Status Quo of Heliostat Field Deployment Processes

Preprint

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STATUS QUO OF HELIOSTAT FIELD DEPLOYMENT PROCESSES

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ABSTRACT

Deployment of the solar field of a concentrating solar power plant is one of many factors that are integral to the success of a project. Knowledge transfer from outside the industry is limited due to the unique nature of heliostats, which redirect sunlight to a receiver with high precision while maintaining a high level of reflectivity. Moreover, learning from project to project can be limited due to the site-specific nature of projects, as the market includes several developers, each with their own unique design. In this paper, we discuss the state of the art in heliostat field deployment. We cover all the key aspects of deployment from project assessment to a fully functioning system, which include site selection, layout development, supply chain, assembly, site preparation and construction, calibration, and operations and maintenance.

Keywords: concentrating solar power, heliostat field, deployment

1. INTRODUCTION

Deployment of a power plant covers all activities required to establish a fully functioning system. The deployment of fossil-fueled plants has a large number of projects to draw from, and as a result is well-studied; much of the recent research in this sector for commercial-scale projects has been related to carbon capture and sequestration [1] while renewables deployment research is focused on the feasibility of early-stage technologies [2] or hybrid projects [3]. Over the past 40 years, 15 concentrating solar power (CSP) heliostat field for tower plants have been deployed, but industry-wide learning has been limited due to the lack of knowledge transfer from project to project. In particular, solar fields of CSP plants are site-specific and most projects have a unique design [4], which can make learning from prior experience difficult. Further, the cost of solar field deployment alone is a significant expense for CSP projects. This article summarizes the state of the industry's solar field deployment practices based on interviews with industry participants and information available in the literature. The identities of the XX participants are omitted for confidentiality.

After discussing the timing of the project and proposal preparation, each of the sections that follow describe a step in the deployment process: (i) site selection; (ii) layout development; (iii) supply chain; (iv) assembly; (v) site preparation, construction, and installation; (vi) calibration; and, (vii) operations and maintenance. The final section concludes.

2. TIMING AND PREPARATION

In a typical scenario, a central receiver CSP plant developer will respond to a request for proposal (RFP) issued by a power company, for which CSP is eligible, within approximately two to three months. The developer must then provide a deployment package including a risk assessment, reliability basis, and a guarantee of performance. This requires a solar field system design, a power purchase agreement (PPA), and a secured capitalization and construction plan requiring a coalition of existing relationships between investors, developers, and engineering-procurement-construction firms (EPCs). Even when a PPA is present, the proposal must show a legal egress to interconnections, and resolve all land use issues. Site selection should also consider the environmental, political, and cultural impacts. Rural and tribal communities should be included early and transparently to garner support and buy-in for the solar projects in a way that is equitable and just, following examples from photovoltaic (PV) plants [5]. Projects have also been withdrawn after opposition from local level officials. In the past, companies did not engage politically or did not anticipate changing political priorities following elections. This led to permitting issues and costly delays. Increasingly, renewable energy deployments in general are opposed by organized groups that proclaim solar fields are eye sores, environmentalists focused on desert habitat preservation or simply object to the technology without offering a clear basis [6]. Public relations campaigns for concentrating solar are relatively rare, and CSP does not often benefit freely from generic pro-renewable energy campaigns that more typically feature images or icons for photovoltaic panels and wind turbines. With such a short time window to respond, it is not clear how these relationships could be successfully forged without an ongoing campaign.

For RFPs that are issued in response to a renewable portfolio standard, the competition will be limited to renewable energy sources. Wind and PV plants are assumed to have a deployment time of 6 months (18 months with batteries) while CSP systems assume 24 to 36 months [7]. Minimizing deployment times is important to both competitiveness and the ability to secure financing. On the surface, a utility may not have the flexibility to accommodate a long deployment time as power companies retire thousands of megawatts of fossil power and are mandated to replace them with renewable generators. Furthermore, financing charges will accrue for 2 to 3 years before any revenue can be generated, making CSP less competitive.

