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Gap Analysis of Heliostat Field Deployment Processes

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Abstract. Deployment of the heliostat field for a tower-based concentrating solar power (TCSP) plant is both a keystone to the success of the project and also a significant portion of upfront project cost. Due to the small number of deployed commercial-scale TCSP projects, the knowledge base of dealing with common problems for projects is limited, adding to the risk of obtaining funding, and sometimes leading to cancellations. In this work, we present a gap analysis of field deployment processes for TCSP plants. The analysis was informed by interviews with subject matter experts in TCSP projects, including project developers, owners, and utilities, which we summarize in what follows. Finally, we present possible pathways to addressing these gaps to reduce the risk of future project deployments. The gap analysis is a part of the Heliostat Consortium (HelioCon), a five-year program funded by the US Department of Energy with the objective of reducing a project's levelized costs by improving heliostat technology.

Keywords: Heliostat field, Gap analysis, Field deployment

Introduction

The U.S. Department of Energy (DOE) Solar Energy Technologies Office has laid out aggressive cost goals to meet a 0.05 $/kWh levelized cost of electricity for TCSP systems by the year 2030. To meet this goal, cost reductions are targeted for the key sub-systems. The collector field is the largest cost contributor because tens of thousands of heliostats are needed for large capacity systems on the order of 100 MW_e. The specific cost-per-area goal for a heliostat is 50 $/m^2. HelioCon is a five-year program funded by the DOE with the objective of reducing costs. As a first task, a roadmap and gap analysis is being conducted to prioritize the ongoing efforts to be performed over the next four years [1]. A series of interviews was held with advisors who work with previously deployed TCSP plants, engineering, procurement, and construction companies (EPCs), heliostat technology developers, investor/owners, and employees of utility companies. The names of the contributors will remain in confidence to remove the implication that the contributors were speaking officially on behalf of their respective organizations; however, we summarize key insights and quotes in what follows.

Utility staff voiced concerns that significant portions of the fleet of old generation plants are slated to be decommissioned and gigawatts of capacity must be replaced in the near term. Renewable portfolio standards are mandating that the replacement be from renewable sources and the speed of this transition is making magnifying the risk of emergent renewable technologies. The categorical opinion of whether TCSP – a technology that has been successfully deployed worldwide – is in fact "emergent" highlights the weight of the first-of-kind commercial scale plants in the US TCSP market (Crescent Dunes and Ivanpah Solar Electric

Generating Station). There is a belief that PV-battery hybrid systems are much more competitive than TCSP with thermal storage. Southern California Edison solicited 4GW of storage over the next 4 years, all of which were batteries; as noted in an interview, the technology is "tested, modular, proven." In addition to gaps in performance confidence, the urgency and speed with which these transitions are happening make the three-year deployment times indicative of TCSP problematic. Another utility contact notes: "Speed is definitely a big deal. Battery supply is tough to get due to a manufacturing bottleneck, so the whole project cycle is 18 months for a battery project." TCSP plant construction by comparison takes 36 months; however, it is difficult to say whether field deployment is necessarily on the critical path for the overall plant, as the tower and receiver also require long lead times.

In addition to construction time, there are delays with permitting and financing in plants worldwide which further delay project timing. The nominal plant price inherently increases deployment risk, and in some cases, by the time all the institutions lined up to finance approximately $1 billion US, the market moves on to other alternatives that are either cheaper or more quickly deployed or tax incentives expire. Furthermore, investors are more scrutinizing on whether the EPCs are properly capitalized to carry the risk and whether these companies are committed to follow through in the face of budget or schedule overruns.

A common theme from industry interviews was that an increase in speed to commissioning is more important to project acceptance than the project costs in the current market: "Don't get too caught up in LCOE! Fields that are more deployable may be more attractive. LCOE will come down with economies of scale." It has been suggested that projects in the $200-300 million range may bridge a balance between LCOE (which is nevertheless very important) and deployability. "Go small! Get deployable with small modules that can meet any spec." In addition to modular deployments relative ease to finance, these designs can eliminate many single points of failure. In reference to Crescent Dunes, a subject matter expert remarked there were "years of zero revenue because technical solutions were difficult to find," which is far less likely with smaller, modular systems.

Gap Analysis

There are generally two categories of cost reduction pathways for field deployment: maturation of heliostat technology and development of cost saving deployment technologies and increasing learning rates and economies of scale.

Gap 1: Field deployment technologies are difficult to justify because each project is site specific and heliostat specific. Each project is time dependent. Cost models for field deployment have high uncertainty and lack validation and information from EPCs.

