An Overview of Heliostats and Concentrating Solar Power Tower Plants

Mackenzie Dennis, Mackenzie.Dennis@nrel.gov
National Renewable Energy Laboratory, March 2022

Abstract

Concentrating solar power (CSP) is naturally incorporated with thermal energy storage, providing readily dispatchable electricity and the potential to contribute significantly to grid penetration of high-percentage renewable energy sources. This overview will focus on the central receiver, or “power tower” concentrating solar power plant design, in which a field of mirrors - heliostats, track the sun throughout the day and year to reflect solar energy to a receiver that absorbs solar radiation as thermal energy. The high-temperature thermal energy can be directly stored with a low-cost heat transfer media, such as molten salt or particles, and, when needed, transfer into electricity through a thermodynamic power cycle. The heliostat represents an integral part of a power tower plant, responsible for collecting and focusing solar energy so that it can efficiently reach the receiver. Heliostat design types and concerns, components, field implementation and performance assessment are summarized along with the standard solar power tower plant design, as a reference to the audience who is interested in heliostats and CSP tower technology.

Introduction to CSP

Concentrating solar power (CSP) is a renewable energy technology that uses mirrors to concentrate solar rays onto a receiver. The receiver converts radiation to thermal energy, which can either be stored in a heat transfer fluid, used to directly generate electricity with a standard steam turbine generator, or used as process heat for industrial processes [1]. There are four standard types, shown in Figures 1-6. The parabolic trough and linear Fresnel designs employ line focus optics, meaning the reflected light is concentrated into a line, requiring a horizontal receiver tube. In contrast, parabolic dish and central receiver (also referred to as “power tower”) designs are point focus, concentrating all incoming rays to a single point. A significant difference is that line focus collectors only require one axis of rotation for sun tracking, while point focus collectors require two, increasing system complexity but resulting in higher concentration of solar ray energy. Each of the technologies has relative advantages and drawbacks [2], and this report will focus primarily on the details of the power tower design.

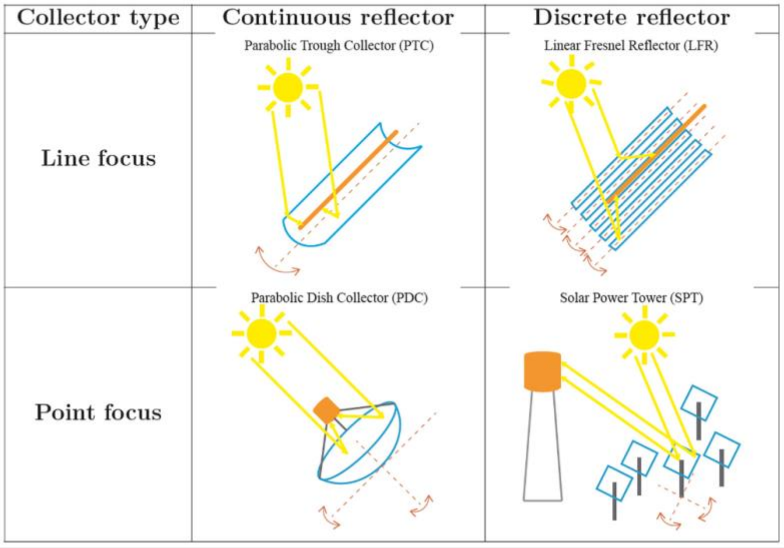


Figure 1: Types of CSP: the basic optics [a]

Figure 2: Parabolic trough plant

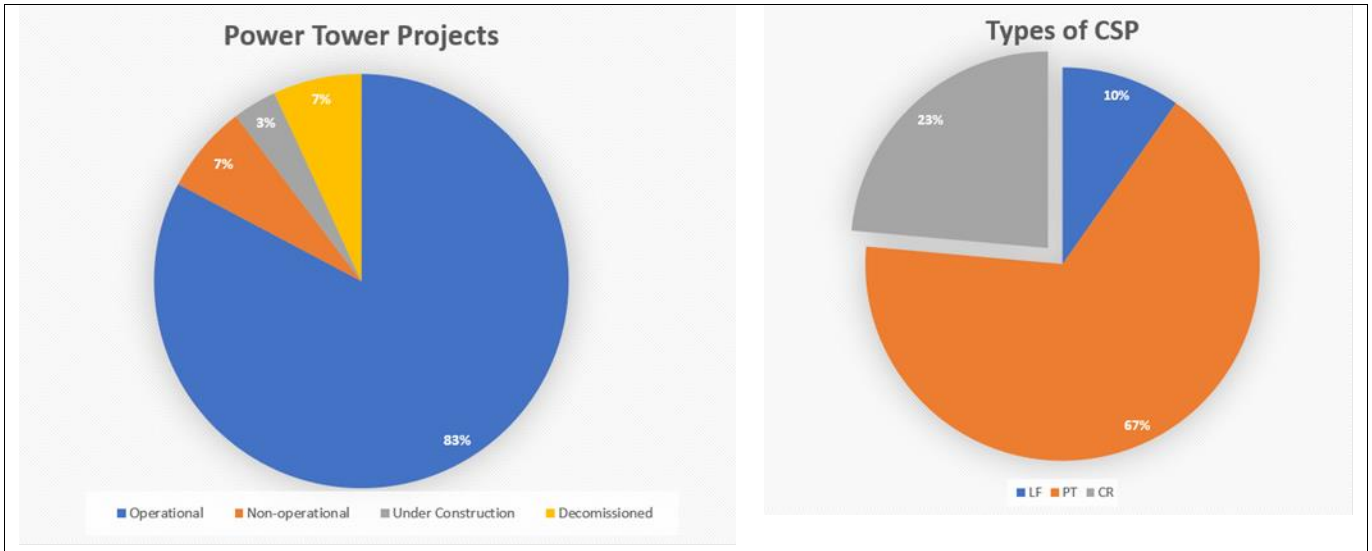
Figure 3: Linear Fresnel collectors at Kimberlina Solar Thermal Power Plant

Figure 4: SunCatcher 38-ft parabolic dish collectors

Figure 5: Crescent Dunes power tower plant, aerial view [b]

Figure 6: Ivanpah solar field (multi-tower)

As of 2021, there are nearly a hundred active CSP plants, including 26 power tower plants, though not all of them are currently operational. A current database of CSP plants and associated information is hosted online by the international group SolarPACES [3], and the current numbers are summarized in Figure 9. A summary of power tower plants is shown in Appendix A, and the SolarPACES site has far more detailed information on all CSP projects, downloadable as an Excel or CSV file.



(a) Operational status of existing power tower plants

(b) Types of CSP plants to date:
LF: Linear Fresnel
PT: Parabolic Trough
CR: Central Receiver

Figure 7: Current CSP Statistics [c]

Benefits of CSP

One of the primary benefits of CSP is easy integration with thermal energy storage (TES), which allows for long term energy storage and readily dispatchable electricity. Solar photovoltaics (PV) can only provide electricity when the sun is shining, and at high renewable grid penetration, this can cause issues with ramping for nighttime energy demand. This phenomenon is often referred to as the duck curve, and is observed in California [4], where PV is heavily used but energy demand is still high after sunset. TES allows for overnight storage and on-demand conversion to electricity, adding resiliency to a highly renewable electrical grid. TES can also be used for industrial process heat, directly replacing the burning of fossil fuels. CSP electricity is currently more expensive than PV, but thermal storage is cheaper than electrical storage, so there are trade-offs to both technologies. A combination of PV and CSP is generally seen as a promising route in the future of solar power.

The Power Tower Plant

The power tower plant is typically the largest of the CSP designs, consisting of a field of mirrors, heliostats, that track the sun throughout the day and year to maintain a constant focal point on the receiver, which consists of absorber panels of tubes near the top of the tower [5]. These tubes are irradiated by the concentrated sunlight and absorb the incoming energy as heat, which is then transferred to the heat transfer fluid (molten salt, steam, etc.). The heat is then either stored or used to generate electricity using a traditional turbine generator, shown in Figure 8.

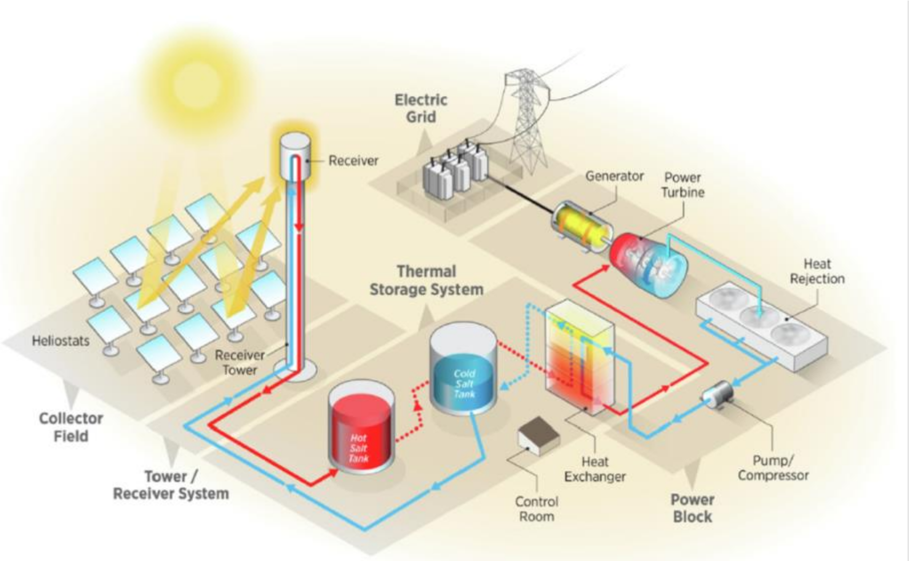


Figure 8: Schematic of a power tower plant with molten salt TES [a]

The two existing power tower plants in the United States are in the California/Nevada desert: the Crescent Dunes Solar Energy Project (Figure 5) and Ivanpah Solar Power Facility (Figure 6). Crescent Dunes was designed with a capacity of 110MW and resides on 1,670 acres, including 296 acres of heliostats, each sized 115m^2. Crescent Dunes has a 200m receiver tower and incorporated thermal energy storage via molten salt tank (Figures 9). Ivanpah has three receiver towers and a total site size of 3500 acres, with a gross capacity of 392 MW. Ivanpah has comparatively smaller heliostats, at 15m^2, and does not incorporate TES, instead operating directly on a steam cycle. These two plants are exemplary of the variety in plant designs, with many differences in design worldwide.

