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Concentrating solar thermal power in the U.S.: lessons from setbacks at Ivanpah, light for the future

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Concentrating solar thermal power (CSP) exhibits promise as a source of firm electricity. The proposed termination of Ivanpah's power purchase agreement hinders confidence in the country's CSP future. This work highlights how the lack of thermal energy storage (TES) undermined the first-of-a-kind plant's economics as California's grid transformed. Then, possible futures of the Ivanpah facility are analyzed; results show retrofitting with state-of-the-art TES systems could provide better returns.

Concentrating solar thermal power (CST or CSP) generates electricity using mirrors to concentrate solar radiation on a receiver, which absorbs the energy as heat and then converts it into electricity through a thermal power cycle. Current CSP installed capacity is approximately 8 gigawatts (GW) globally with about 1.3 GW in the U.S. The five major (i.e., > 100-megawatt (MW)) CSP power plants in the U.S. are Ivanpah (392 MW), Crescent Dunes (110 MW), Mojave (280 MW), Genesis (250 MW), and Solana (280 MW); fact sheets for each plant are in Supplemental Information Section A. Ivanpah and Crescent Dunes employ a tower design while the rest utilize parabolic trough collectors. Tower CSP plants can achieve higher temperatures and, therefore, higher efficiencies and potentially lower levelized costs compared to the more deployed trough design. These facilities rely on high amounts of direct normal irradiance (DNI), and, therefore, all are in California, Nevada, or Arizona. CST typically refers to systems that only deliver thermal, instead of electrical energy. CST systems can and have been used to supply industrial process heat, which represents around 20% of annual energy consumption globally. Examples of CST industrial process heat applications include integration with enhanced oil recovery, textiles, and food and beverage processing, including a 30 MW-thermal facility owned by Heineken¹. Industrial process heat is seen as a key market for CST growth to reduce industrial energy costs.

While the technology exhibits potential as a clean source of dispatchable (i.e., load-following) energy generation that also provides ancillary services to the grid², CSP deployment in the U.S. has been limited recently. One salient setback has been the announcement that Ivanpah, the largest CSP plant in the U.S., entered negotiations to terminate its power purchasing agreement (PPA) for two out of three generation units within a year. The electric utility offtakers, Pacific Gas & Electric and Southern California Edison, cited underperformance and high costs as justifications to cancel the PPAs almost 15 years earlier than expected. This paper will cover the economic issues with the Ivanpah PPA, what lessons can be learned from Ivanpah and other CSP deployments since Ivanpah was built, and, lastly,

options for Ivanpah and the CSP industry to meet grid requirements economically moving forward.

History of Ivanpah

Construction for Ivanpah broke ground in October 2010 in California near the Nevada border, and it started delivering power to the grid in Fall 2013. The 392-MW plant supplanted the 20-MW Planta Solar 20 (PS20) CSP plant built in the late 2000s in Spain by Abengoa Solar as the largest solar power tower plant in the world. In 2010, the levelized cost of energy from solar photovoltaics (PV) was over 30 cents/kWh³ while Ivanpah's PPA price, while not explicitly publicly disclosed, has been cited at close to 20 cents/kWh⁴. However, in the past 15 years, rapidly increasing deployment of solar PV projects reduced costs to an average PPA price of 6 cents/kWh as of 2024³.

Environmental groups expressed concerns over the threat to wildlife; however, such impacts were subject to significant speculation and misinformation. A peer-reviewed publication places the levelized avian mortality rate between 0.7 and 3.5 fatalities per GWh for the first year of operation⁵. The industry implemented mitigation efforts such as nonlethal irritants, high-pitched noises, and different aiming strategies, which led to significant reductions in avian mortalities, down to 0.34 fatalities per GWh in 2022⁶ which is lower than those associated with fossil-fueled plants (5.2 fatalities per GWh) and comparable to wind turbines (0.3 fatalities per GWh)⁵. Future CSP developments have access to improved siting tools and can incorporate active and passive wildlife mitigation measures to minimize environmental impacts.

