Energy Agency (IEA) estimates that approximately 6.7 GW of CSP capacity is needed every year from 2020 to 2030 (IEA 2021)—about 67 GW of new installed capacity by the end of the decade—to keep on track with the IEA Net Zero scenario. In 2020, approximately 0.2 GW was installed (IEA 2021), and approximately 0.1 GW came on line in 2021 (REN21 2021), for a total of about 0.3 GW in the last 2 years. In 2020, nearly 0.3 GW of power tower systems were being constructed (REN21 2021). This low annual global demand and the inconsistent pipeline make it difficult to build and operate manufacturing facilities, which are best suited to consistent demand to utilize the facility fully.

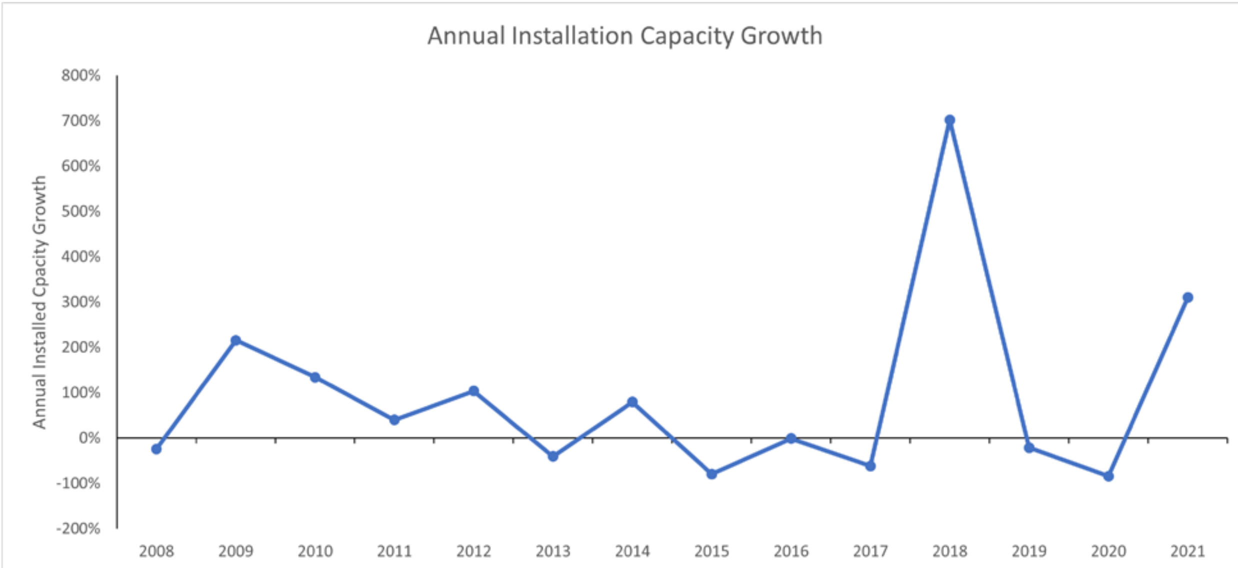

Figure 9. Year-on-year global annual installed capacity for the CSP industry.

Data from BNEF Desktop Portal 2021 (BNEF 2021)

5.4 Global Supply Chain Disruptions

Global events and the interconnectedness of today's economies and supply chains have had significant impacts on the cost of commodities, access to materials, and deployment of renewable energy technologies such as wind, PV, and CSP. For example, COVID-19 led to construction delays for plants already being built (REN21 2021) and postponement of plants that were due to start construction. Although supply chains were disrupted in many countries, solar PV in 2020 still had the largest renewable energy capacity increase in the world, at an additional 139 GW (REN21 2021). CSP was negatively affected, as very few plants were finished in 2020 (only 100 MW_e).