Figure 9: A molten salt tank for thermal energy storage [d]

Benefits of the Power Tower Design

The main benefit of the power tower plant design, in addition to general CSP benefits, comes from the large scale coupled with design-based efficiency. Because all incoming energy is focused onto a relatively small area on the tower, the flux on the receiver is four to six times as concentrated as the light hitting the heliostats in the field [6]. This relation is known as a high concentration ratio and corresponds to higher working temperatures (usually around 560°C), which results in better thermodynamic efficiency for both electricity generation and thermal energy storage. While the investment and infrastructure for a power tower plant is expensive when compared to other technologies, the large scale and high efficiency make it a good candidate for substantially increasing renewable energy generation, especially as the technology improves.

History and Development of CSP and Heliostats

CSP development and research on heliostats for CSP began in the 1970s, upon establishment of DOE sponsorship in the United States and similar initiatives internationally. This report is primarily focused on heliostats, for which the technology has progressed through three distinct phases, to date. First generation heliostats were made of laminated glass and sized about 40m^2 on average. The second generation was a transitional phase in the late 1970s and early 1980s, with the primary change being an increase in size (44-57m^2). The goal was to decrease cost per unit collection area by minimizing cost of components that are needed for each heliostat, regardless of size (control mechanisms, structural support, etc.). During this period, some preliminary design specifications and standards were also suggested, to place controls on performance, survival, and lifespan of components. A 30 year lifespan was suggested, and has remained the standard. The third generation is the current state of the art technology, which brings even larger sizes (often over 100m^2) in addition to a greater variety of research including much smaller heliostats (<1m^2) and several novel designs. Optimal size, shape and design are still topics of debate, and there are many opportunities for optimization that will effect the overall cost and impact of the technology.

The Future of Power Tower CSP

An increase in research in CSP is needed to effectively scale implementation of the technology and make it competitive with traditional energy sources. The primary limitation, as of 2022, is the effective cost of the electricity generated by power tower plants, which the industry quantifies as levelized cost of electricity (LCOE). In 2011 the SunShot initiative set aggressive LCOE goals for CSP, and the industry is necessarily very focused on cost reduction to meet those goals. While cost is a function of the entire plant, including construction and operational costs, heliostats represent about 40% of the total cost of a power tower plant [7], and are highly impactful to overall cost of power tower CSP. Heliostats also largely dictate production, and improvements in optical performance and reliability are very important to overall plant performance. Almost all aspects of heliostats and power tower plants are being actively researched, and the technology is rapidly improving.

References for Introductory Information

[1] Merchán, R.P., Santos, M.J., Medina, A., Calvo Hernández, A., 2021. High temperature central tower plants for concentrated solar power: 2021 overview. Renewable and Sustainable Energy Reviews 155, 111828. https://doi.org/10.1016/j.rser.2021.111828

[2] Kincaid, N., Mungas, G., Kramer, N., Wagner, M., Zhu, G., 2018. An optical performance comparison of three concentrating solar power collector designs in linear Fresnel, parabolic trough, and central receiver. Applied Energy 231, 1109–1121. https://doi.org/10.1016/j.apenergy.2018.09.153

[3] SolarPACES. https://solarpaces.nrel.gov/. Accessed Jan. 2022.

[4] Denholm, P., O'Connell, M., Brinkman, G., Jorgenson, J., 2015. Overgeneration from Solar Energy in California. A Field Guide to the Duck Chart (No. NREL/TP--6A20-65023, 1226167). https://doi.org/10.2172/1226167\

[5] Ho, C.K., 2017. Advances in central receivers for concentrating solar applications. Solar Energy 152, 38–56. https://doi.org/10.1016/j.solener.2017.03.048

[6] Mehos, M., Price, H., Cable, R., Kearney, D., Kelly, B., Kolb, G., Morse, F., 2020. Concentrating Solar Power Best Practices Study. Renewable Energy 269.

[7] Pfahl, A., Coventry, J., Röger, M., Wolfertstetter, F., Vásquez-Arango, J.F., Gross, F., Arjomandi, M., Schwarzbözl, P., Geiger, M., Liedke, P., 2017. Progress in heliostat development. Solar Energy 152, 3–37. https://doi.org/10.1016/j.solener.2017.03.029

Heliostat Design and Components

Heliostat Optics

The ability to control the focal point of each heliostat is based on the law of reflection, pictured in Figure 10, which states that the angle of incidence (the angle between the surface normal of the mirror, and the incoming ray) equals the ray of reflection (the angle between the normal and the reflected ray). This always holds true for perfectly specular (mirrored) surfaces, so the required position of the heliostat can always be calculated to focus light onto the receiver, regardless of sun position in the sky.

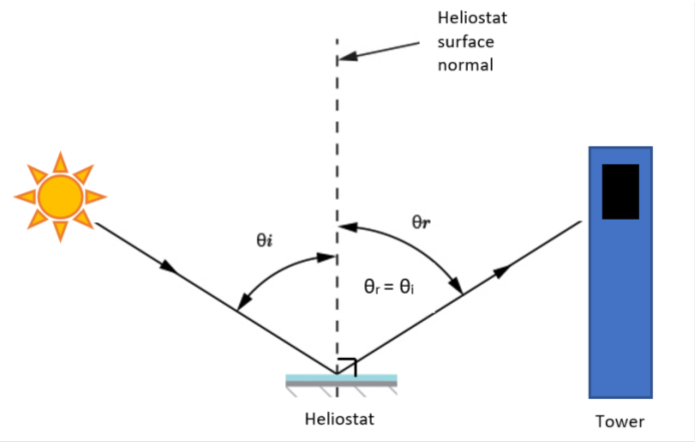


Figure 10: Law of reflection for specular surfaces (modified from [e])

Collector Design

Optical focusing is achieved by a combination of features of a heliostat. Each heliostat is often a collection of smaller mirrors, called facets, shown in Figure 11, which are usually square or rectangular, and either flat or slightly curved. Each facet is canted (tilted) to give the larger heliostat an overall parabolic shape, concentrating all incoming light to a single optical focal point on the receiver, similar to the parabolic dish collector in Figure 1. For this traditional design strategy, heliostats at different distances from the tower have different shapes, and cannot be used interchangeably. As mentioned in the introduction, they can be quite large, and because of the favorable optics, provide high output.

Alternatively, newer models have also shown the efficacy of much smaller, simpler heliostats made of flat mirrors and only one or two facets. For these designs, heliostats are all the same and do not focus as effectively, but can be much cheaper. Because cost is a driving factor in the success of CSP, some argue that the industry will be experiencing a trend towards smaller and simpler heliostat designs [8].

Regardless of design, once the facets are assembled and canted, usually in the manufacturing plant, their position is fixed relative to the heliostat frame, and the heliostat moves as a single unit. A controls system provides input to the drives (one for each of the two tracking axes), which are responsible for moving the heliostat periodically throughout the day, as the sun moves in the sky.

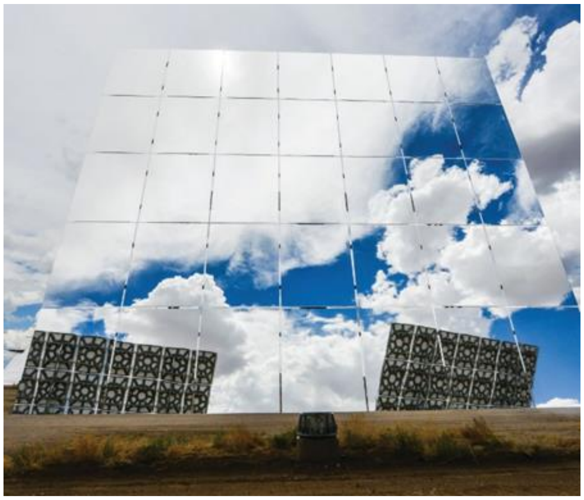


Figure 11: A single Heliostat with 35 facets

Figure 12: Scale of heliostats, stamped backing

Sun Tracking Calculations

The sun tracking control system is based on astronomical data regarding the apparent sun shape in the sky and known data for the sun's relative position to the heliostat, based on physical geographical location (latitude and longitude)[9]. The relative positions of the sun, heliostat and tower are used to calculate the optimal orientation for the heliostat, which is then attained through the two degrees of freedom controlled by the drives. Though there are various tracking methods, the basis for the calculation of optimal surface normal (orientation) of the heliostat remains the same, and the methods usually refer to different strategies for achieving the optimal positioning via drive mechanics.

Mirror Facets

Heliostat facets are typically mirrored glass, though reflective films, plastics, and other technologies have been researched, though durability issues have been common with alternative materials. Thinner glass is more optically efficient, since light can be refracted within the small thickness of glass between the surface and the mirrored back, producing optical errors. Thinner glass also reduces weight, which can contribute in beneficial ways to wind loading and cost of components. To this end, some heliostat manufacturers and designers use sandwiched panels, which are made of thin mirrored glass with a stiff foam core. The foam core allows for thinner glass without sacrificing stiffness, which also has an impact on optical errors and efficiency.

Support Structure

The facets are bound together by a support structure that mounts to the drives for each heliostat. Though there are several designs, the standard heliostat is a T-bar, pictured in Figures 12 and 13, which provides the axes of rotation and supports the structure. The facets are then supported in a variety of manners, with struts of different formations, or a stamped structure, as in Figure 12. Some support structures require pins and adhesive, as in Figure 13, to account for different thermal expansion ratios of the facets and support material. The pins and/ or adhesive absorb the difference in material expansion ratios, so that the facet maintains its shape under temperature changes and does not alter the optical efficiency. Other support structures and heliostat shapes have also been explored and are summarized by Pfahl et al. [10], with some examples shown in Figures 14-16.