Similar to PS20, Ivanpah used a direct steam design which works by producing steam for the power cycle directly in the solar receiver as opposed to heating an intermediate heat transfer fluid (e.g., thermal oil or molten salt). Indirect systems are compatible with thermal energy storage (TES) which acts as a buffer to control and extend output after sunset, as shown in Fig. 1. Ivanpah demonstrated that the direct steam

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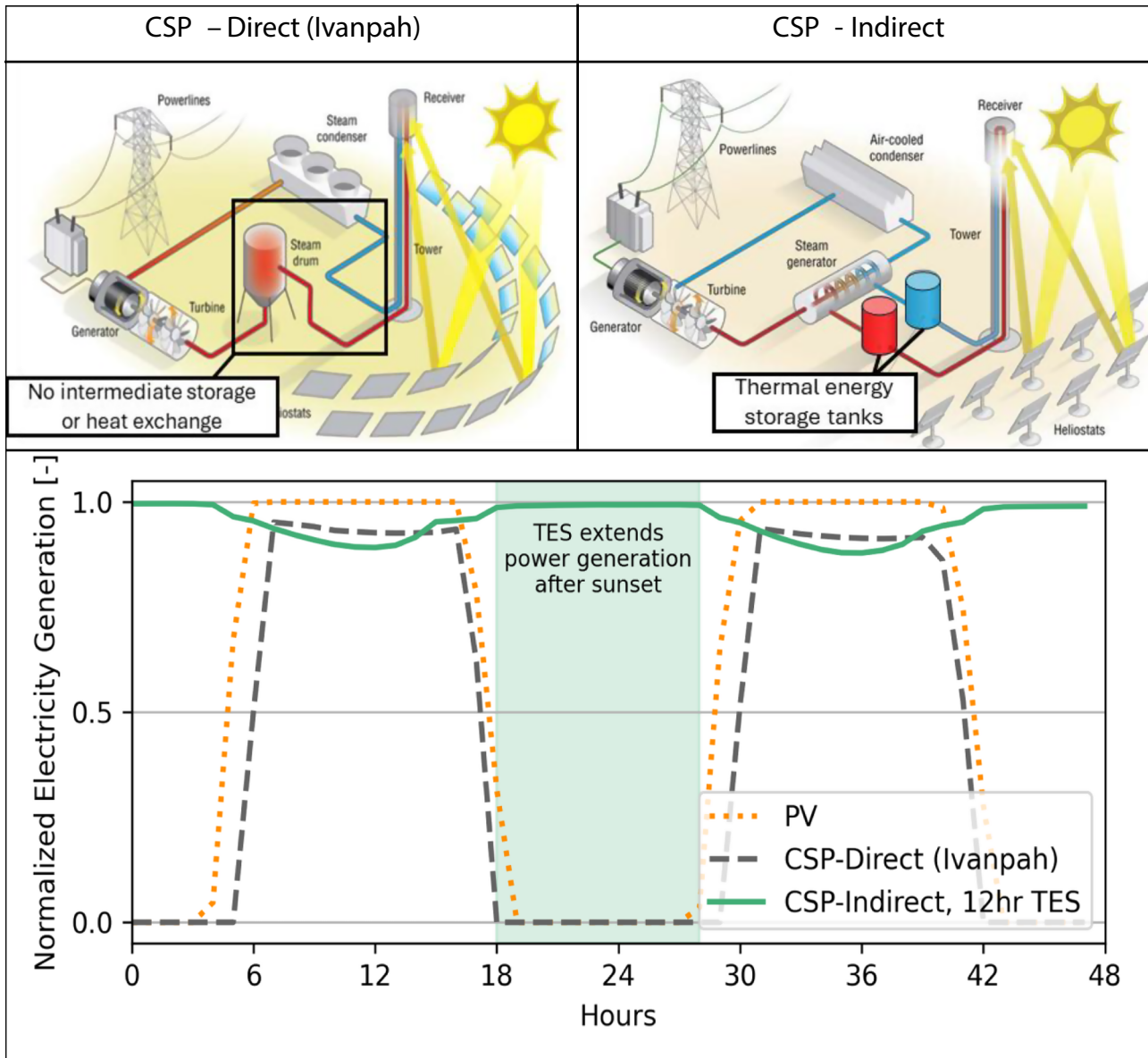