The COVID-19 supply chain impacts and labor restrictions led to labor shortfalls in countries such as China, South Africa, and UAE (REN21 2021), where CSP plants were in construction in 2020. In Chile, although delayed by the pandemic, the Cerro Dominador 110-MW_e plant with 17 hours of TES was able to continue construction in 2020 (Chamberlain 2020). Discussions with CSP suppliers in 2021 highlighted that the price of shipping in 2020 and 2021 went up four times, to nearly $8,000 per 40-foot (ft) container. Other sources similarly highlighted that a 40-ft container was approximately $8,400 in 2021 and had quadrupled in price compared to 2020 (Menapace 2021). Depending on the location of destination, that figure increased to approximately $12,000 for containers coming from China in 2021. In 2021, the container price to the United States from China was at nearly $20,000 (Khasawneh and Xu 2021). At present, shipping container costs to the United States have decreased to more reasonable ranges of $2,700–$4,200 per 40-ft container (Container Xchange 2021).

A more recent global supply chain disruption has been the Russian war with Ukraine. For example, in 2021, the United States imported nearly 7.9% of its crude oil and petroleum products from Russia (Eaton 2022). In 2022, the United States decided to ban Russian crude oil and petroleum products (Eaton 2022), which could further increase fuel prices and shipping and transport costs, potentially leading to increased project costs. The war in Ukraine is also having global impact on key CSP commodities, such as steel. With Russia and Ukraine being large steel exporters (second after China), global markets are seeing increases in steel and nickel prices. For example, in Europe, the price of hot-rolled-coil (HRC) steel has increased by nearly 40%, while in the United States, HRC steel prices have increased by about 8% (Halaschak 2022).

5.5 Uncertain U.S. and Global Growth Prospects

For U.S.-based manufacturing, the potential lack of a steady, large, near-term (e.g., 2022–2030) domestic market for the electricity sector is also a formidable challenge. Without significant development or establishment of a U.S. pipeline for CSP electricity projects, it is unlikely that U.S. firms will set up manufacturing facilities for heliostat components (e.g., drives, mirrors, and steel structures). To be profitable, manufacturing facilities require high CAPEX and sufficient amortization of the product. In the global CSP landscape at present, without a short-term pipeline of several hundred MWs to GWs of development and installation capacity (Sayles 2021), automated manufacturing facilities, economies of scale, and cost reductions through deployment and innovation are unlikely.

The largest U.S. CSP power tower projects from 2014 to 2021 have been cancelled, postponed, or abandoned. This includes the Palen Solar Holdings 500-MW_e plant, which was reduced in scope from a two-tower plant to a one-tower plant and then was scrapped (Parnell 2014). With the molten salt tank issues and bankruptcy and insolvency of SolarReserve in the United States (Wesoff 2020), projects that were being developed such as the Rice Solar Energy project (150 MW_e) and the Sandstone project (proposed as 2,000 MW_e) have also been cancelled or had their federal permits revoked (Renewables Now 2019). The rapidly declining cost of PV in the last decade has also impacted CSP acceptance and deployment. This has been a major factor in influencing several large projects to transition from CSP to PV technologies (Mark Mehos et al. 2016).

When CSP is considered from a global perspective, particularly if the deployment of the technology is on pace for meeting the 1.5°C goal, recent data highlights a negative trend. CSP as a globally deployed electricity generation technology is lagging, and the pace of deployment is unlikely to be sufficient by 2030 (IEA 2021). As mentioned earlier, ~6.7 GW of CSP capacity installation per year until 2030 is needed to stay on track to meet the global CSP goal and, in turn, meet the 1.5°C goal. This is tied to the global growth rate of CSP, which has been slowing down relative to the global expansion of PV. In the United States alone, in just the first quarter of 2021, nearly 4.9 GW_{DC}[1] of PV was deployed (Feldman, Wu, and Margolis 2021), compared to 6.3 GW of CSP installed globally by 2021 (World Bank 2021).

[1] Note that to utilize and operate 4.0 GW of alternating current (AC) PV, 4.9 GW of direct current (DC) PV must be installed due to the inverters that convert the DC electricity to AC electricity for the grid.

6 Opportunities

6.1 Near-Term Global and Long-Term U.S. Growth Potential

Although near-term capacity expansion for CSP is currently lagging, there is near- to mid-term global market potential (e.g., to 2030), and long-term (e.g., to 2050) U.S. potential for CSP electricity deployment. The global trend also indicates CSP being built alongside PV plants.