Figure 13: T-bar heliostat support with pins [f]

Figure 14: Heliogen pentagonal heliostat with spot supports [g]

Figure 15: Pentagonal Heliostat Supports, Hami [h]

Figure 16: Hoop backing at Sandia National Solar Thermal Test Facility [i]

Foundation

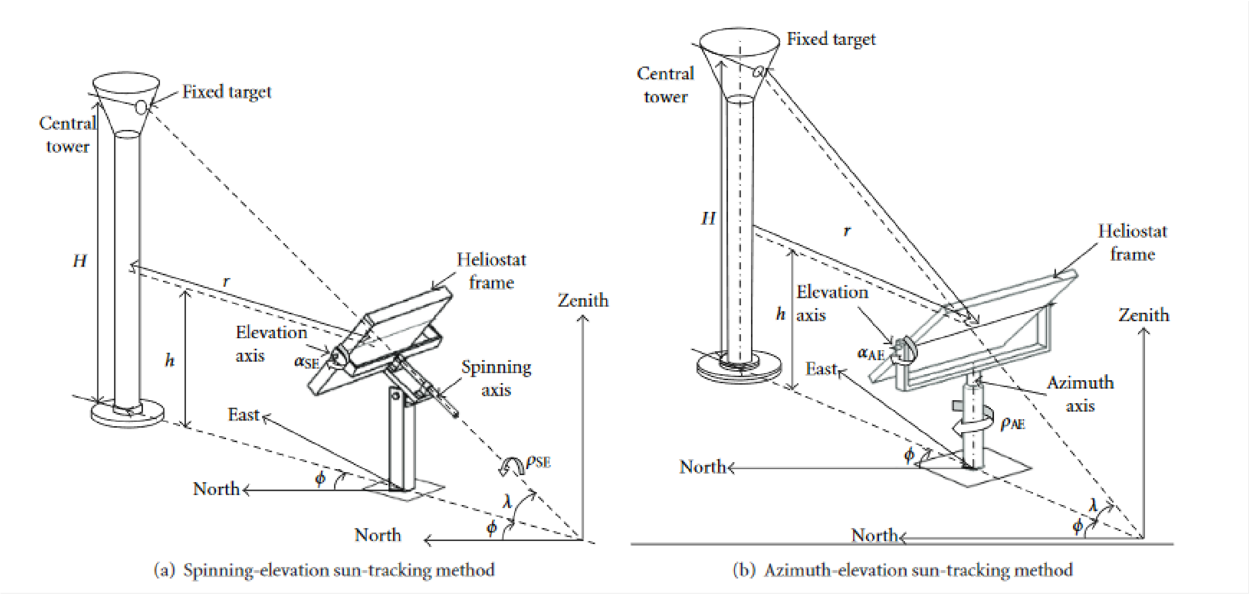
The heliostat structure is supported by a pylon, usually with a concrete foundation. Pylons can be pile driving, ground anchor, or ballast type, and there has been additional research into pre-fabricated ground-anchor structures that could reduce costs [11]. The necessity of an anchor has also been avoided altogether by a modular pod structure, as in Figure 17, though this design is only appropriate for smaller scales.

Figure 17: Modular Heliostat Pods [j]

Drives

The drives, the mechanisms that mechanically move the heliostat into position, are some of the most costly components of each heliostat, largely due to sensitivity requirements. High accuracy is especially important in power tower plants, where the distance between the heliostat and the receiver is large, and small errors can cause large losses. In a typical field layout, 360 degrees of azimuthal (rotational) and 90 degrees of elevation (tilting) range of motion are needed to focus sunlight on the receiver throughout the day and year. Rotary drives are standard for at least one axis, though simpler rim drives and linear drives have also been explored for cost reduction, though they come with accuracy and range of motion tradeoffs [11][12]. While heliostat drives require more strenuous performance than for other industries, drives can be used “off the shelf,” and do not necessarily need to be designed for heliostat use.

Physical Sun Tracking



(a) Spinning-elevation sun-tracking method

(b) Azimuth-elevation sun-tracking method

Figure 18: SE and AE tracking setup for heliostats [k]

Drive type is related to, but distinct from the tracking technique used by the heliostat. The traditional method of sun tracking is the azimuth-elevation (AE) tracking method, where one axis of rotation points towards the zenith (vertically) and the other is tangential to the heliostat surface, creating rotation and tilting of each heliostat as seen from a bystander's reference frame, as in Figure 18(b). One downside of this method is that it requires greater spacing between heliostats to accommodate the rotational range of motion and potential for corner clipping with rectangular heliostats, though this problem can be overcome with advanced control systems [13][14]. Spinning-elevation tracking [15][16] is also becoming more common, where one axis of rotation points in the direction of the target (the tower) and the elevation axis is once again tangential to the heliostat surface, as in Figure 18(a). Benefits of the spinning-elevation method (also called target-aligned) are better shadowing and blocking efficiency between heliostats and, some have argued, more consistent optical performance [15]. Horizontal primary axis tracking has also been explored to accommodate cheaper linear drives, as well as higher heliostat field density [17], though this type is not currently as widespread as the others.

Current trends

As mentioned earlier, due to the high degree of complexity of each heliostat, there has been some movement towards simplifying heliostat design to simplify manufacturing and installation and improve reliability. Though the historical trend has been to steadily increase collector size, improvements in software allow for competitive small heliostats [8] that are more compatible with pre-fabrication techniques [13] and automated installation and cleaning. With smaller heliostats, plant size can be easily scaled up or down, with the flexibility of including multiple receiver towers if desired, due to heliostat design uniformity and inherently modular characteristics [18]. Each heliostat still requires its own drives and components, regardless of collector size, but these components can be smaller and lighter weight (especially due to less need for stabilizing under wind load), which usually corresponds to lower costs per heliostat that can balance the difference in costs per unit collection area. As mentioned earlier, large heliostats are still actively used and researched, and there is no industry-wide consensus on size or design style. It may be that site specific aspects of deployment continue to encourage a variety of approaches, and innovation in the field is ever evolving.

References for General Power Tower Design and Components

[8] Heliogen-Presentation-Sept-30-2021.pdf, 2021.

[9] Chen, Y.T., Lim, B.H., Lim, C.S., 2006. General Sun Tracking Formula for Heliostats With Arbitrarily Oriented Axes. Journal of Solar Energy Engineering 128, 245–250. https://doi.org/10.1115/1.2189868

[10] Pfahl, A., Coventry, J., Röger, M., Wolfertstetter, F., Vásquez-Arango, J.F., Gross, F., Arjomandi, M., Schwarzbözl, P., Geiger, M., Liedke, P., 2017. Progress in heliostat development. Solar Energy 152, 3–37. https://doi.org/10.1016/j.solener.2017.03.029

[11] Pfahl, A., Randt, M., Holze, C., Unterschütz, S., 2013. Autonomous light-weight heliostat with rim drives. Solar Energy 92, 230–240. https://doi.org/10.1016/j.solener.2013.03.005

[12] Coventry, J., Pye, J., 2014. Heliostat Cost Reduction – Where to Now? Energy Procedia 49, 60–70. https://doi.org/10.1016/j.egypro.2014.03.007

[13] Coventry, J., Campbell, J., Xue, Y.P., Hall, C., Kim, J.S., Pye, J., Burgess, G., Lewis, D., Nathan, G.,Arjomandi, M., Stein, W., Blanco, M, Barry, J., Doolan, M., Lipinski, W., Beath, A., 2016, Heliostat Cost Down Scoping Study – Final Report. ANU Document Reference: STG-3261 Rev 01, ASTRI, Australia.

[14] Burisch, M., Mutuberria, A., Olasolo, D., Villasante, C., 2016. Influence of limited heliostat motion onto the efficiency of a solar field. Presented at the SOLARPACES 2015: International Conference on Concentrating Solar Power and Chemical Energy Systems, Cape Town, South Africa, p. 020004. https://doi.org/10.1063/1.4949028

[15] Chong, K.-K., Tan, M.H., 2012. Comparison Study of Two Different Sun-Tracking Methods in Optical Efficiency of Heliostat Field. International Journal of Photoenergy 2012, 1–10. https://doi.org/10.1155/2012/908364

[16] Schramek, P., Mills, D.R., 2004. Heliostats for maximum ground coverage. Energy 29, 701–713. https://doi.org/10.1016/S0360-5442(03)00178-6

[17] HelioTower Cordes S, Prosinecki TC, Wieghardt K. An approach to competitive heliostat fields. In: 18th annual SolarPACES symposium. 2012. Marrakesh

[18] Crespo, L., Ramos, F., 2020. Making central receiver plants modular, more efficient and scalable. Presented at the SOLARPACES 2019: International Conference on Concentrating Solar Power and Chemical Energy Systems, Daegu, South Korea, p. 030010. https://doi.org/10.1063/5.0028916

Wind Loading

Wind loading is important aspect of heliostat design and has significant effects on component choice, field design, and site selection. Wind can reduce optical efficiency due to collector movement or oscillations, and is also an important structural threat [19][20]. Naturally, wind effects are site specific, and need to be forecasted with high resolution data to appropriately select design parameters, including stiffness, strength of materials, and dimensioning. Larger heliostats weigh more, in addition to experiencing higher deflection during wind events, thus requiring heavier duty supports to withstand both daily and storm winds and greater static and dynamic structural loads. While strong winds can result in mechanical failure, fluctuating winds can cause pressure oscillations from buffeting that can result in fatigue failure of components. Heliostats are usually moved into a horizontal stow position above winds of a certain speed, to avoid damage. A typical metric is the design wind speed, which dictates the amount of wind a heliostat is expected to withstand.

Wind design speeds are determined via a combination of modelling and testing. Wind loading is quantified by mean and peak load coefficients, determined by both site data and heliostat design specifications. This process usually consists of some computational fluid dynamics and finite element analysis simulations, as in Figure 19, as well as scaled wind tunnel experiments (Figure 20) for numerical validation and experimental results. Wind effects on heliostats occur in the atmospheric boundary layer, which exhibits complex turbulent behavior that is computationally expensive to model and hard to simulate in a wind tunnel due to scaling issues [20].

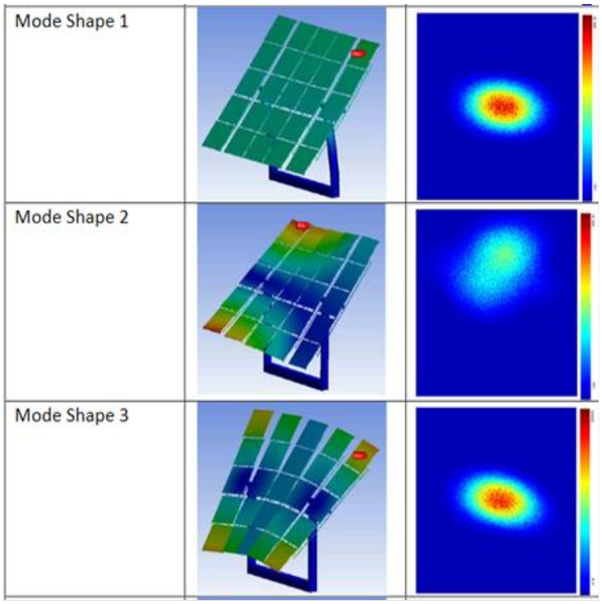


Figure 19: Numerical examples of wind loading effects on beam shape [l]

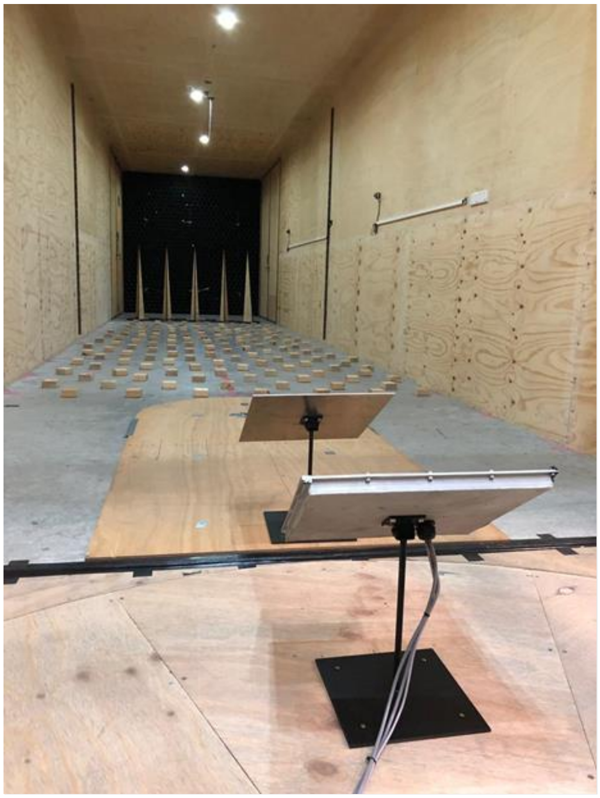


Figure 20: Atmospheric boundary layer wind tunnel heliostat testing, University of Adelaide [m]

There are several strategies for mitigating wind effects in the field, including the placement of wind barriers and heliostats designed to deflect in high winds and return to their original position. Orientation and shape of the heliostats play a role, as does the layout and spacing of the field, including the local topology. Wind loading is a huge topic in CSP, with a long history and future of research in the area [21][22].