Fig. 1 | Examples of a direct (left) versus indirect (right) CSP tower system; CSP tower system figures adapted and annotated from²⁹. Normalized electricity production generation profiles for each type of CSP system plus a PV system without

any storage in the same location for comparison (bottom). Normalized electricity generation profiles calculated using NREL SAM v2025.4.16 by dividing each hour of net electricity generation by the annual net peak generation.

approach, and tower projects in general, can generate electricity at a scale previously untested by producing hundreds of gigawatt-hours (GWh) of electricity from solar every year. However, historical generation data shows the plant typically only produced between 70 and 80% of its expected generation; 940 GWh was expected for a typical weather year, and the summary of Ivanpah’s historical generation in Fig. 2 adjusts expected generation in response to historical weather data (see Supplemental Information Section B for details).

The choice to use direct steam is the root of many of Ivanpah’s challenges, most notably because direct steam systems cannot provide meaningful energy storage capacity. Therefore, Ivanpah’s production profile was directly related to the solar radiation; passing afternoon clouds could cause the power cycle to shut down until solar conditions improved. Natural gas is burned at start-up and during standby operations due to the lack of a thermal reservoir. Evolving market and pricing signals meant Ivanpah was the last CSP facility to be built with no storage in the U.S., and one of the last to be built worldwide. Since then, CSP plants have typically been built with between 6 and 18 hours of storage to extend production after sunset, reduce

or eliminate natural gas consumption during start-up, and allow the power cycle to operate continuously through solar radiation variability, reducing operations and maintenance costs.

When Ivanpah first unit began synchronization testing with the grid in 2013, solar PV represented less than 2% of annual generation in California (versus 18% today), utility-scale battery power capacity was only 8 MW⁷, and time-of-delivery (TOD) rates were nearly flat with no price signal to compensate storage assets. Today, the LCOE of standalone, utility-scale solar PV has reduced to 6 cents/kWh³, over 16,900 MW of battery capacity has been installed in California alone⁷, and curtailment and locational marginal prices commonly drop to negative values. The California electricity market has fundamentally changed since Ivanpah was conceived.

Lessons of Ivanpah

With storage, Ivanpah could have shifted generation to meet the peak loads in the late afternoon and early evening as solar PV production wanes and electricity demand rises. An analysis using NREL’s System Advisor Model (SAM)⁸ shows Ivanpah’s internal rate of return (IRR) plummets into

Fig. 2 | Historical cumulative solar-only generation data for Ivanpah’s three units (green) according to EIA⁷. Underperformance calculated as difference between actual generation and adjusted expected generation (black). Adjusted expected generation calculated based on the published expected generation, actual solar weather using historical DNI and typical meteorological year DNI. Percentage of the expected adjusted generation met by solar (white). Note: In 2014, underperformance was expected as the plant’s operation ramped to full capacity.