Large baseload CSP plants are high-risk and cost more than a billion dollars, such as the estimated $2.2 billion construction cost of the Ivanpah project [8]. Developers say this can complicate and delay financing as multiple parties are recruited to fully fund the project; in some cases, the delay associated with financing the project can terminate it due to the market moving to other options. For example, the Redstone project in South

Africa took 7 to 8 years from project selection to final commissioning. In another case, by the time Rice Solar was ready to begin construction for a US-based project, the political priorities had changed and the investment tax credit for renewable energy dropped from 30% to 10%, making the project financially inviable. Smaller modular projects on the order of 10 MW_e may reduce investment risk by eliminating single points of failure, costing in the range of 200 to 300 million dollars, and reducing deployment time; however, it is unclear whether economies of scale can be achieved to reduce the levelized cost of energy (LCOE) of smaller projects to be competitive in the market.

Historically, financing includes a government incentive such as a loan guarantee program, investment tax credits or production tax credits, and a large portion of the cost to be made up by several large capital investors. Due to the relatively few CSP and CST projects that have been deployed, investors will often evaluate whether the EPCs are materially invested in the project and large enough to absorb unforeseen losses without abandoning the project.

EPCs primarily build plants to specifications and verify required inspection points throughout the process. However, without significant upfront coordination, it may be difficult for a technology developer to truly understand the required checkpoints. Heliostat technology is still under development and discoveries made through the manufacturing and installation process may require a responsiveness to new information. Inspection points may be negotiated into the contract a priori but fail to capture important issues.

3. SITE SELECTION

An ideal site would have exceptionally high direct normal irradiance (DNI) and visibility, a large flat land type, low winds, a convenient grid tie connection, and a nearby labor force and water source. Given the short response time required for RFPs, developers are assumed have a portfolio of sites preselected. The developer must acquire a compelling body of evidence on available solar resources. Project developers are continuously scouting locations and have ongoing metrology stations gathering high-fidelity data in prospected sites. Once the exact site is known, remote weather stations are deployed to take data every 1 second, average the data by 15 minutes, and roll them up into hourly data. There is typically sufficient time to collect data at the given location prior to the field design, though often there is no time to take data prior to the site selection, because the heliostat developer frequently does not get to choose the site and must design the field to meet the power requirements regardless of the DNI, transmittance, or other environmental factors. There are several examples where the site has been predetermined by the governing body and utility for reasons that pertain more to a desire to create jobs in a certain district, or to build out civil infrastructure (roads, gas pipelines, etc.) in a low-populated area. These locations have had less ideal sun or atmospheric clarity and thus mandated a larger field resulting in a higher levelized cost of energy (LCOE) or levelized cost of heat (LCOH).

The utility will also specify the service life requirements – a factor that affects the optimization of cost and life-cycle reliability. While there may be LCOE-lowering opportunities by increasing the service life by five to ten years or performing life extension programs, it would not make sense to invest in increasing the product life without getting credit for those increases from the investors/customers interested only in the utility requirements. Many projects do not require an end-of-life removal program. Solar Two was entirely removed and recycled [9]. Ivanpah required the cost to include complete removal of the entire site. Ideally, the site developer chooses a location with ideal technical characteristics such as weather or ground conditions. Heliostats typically use highly recyclable and non-hazardous materials.

Average irradiance intensity maps typically consider cloud cover and precipitation but may not reflect the effects of airplane contrails or atmospheric attenuation from environmental factors, such as forest fires, dust, and haze. Wind measurements are also very important in selecting a site as sustained winds or gusts over ~9 m/s may require stowing the heliostats for protection. Wind velocities may vary seasonally and stochastically, so data sets less than a couple years may carry risk. Without knowing the exact location, the only available weather inputs at time of RFP may include hourly averages for weather at nearby locations including Typical Meteorological Year (TMY) data, which significantly underestimates the frequency of required wind stow events due to the lack of coverage of high-velocity gusts or metrology towers located in close proximity but that may miss conditions at the exact location such as the mountain shading effects in Ivanpah.. Similarly, weather data lacks information on severe dust storms that can cause significant soiling; frequent dust storms have results in lower-than-expected output in the Acme Solar Tower plant in India. Heavy soiling can be mitigated through appropriate planning, such as having additional wash vehicles on standby [10], and by design, as the heliostats at Ashalim include automated dry-cleaning mechanisms that remove dust multiple times per day.

Geotechnical and environmental data is also an important consideration. The primary considerations are soil conditions and seismicity. Soft soils may require deep pylons to support large heliostats, while hard soils may only require piles to be driven into the ground. Another consideration is the propensity of a specific type of soil to stick to the facets or blow off, combined with availability of water and labor for cleaning of the facets. A mapping of soil quality by site to these different operating characteristics does not currently exist. Environmental considerations should also consider the migration patterns of wildlife. Intersections with bird migrations have been shown to be avoidable through aiming strategies that do not concentrate beams at aimpoints other than the receiver [11].