References for Wind Loading

[19] Mehos, M., Price, H., Cable, R., Kearney, D., Kelly, B., Kolb, G., Morse, F., 2020. Concentrating Solar Power Best Practices Study. Renewable Energy 269.

[20] Pfahl, A., Coventry, J., Röger, M., Wolfertstetter, F., Vásquez-Arango, J.F., Gross, F., Arjomandi, M., Schwarzbözl, P., Geiger, M., Liedke, P., 2017. Progress in heliostat development. Solar Energy 152, 3–37. https://doi.org/10.1016/j.solener.2017.03.029

[21] Emes, M., Jafari, A., Pfahl, A., Coventry, J., Arjomandi, M., 2021. A review of static and dynamic heliostat wind loads. Solar Energy 225, 60–82. https://doi.org/10.1016/j.solener.2021.07.014

[22] Sun, H., Gong, B., Yao, Q., 2014. A review of wind loads on heliostats and trough collectors. Renewable and Sustainable Energy Reviews 32, 206–221. https://doi.org/10.1016/j.rser.2014.01.032

Standards, Guidelines and Test Protocols

Standards for heliostats are still under development, with no current formal standards for heliostat manufacturing, design, or performance assessment. However, the international network of industry experts and researchers in CSP, SolarPACES, has published a guideline on heliostat performance testing, [23] which defines specific parameters to describe the variety of errors (and their sources) with detrimental effects on heliostat performance. SolarPACES has also developed a reflectance guideline [24] that helps standardize the process for consistently measuring the reflectance of a heliostat's mirrors. Additional reflectance parameters and measurement methods have been addressed by several others, as well [25][26]. A set of standards for CSP components has been published [27], addressing performance as well as wear and tear of both the solar mirrors and other components, though it focuses more on line focus CSP technology than point focus heliostats. Nieffer et al [28] documents the iterative testing and design process of a heliostat designed along the SolarPACES guidelines, with some insights to the benefits of standardization. Finally, a preliminary standard for assessing performance and plant yield has been proposed [29], as have guidelines for modelling [30].

Because the intended lifespan of heliostat components is about 30 years, both real time and accelerated wear testing are used to determine durability and reliability [31]. A standardization protocol for assessing solar reflector materials has also been developed by the Spanish entity AENOR, and aged reflectors have been assessed against this standard [32]. An important goal for current CSP work is to create more rigorous standards in all areas of development and implementation, to provide both cost reduction and reliability for the technology.

References for Standards and Guidelines

[23] Marc Röger, 2018. SolarPACES Guideline for Heliostat Performance Testing.

[24] Fernandez-Garcia, A., Sutter, F., Montecchi, M., Sallaberry, F., Heimsath, A., Heras, C., Le Baron, E., Soum-Glaude, A., 2018. SolarPACES Reflectance Guidelines V3.

[25] Meyen, S., Montecchi, M., Kennedy, C., Zhu, G., Crawford, J., Heimsath, A., Ise, F., ONeill, M., Ziegler, S., Brändle, S., 2013. PARAMETERS AND METHOD TO EVALUATE THE SOLAR REFLECTANCE PROPERTIES OF REFLECTOR MATERIALS FOR CONCENTRATING SOLAR POWER TECHNOLOGY 38.

[26] Aránzazu Fernández-García, Florian Sutter, Marco Montecchi, Fabienne Sallaberry, Anna Heimsath, Carlos Heras, Estelle Le Baron, Audrey Soum-Glaude, 2020. Official Reflectance Guideline Version 3.1: PARAMETERS AND METHOD TO EVALUATE THE REFLECTANCE PROPERTIES OF REFLECTOR MATERIALS FOR CONCENTRATING SOLAR POWER TECHNOLOGY UNDER LABORATORY CONDITIONS.

[27] Sallaberry, F., Bello, A., Burgaleta, J.I., Fernandez-García, A., Fernandez-Reche, J., Gomez, J.A., Herrero, S., Lüpfert, E., Morillo, R., Vicente, G.S., Sanchez, M., Santamaria, P., Ubach, J., Terradillos, J., Valenzuela, L., 2016. Standards for components in concentrating solar thermal power plants - status of the Spanish working group. Presented at the SOLARPACES 2015: International Conference on Concentrating Solar Power and Chemical Energy Systems, Cape Town, South Africa, p. 110003. https://doi.org/10.1063/1.4949200

[28] Nieffer, D., Effertz, T., Macke, A., Röger, M., Weinrebe, G., Ulmer, S., 2019. Heliostat testing according to SolarPACES task III guideline. Presented at the SOLARPACES 2018: International Conference on Concentrating Solar Power and Chemical Energy Systems, Casablanca, Morocco, p. 030039. https://doi.org/10.1063/1.5117551

[29] Hirsch, T., Bachelier, C., Eck, M., Dersch, J., Fluri, T., Giuliano, S., Goebel, O., González, L., Haller, U., Meyer, R., Puppe, M., Rau, C., Schenk, H., Schmidt, N., Seitz, M., Westphal, B., Yildiz, E., Yu, Q., 2017. The first version of the SolarPACES guideline for bankable STE Yield assessment. Presented at the SOLARPACES 2016: International Conference on Concentrating Solar Power and Chemical Energy Systems, Abu Dhabi, United Arab Emirates, p. 160014. https://doi.org/10.1063/1.4984548

[30] Kesseli, D., Wagner, M., Guédez, R., Turchi, C.S., 2019. CSP-plant modeling guidelines and compliance of the system advisor model (SAM). Presented at the SOLARPACES 2018: International Conference on Concentrating Solar Power and Chemical Energy Systems, Casablanca, Morocco, p. 170006. https://doi.org/10.1063/1.5117676

[31] Lahlou, R., Al Naimi, K., Al Yammahi, H., Wette, J., Sutter, F., Fernández-García, A., Armstrong, P.R., Calvet, N., Shamim, T., 2018. Study and comparison of naturally-aged and As-received silvered-glass reflectors. Presented at the SolarPACES 2017: International Conference on Concentrating Solar Power and Chemical Energy Systems, Santiago, Chile, p. 230007. https://doi.org/10.1063/1.5067235

[32] Fernández-García, A., Martínez-Arcos, L., Sutter, F., Wette, J., Sallaberry, F., Erice, R., Diamantino, T., Carvalho, M.J., Raccurt, O., Pescheux, A.-C., Imbuluzqueta, G., Machado, M., 2018. Accelerated aging test of solar reflectors according to the new AENOR standard – results of a round Robin test. Presented at the SolarPACES 2017: International Conference on Concentrating Solar Power and Chemical Energy Systems, Santiago, Chile, p. 230003. https://doi.org/10.1063/1.5067231

Field Deployment

Site Selection

Before a CSP plant site is selected for construction, several environmental factors are quantified to estimate plant performance. A major metric for potential CSP sites is the amount of usable sunlight, often referred to as “solar resource” in the industry, a given geographical location typically receives. This is usually quantified as DNI (direct normal irradiance), an analysis of high resolution environmental solar incidence data. DNI is a measurement of the angle of the sun in a specific geographic location, which depends heavily on latitude, and accounts for cloud coverage and weather patterns typical of the region. Terrain also plays a role for a given location, as most heliostat fields are designed to be level, and flat areas of the size needed for a power tower plant can be difficult to find and similarly difficult to create. This issue can be addressed by varying heliostat pylon heights, either to bring them to the same uniform level, or optimize for an unlevel field, but this adds complexity to the system and is usually avoided.

Other environmental factors are also very important, including the accumulation of dust and particulates on the mirror surfaces, known as soiling, which can have large impacts on plant efficiency. Higher levels of soiling require more regular cleaning, which usually requires water, an additional resource for which availability needs to be assessed during site selection. As mentioned earlier, wind is also a large factor in the overall feasibility of a location, and directly impacts costs. Each of these environmental factors come into play substantially, as locations with high DNI and the space for plant construction are often in desert climates, where dust and wind are plentiful, and resources like power, water, and labor can be difficult and expensive to attain.

Performance Modelling

Plant performance is modelled before construction to ensure cost effectiveness. Simulations most often use ray tracing algorithms, which simulate incoming solar radiation as a discrete collection of individual rays (an approximation to reality) that are reflected to the receiver by the heliostats. This method allows for quantification of the radiation flux on the receiver and the corresponding power output to be expected from the plant design. There are several different pieces of software and approaches to ray tracing analysis, and due to complexity, computation time and power are not insignificant [33-36].

Field Layout and Receiver

Receiver Types

Another aspect of plant design is the field layout, which depends on the type of heliostats as well as the receiver type. Receivers are generally of two types: cavity and external receivers [37], shown in Figures 22 and 21, respectively. A cavity receiver is generally more efficient, channeling solar radiation into a cavity, where it is absorbed by panels that collect the reflected radiation (losses) from the surrounding panels. Cavity receivers are less easily integrated into a surround (360 degree) heliostat field, because they are necessarily directional with the cavity opening, and thus are often deployed with asymmetric heliostat fields. An external receiver has the absorber panels on the exterior, and can receive flux from heliostats from any direction. However, there are losses as the absorber panels do reflect some of the incoming radiation back out to the environment that cannot be recovered. Receiver type is closely linked to the heliostat field layout and required optical efficiency of the heliostat field, and some plants, like Ivanpah (Figure 2), employ multiple receivers amongst the heliostat field to optimize efficiency while increasing plant output.