Gap 2: TCSP does not benefit from steady learning or economies of scale because too many deployments have been cancelled due to permitting challenges, lack of market stability, and difficulty in securing financing.

Gap 1: Deployment technologies

Subject matter experts convened in a workshop to discuss the potential of deployment technologies to reduce costs. The overarching conclusion was that it was difficult to justify such investments because it was unknown when or where the next project would be sited and each project's heliostat design and field had unique requirements. Some developers spoke of the costs of grading or leveling the field while others touted the benefits of leaving fields in their natural state with vegetation and contours. Some used mirror washing trucks while others employed a team of manual facet washers. Trucks were less labor intensive but subject to issues with dirt road erosion while manual crews could traverse the natural ground with erosion mitigating vegetation. Some developers suggested trenching and wiring was a major expense while others deployed wireless heliostats with independent PV panels and wireless communicators.

A study by Kurup et al. used Design for Manufacture and Assembly (DFMA) software to calculate the material cost of each part and labor/machining processes to fully assemble and deploy a heliostat [2]. The DFMA calculation showed that foundation costs could be reduced by 0.86 $\$/m^2$ if the heliostat size were reduced. The smaller heliostat was also shown to reduce base assembly costs by 8.84 $\$/m^2$ and site labor by 8.60 $\$/m^2$, but these savings may be offset by increases the number of individual heliostat costs (weatherproof connectors for example). The study also highlights savings in moving from a wired field to a wireless field. The cost of the control system material and labor could be reduced by 7.69 $\$/m^2$ when the trenching and cabling costs are eliminated. Individual PV power and battery storage may also save 1.98 $\$/m^2$ relative to centrally powered fields and may reduce single-point failures.

Residual gaps in these approaches pertain to an accompanying optical analysis. A technoeconomic analysis by Zhu et al. shows the overall system cost increase as a function of each milliradian increase in optical error [1]. Here, the lower cost heliostat could only tolerate a 1.5 mrad increase in optical error before the cost savings would be washed out in cost increases elsewhere in the system.

There is still a gap in understanding the overall cost of field deployment. The Kurup study identifies less than 20 $\$/m^2$ in costs associated with deployment using the bottom-up approach. This figure confounds the component cost with the installation costs. However, top-down cost estimates which assume the field is 1/3 of the total plant cost and deployment is 1/3 of the field cost would result in a field cost assumption of 180 $\$/m^2$ for recent projects. Furthermore, unlike the rest of the heliostat lifecycle, field deployment costs are driven by the interaction of heliostat design and location which posits that the true cost of field deployment can only be understood with certainty once the same heliostat has been deployed in a sufficient variety of factors such as DNI, wind, soil type, proximity, labor rates, and water resources.

Gap 2: Learning and Economies of Scale

Previous studies by Lilliestam et al. average PV learning rate has been 20% since 1990. Trough-based learning rates exceeded 25% [3]. Three conclusions from this study are taken as a launching point for the gap analysis herein:

- discontinuities in policy and incentives had strong negative impact on CSP cost development
- three key factors were present during periods of greatest cost reductions: growth within a single company/organization, policy continuity, and diversity and competition among suppliers
- financial problems in major CSP companies threaten not only that company but CSP development in general

Since 2014, PV, wind, and battery prices have continued to decrease at the projected learning curve and are now mature stable technologies that can meet renewable energy portfolio (REP) standards without CSP for another decade or two. At that point, many of the future scenarios show a need for CSP to meet the last 10% of total generation by 2050 (98 GW) as well as contributing to the long term storage and industrial process heat needs [4]. These scenarios foreshadow a dilemma for CSP where it is known that the characteristics of CSP fill a key niche in the future decarbonized world that must be mature and ready to deploy beginning in 2035 but whose characteristics (>4 hr storage, high temperature, synchronous loading etc.) are not economically attractive in the short term relative to other renewables.

Utility skepticism in the deployability of CSP is not unfounded. There is a gap in understanding how to avoid the historic reasons for interrupted deployments. The environmental risk mitigation requirements are quite comprehensive and expensive for power plants. This may be a key factor to explain the discrepancies in final deployed field cost.

Crescent Dunes exposed technical risks to unforeseen reliability and performance issues including production of only half of the promised output and shutting down for 8 months in 2016-2017 due to a leaking molten salt tank and again in 2019 when the power purchase agreement was terminated by Nevada Energy [5] leading to the bankruptcy of Solar Reserve.