CSP projects are currently being built in South Africa, Morocco, UAE, and China (World Bank 2021; Energy Trend 2022). Within other parts of Africa, there have been tender notices for CSP. These include 2x100 MW_e in Botswana, where the tender is open until April 2022 (RenewAfrica Biz 2022), and a planned tender of up to 130 MW_e in Namibia (Energy and Utilities 2021).

Spain, the current global leader in terms of installed capacity (2.3 GW), aims to allocate 200 MW_e for CSP in 2022 (Molina 2021). As part of the Spanish National Integrated Energy and Climate Plan (PNIEC), there is potential to increase its CSP installed capacity to 7.3 GW by 2030 (Reuters Events 2021), although at present, the tenders specifically for CSP seem to be lagging. China is another emerging CSP market that has the potential to be the world leader by 2030, with potential installed capacities ranging from 15 to 30 GW (Wantenaar 2022; Zhang, Dong, and Li 2021). Similar to UAE or Morocco, CSP plants are being planned along with PV plants in China, although with PV, wind and CSP plants are being tendered and constructed at an increased scale. 1-GW complexes are being tendered for, typically with 100 MW_e for CSP (Wantenaar 2022).

The most recent "Solar Futures Study" released by DOE (Ardani et al. 2021) had key core scenarios that explored future energy scenarios within the United States to determine how technology costs, electricity demand, carbon dioxide (CO_2) emission reduction policies, and demand flexibility will impact future electricity generation and storage. The key results of the three main scenarios investigated are summarized in Table 9. The Decarbonization (Decarb) scenario utilizes the advanced ATB cost projections (PV and CSP) and assumes an aggressive 95% reduction in grid CO_2 emissions from 2005 levels by 2035 and a 100% reduction by 2050. The Decarb+E scenario further assumes increased end-use electrification, such as charging EVs, as described in the high electrification scenario of the NREL "Electrification Futures Study" (EFS) (Mai et al. 2018). It also assumes demand-side flexibility to shift loads, as described in the EFS enhanced demand flexibility case.

As seen in Table 9, even in the Reference scenario, nearly 380 GW of solar could be installed with a reduction in emissions of 45%. This highlights that wind and solar (PV) without aggressive cost reductions would still account for a large increase in renewable energy capacity and decreased emissions based on current growth and policies. In the Reference scenario, which assumes existing policies, no additional CSP is deployed in the United States, and existing CSP capacity retires by 2050. With the Biden administration's aggressive goals of a decarbonized electric grid by 2035, the Decarb scenario highlights a necessary doubling in PV to 760 GW (Ardani et al. 2021). This has the potential to lead to 500,000–1,500,000 direct and indirect solar PV jobs by 2035 (Ardani et al. 2021).

Table 9. Key Summary Results From the Solar Futures Study

Scenario	Potential GW of Solar Deployed by 2035	Potential GW of Solar Deployed by 2050	Emissions Reductions by 2035
Reference	380	670	-45%
Decarbonization of the grid by 95% in terms of emissions by 2035 (Decarb)	760	1,050	-95%
Decarbonization with electrification (Decarb+E)	1,000	1,570	-105%

CSP is deployed at the greatest capacity under the Decarb scenario, with new deployments starting after 2035 and reaching 39 GW_e by 2050 (Augustine, Turchi, and Mehos 2022). Due to the value to the grid and dispatch capabilities (M. Mehos et al. 2015) and by hitting low cost targets, CSP could be between 35–158 GW by 2050 in the United States (Murphy et al. 2019). CSP could potentially supply 3%–16% of generation in the United States under aggressive cost reductions (Murphy et al. 2019).