4. SOLAR FIELD LAYOUT DEVELOPMENT

Once a site has been selected, the receiver is selected and positioned, which constrains the field. A developer will then design a field layout using optical ray tracing software such as SolarPILOT [12], SolTrace [13], or HLCAL to determine the minimal-cost arrangement that achieves the designed power requirements. Software can account for shading and blocking at various times of the day and year, and gradients in ground elevation. The design will include a performance assessment over the life of project with the known weather constraints and power generation simulated to inform the estimated return on investment.

After modeling determines the field layout and heliostat size, a plan for heliostat installation is developed. For large heliostats, piles are driven into the ground to quickly install foundations for the heliostat pedestals. An economic advantage for small heliostats is that ballasting may be sufficient to stabilize during wind events, and the bases can be set in place manually or autonomously; this removes significant costs due to ground preparation, leveling, and the required digging and foundation pouring for poles and pylons [14]. Developers have cited other approaches that connect small heliostats together with light framing so the group of heliostats cannot be tipped by wind. Wind loading in a heliostat field is still an active field of research. Inner field shielding effects may allow for reductions in the heliostat mass requirements, but there is not a dependable model. Measurements of load in the base of the heliostat where it connects to the pile may be possible, and some precedent exists in the wind turbine industry where instrumentation for the hinge moment was proposed by Peterka et al. [15].

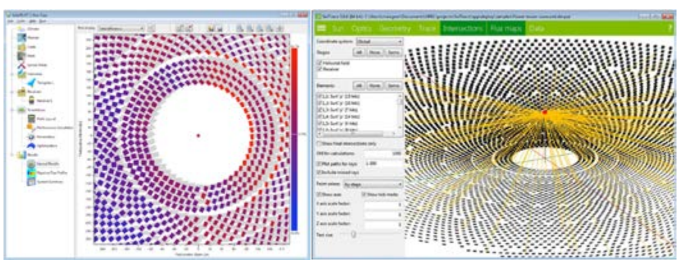

Figure 1. SCREENSHOTS FROM OPEN-SOURCE SOLAR FIELD CHARACTERIZATION TOOLS SolarPILOT (LEFT) AND SolTrace (RIGHT)

BrightSource adheres to a philosophy of maximizing packing density of the heliostats while working with and preserving the natural features of the land to minimize environmental impact. In 2013, over $10 million was spent to discover desert tortoises and remove them from the field. The most effective layouts result in a receiver view of the field that is nearly a solid reflector with blank spots to protect existing trees and natural watershed canals. The cost of a slightly less dense field that preserves habitats is much lower than the removal process. Pylons are located by drilling a 30–38 cm deep hole, holding the pylon with a tripod, and only filling the hole halfway with concrete so that 15 cm of topsoil is left to provide an erosion allowance and allow plants and burrowing animals to remain. There are also several passages under the site perimeter fencing to facilitate easy animal migration through the field and beyond while preventing human encroachment.

For unleveled landscapes, field designers maximize heliostat packing density by considering the variations in elevation of the terrain. Computational algorithms have been developed that scan the terrain with high fidelity and optimize the spacing of heliostats. High-precision GPS is used to locate the heliostats within a 5-cm margin. Algorithms have been developed that communicate with neighboring heliostats and calculate safe combinations of azimuth and elevation position to avoid collisions, which allows for an over-dense field arrangement and minimizes land area and the related atmospheric attenuation.

Cabling and trenching needs have mostly been removed by mounting small PV panels, battery packs, and wireless communications devices on each heliostat to fulfill power and communication needs. BrightSource has deployed this approach on Ashalim, Dubai Electricity and Water Authority (DEWA) and is planning on implementing at Redstone. BrightSource has experienced issues with attenuation and interference and has overcome the issue in the two deployed fields. The wireless transponders communicate with hubs that handle about 1,000 heliostats each with a redundant connectivity solution for each. These hubs require wired power and communication lines but reduce wiring and trenching costs considerably. Wiring is also required for weather metrology stations (DNI, wind velocity, attenuation, humidity, and temperature). Ashalim uses four weather stations positioned around the edge of the field and a single central station. These stations also hold camera systems used for machine vision of cloud cover.