The 150 MW Rice Solar Energy project in Riverside County, CA by Rice Solar Energy, LLC, a wholly owned subsidiary of Solar Reserve, was certified by the by the California Energy Commission in 2010 but was put on indefinite hold in 2014 when it became clear that delays would push the production start date beyond the qualifying date for the 30% investment tax credit [6]. These delays were caused by an inability to secure financing and to comply with 186 environmental mitigation plans including: Hazardous Materials Plan; the Revegetation Plan; the Weed Management Plan; the Special-Status Plant Impact Avoidance and Minimization Plan; the Desert Tortoise Translocation Plan; the Raven Monitoring, Management, and Control Plan; the Burrowing Owl Relocation and Mitigation Plan; the Streambed Management Plan; the Evaporation Pond Design, Monitoring, and Management Plan; and the Avian and Bat Protection Plan; the Biological Resources Mitigation Implementation and a Monitoring Plan that included up-to-date maps depicting the location of sensitive biological resources requiring temporary or permanent protection during construction and operation and a plan to abide by the Biological Opinion (BO) issued by the U.S. Fish and Wildlife Service (USFWS). The owner filed to terminate the project in 2019 [6, 7]. Later, Solar Reserve would face a two-year delay of the PPA approval for the Red Stone project in the Northern Cape Province of South Africa which was eventually signed in April of 2018 on the brink of the 2019 shuttering of Crescent Dunes [8].

The Rio Mesa Solar Electric Generating Facility was suspended by BrightSource Energy in 2013 citing concerns with bird mortality, Colorado River resource disputes with tribes, large fossil beds, rare elf owls. BrightSource then focused on the Palen Solar Project, which was met by local opposition groups citing a need to keep the desert habitat pristine.

Proposed Path Forward

Solutions to Gap 1

There may be no single EPC or heliostat technology developer that has deployed in a large enough variety of conditions to complete a factorial model of cost drivers for field deployment but on aggregate, a generalized linear model of a comprehensive database of all deployment and O&M related costs, heliostat design and cost information, and local financial information may be sufficient to identify key correlations. Then the most correlated factors could be evaluated to discover any potential for cross cutting deployment cost reduction strategies.

To illustrate the approach, LCOE can be used as a proxy for deployed field costs. **Figure 1** builds an overview of operational power towers, or towers under construction using data from the CSP Guru [9]. The TCSP plants are arranged chronologically by construction date with levelized cost of electricity (LCOE) on the ordinate. Along with the plant name, the host country and heliostat size is categorically mentioned. The local DNI is indicated by color, and the plant size is qualitatively indicated by the symbol size which corresponds to the heliostat developer.

There is an obvious delineation between what will be referred to as the <u>first</u> and <u>second</u> wave of deployments occurring prior to 2015 and after 2015 respectively, making time a key factor; however, within the second wave, the LCOE has no correlation to time. Within both groups there is a weak correlation to DNI indicating non-physics-based factors may be affecting LCOE. Lilliestam et al. show the impact of low financing costs and additional revenues [10]. The second wave is dominated by Chinese deployments with relatively low DNI resources and modest plant capacities which intuitively would show a higher LCOE. Cerro Dominador has outstanding solar resource and predictably the lowest LCOE. Red Stone has no LCOE data at the time of writing.

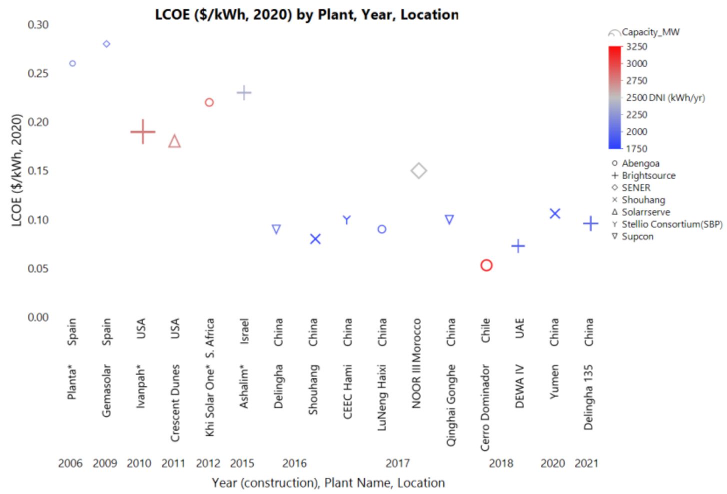

Figure 1. Overview of operational and under construction power towers

A linear regression model was run to try to identify factors correlated to LCOE. There is a strong correlation to year (F Ratio = 4.95), suggesting a series of first-of-its-kind towers were developed between 2006-2012 that were predictably more expensive as the technology was being commercialized and drops by about half in the second group of plants beginning in 2015. When one looks only at the second group, there is no correlation between LCOE and year of construction at all (F Ratio = 0.0001). (Ashalim was removed from the second group as an outlier, though it is a modern plant that benefits from learning at Ivanpah.)