Cost reductions are needed for significant change in the deployment trajectory of CSP compared to the Reference scenario. Here, we use the ATB 2022 projections to highlight the cost reductions that could be achieved through R&D, increased deployment, and other institutional efforts (NREL 2022a). Table 10 shows that in the Base scenario, the CSP power tower overnight cost of capital (OCC) is \$6,242/kW_e. In the Moderate and Advanced scenarios, the potential projected CSP OCCs are \$4,069/kW_e and \$3,163/kW_e, respectively, by 2035 (assuming CSP power tower costs continue to decline globally). Note that in the 2022 ATB, the OCC does not include the grid connection or the construction finance leading to the CAPEX.

Table 10. Overnight Cost of Capital (OCC) and CAPEX From ATB 2022 Projections in 2035 and 2050

ATB 2022 Scenario	Year	Turbine Capital Cost (\$/kW_e)	Storage Capital Cost (\$/kW_e)	Field Capital Cost (\$/kW_e)	ATB 2022 OCC (\$/kW_e)	ATB 2022 CAPEX (\$/kW_e)
Base	2020	1,910	767	3,566	6,242	6,505
Moderate	2035	1,242	499	2,318	4,059	4,230
Advanced	2035	965	388	1,802	3,155	3,288
Moderate	2050	1,143	459	2,135	3,737	3,894
Advanced	2050	814	327	1,519	2,659	2,771

6.2 U.S. Innovation and Funding Landscape

Looking at the U.S. market and economy, there are structural advantages that can be leveraged for CSP and heliostat deployment. The United States typically has low industrial electricity prices, high automation capabilities, and a trained manufacturing workforce. This can make the production of advanced components competitive in the United States. (Reese et al. 2018;

Horowitz, Remo, and Reese 2017). Even though labor costs tend to be high relative to areas like China, commodity products, such as automotive glass, are produced in high quantities in the United States, once there is sufficient local demand.

The national laboratory network and its continued expansion for innovations in the United States can be utilized to help spur CSP and heliostat deployment. HelioCon envisions bringing together global knowledge and research to bring down costs and solve assembly and installation issues with heliostats (NREL 2021c). HelioCon may also pursue further research to assess and evaluate the supply chain, which could also reduce future costs.

An important area to leverage in the United States is the highly liquid capital markets and the availability of funding and loans. Through DOE, for example, the Loan Programs Office (LPO) has already funded nearly $35 billion of projects, and has helped launch the early stage PV and EV industries in the United States (Kennedy 2021). At present, with the likely relaunch and reuse of the LPO, there is nearly $40 billion available for innovative and emerging technologies in different sectors, with nearly $4.5 billion available for renewable energy and energy efficient technologies (Holland & Knight 2021; DOE 2020).

6.3 Potential for Other Markets

The demand for industrial process heat (IPH) is, for the majority of processes, met through the combustion of fossil fuels. In the United States, nearly two-thirds of the demand for heat in industry is below 300°C (McMillan et al. 2021). CST is currently well suited for applications in industries such as food processing, dairies, petrochemical, and textiles. For example, in California, researchers found that the technical potential for CST is on the order of 23,000 terawatt hours (TWhth), compared to the 48 TWhth of thermal demand from the top five industrial sectors in the state (Kurup and Turchi 2015). All states have CST potential (e.g., with parabolic trough or linear Fresnel), and for nearly 30% of counties in the United States, more than 45% of the counties' load could be met with CST coupled with TES(McMillan et al. 2021). Recent modeling highlighted the use of a direct steam generation (DSG) system for providing steam for food processing (Akar et al. 2021).

In the United States, there are a few emerging CST players, although the largest power tower and heliostat developer is Heliogen. Outside the United States, Aalborg CSP, for example, has already built a power tower producing heat, desalinated water, steam, and electricity for a tomato farm in Australia (Aalborg CSP 2016). Power tower and heliostat-driven solutions for IPH are emerging. For example, the Barilla pasta factory in Italy will pilot a centrifugal ceramic particle receiver designed by DLR (Sayles 2020).

6.4 Jobs and Domestic Content

In 2020, there were nearly 12 million jobs in the entire U.S. manufacturing sector (US Census 2020). As such, there is potential to develop CSP supply chains and jobs in the United States. With increased demand for heliostats and CSP power towers, it would be possible to set up more permanent supply chains and increase jobs in the industry. With the U.S. manufacturing experience, there could be a reutilization of supply chains and labor in similar markets. For example, with sufficient demand and opportunity, existing supply chains and trained labor could be shifted toward the production of CSP components, and a heliostat supply chain could be developed.