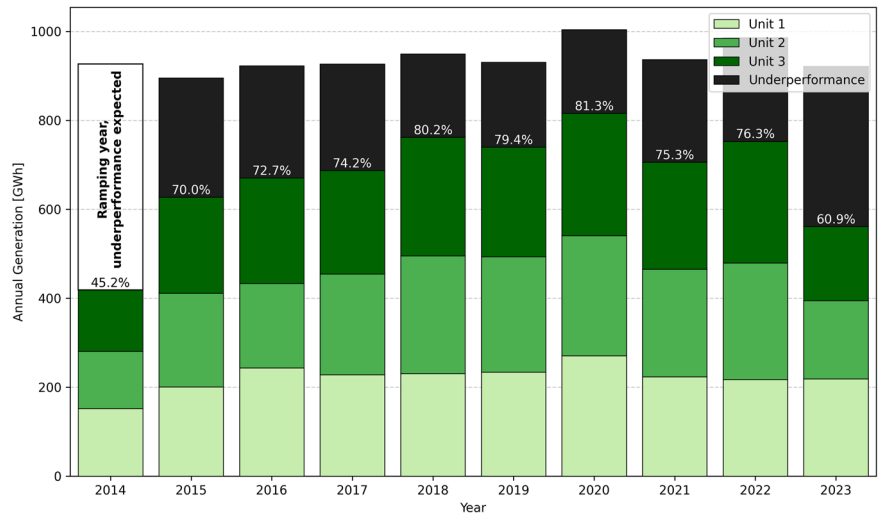
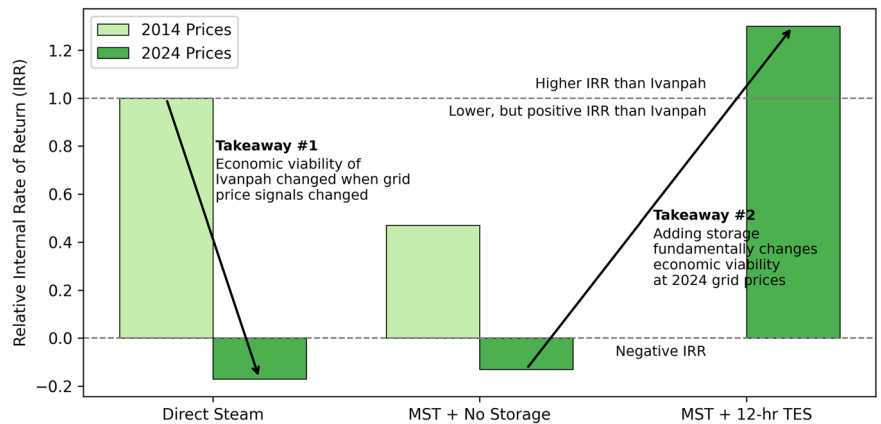


Fig. 3 | Relative internal rate of return (IRR) of different CSP tower configurations at different grid pricing scenarios with a fixed PPA price of \$0.20/kWh. Relative IRRs are relative to the Direct Steam case at 2014 grid prices (where IRR was 33.7%). For more details, see Supplemental Information Section B (grid prices), C (sensitivity analysis), and D (supporting files). MST = Molten Salt Tower. Note: Dispatch optimization was used for MST + 12-hr TES case.



negative territory using today’s grid prices compared to estimates for 2014 (i.e., flat time-of-day (TOD) pricing)—see Fig. 3. Today’s TOD factors were determined by normalizing the hourly Locational Marginal Price (LMP) for the SP-15 pool in CAISO, where Ivanpah is located—see Supplemental Information Section B for details. TOD factors are applied as a multiplier to the base PPA price to factor in actual grid conditions and the time value of electricity delivered to the grid (i.e., electricity is more abundant and affordable during the middle of the day compared to late-afternoon/evening when electricity is less abundant and in greater demand). Contrastingly, a notional molten-salt tower system located at Ivanpah with 12 hours of storage has an IRR 30% higher at today’s grid prices than Ivanpah did at 2014 grid prices (with the same PPA). This exercise demonstrates how the changing CAISO market decimates Ivanpah’s economics in the absence of storage. Without storage, Ivanpah became an expensive source of electricity during the lowest-cost (or in some cases, negative-cost) time of day in California. For more details on the analysis, see the Supplemental Information Section C. This market dynamic is the primary motivator for the utilities (i.e., offtakers) to buy out Ivanpah’s existing PPA contract(s).

In addition to the lack of storage hurting the plant’s economic value, the direct steam system leaves limited operational recourse during cloud passage, which leads to operational issues for the plant; clouds and jet contrails could cause the plant to trip offline. As a result, the steam turbine undergoes frequent thermal cycling which, in turn, lead to rapid degradation, reduced turbine efficiency, lower turbine availability, and, eventually, reduced overall plant performance. This was costly with some estimating \$50,000 per cycle in added wear-and-tear after accounting for revenue losses associated with an extended