Predictably, DNI has a significant role in driving down costs as it directly decreases the required field size but the significance does not appear when LCOE is plotted against DNI alone (P=0.569). Only in the context of other factors does DNI emerge as significant (P=0.06). The model of LCOE as a function of DNI, Heliostat Size, and Plant Capacity has an F Ratio of 28.6.

Another contributing factor of interest is the presence or non-presence of technology. Autonomous heliostat controls with machine learning have provided an opportunity for the field packing density to increase due to smart routing that can avoid collisions and optimizations in the number of heliostats required due to advanced aiming strategies that respond continuously to fluctuations in DNI, turbine performance, and receiver heating. Furthermore, it is hoped that enough deployments with and without individual PV power sources and wireless communication devices will be available to determine the cost impact. O&M technologies have been deployed by Cosin and some Chinese fields are washed by autonomous machines.

Solution to Gap 2

Gap 2 is focused on issues that cause plants to fail before they have been deployed. The objective is to divide broad overarching problems into concise technical objectives with defined scope. There is a broader effort within HelioCon to address the technical causes for underperformance as they may relate to heliostats including extensive full-field wind and soiling studies, metrology, and refinements to technoeconomic models. These models are being used to inform what the most likely sources of uncertainty are that contributed to historic underperformance. The CSP industry has the burden of presenting assurance to investors and utilities that overwhelms currently held skepticism.

In discussions with subject matter experts, there was cynicism that if pre-construction mitigation plans must span the course of years, the project is vulnerable to financing and permitting changes related to shifting tax incentives, changes in financial commitments, and the potential for fossil power plants to come offline before a renewable replacement can come online. A 2021 study published by Reuters said that 1.7 GW of proposed solar was cancelled in the permitting phase just in the year 2021 and that site acquisition is a top threat to growth in the solar industry [11]. Figure 2 categorizes the motivations of various opinions quoted in the study and in the Record of Decision for Rice Solar [6].

Figure 2. Categorical reasons for plant opposition.

Despite the overwhelming impacts of climate change on desert habitats, there are still sound ecological impacts of TCSP deployments that should be considered. The mitigation plans for all renewable energy projects address similar concerns and experience can be appropriated from other industries including PV and wind power and even aviation companies who also contend with interactions with birds. The work being proposed for the next phase of HelioCon is to work with biologists to review the environmental impact plans from fielded and non-fielded projects to identify opportunities for technical solutions that would accelerate wildlife detection, avoidance, and deterrence. Biologists can also work with field layout designers to create software models informed by the natural environment. Current open-source field layout tools have the capability to render the locations of heliostats around a receiver to optimize the layout to minimize the land use and maximize the usable heat. These same tools could be expanded to consider data from sources such as mapping software that identify migration patterns, water shed patterns. Glare tools exist that calculate when glare will occur at a certain location could be incorporated with field layout tools to optimize the incident power while minimizing glare on a particular location such as a national park or community [12].

Furthermore, while CSP plants deploy dry cooling and use substantially less water than conventional thermal power plants, they still do use a small amount of water for mirror washing. While the water use is limited by contract [13], water use disputes with communities and tribes can prevent projects from moving forward. Even when disputes are resolved, the delays can render projects unviable if the market changes in the interim. Therefore waterless facet washing technologies may be beneficial even if they prove to be more costly than water-based methods [14].

The same Reuters study characterized renewable energy as a "culture war" [11]. For every proposed project there are dozens of well-organized opposition groups. These groups raise objections based on environmental impact and land use disputes. There may be little that a project developer can offer to a group that does not want a plant to be built under any circumstances. This problem may be addressed by using statistical modeling to identify the strongest correlations between demographic and sociopolitical data and likelihood of permit rejection. A research study has been proposed to compile a database of successful and unsuccessful project proposals that includes the factors that drive power performance such as weather and DNI as well as demographic data on the surrounding communities. This data would leverage deployments from the solar and wind power sector to enhance the power of the model. The hypothesis is that a correlation matrix could be produced that would quantify the likelihood of a permitting dispute being upheld based on the location of the proposed site. This could help TCSP developers avoid the costly process of developing proposals only to have them rejected by local authorities.