Prior work has estimated that approximately 500 direct and indirect jobs could be associated with the construction of a 100-MW molten salt power plant with 6 hours of TES (C. Turchi et al. 2015). Based on the CSP capacity estimations from the "Solar Futures Study," the construction of 39 GW of CSP (assuming that it is mainly power tower and that ~500 jobs are created per 100 MW molten salt power tower plant with 6 hours of storage), the United States could have an estimated 195,000 CSP-related jobs (e.g., in manufacturing, construction, and O&M) by 2050. This does not include the longer-term jobs and economic impact (e.g., taxes from plant operations staff) from operating the plants once constructed. Table 11 shows the potential direct and indirect jobs for glass and steel (based on the analysis of the commercial and advanced designs in Kurup et al. (2022)) associated with the construction of 100 and 1,000 commercial and advanced design fields. One hundred heliostat fields would be suited for at least 100 power tower plants.

Table 11. Potential Direct and Indirect Jobs for Constructing 100 and 1,000 Heliostat Fields Utilizing Current Analysis

Material/Area	Metric Tons of Material (MT) for Single Field	Direct and Indirect Potential Jobs for 100 Heliostat Fields	Direct and Indirect Potential Jobs for 1,000 Heliostat Fields
Commercial Design, Glass	10,786	9,480	94,798
Advanced Design, Glass	10,800	9,486	94,860
Commercial Design, Steel	13,343	6,761	67,609
Advanced Design, Steel	17,443	8,838	88,384

7 Recommendations

In this section, we provide three recommendations based on this initial work and analysis.

7.1 Future Detailed Market, Manufacturing Capacity, and Economic Impact Analysis

An important next step will be to undertake further detailed analysis of the U.S. and global markets for heliostat components, manufacturers, and developers. This work should also consider aspects such as commodity price tracking (e.g., for steel and glass) to help determine factors that drive heliostat costs in the United States. This type of detailed analysis would help form the basis for a heliostat component, manufacturer, and developer database.

A core feature of the future study will be to evaluate the potential of higher-value U.S. manufacturing that could be developed and the value retained, rather than the technology being imported. For example, in the bottom-up heliostat analysis (Kurup et al. 2022), discussions with heliostat developers highlighted that it would be likely that Chinese components for the mirror facets and steel structures would be utilized for a project in the United States, due to cost differentials and a lack of readily available U.S. heliostat facets.

Future analysis efforts should look at the economic value-add along the supply chains of heliostats and extraction technologies that feed into subsequent technologies, similar to the analysis that has been done for EVs and lithium-ion battery supply chains (Chung, Elgqvist, and Santhanagopalan 2016). More importantly, opportunities for investment, policies, and workforce training could be identified. The analysis would develop metrics such as direct jobs that could be created by growing manufacturing capacity to meet the local market or global export demands, and indirect associated jobs.

For CSP electricity deployment in the United States (e.g., with power towers) to meet the potential of 39 GW by 2050 (Augustine, Turchi, and Mehos 2022), analysis will be needed to determine existing U.S. manufacturing capacities for key components and structures, as well as gaps such as U.S. heliostat facet manufacturing. For example, Table 11 shows the material content needed based on the design; if 1,000 heliostat fields were constructed in the United States, it could lead to roughly 67,000–88,000 steel direct and indirect jobs. This next level of analysis would build upon efforts such as the Jobs and Economic Development Impact (JEDI) model and would help determine location effects. Although there is a CSP JEDI model for the trough (NREL 2008), at present, this work has not been done for a CSP power tower. The heliostat analysis, database, and the manufacturing capacity analysis would contribute to a future CSP Power Tower JEDI model.