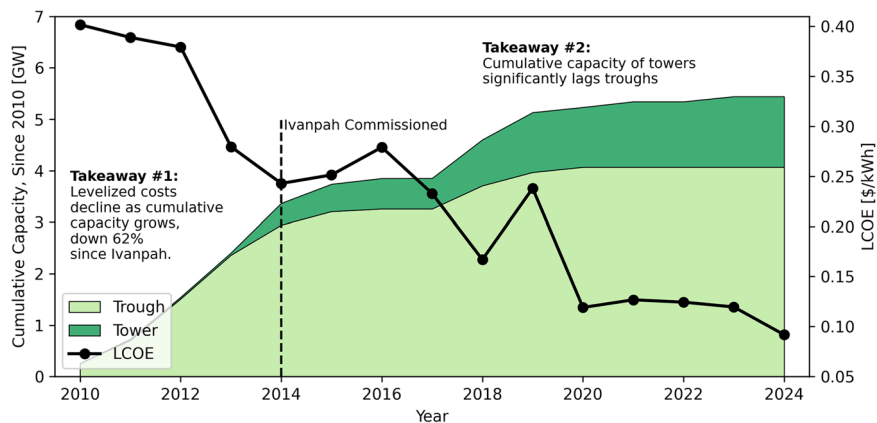
outage⁹. TES is therefore both a feature and necessity of CSP systems, a finding consistent with recent analysis work^{10,11}.

Additionally, Ivanpah performed worse compared to other non-dispatchable CSP systems in the U.S.; Genesis and Mojave, both trough plants, also lack thermal storage but have not had similar issues. They both use an intermediate heat transfer fluid, synthetic oil, to collect solar energy and indirectly generate steam with no storage. Trough collector fields have a much higher thermal mass than a direct steam system, damping transient effects from cloud passage better than the Ivanpah’s central receivers. Ivanpah also used a Rankine cycle with reheat, which has longer start-up times and more complexity compared to the simple Rankine cycle at Genesis¹². Additionally, Genesis and Solana were built by Abengoa, which had the benefits of more internal and general industry legacy knowledge on best practices for trough systems; none of the U.S. trough plants were a first-of-a-kind (FOAK) plant like Ivanpah. TES enables robust CSP tower plant operations and maximizes the economics of production.

Adding storage in the form of molten-salt tanks to a CSP facility can unlock significant value, but projects with high-temperature (i.e., >500 °C) molten-salt tanks have encountered operational challenges. Floor fabrication, welding defects, and temperature gradients leading to thermal stress, stress relaxation cracking, buckling, and creep are identified failure mechanisms. Design and fabrication improvements (e.g., better welding, different materials, and sparger designs^{13,14}), show promise to resolve these issues, and other molten-salt CSP facilities have been successfully built and operated in recent years.

Indeed, BrightSource, the company behind Ivanpah, subsequently deployed two successful molten salt CSP tower plants globally: (1) Noor

Fig. 4 | Cumulative installed capacity of CSP systems since 2010 separated by parabolic trough and molten salt tower systems (left) and weighted average LCOE of all CSP plants over the same timeframe (right)^{11,19}.



Energy 1 in Dubai, rated at 100 MW with 15 h of storage TES, was built in 2023; and (2) Redstone in South Africa, rated at 100 MW with 12 h of TES, was built in 2024. Additionally, there are several other successful deployments of tower projects by other companies globally with learning curves which vary by region. One notable country is China, where over 10 CSP demonstration projects totaling 838 MW have been constructed, and an additional 8 GW are under construction or under development as of 2024¹⁵.

These successful follow-on deployments represented viable options at the time of their deployment when Ivanpah is viewed as a FOAK demonstration with many lessons to be learned by BrightSource and the CSP industry. Similar learning patterns are observed in many other energy technologies. For example, the first 1-MW wind turbine only lasted for 1000 hours of operation, but multi-MW wind turbines are standard today¹⁶. Additionally, A123 Systems was an early developer of lithium ferrophosphate (LFP) chemistries and went bankrupt, yet LFP is now a common battery chemistry for electric vehicles and utility-scale grid storage, as the market, economics, and technology have improved and evolved since then¹⁷. Similar stories can be found in the early growth of oil and gas infrastructure¹⁸, nuclear, and more. FOAK demonstrations will always have successes, challenges, mistakes, and lessons to be learned because all energy technologies at some point were inherently novel. Therefore, like all others, CSP has gone (and will continue to go) through iteration and constant improvements until mastery and consistency are achieved. As deployments have increased, lessons have been learned and CSP levelized costs have fallen by 62% since Ivanpah started operating—see Fig. 4. Further cost reductions may be achieved as tower CSP deployment continues¹⁹.