Figure 21: External Receiver at Sierra Suntower in Lancaster, CA

Figure 22: Cavity Receiver (with spillage) at Khi Solar One [n]

Within the cavity and external receiver classifications, there are several different designs for thermal energy absorption, grouped into liquid, gas and solid particle receivers [37]. The most common CSP receiver uses a liquid as the heat transfer fluid: water for direct-to-steam and molten salt for TES. Gas receivers are much less common due to higher thermal losses and less readily transferrable heat. Air is usually the working fluid, used in a Brayton cycle or to heat a different storage media. Solid particle receivers are an active area of research with promise for future use, though not widely deployed yet. Small solid particles, often ceramic, fall through the receiver and are directly irradiated by the incoming solar radiation. The primary benefit is that solid particles can be heated to higher temperatures and used directly for TES or to heat a fluid for a thermoelectric power cycle.

Receiver Focusing

A CSP plant design constraint is the operating heat transfer fluid, which dictates the optimal and maximum operating temperatures of the plant. The working fluid cannot be brought above its boiling point (for the operating pressures), or damage will occur. This issue is largely avoided with particle receivers, which can handle temperatures of over 1000°C [37]. To avoid overheating at the receiver, sometimes a portion of the heliostats in the field need to be deflected away from the receiver (put on standby). The thermal energy at the receiver is quantified as the flux distribution, which maps the intensity and spatial variations in flux on the receiver. The distribution needs to be relatively balanced to avoid overheating certain zones of the receiver and underheating others. Flux distribution needs to be regularly monitored for proper plant operation, and is refined by aimpoint optimization, a method that calculates the optimal positioning of heliostats in the field to provide the optimal flux distribution on the receiver.

Environmental Concerns

One of the potential downsides of the power tower CSP plant that made mainstream news was the death of birds flying through the airspace above heliostat fields. However, flux from any single heliostat is not enough to kill a bird, and this was only occurring because heliostats on standby were all being focused at the same point, in the air above the tower, creating a focal point where birds could fly into highly concentrated solar rays that would otherwise be concentrated on the receiver. While this specific issue can be effectively mitigated, it is important to consider similar environmental effects of a CSP plant, as well as social and economic effects on the local area, especially because the scale of the technology is so large.

Heliostat Field Layout

Layout of the individual heliostats in the field also has large effects on overall performance. Fields are classified as surround or polar, shown in Figures 23 and 24, where polar fields are oriented depending on the hemisphere for a given plant. Layouts can be either patterned and non-patterned, with the most common being the radial dense staggered, Figure 24, which is a balance between highly complex optimized fields, and simpler, easier to manage patterns. There are many optimization strategies for using advanced algorithms to simulate and optimize field layout and performance [38].

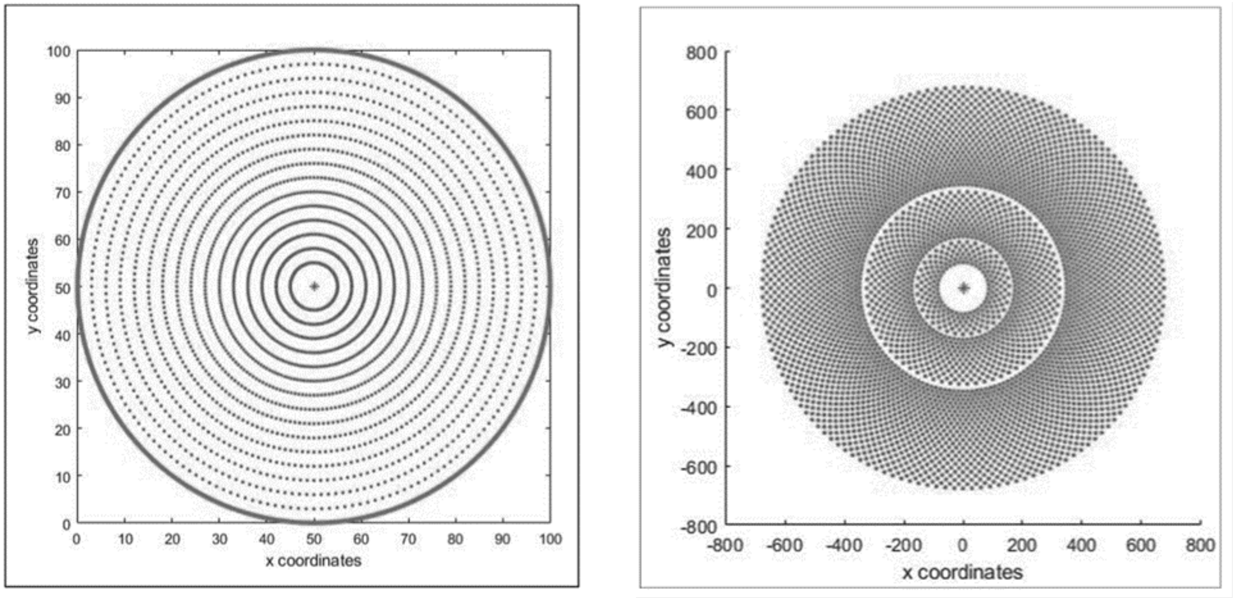


Figure 23: Radial Cornfield Layout (left) and Radial Dense Staggered (right) [o]

Figure 24: Radial Heliostat Field at Shouhang Dunhuang [p]

The main goals of layout optimization are to minimize losses via shading and blocking, increase optical efficiency, and allow the necessary space for heliostats to use their full range of tracking motion without collisions, while also covering as much ground near the tower as possible [39]. While most of these layout issues need no further explanation, optical effects are less intuitive. Though all heliostats in the field do focus on the receiver, they do not have equal output. Generally, heliostats closer to the tower are more efficient due to an optical quantity called cosine efficiency. A light beam will spread at angles further from the normal, perpendicular to the mirror surface (the cosine). Heliostats near the edges of the field behave similarly to all heliostats at the end of the day, because in both cases the angle between the sun, heliostat and receiver is wide. This causes distortion of the reflected sunbeam, which often causes some of the light to miss the receiver (referred to as spillage). Because of these properties, there exists a threshold where building an additional receiver tower becomes more cost effective than simply adding additional heliostats to a single receiver's field.

Heliostat spacing and layout also have an impact on wind loading, which can undermine optimizations made for efficiency [40]. Layout optimization is a complex topic, with many interdependent variables, and many techniques and software packages have been implemented for the task [41][42]. While many models show significant possible improvements, simpler patterns have been favored in practice, for ease of implementation and operation.

Install and Calibration

Due to the scale of the typical power tower plant, construction and installation can be a time consuming and labor-intensive process. While some aspects can be automated, many installation procedures are manual, as shown in Figure 25. Because heliostats can be large and are assembled during manufacturing, before transportation, installation may involve machinery, as in Figure 12. This is an aspect of implementation where smaller, simpler heliostats provide large benefits [43].

Figure 25: Heliostat installation at Solar Field One in 2012 [q]

Once installed in their respective locations in the field, each heliostat needs to be calibrated. There are a variety of different methods, but the calibration at this point in the deployment process is primarily focused on calibrating the tracking of each heliostat, since the angle of each facet (called the cant) and the focal point of the whole heliostat are already fixed and difficult to alter. Each heliostat is calibrated as a single unit, with methods generally falling into one of five groups: camera on ground, camera on tower or UAV, central laser or radar measurements, central focus position detection by camera or sensor on tower, or camera or sensor on heliostat, summarized in Figure 26 [44]. The camera methods all operate based on the law of reflection, and exploit the fact that if the position of camera, heliostat and tower are all known, then the error in heliostat angle can be determined based on a comparison to what it should be. The most common way of calibrating by the central focus position is Sandia National Laboratory's Beam Characterization System (BCS)[45], which measures the flux density of the beam reflected by the heliostat to calibrate its actual versus ideal position. Calibration techniques overlap heavily with metrology techniques.

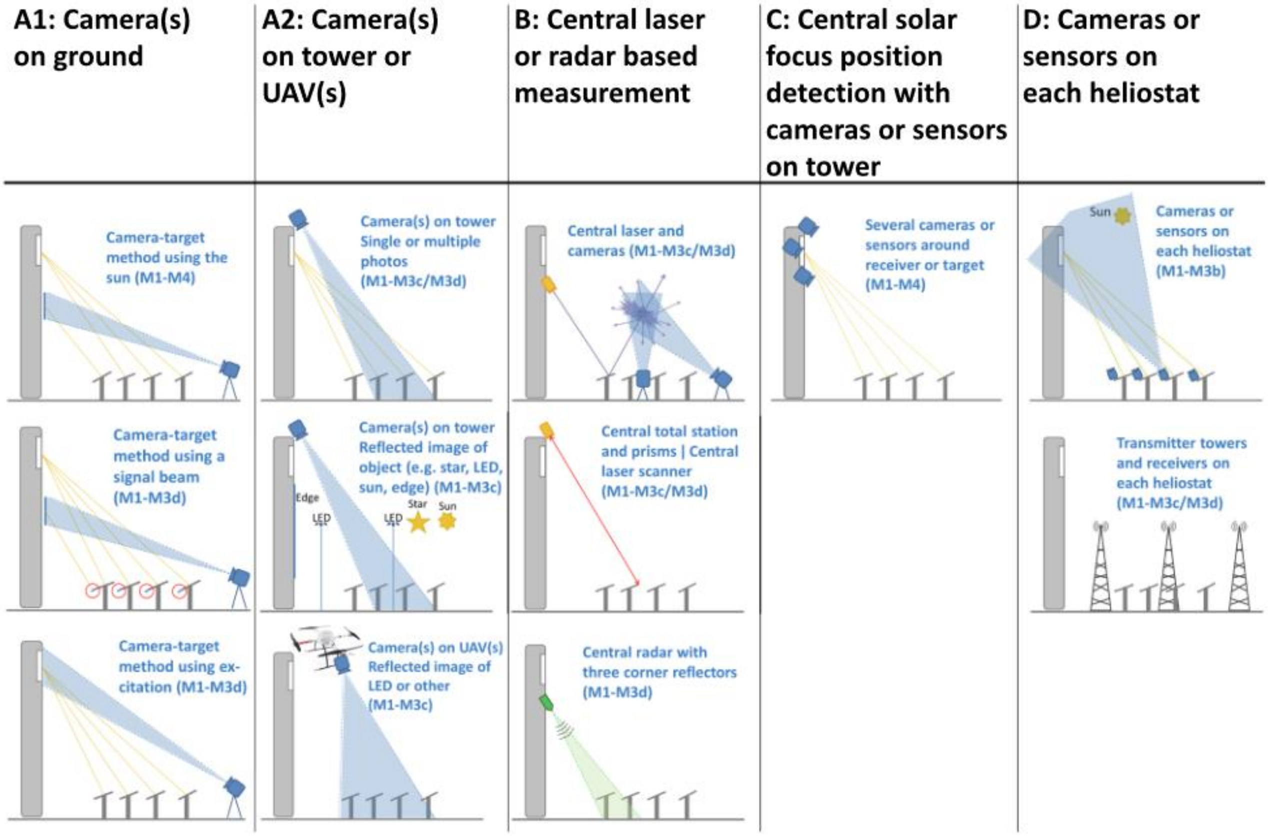


Figure 26: Calibration method types as outlined by Sattler et al. [r]

Operations and Maintenance

Though most of the power tower CSP plant controls are automated, there are additional transient, regular operations including start up and shut down operations, as well as stow overnight and in storm situations, that require additional adjustments and capabilities. Historically there have been inaccuracies with performance modelling due to these processes, and they should be considered in plant design [46].