Next, this future analysis would identify the regional benefits and impacts of developing important supply chains, and connect R&D to downstream deployments of the technology. Five main areas and impacts are highlighted for future efforts:

- Techno-economic analysis (TEA), including benchmarking of costs for current and future heliostats, and road-mapping through HelioCon. This effort would also connect with the bottom-up trough work (Kurup, Glynn, and Akar 2021) and look at how it can be leveraged for heliostats and linear Fresnel collectors.

- Life cycle analysis (LCA) for heliostats via different paths and impacts on the broader circular economy. This includes end-of-life issues and recycling (e.g., of steel and glass) to bring back the materials used into the U.S. supply chain.
- U.S. competitiveness, value addition, and jobs, including where investment is needed in both capacity expansion and key components. For power towers and heliostats, a model similar to the Parabolic Trough JEDI model (NREL 2008) can be developed.
- Supply chain mapping of existing and future heliostat paths and the crosscutting potential of heliostats in other sectors, including the use of existing supply chains through modification or labor retraining.
- Legal and regulatory framework and policy option analysis for manufacturing investments, CSP use, and environmental impacts.

7.2 Development of a Heliostat Supply Chain Model

The installation of clean energy technologies and the development of new materials/technologies will lead to manufacturing supply chain competition and provide an opportunity for business growth. In a preliminary analysis, McCall (2020) developed a visualization of four clean energy manufacturing supply chains and their associated interactions, shown in Figure 10. The focus was on wind turbines, PV modules, light-emitting diode (LED) systems, and EV vehicle battery packs. It is worth noting that the thickness of the flow is representative of metrics such as the MT needed for a product. Each material flow (e.g., the raw materials needed) is based on a "recipe" or common BOM for an estimate of the materials and processes needed at each stage.