Despite Ivanpah’s headline challenges, the large heliostat field proved itself to meet the design-point needs of the power cycle, a significant technical achievement for the industry and proof of the scalability of heliostat technology. Tens of thousands of heliostats have individually controlled autonomously for many years at Ivanpah. The solar field achieving 92–94% availability allowed the turbine to operate at design most days.

While a prominent achievement, Ivanpah’s solar field also taught the CSP industry many lessons. First, the field was oversized, leading to higher capital costs; newer facilities have access to improved heliostats and performance modeling tools to better control capital costs. Second, the terrain of Ivanpah requires hand-washing the heliostats, a labor-intensive process that increases operational costs. CSP facilities must be designed with soiling in mind. Aiming strategies have also improved to increase efficiency, reduce wildlife impact, and avoid damage to the tower and receiver. Finally, Ivanpah demonstrated the importance of a heliostat supply chain and labor pool to deal with infrequent but significant damage from weather events. Recent international deployments have incorporated these lessons.

Alternative futures for Ivanpah

In the event of a PPA termination, there are multiple options for Ivanpah to continue operations. One option is to keep Ivanpah’s operational solar

fields which collectively include more than 170,000 functioning heliostats and retrofit new molten salt receivers on the towers while adding storage. A notional retrofit molten salt tower with 12-hour TES could have a PPA price as low as 6.99 cents/kWh at 2024 TOD schedules, assuming negligible tower and heliostat costs. Because retrofit costs such as tower modifications to support a heavier media are highly uncertain, the analysis includes a sensitivity on contingency costs; assuming an additional 50% contingency raises this notional facility’s PPA price by 33%. Option #2 would be replacing the CSP facility with a PV array with a 4-hour lithium-ion battery storage, a now-ubiquitous configuration in California and hinted as a likely outcome in a recent statement by NRG²⁰. Electricity from the PV+Li-ion system could be 40–80% more expensive than the retrofit option and 20% more expensive than an entirely brand-new molten salt tower with 12 hours of TES with the same IRR and similar land use. The CSP system would also have a capacity factor over 60% while the PV+Li-ion’s capacity factor would be under 30%, providing power when the market needs it the most. See Supplemental Information Section C for more details.

Opportunities and challenges for future U.S. CSP

For the general CSP industry in the U.S., first, any new CSP systems built in the U.S. will require substantial TES capacity to match dynamic TOD rates and to provide valuable and critical dispatchability as time of delivery increases in importance. The U.S. grid seeks firm power sources to balance the increasing penetration of variable renewable energy sources and meet the expected demand growth from data centers, industry, and transportation. Grid planners use more sophisticated metrics than just levelized cost of electricity (LCOE), such as effective load carrying capacity (ELCC), to better assess the trade-offs between cheap electrons from variable renewable energy sources and firm capacity resources. CSP systems with sufficient TES should have ELCC values higher than PV+Li-ion which is closer to 50%³ and is expected to fall in the coming years as the 4-hour energy storage market saturates²¹. The higher expected ELCC for CSP is due to the greater dispatchability and longer storage duration, reducing the saturation effect of available electrons that occur with standalone PV and, to a lesser extent, PV+Li-ion systems.

Advocacy for inclusion into utilities capacity expansion models and integrated resource plans allows not only to quantify ELCC, but to also fully capture other grid services and benefits CSP can provide. CSP is currently omitted from consideration during this critical step in the planning process. Consequently, utilities look elsewhere for firm power, which may lead to very large capital expenditures later if clean-energy goals such as those in California established by Senate Bill 100 are met²². CSP systems provide controllable output (i.e., dispatchability) and grid services such as spinning reserves and inertia, which may provide additional value to grids as penetration of inverter-based resources increases⁷.

Data center growth has led to a large rush of demand for firm power, mostly in the form of natural gas turbines, which currently suffer from

supply constraints and rising costs²³. Consequently, small modular nuclear reactors and geothermal power plants are growing in interest. Outreach by the CSP industry to this growing industry as an alternative source of firm power could open additional market opportunities. CSP developers could point to Noor Energy 1 providing power continuously for over 39 days straight as a success story²⁴.