Heliostat Cleaning

Mirror cleaning is a major operational cost for power tower CSP plants, as soiling is a constant process [47]. There are several different methods for cleaning, but the traditional approach is water-based, consisting of either a high pressure spray or a deluge spray (non-contact cleaning), or contact cleaning, which involves brushing, wiping or scrubbing of the mirror surface, followed by a rinse. Additives and detergents are sometimes used for additional cleaning power, though runoff and mirror surface damage are relevant concerns. Additional non-water-based methods such as ultrasonic and weather cleaning have been explored but are generally more complex and less effective, and thus not widely deployed yet. Anti-soiling mirror coatings have been shown to be effective in preventing particle accumulation on heliostat surfaces, and thus reduce the need for cleaning, though none are widely used in existing plants due to reliability and durability concerns.

Cleaning can either be done manually, semi-autonomously (Figure 27), or fully autonomously, with most current plants employing a semi-autonomous system. Cleaning every heliostat in a large field can be a long and costly process, so accurate soiling and cleaning forecasts and optimization strategies can have a substantial impact on overall plant performance [48].

Figure 27: Semi-automatic heliostat cleaning [s]

Wear and Degradation

Degradation is another operational issue, caused by either environmental factors or design effects. If damaged, heliostats may be replaced, but at a high cost. This is another reason accurate modelling and testing of transient loads and processes need to be tested before implementation, as changes to an existing solar field are often impractical.

Project Financing, Construction and Deployment

CSP projects are a large investment, and there are many logistical steps to project deployment, in addition to the design strategies discussed so far. A project is conceptualized, followed by site selection, permitting, bidding and negotiation with developers, design refinements, and financing. The supply chain for materials needs to be established and streamlined, and field acceptance tests need to be completed in the construction phase. Finally, after plant performance modelling and acceptable techno-economic analyses, the project moves into an operational phase, which involves agreements between owner and operator and transfer of responsibilities. Heliostat design and performance requirements are involved with each step, as is the case for all other components. Large scale and complexity require many collaborators to successfully implement a power tower CSP plant, and documentation of past issues with existing plants should help with more seamless implementation for future facilities [46].

References for Field Deployment

[33] Cruz, N.C., Redondo, J.L., Berenguel, M., Álvarez, J.D., Ortigosa, P.M., 2017. Review of software for optical analyzing and optimizing heliostat fields. Renewable and Sustainable Energy Reviews 72, 1001–1018. https://doi.org/10.1016/j.rser.2017.01.032

[34] Bode, S.-J., Gauché, P., 2012. REVIEW OF OPTICAL SOFTWARE FOR USE IN CONCENTRATING SOLAR POWER SYSTEMS 8.

[35] Garcia, P., Ferriere, A., Bezian, J.-J., 2008. Codes for solar flux calculation dedicated to central receiver system applications: A comparative review. Solar Energy 82, 189–197. https://doi.org/10.1016/j.solener.2007.08.004

[36] Belhomme, B., Pitz-Paal, R., Schwarzbözl, P., Ulmer, S., 2009. A New Fast Ray Tracing Tool for High-Precision Simulation of Heliostat Fields. Journal of Solar Energy Engineering 131, 031002. https://doi.org/10.1115/1.3139139

[37] Ho, C.K., Iverson, B.D., 2014. Review of high-temperature central receiver designs for concentrating solar power. Renewable and Sustainable Energy Reviews 29, 835–846. https://doi.org/10.1016/j.rser.2013.08.099

[38] Rizvi, A.A., Danish, S.N., El-Leathy, A., Al-Ansary, H., Yang, D., 2021. A review and classification of layouts and optimization techniques used in design of heliostat fields in solar central receiver systems. Solar Energy 218, 296–311. https://doi.org/10.1016/j.solener.2021.02.011

[39] Schramek, P., Mills, D.R., 2004. Heliostats for maximum ground coverage. Energy 29, 701–713. https://doi.org/10.1016/S0360-5442(03)00178-6

[40] Poulain, P.E., Craig, K.J., Meyer, J.P., 2016. Influence of the gap size on the wind loading on heliostats. Presented at the SOLARPACES 2015: International Conference on Concentrating Solar Power and Chemical Energy Systems, Cape Town, South Africa, p. 020019. https://doi.org/10.1063/1.4949043

[41] Zolan, A., Hamilton, W., Wagner, M., Liaqat, K., 2021. Solar Field Layout and Aimpoint Strategy Optimization (No. NREL/TP--5700-80596, 1813972, MainId:66327).

[42] Hamilton, W.T., Wagner, M.J., Zolan, A.J., 2021. Demonstrating SolarPILOT's Python API Through Heliostat Optimal Aimpoint Strategy Use Case: Preprint. Renewable Energy 9.

[43] Crespo, L., Ramos, F., 2020. Making central receiver plants modular, more efficient and scalable. Presented at the SOLARPACES 2019: International Conference on Concentrating Solar Power and Chemical Energy Systems, Daegu, South Korea, p. 030010. https://doi.org/10.1063/5.0028916

[44] Sattler, J.C., Röger, M., Schwarzbözl, P., Buck, R., Macke, A., Raeder, C., Göttsche, J., 2020. Review of heliostat calibration and tracking control methods. Solar Energy 207, 110–132. https://doi.org/10.1016/j.solener.2020.06.030

[45] Strachan, J.W., 1992. Revisiting the BCS, a measurement system for characterizing the optics of solar collectors 2–6.

[46] Mehos, M., Price, H., Cable, R., Kearney, D., Kelly, B., Kolb, G., Morse, F., 2020. Concentrating Solar Power Best Practices Study. Renewable Energy 269.

[47] Costa, S.C.S., Diniz, A.S.A.C., Kazmerski, L.L., 2018. Solar energy dust and soiling R&D progress: Literature review update for 2016. Renewable and Sustainable Energy Reviews 82, 2504–2536. https://doi.org/10.1016/j.rser.2017.09.015

[48] Bouaddi, S., Fernández-García, A., Sansom, C., Sarasua, J., Wolfertstetter, F., Bouzekri, H., Sutter, F., Azpitarte, I., 2018. A Review of Conventional and Innovative- Sustainable Methods for Cleaning Reflectors in Concentrating Solar Power Plants. Sustainability 10, 3937. https://doi.org/10.3390/su10113937

Metrology

Errors in heliostat tracking and optical performance are very important for the viability of the entire power tower CSP plant. Improving performance can often have a bigger impact on reducing the cost of electricity (LCOE) than reducing the cost of the CSP infrastructure. For this reason, metrology is an area of ongoing research, both in manufacturing as well as in-situ [49].

Metrology Overview

Types of Errors

Heliostat optical errors are broken down into three types: slope error, canting error, and tracking error [50], shown in Figure 28. The slope error is specific to a given point on a mirror facet, and describes the deviation of the actual surface normal of the mirror relative to the design shape. Slope error can be a product of the manufacturing process, or can develop due to surface degradation or structural effects on the heliostat that result in mechanical strain to the surface. Slope error can be measured directly. Canting error is the pointing error for a given facet, which can affect the ability of the heliostat to focus effectively. Canting error is usually calculated as the average of the slope errors on a facet, and is fixed after the heliostat is assembled in factory. Finally, tracking error is the pointing error of the whole heliostat, and is calculated as the remaining error once slope and canting errors are accounted for in the overall error measurements. Because heliostat tracking is transient and controlled by the drives, if tracking error can be measured in-situ, it can be corrected for very quickly, often even while the heliostat is in use.

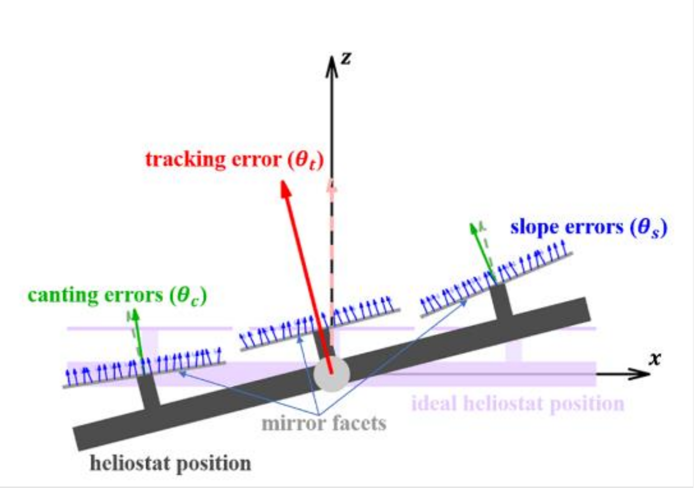


Figure 28: Types of optical errors for heliostats [t]

Sources of Errors

Aside from manufacturing induced errors and software or calibration errors, optical errors can also be introduced by a variety of environmental factors. A significant source of error is atmospheric attenuation, the absorption or scattering of light in the atmosphere due to particles. Attenuation is location-specific and sometimes transient, introducing error to even a perfectly calibrated solar field. Soiling is also a very large source of errors and loss of efficiency, and is also caused by particles scattering and absorbing rays of light. Soiling can be effectively addressed by heliostat cleaning protocols, but needs to be monitored in order to assess accumulation rates. Gravitational sag and foundation settling, as well as other mechanical strains, can introduce errors over time, requiring that performance be monitored throughout the CSP plant’s lifetime to maintain the required performance.

Metrology Methods and Techniques

There are many techniques for assessing optical errors of a heliostat, including both those performed during the manufacturing process (inside a controlled environment) and those done in-situ, after installation and calibration. Both are necessary to achieve the required optical accuracy.

Manufacturing Metrology

Facets of a heliostat are canted and focused during the manufacturing phase, before transportation to the CSP plant site, so most quality assurance measurements are conducted in a controlled environment. A common and very robust technique is structured light reflection, or deflectometry [51], which uses a projection screen to display a fringe pattern consisting of phase shifted sine waves. A camera is used to view the pattern as a reflection in the mirror, and distortion of the image can be used to back-calculate deviations in mirror shape with respect to design specifications. A commonly used software developed by Sandia National Laboratory, SOFAST [52], shown in Figure 29, uses this technique and is very accurate. There are also methods that use theoretical image overlay for optical error measurement, comparing the actual reflected image for a given mirror to the expected result, which can be computed. Other tools that work similarly are AIMFAST by Sandia, and Qdec by DLR. AIMFAST is an extension of SOFAST that automates data collection, implements alignment strategies, and provides real time mirror angle corrections. Qdec is an optical measurement system for control of the shape accuracy of solar reflector panels and concentrators [53].