5. SUPPLY CHAIN

The supply chain for the entire project will often be stated upfront to reduce the risk of a bid. The receiver and heliostat designs are predetermined at the time of the bid, and it is difficult for the engineering team to make changes because the required re-analysis can be system-wide and time consuming, which poses risk to meeting the project timeline. The fabrication team also has input to ensure the heliostat design can be manufactured and costed. Furthermore, it may be difficult to end trusted relationships with suppliers after they have been strengthened by years of collaboration and favored cost discounts. The economics of heliostat costs are improved by economies of scale, which favor larger fields, but with each project being several years or decades apart, there are not enough projects to standardize heliostat technology. Modular systems may eventually even out supply and demand. For heliostats, the modular model reduces atmospheric attenuation and spillage from faraway heliostats by reducing the number of heliostats in each field. However, past attempts to pipe heat from a modular tower system to a central reactor were thwarted by onerous costs in the piping system. These issues could be avoided by having a power cycle in every tower at the cost of economies of scale and reactor efficiency.

The supply chain for heliostats is vulnerable, and interruptions in solar tower projects make the economics prohibitive. There are a small number of facet manufacturers in the world that can achieve reflectivity >94%. Heliostat technology developers have working relationships with key suppliers (AGC) that have in-house processes that have shown to result in better quality glass. These processes could be categorized as institutional knowledge that is protected as the intellectual property of the glass manufacturers. The knowledge of backing formulations is similarly guarded. Developer understanding of backings has greatly improved since their first tower project of 2012. In particular, the mapping of humidity and oxidation rates to the backing material formulations required to avoid oxidation was developed through research and testing and was refined through field trials in a limited number of projects. Furthermore, the optimization of backing materials and thicknesses has received considerable development by industry who have discovered the minimum material required even to the point of taking advantage of lower-humidity regions where less backing material can be used without risk of corrosion. There have been similar gains in pedestal manufacturing where enough fields have been deployed in a great enough variety of environments to discover the key dependencies of humidity and alloy constituents. Some of the heliostat developers have worked to build relationships with manufacturers in China.

There is a lot of competition in getting products made in the low-cost labor market. For those who succeed in securing a manufacturing relationship, costs can be lower for some components on the heliostats. 2021 supply chain issues with China make these partnerships even more difficult to establish and equivalently more valuable to maintain. Industry experts agree that stable demand for heliostats will help. There are about three main suppliers of facets in the world. The most prolific heliostat technology developers in the world are Abengoa, BrightSource, Cosin Solar, Shouhang, and SENER with a range of 2-7 deployed projects per company [8]. The supply chain has a significant interaction with the assembly and construction tasks, as more fabrication prior to delivery can save installation steps but possibly at the expense of greater shipping costs. The existing literature lacks a complete assessment of all the tradeoffs in this setting.

6. ASSEMBLY

As mentioned previously, there is no standard for the size of a heliostat. Larger fields may be more economical with large heliostats, and small modular systems may reap the benefits of smaller heliostats that are more easily deployed and demand less assembly steps on-site. Per-heliostat costs can be substantial, though, so either heliostats should be as large as possible or novel approaches must be taken. For example, a single $10 water-tight connector at each heliostat would have very high unit cost in a 4-m heliostat. On the contrary, small heliostats have many more opportunities to be creative because wind forces are proportionally lower because of the smaller area and second order reductions in wind speeds. For these reasons, small heliostats offer savings by eliminating pylons for ballasted connections and removing mass from the structure.

The heliostat components are manufactured to the farthest practical extent that can be transported to the site. An assembly line is then created to finish building the heliostat. Heliostats should be designed with the intention of measuring what is important throughout the service life and not just upon arrival. A pre-inspection process should be worked out with the manufacturer. Often the heliostat components will arrive long before they are deployed, precluding the discovery of defects or other issues. The procurement process for heliostats can be onerous. In one case, proposals and bids were reviewed for 2.5 years before a final order was made. These types of delays have caused projects to be late or drop out.