In addition to avoiding areas likely to reject TCSP deployments, HelioCon could provide technoeconomic analysis and best practices study for engaging with communities who do want to deploy renewables. In New Mexico, for example, there is a strong willingness to replace jobs lost due to the closure of large coal-fired San Juan Generating Station near the Navajo Nation with renewable energy careers. These jobs have not materialized in time for many [15]. Many who live in tribal communities do not have access to the electricity grid and autonomous solar energy with storage is an attractive solution. Picaris Pueblo has recently deployed over 1 MW to solar power [16]. In 2022, the US Department of Energy awarded $9 million to tribal communities to enhance energy security and resilience [17]. Figure 3 shows an overlay of the solar resource heat map, the electricity grid, and Native territories shown as pink districts. HelioCon has proposed to work with developers of tribal PV installations to engage in dialog with community leaders to help educate the TCSP community on the needs and concerns of TCSP plants in these communities as well as look for opportunities where TCSP may be mutually beneficial.

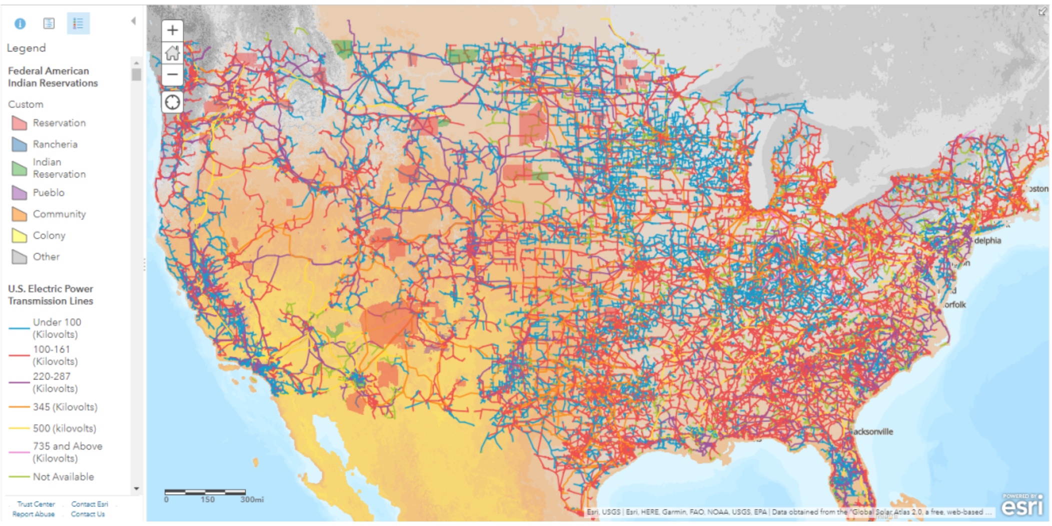

Figure 3. Map of US solar resource contour plot as background with grid overlay and tribal borders (red). Maps were created using ArcGIS ® software by Esri.

Discussion

The work on field deployment cost reduction strategies began with a roadmapping process conducted in year 1 of the Heliostat Consortium [1]. The gap analysis is a fundamental part of this roadmap and it directs the work to be performed over the remaining four years of the project. Two primary gaps were identified: first that deployment and O&M cost data is largely unavailable and there is too much uncertainty in environmental mitigation costs and financing costs confounded in the LCOE numbers to assume a cost with reasonable certainty. second, the CSP industry has been hobbled by permitting delays that can be so extensive that market conditions move on before breaking ground and there does not appear to be a known way to avoid these challenges.

The proposed solutions to be worked on in future work is to consolidate actual cost data from industry and aggregate statistical cost bounds and highly correlated factors. To address permitting issues, work needs to be done to find more cost effective methods of mitigating bird interactions, no-water washing methods, and field layout strategies the minimize visual impacts to communities and that leave the desert habitat below the heliostats unscathed. Opposition should be assumed during the site selection process and early engagement with local residents and leaders to address concerns and educate should be pursued. Local residents have benefitted from jobs and economic stimulus from CSP plant construction, but more work needs to be done to balance the benefits of CSP with the externalities to neighboring communities.

Data availability statement

The data used in this paper was taken from the CSP GURU spreadsheet by Lilliestam et al [9].

Author contributions

Jeremy Sment: Writing – Original Draft; Writing – Review and Editing; Methodology; Visualization; Formal Analysis. Alexander Zolan: Writing – Review and Editing; Formal Analysis. Guangdong Zhu: Supervision; Methodology.

Competing interests

The authors declare no competing interests.

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