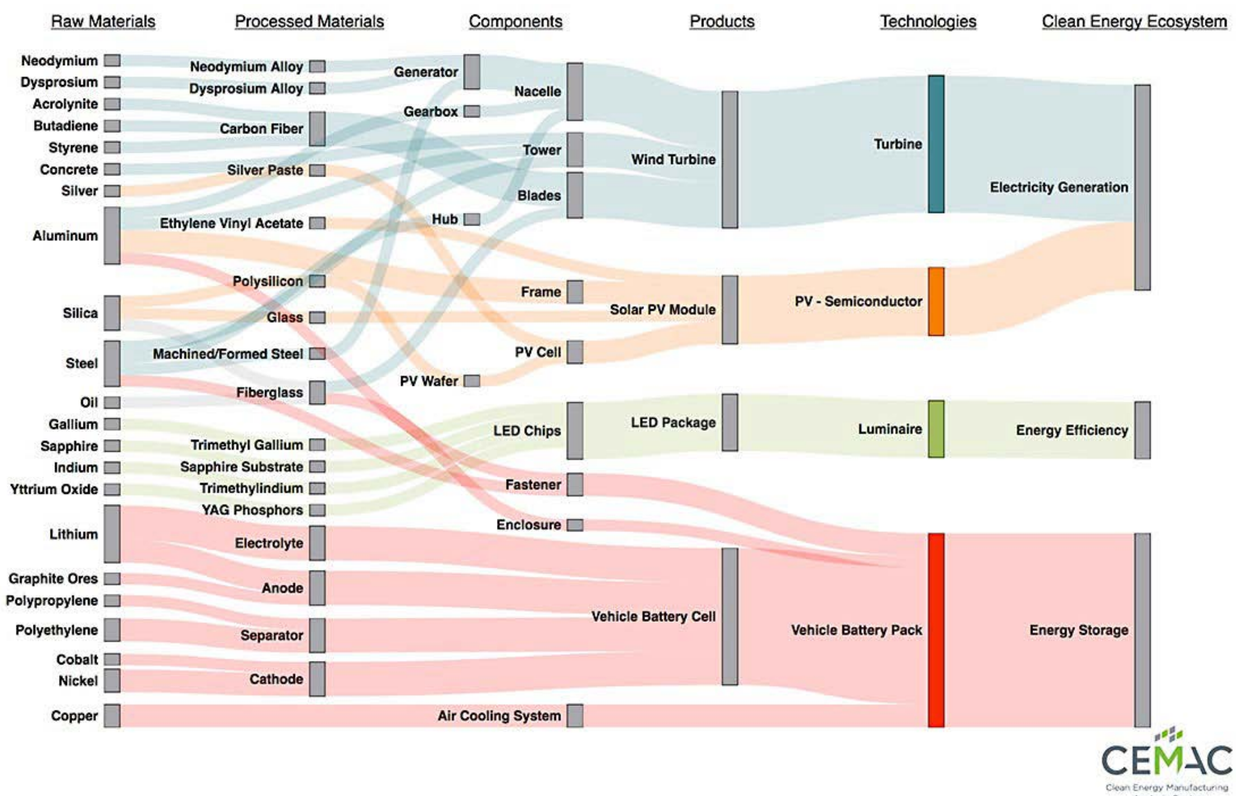

Figure 10. Material flow for clean energy supply chain example.

Although there is little overlap in the supply chains shown, adding more technologies like CSP heliostats will develop areas of supply chain interaction (e.g., steel and glass). We identified four areas of improvement to this initial analysis:

1. An interactive online supply chain map
2. A global manufacturer database for different products
3. Supply chain quantification using “recipes”[2] of clean energy technologies
4. Development of a supply chain impact and vulnerability tool.

At present, there is no heliostat supply chain model that directly models the material flow for heliostats. We recommend that a heliostat supply chain model be built that can incorporate at least one commercial heliostat recipe initially. The bottom-up heliostat analysis (Kurup et al. 2022) can form the basis for a generic commercial heliostat. From a material perspective, heliostat recipes based on different heliostat sizes should be created. This would include the materials, processed materials, and quantities needed for a heliostat field, as well as scenarios for multiples of heliostat fields.

As part of this analysis, it will be important to undertake detailed bottom-up analysis and obtain BOMs for heliostats of a variety of sizes to create different baselines. Once these baseline recipes are created, the data and information could be used with tools such as the Material Flow Through Industry (MFI), which allows manufacturing scenarios to be modeled to track the material and energy demands based on the processes used (NREL 2022b). Different scenarios can highlight the impact of changing upstream and downstream processes on the material and energy consumption of large heliostat fields.

Eventually, with development of the heliostat supply chain mapping tool and analyses, power tower supply chain mapping could be undertaken. In the future, the CSP supply chain mapping will also need to include parabolic trough, linear Fresnel, other CSP collectors and systems in the U.S. supply chain. With further success, non-concentrating solar thermal heating systems could also be explored.

7.3 Future CSP Supply Chain Modeling and Development Efforts

In response to Executive Order 14017 on American supply chains for the energy transition, DOE, other U.S. government departments, and national laboratories like NREL have been identifying and evaluating the U.S. supply chains (DOE 2022). As part of ongoing work with DOE, NREL will publish deep dive assessments for key technologies in the United States. Both PV and wind assessments have been published (Basore and Feldman 2022; Baranowski et al. 2022). Recent work has also looked at the offshore wind supply chain needs in the United States (Shields et al. 2022). This report represents the initial assessment of the U.S. and global heliostat supply chain, and further work is needed to improve the quantification of the CSP supply chain in the United States.

As future supply chain tools and models are built, it is important that CSP components (e.g., heliostats) and CSP supply chain models are incorporated. We propose that once heliostat and

[2] The BOM from raw materials to components that are incorporated into a final clean energy product.

CSP system supply chain models are built, they should be integrated with existing or developing supply chain models that include PV, steam turbines, and other related clean energy technologies. This will help highlight the connections between elements of certain supply chains and the establishment of robust supply chains.

Heliostats are a good candidate for future addition to such an integrated supply chain model due to the potential for having mass-produced components, such as steel structures and mirrors. Incorporating heliostats will shed light on:

- Near-term manufacturing opportunities in the global market; mid- and long-term opportunities for domestic markets
- Simple supply chain and components

Jobs and economic impacts in states like California, Arizona, and Nevada, where CSP (both tower and trough) has already been developed and constructed.

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