Laser projection has also been used to calculate slope errors and can give detailed point-wise error maps of a heliostat or facet. While these techniques are robust, they can only be used in a factory or laboratory setting, and cannot be used on heliostats in the field.

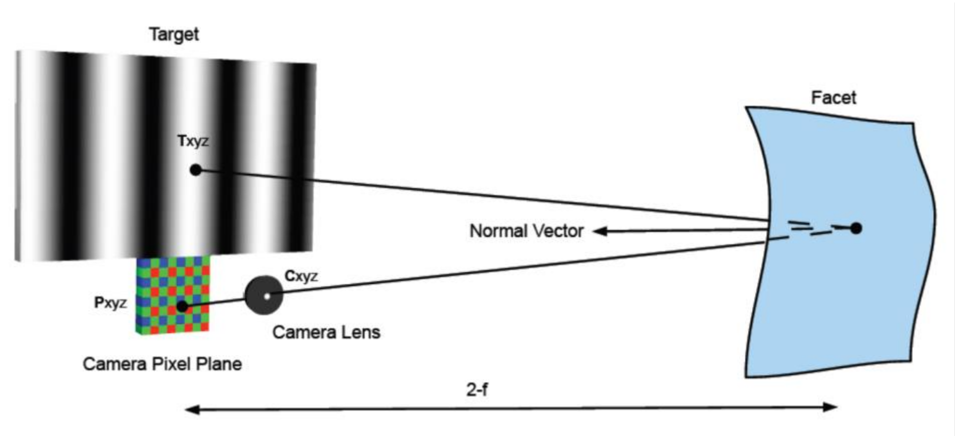


Figure 29: SOFAST layout, where target is an LCD screen displaying sinusoidal patterns [u]

Measurement Types and Types of Errors

For a given heliostat field, the optimal performance assessment would be beam (flux) control on the receiver surface with respect to the maximized efficiency and minimized failures of flux. Contributing factors to the flux control are the Sun Shape, Incidence Angle (sun position relative to individual heliostat), Heliostat Shape, Attenuation, Solar-Weighted Specular Reflectance, Opto-Mechanical Errors such as slope error, canting error, and tracking error; the soiling, structural or wind load, coating properties and the receiver geometry. There are many tools that measure these factors.

For the sun shape the metrology tools include charged coupled device (CCD) camera techniques and pyrheliometers that measure solar irradiance coming from the sun. Sun shape is measured by the size of the solar disc or the angular distance between the center of the disc and its edge. The distribution of the spectral radiance from the disc is the sun shape and defines the distribution of incident light. The incidence Angle or sun position can affect this measurement.

Opto-Mechanical Errors are a combination of optical errors and the mechanics of disc tracking. These are described above in the Types of Errors section and in the In-Situ Metrology section below.

The heliostat shape is another major category that is measured for improving accuracy of the solar flux. Laser scanning and photogrammetry are often used here. A LiDAR technique developed by Sandia acquires a highly accurate point cloud measurement across several heliostats revealing any optical errors on the mirror itself. Reflected Target Non-Intrusive Assessment (ReTNA) is another technique that is under development at NREL that measures mirror surface slope and uses photogrammetry methods to measure slope and canting errors of a heliostat in a warehouse or laboratory. Deflectometry measures the surface slope. Photogrammetry techniques involve a network of multiple photographs of a targeted object or heliostat taken from a range of viewing positions to obtain 3D coordinate data for the target. A variety of techniques use this method to determine heliostat shape and its errors. Hartman type methods are optical error type measurements. SHOT and VSHOT developed by Sandia and NREL are methods for characterizing the surface figure and optical performance of the solar concentrators.

Solar-Weighted Specular Reflectance is purely a reflectometry measurement mostly done via reflectometers such as 410 Solar. There are various handheld reflectometer devices that measure the solar reflectance of a heliostat. Figure 30a

Atmospheric attenuation is where the solar radiation after reflection from the disc travels further through the atmosphere to reach the receiver. Aerosols and dust particles attenuate the radiation in the atmosphere. There are currently no standardized measurements of attenuation within CSP. There are currently measurement techniques under development.

[54, 55]

In-Situ Metrology

Techniques that can be used in-situ vary widely, with the most basic being the use of mechanical gauge blocks and electronic inclinometers (a manual and slow process for an entire field). Most in-situ techniques involve a camera and target, similar to many calibration techniques (Figure 26). A method called “camera look-back” places a camera on the tower, at the assumed focal point of the heliostat, so that the heliostat can be adjusted to center the camera in the reflection. A camera can also be fixed on the tower, looking at the reflection of a patterned target on the heliostat to calculate heliostat pointing errors. This method can be used for multiple heliostats at once, though as with the camera look-back method, it cannot be done while the heliostats are in use.

There are drone-based measurement tools under development to assess optomechanical errors, which include the Non-intrusive Optical method (NIO) developed by NREL, and Universal Field Assessment, Correction, Enhancement Tool (U-FACET), developed by Sandia National Laboratories. NIO is currently under development by NREL. Sandia developed a technique that uses reflections between heliostats called U-FACET, which can be done during heliostat use. The reflections of the back of the heliostat in front of the heliostat under study are compared to an optical model, using facet edges as reference features to back-calculate position and geometry from the collected images. This method can be used while the heliostats are operational, avoiding interruptions to the CSP plant under study.

NREL has a similar technique named NIO, a non-intrusive optical approach to characterizing heliostats, that consists of a camera mounted on a drone that can fly over an operational CSP plant and collect images of many heliostats in a short period of time, allowing for assessment of an entire field [50]. The camera collects a series of images as it moves across each heliostat, and then edge detection [56] is used to find the tower edge in the reflected images. Using photogrammetry, a process to extract three-dimensional information from two dimensional photographs, image information is used in conjunction with the known locations of the camera, heliostat and tower to calculate the error for each heliostat. One benefit of NIO is its ability to collect and differentiate slope, canting and tracking error data at the same time, though as mentioned earlier, once the heliostat is installed, tracking errors are the only ones that are practical to correct. NIO, like U-FACET, can also be used on active heliostats.


(a) (b)

Figure 30. (a) reflectometer measurement. (b) field drone measurements for BCS target

Reflectometers are tools that measure the reflectance or reflectivity of a heliostat. The reflectance of a mirror sample is a function of the incident light wavelength, angle, and surface size. In Figure 30a the SOC handheld spectrometer is used to measure the reflectance of the heliostat mirror on a specific area. The beam characterization system (BCS) used for calibration is also used for metrological purposes, though the error data is far less detailed. (Figure 30b) There are many additional methods and variations on methods mentioned here, though not all have been implemented for plant use [57-59]. Some methods are more appropriate for research, as some errors are not practical to correct once the heliostats are installed at a plant. Other methods are focused on improving existing plant performance, a field expected to expand as the technology progresses.

Software

In addition to the metrology tools there are numerous types of software that do more complex optical modeling, ray tracing, technoeconomic plant analysis, and field optimization. These software tools overall characterize the economic and optical performance of CSP plants. SolTrace is a software that analyzes optical performance and models CSP systems. There are many other examples that analyze or measure these properties with various tools. DelSol is a field layout optimization tool that finds the best design based on energy cost. Another example of software that is used in technoeconomic analysis is Solergy which simulates the operation of a CSP plant for a year. NREL has developed the System Advisor Model (SAM), which is a comprehensive software used to model renewable energy systems from a techno-economic perspective. This allows for project managers, engineers and developers to assess the viability of projects.

Given a location and weather reports it can determine simulated power output and helps to determine the best location for a CSP plant. Other software tools model the power system as a whole and helps developers understand the impacts of variability and uncertainty on the operations. Table 1 includes a list of commonly used Optical Modeling and Ray Tracing tools for CSP plants. See (list) for more available software tools.

Table 1. Ray Tracing Tools for CSP plants

Software	**Description**	**Source**
SolTrace	Analyzes and models CSP systems and optical performance	https://www.nrel.gov/csp/soltrace.html
Sunntics	Optimizes CSP design and operation to lower LCOE	https://www.sunntics.com/
HelioSim	Integrated model for optimization and simulation of CSP	https://doi.org/10.1063/1.5067213
sbpRAY	A framework that simulations and optimizes performance of CSP plants with ray tracing tech that can utilize GPUs	https://doi.org/10.1063/1.5117674
TieSOL	Optimizes and simulates CSP plant design and solar field operations. Utilizes GPU to make flux mapping traceable	https://doi.org/10.1016/j.egypro.2014.03.259
Tonatiuh	Monte Carlo ray tracer. Includes GUI.	https://doi.org/10.1063/1.5067212
STRAL	Ray tracing tool that allows for co-simulation of plants in multiple environments	https://elib.dlr.de/78440/
Tracer	Python based ray tracing package	https://github.com/anustg/Tracer
Solstice	Solar Simulation Tool in Concentrating Optics. Parallel processing capabilities. Uses Monte Carlo algorithm	https://www.meso-star.com/projects/solstice/solstice.html

References for Metrology

[49] Schedler, S., Ulmer, S., Koch, H., Röger, M., Benitez, D., Prahl, C., Weinrebe, G., 2019. From research to industry: Development of a high-resolution measurement system for mirrored heliostats in series production. Presented at the SOLARPACES 2018: International Conference on Concentrating Solar Power and Chemical Energy Systems, Casablanca, Morocco, p. 030051. https://doi.org/10.1063/1.5117563

[50]_Mitchell, R.A., Zhu, G., 2020. A non-intrusive optical (NIO) approach to characterize heliostats in utility-scale power tower plants: Methodology and in-situ validation. Solar Energy 209, 431–445. https://doi.org/10.1016/j.solener.2020.09.004

[51] Huang, L., Idir, M., Zuo, C., Asundi, A., 2018. Review of phase measuring deflectometry. Optics and Lasers in Engineering 107, 247–257. https://doi.org/10.1016/j.optlaseng.2018.03.026

[52] Finch, N.S., Andraka, C.E., 2013. Uncertainty Analysis and Characterization of the SOFAST Mirror Facet Characterization System. J. Sol. Energy Eng. 136, 011003. https://doi.org/10.1115/1.4024251

[53] https://www.cspservices.de/wp-content/uploads/CSPS-QDec.pdf

[54] Handbook of Solar Thermal Technologies: Volume 1: Concentrating Solar Power — Principles and Applications. World Scientific, 2022.