Developers must consider the global supply chain in the design. Mirrors are sized to fit efficiently in standard 40-foot cargo containers. The number and size of the mirrors are usually limited to allow for standard sizes to avoid the costs associated with extra-large mirrors that require custom fabrication, as was the case with Ivanpah. Thus, the glass suppliers can use standard equipment. Process engineers try to maximize “pre-fabrication” or the number of steps performed in a factory as opposed to on-site assembly lines. This strategy has improved prefabrication and shipping methods resulting in cost reductions on the order of $25 million for large projects. The exact number of steps performed in the on-site assembly line or in a factory can also depend on the local labor situation or requirements.

7. SITE PREPARATION, CONSTRUCTION, AND INSTALLATION

Construction drives the largest labor demand in the plant’s life. There may be a mix of local labor and experienced construction crews that are deployed internationally. The impacts to nearby economies may be mixed as there is a boom-and-bust cycle, but ordinarily the creation of jobs supporting the construction crews is welcome. Government incentives drive the feasibility of large CSP projects, and job creation is integral to motivating politicians to support tax incentives, PPAs, and loan guarantees. For this reason, minimizing labor through autonomous field deployment may not be as attractive depending on the incentives sought by the developer. Furthermore, government incentives may come with union labor standards. Project cost models should carefully consider these provisions when a PPA or loan guarantee is part of the deployment package.

Field preparations begin with trenches to run power and/or data lines. Ground leveling can result in increased erosion, and the removal of natural vegetation can result in increased dust that causes soiling and atmospheric attenuation. Ivanpah heliostats follow the natural land contours and allow vegetation to grow and only trim or remove plants that are directly impacting the function of the heliostat. As mentioned earlier in this section, environmental impacts to indigenous wildlife, such as the desert tortoise or the crucifixion thorn shrub that delayed the Rice plant, must be considered. Preserving the habitat between heliostats is the most beneficial. Tonopah had issues with erosion, which in a few cases led to foundational issues with the heliostats. Pavement can help with both erosion and maintenance vehicle access but is expensive to apply and to maintain. Sometimes the trenches lead to data hubs which control a region of heliostats wirelessly. Other designs are completely wireless and employ a solar panel and battery pack on each heliostat. There is currently no known standard for wireless communications in heliostat fields. There is also a risk of locking in a wireless protocol when a 30-year service life is required since wireless communications technology evolves relatively quickly and may become obsolete. Wireless controls and solar power supplies may favor large heliostats since the cost of hardware is necessary at each stand. Lightning remains a risk which can propagate through wired connections, potentially taking down many heliostats or, in the case of wireless heliostats, communications devices, at once.

8. CALIBRATION

Once the heliostats are installed, they are calibrated to account for slight pointing inaccuracies. The most precise calibration methods are performed on a beam characterization system at a representative height on the tower. This creates schedule dependency whereby the field must wait until the tower is constructed to start the calibration process. Attempts to compress the schedule have been made such as using portable targets to calibrate. Unmanned aerial vehicles (UAVs) may have the potential to accelerate calibration prior to tower erection; quantifying the time savings and operational benefits is a focus of ongoing research [16].

During the development phase, heliostats should also be designed for maintenance and ease of adjustment. Prior designs required canting and focus adjustments by hand, including inserting wrenches into hard-to-reach places. Other single-facet heliostats arrive in only three parts: base, universal joint, and facet assembly, and are capable of self-adjusting and do not require manual focusing or canting. State-of-the-art pre-inspection routines may use feeler gauges or a gantry of lasers to scan heliostats in the assembly line. There have been issues with well-adjusted heliostats falling out of compliance during the bumpy ride to the field location. Starlight calibration methods that use imaging software to analyze the reflected point of starlight in the heliostat can be effective, but issues with thermal expansion during the day have impacted the usefulness of these methods.

Initial calibration routines are performed during assembly at the factory, and the facets are shipped pre-canted and focused. Four canting/focus positions were used in Ivanpah, but BrightSource studies found that this was unnecessary and sufficient concentration was found to be possible with only two positions as a cost-cutting measure. A quick calibration is performed during initial install and fine calibrations are performed on a continuous cycle through the field thereafter. Calibration systems are autonomous. Optimization routines select which heliostats are most important based on the time and day of the year. Over time the heliostat is calibrated for every position relative to the sun, considering any tracking error due to sag. These heliostats are taken off target and calibrated using camera-based techniques. All heliostats are calibrated in three weeks. Aiming inaccuracies are learned by the central control system and factored into the flux-on-receiver calculations.