For use cases in which high capacity factors (e.g., data centers) are required, PV + CSP hybrids with TES exhibit potential as cost-effective solutions²⁵. The PV system provides low-cost electricity during the day. Simultaneously, the CSP system charges relatively inexpensive TES (compared to Li-ion) to maximize continued power production after the sun sets. These PV + CSP hybrids are an emerging system configuration (e.g., Noor Energy 1), including China's recent and planned CSP deployments which are co-located with PV¹⁵.

Additionally, the U.S. Department of Energy has been funding innovations that focus on reducing the capital costs and increasing the efficacy of the heliostat field, which often comprises 30-50% of capital costs²⁶, and newer heat transfer media in addition to molten salt, such as solid particles²⁷.

Lastly, the CSP industry is advancing smaller-scale, modular CSP designs, including scaled down versions of the large-scale CSP towers (e.g., Vast) and more novel technologies (e.g., Exowatt). Modularity supports lower capital costs, more rapid and incremental improvements, and eases manufacturing, potentially at the cost of economies of scale; modularity is also seen has a key advantage of solar PV, wind, and batteries.

Outside of the electricity sector, a growing number of deployments of CST systems supply heat directly to industrial facilities. Process heat applications require neither the capital expenditure of a power cycle nor the efficiency loss associated with conversion to electricity, significantly reducing levelized costs compared to electricity-producing plants. In this sector, industrial facilities can reduce or completely offset their natural gas consumption by building CST systems onsite, with the ability to reduce energy costs. The market conditions depend heavily on the facility's natural gas and electricity prices, land availability, and local solar resources. Deployment of CST for industrial heat currently exhibits growth in these conditions, with 277 MW of deployments planned globally between 2025 and 2027²⁸. The economics may be especially favorable in the southwest U.S. states, particularly California, where there is significant industry in the agriculture and the food and beverage sectors, abundant solar resource, and high natural gas prices relative to the rest of the U.S. Tower systems are promising for processes that require higher temperatures, such as chemical manufacturing that requires > 500°C for various endothermic reforming reactions. Industrial heat consumes around 20% of the world's primary energy, making it a significant opportunity for expansion of CST.

Conclusions

Ivanpah was a FOAK CSP tower system that although failing to achieve long-term economic viability in a rapidly shifting electricity market, was still an important step towards the successful deployment of dozens 100-MW + CSP tower facilities globally. As with any FOAK demonstration of a given technology, much has been learned by and since the project. Despite its challenges, Ivanpah generated hundreds of gigawatt-hours of electricity every year, and proved thousands of heliostats can be controlled to generate over 100 MW of electricity. The challenges showed the operational limitations of using the direct-steam tower design and highlighted the value of TES to CSP economics. This study showed the degree to which TES would have improved this particular plant's economics. Additionally, the analysis preliminarily evaluated alternative plans for the plant and found favorable results for retrofitting with new, state-of-the-art CSP systems. These results are just indications of possible directions, with more detailed evaluations on feasibility following. Future analyses should evaluate which components could be reused (i.e., more detailed retrofitting costs), sensitivity to TOD factors, and capacity expansion modeling with different alternatives.

CSP resurgence in the U.S. will require the CSP industry to address the market need for dispatchable electricity sources and effectively compete

and/or complement effectively with other firm capacity assets (e.g., natural gas, nuclear, batteries, and long-duration energy storage). The U.S. CSP industry can move on from the FOAK facilities and meet current opportunities with the maturity of decades of development and lessons learned from successes and setbacks.

Data availability

Models are being published through an open access Zenodo repository (<https://doi.org/10.5281/zenodo.17581767>). Additional data can be made available upon request.

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Author contributions

J.G.—Wrote main manuscript text, figure generation, conducted analysis revision and editing; A.Z.—Supported main manuscript writing, conducted analysis, revision and editing; G.Z.—Conception of the work, funding acquisition, supplied data, revision and editing, supervision; M.M.—Acquisition and interpretation of data, supervision, revision and editing; S.S.—Acquisition and interpretation of data, supervision, revision and editing. All authors have read and approved the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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