[55] Zhu, Guangdong, et al. 2022. Roadmap to Advance Heliostat Technologies for Concentrating Solar-Thermal Power. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5700-83041. https://www.nrel.gov/docs/fy22osti/83041.pdf

[56] Röger, M., Prahl, C., Ulmer, S., 2010. Heliostat Shape and Orientation by Edge Detection. Journal of Solar Energy Engineering 132, 021002. https://doi.org/10.1115/1.4001400

[57] Yellowhair, J., Ho, C.K., 2010. Heliostat Canting and Focusing Methods: An Overview and Comparison, in: ASME 2010 4th International Conference on Energy Sustainability, Volume 2. Presented at the ASME 2010 4th International Conference on Energy Sustainability, ASMEDC, Phoenix, Arizona, USA, pp. 609–615. https://doi.org/10.1115/ES2010-90356

[58] Ren, L., Wei, X., Lu, Z., Yu, W., Xu, W., Shen, Z., 2014. A review of available methods for the alignment of mirror facets of solar concentrator in solar thermal power system. Renewable and Sustainable Energy Reviews 32, 76–83. https://doi.org/10.1016/j.rser.2013.12.006

[59] Xiao, J., Wei, X., Lu, Z., Yu, W., Wu, H., 2012. A review of available methods for surface shape measurement of solar concentrator in solar thermal power applications. Renewable and Sustainable Energy Reviews 16, 2539–2544. https://doi.org/10.1016/j.rser.2012.01.063

Other Heliostat Uses

Heliostats are also used in other applications, not relating to solar power. Heliostats and similar tracking mirrors have been used to track celestial bodies for astronomical study, especially in cases where a very large telescope is required. In this case it becomes convenient to track the body with a smaller, auxiliary mirror, and the telescope remains stationary. In Sydney, Australia, an urban application has been found, and at the One Central Park plaza, heliostats are mounted on a building to reflect sunlight into alleys in between tall buildings that would otherwise never get direct sunlight. In France, heliostats have been used at the Odeillo solar furnace since 1969, where a terraced field of heliostats reflect sunlight into a parabolic mirror that further concentrates the incoming energy to a control tower, where materials are tested at extreme temperatures (over 2500C). There has even been research regarding power tower CSP implementation on the moon, to produce hydrogen in space and allow spacecraft to refuel without needing to re-enter Earth’s atmosphere. Heliostat research and development is still primarily focused on CSP applications, and progress will continue to expand their effectiveness.

Summary and Outlook

In summary, the power tower concentrating solar power plant, at the heart of which lies the heliostat, is a very promising area of renewable energy. Benefits include high optical concentration ratios and operating temperatures, corresponding to high efficiency, and an ability to easily incorporate thermal energy storage. As components and processes are further standardized, improved, and scaled, the cost of the technology is expected to drop, making CSP a competitive source of electricity that can help decrease reliance on non-renewable energy sources and contribute to grid resilience.

Appendices

Appendix A: Power Tower Plant Spreadsheet (Select SolarPACES data [link])

Power station	Country	Status	Capacity, MW	Year operational	HTF medium	Storage capacity, hours	Tower height, m	Number of heliostats	Mirror area per heliostat, m2
Planta Solar 10 - PS10	Spain	Operational	11	2007	Water	1	115	624	120
Jülich Solar Tower	Germany	Operational	1.5	2008	Air	1.5	60	2153	8
Planta Solar 20 - PS20	Spain	Operational	20	2009	Water	1	165	1255	120
ACME Solar Tower	India	Operational	2.5	2011	Water			14280	1
Gemasolar Thermosolar Plant / Solar TRES	Spain	Operational	20	2011	Molten salts	15	140	2650	120
Lake Cargelligo	Australia	Non-Operational	3	2011	Water			620	10
Badaling Dahan 1 MW Tower	China	Operational	1	2012	Water	1	118	100	100
Greenway CSP Mersin Tower Plant	Turkey	Operational	1.4	2012	Water				
SUPCON Delingha 10 MW Tower	China	Operational	10	2013	Water	2	80	22500	2
Ivanpah Solar Electric Generating System	United States	Operational	377	2014	Water		140	173500	15
Crescent Dunes Solar Energy Project	United States	Operational	110	2015	Molten salt	10	195	10347	116
Khi Solar One	South Africa	Operational	50	2016	Water/Steam	2	200	4120	140
Shouhang Dunhuang Phase I - 10 MW Tower	China	Operational	10	2016	Molten salt	15	138	1525	116
Sundrop CSP Project	Australia	Operational	1.5	2016	Water		127	23712	

Power station	Country	Status	Capacity, MW	Year operational	HTF medium	Storage capacity, hours	Tower height, m	Number of heliostats	Mirror area per heliostat, m2
Jemalong Solar Thermal Station	Australia	Operational	1.1	2017	Liquid sodium	3	30	3500	
NOOR III	Morocco	Operational	150	2018	Molten salt	7	247		
Shouhang Dunhuang Phase II - 100 MW Tower	China	Operational	100	2018	Molten Salt	11	263	12121	116
SUPCON Delingha 50 MW Tower	China	Operational	50	2018	Molten Salt	7	200	27135	20
Ashalim Plot B / Megalim	Israel	Operational	121	2019	Water		240	50600	21
CEEC Hami - 50MW Tower	China	Operational	50	2019	Molten Salt	13	220	14500	50
LuNeng Haixi - 50MW Tower	China	Operational	50	2019	Molten Salt	12	188	4400	138
Power China Qinghai Gonghe - 50MW Tower	China	Operational	50	2019	Molten salt	6	210	25795	20
Atacama I / Cerro Dominador 110MW CSP + 100 MW PV	Chile	Operational	110	2021	Molten Salt	17.5	243	10600	140
Noor Energy 1 / DEWA IV - 100MW tower segment	United Arab Emirates	Under Construction	100	2021	Molten Salt	15	260	70000	
Sierra SunTower	United States	Non-Operational	5		Water		55	24360	1
Shouhang Yumen 100 MW Tower	China	Under Construction	100	2021	Molten Salt	10			
Supcon Delingha 135 MW Tower	China	Under Construction	135	2022	Molten Salt	11.2			

Power station	Country	Status	Capacity, MW	Year operational	HTF medium	Storage capacity, hours	Tower height, m	Number of heliostats	Mirror area per heliostat, m2
Solar One	United States	Decommissioned	10	1982	Steam		90	1818	40
Solar Two	United States	Decommissioned	10	1995	Molten Salt	3			
National Solar Thermal Test Facility	United States	Operational	5	1976			63	222	
CRS Sales	Spain	Operational	5	2012	Molten Salt			88	120
SEDC	Israel	Operational	6	2008	Steam		60	1600	

Appendix B: Image and Figure Sources

[a] Merchán, R.P., Santos, M.J., Medina, A., Calvo Hernández, A., 2021. High temperature central tower plants for concentrated solar power: 2021 overview. Renewable and Sustainable Energy Reviews 155, 111828. https://doi.org/10.1016/j.rser.2021.111828

[b] OpenStreetMap contributors. Crescent Dunes Solar Energy Project, Tonopah, NV. https://en.wikipedia.org/wiki/Crescent_Dunes_Solar_Energy_Project. Accessed Jan. 2022.

[c] SolarPACES. https://solarpaces.nrel.gov/. Accessed Jan. 2022.

[d] SolarPACES. https://www.solarpaces.org/how-csp-thermal-energy-storage-works/. Accessed Mar. 2022.

[e] https://mammothmemory.net/physics/mirrors/flat-mirrors/the-three-laws-of-reflection.html

[f] PV Tech. Ivanpah Solar Electric Generating System, San Bernardino County, CA. 2016. https://www.pv-tech.org/fire-at-embattled-ivanpah-csp-plant/. June 2020.

[g] Evwind. Heliogen Lancaster Tower, Lancaster, CA. 2020. https://www.evwind.es/2020/02/13/self-aligning-heliostats-arrive-to-slice-concentrated-solar-power-costs/73563. Accessed Jan 2022

[h] Evwind and CSP Focus. Hami 50MW Molten Salt Tower CSP Project, Xinjiang Province, China. 2019. https://www.evwind.es/2019/12/30/xinjiangs-first-concentrated-solar-power-plant-operational/72831. Accessed Jan. 2022.

[i] Sika Ireland. National Solar Thermal Test Facility, Albuquerque, NM. https://sika.scene7.com/is/image/sika/glo-sandia-national-laboratories?wid=1148. Accessed Jan. 2022.

[j] Pfahl, A., Coventry, J., Röger, M., Wolfertstetter, F., Vásquez-Arango, J.F., Gross, F., Arjomandi, M., Schwarzbözl, P., Geiger, M., Liedke, P., 2017. Progress in heliostat development. Solar Energy 152, 3–37. https://doi.org/10.1016/j.solener.2017.03.029

[k] Chong, K.-K., Tan, M.H., 2012. Comparison Study of Two Different Sun-Tracking Methods in Optical Efficiency of Heliostat Field. International Journal of Photoenergy 2012, 1–10. https://doi.org/10.1155/2012/908364

[l] Ho, C.K., Griffith, D.T., Sment, J., Moya, A.C., Christian, J.M., Yuan, J.K., Hunter, P.S., 2012. Dynamic Testing and Analysis of Heliostats to Evaluate Impacts of Wind on Optical Performance and Structural Fatigue 14.

[m] University of Adelaide. https://set.adelaide.edu.au/news/list/2022/02/07/researchers-develop-wind-tunnel-technology-for-solar-mirrors. Accessed April 2022.

[n] Khi Solar One, Upington, South Africa. https://en.wikipedia.org/wiki/Khi_Solar_One. Accessed Jan. 2022.

[o] Rizvi, A.A., Danish, S.N., El-Leathy, A., Al-Ansary, H., Yang, D., 2021. A review and classification of layouts and optimization techniques used in design of heliostat fields in solar central receiver systems. Solar Energy 218, 296–311. https://doi.org/10.1016/j.solener.2021.02.011

[p] CSP Focus. Shouhang Dunhuang 10 MW Phase 1, Dunhuang, China. 2018. http://www.cspfocus.cn/en/market/detail_972.htm. Accessed Jan. 2022

[q] Time. https://time.com/3802649/the-ivanpah-solar-project-generating-energy-through-fields-of-mirrors/. Accessed April 2022.

[r] Sattler, J.C., Röger, M., Schwarzbözl, P., Buck, R., Macke, A., Raeder, C., Göttsche, J., 2020. Review of heliostat calibration and tracking control methods. Solar Energy 207, 110–132. https://doi.org/10.1016/j.solener.2020.06.030

[s] http://en.people.cn/n3/2019/1025/c90000-9626596-3.html. Accessed March 2022.

[t] Mitchell, R.A., Zhu, G., 2020. A non-intrusive optical (NIO) approach to characterize heliostats in utility-scale power tower plants: Methodology and in-situ validation. Solar Energy 209, 431–445. https://doi.org/10.1016/j.solener.2020.09.004

[u] Andraka, C., 2018. SOFAST: Sandia Optical Fringe Analysis Slope Tool for Mirror Characterization 10.