Plant operators must comply with the standards for cybersecurity that apply to all power plants; there are no unique standards for solar towers. The plant will be audited by regulators and simulated attacks are attempted by electric grid officials periodically to test plant resiliency. Small plants do not have cyber codes. Plant operations can be monitored by operators in other parts of the world in real time, which can augment the remote labor force with co-operators in populous areas. The risks associated with loss of heliostat control are significant; misplaced aiming can cause fires in the receiver tower [4].

Plant operators use sophisticated data management and analysis tools to further improve performance. Effective operations will have SCADA systems where data can be sorted and retrieved, and mathematical operations can be performed to compare performance metrics under specific plant conditions.

9. OPERATIONS AND MAINTENANCE

Once the field is calibrated, canted, and focused, the system will be proven by the EPC and handed off to the operator company (which may be the same company). Past projects have suffered because planning assumed success. Plans that expect significant adjustment, change, and resiliency may be better suited for developing technologies if the case can be made to investors. The most labor-intensive process is mirror washing. Successful operations have employed people to manually wash medium-sized heliostats. Larger heliostats are cleaned with mobile trucks. The washing and maintenance are often performed by local workforces. Heliostats are typically very reliable, and availability is expected to be above 90%. Performance monitoring typically involves recalibrations that cycle through the field on the beam characterization system. UAVs are being developed to quickly fly over fields and identify canting or focusing issues [16]. Degradation of facets and structures can also be quickly detected with UAVs.

Figure 2. TRUCK WASHES LARGE HELIOSTAT AT CRESCENT DUNES (LEFT); WORKERS MANUALLY WASH HELIOSTATS AT IVANPAH (RIGHT). IMAGE SOURCE: [17]

Due to a lack of CSP plant retirements to date, a consensus for the end-of-life process for heliostats has not been established. Solar One, completed in 1981, completed a successful life extension program and was developed into Solar Two in 1995. Solar Two is now closed, but many of the heliostats remain functional 40 years later. Heliostats should be designed for ease of disassembly with recyclable materials where drives and limited life components can be easily pulled out and replaced for ongoing life extension programs.

Figure 3. SOLAR TWO. IMAGE SOURCE: [17]

Operations include startup steps, operation on receiver, shutdown, not operating, waiting, calibration, and protect field. A new plant may employ approximately eight field maintenance personnel and approximately five operators who also perform maintenance as part of their routine job description. For manually washed fields, a night crew of two facet cleaners can wash 50,000 heliostats by hand 20–25 times a year using an average of 3 liter of water per heliostat. Flood reservoirs are used to catch the water to avoid disrupting the natural habitat or watering plants to create larger than normal plant sizes. Economics favor hand cleaning depending on the regions, field density, and whether the landscape is natural or leveled. Major dust storms can impair all production for several days while tens of thousands of heliostats are cleaned and restored. For these events, autonomous cleaning machines may be justified. One interviewed organization has developed a waterless cleaning systems which has been designed and tested using a dry brush over the facets at a cost of $117/heliostat (5 $/m2) and takes 15 minutes to install. The brushes must be replaced every 5 years. The costliest maintenance task is the replacement of the azimuth drive, which requires lifting the facet structure off the drive, swapping it out, and reinstalling the facet structure. This takes two people 2 hours. Azimuth drives have 99.9% reliability but given the quantities, a small number do fail. All components comply to the IP6 Standard, which necessitates accelerated life cycling with loads, thermal cycling, and dust. Reliability tests currently performed also include equatorial mount with mirrors for acceleration with water (EMMAQUA) [18], ultraviolet (UV), cast austenitic stainless steel (CASS), cycling, and manufacturer quality inspections and audits.

Plants are left to grow beneath the heliostats and are cut by another crew to prevent interference with the heliostats but not removed or killed. Intelligent operating systems now optimize which heliostat gets priority cleaning based on the effective power from each heliostat and the most efficient balance of flux on the receiver. Algorithms have been developed to determine the flux on the receiver in real time by convolving the sources of optical error into an analytical function to allow for quick calculation of a heliostat's productivity, which allows for the operator to prioritize which sections of the field to clean over time.

In addition to cost reductions in cabling and trenching, the PV cells are integral to the operation strategy of the field. When a cloud covers part of the field, the operator ideally matches the flow rate inside the receiver to the available flux to maintain a constant working media temperature. However, if the operator is wrong, and flux is higher than assumed, the additional flux to flow ratio can damage the receiver. Accurate knowledge of the available flux on the receiver is needed to maximize performance during periods of partial cloud cover, uneven reflectivity, or partial dusting. In Ivanpah, there were approximately 50 nips, or devices that measure DNI, throughout the field. In Ashalim, mounted PV cells effectively provide 50,000 nips in the sense that the DNI above each heliostat can be precisely known. BrightSource has an operating system that incorporates this DNI data with computational mapping of shading and blocking at each time of the day, with flow rate information through the receiver, to optimize turbine performance for DNI conditions within 0.1 second windows. The PV cells are used to measure attenuation, which is calculated as the instantaneous difference between (i) the DNI-weighted heliostat contribution over the entire field and (ii) the thermal power input to the receiver measured by infrared cameras.

Heliostat field operations must match the flux on the receiver to the needs of the turbine. This requires constant adjustment of the focus and intentional spillage. Aiming strategies are thought to be a relic from times of low computational speeds. The most modern fields use machine learning techniques to constantly read the state of the turbine, receiver, transient flow of the heat transfer fluid and available DNI to best match the instantaneous supply to the demand. Detailed market analysis is used to size the field in such a way to maximize the available energy for the time(s) of day with the greatest earning potential. This is an improvement from earlier systems that would optimize the field for a certain time of the year such as solar noon on the equinox. The control system contains machine learning algorithms that monitor grid demand and respond with the most valuable output.

Flux is increased by adding heliostats or increasing concentration and is decreased by decreasing concentration, increasing spillage, or reducing heliostats by defocusing them. Standby positions have improved since 2013 interactions with birds and now use a low concentration ring around the receiver that is not hot enough to harm birds. Pigeons are naturally attracted to towers. To keep them safe from beams, they are caught in traps and released unharmed in a remote location. Fully autonomous field operations have been achieved in Ivanpah and will be incorporated into the DEWA and Redstone plants. Transitioning to autonomy does require operator involvement to work through tuning of the plant. Ivanpah started with three field operators (one for each of three fields). This was reduced to one operator for all three fields, and now there are zero dedicated field operators. Operations are fully automated, and the board operator can handle the needs of the field. Atmospheric measurement metrology systems that use nephelometry, Rayleigh scattering, angular sensitivity, hygroscopic effects, water vapor absorptive techniques, and spectral shifting techniques to confirm the atmospheric attenuation measurement to within 1%–2% have been commercially deployed.

The plant operator also checks for stow wind limits (19 m/s) but plants rarely shut down for wind and do not typically stow after a single event but rather after a set of warnings and use judgement to protect the field as needed. In addition to manual shutdown, autonomous controls have more flexibility and can be made using learning algorithms that stow the edge of the field and leave the center active. To ensure fast shutdown without collisions with overlapping facets from other heliostats or hazardously heating the tower or stressing the receiver, at every timesteps each heliostat has predetermined its unique pathway to safe emergency shutdown, calculated as a set of available and unavailable azimuth and elevation coordinates. There are also safety protocols for unresponsive heliostats. The control system pings each heliostat on a regular pulse. If the response is not received after a prespecified number of attempts, the heliostat will move to standby and await reset to ensure it is not left in tracking when not desired. For PV powered heliostats, the heliostat battery has onboard programming to ensure that there is always enough charge to run an emergency shutdown routine, discharge during the night for software updates, and return to operation in the morning whereafter the solar panel would be able to charge.

Separate subroutines handle the communication and maintenance of the solar field. Maintenance largely involves firmware updates and camera calibrations, which can happen daily. Downloads are delivered to a subset of heliostats to ensure the whole field is not affected by any issues with the process or the code. Manual labor is required to change drives and facets, as well as troubleshoot heliostats that don't function as intended due to problems such as motor failure, bolts attaching the heliostat assembly to the pedestal, or worn or detached communication or power lines for wired heliostats.

10. CONCLUSION

This study summarizes the current state of the art in heliostat field deployment for CSP tower projects. Key opportunities for future research include a soil quality database to aid site selection, as well as a better understanding of the tradeoffs between supply chain, assembly, and construction costs. O&M is site-specific and should be considered with the field and heliostat design. Autonomous systems with closed-loop controls, machine learning enhanced aim strategies, self-calibration, and intelligent weather and emergency response protocols exemplify modern field operations.

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