Molten Salt CSP Hybrid Opportunities in China

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Abstract. Coal-fired power plants are the largest contributor to electricity production in China, and much of China's total capacity in coal plants has been added within the last 10 years. However, the Chinese government has recently shifted from supporting the development of coal power plants to cancelling many proposed projects. In addition, government support of renewables, including solar, has increased dramatically. Combined with a stable or slowing national energy demand, China's energy generation capacity is outpacing need. Curtailment in China typically begins with coal, and as such, the capacity factors on coal-fired plants are decreasing. All indications are that this trend will continue and extend to other fossil-fuel based generation in the future.

Many Rankine power cycles found in fossil-fuel based electricity generation operate at steam temperatures around 550°C, a temperature that can be matched by Concentrating Solar Power (CSP) technologies operating with molten salts. An advantage of installing CSP technology as a hybrid with existing plants is the complete utilization of existing power block equipment, including the turbine, cooling, and power transmission systems. In addition, direct molten salt thermal energy storage allows the solar portion of the plant to operate through transient events or, if desired, up to 24 hours a day. The steam turbine can operate consistently at full load, and therefore the highest efficiency, while still directly reducing fuel consumption or maintaining the low capacity factor of the coal boiler. There are other advantages, such as a potential increase in plant capacity factor if currently limited by governmental regulations on the quantity of fossil fuels used, or increased revenue if a power purchase agreement or carbon emission credit can be reached valuing the solar portion of plant generation higher than the fossil-fuel portion.

This paper examines the current state of the Chinese energy market and the variables above are explored to determine the engineering challenges, economic feasibility, and potential market for CSP hybridization with existing coal-based plants in China. Example sites are identified and evaluated, risks and challenges are addressed, and the final Levelized Cost of Energy (LCOE) and power generation results are compared to current Chinese pricing for greenfield CSP projects. The LCOE calculations used do not include generation from the coal side of the plant. These projects are economically attractive, achievable with today's technology, and provide a market on the scale of gigawatts of installed CSP capacity.

CURRENT MARKET FOR ENERGY GENERATION IN CHINA

Coal Power Plants: Operation, Cancellation, Capacity Factors

Coal-fired power plants accounted for 63% of China's electrical capacity in 2013, and from 2010 to 2015 alone, China installed 297 GW of coal-fired capacity (1). However, these numbers only represent half of the coal picture; in the same time frame, the Chinese government cancelled 164 GW of proposed coal plants in various phases of development, and the country has seen an overall decline in the use of coal to meet electricity demand (1). This juxtaposition is the primary driver creating a massive potential market for CSP hybridization. The key indicator of this market is the capacity factor of existing coal plants.

Capacity Factor is defined as the fraction of actual generated electricity to the maximum possible generated electricity in the same time frame. Since coal is a source of fuel that can be utilized at any time of day, it can be assumed that the maximum electricity generated in a single day is the net capacity of the turbine multiplied by 24 hours. In China, the capacity factor of coal-fired power plants fell from 60.4% in 2011 to 49.4% in 2015 (1). Typical financial models for new coal-fired power plants assume a capacity factor of 85% (2), and reduced operation from that metric is a financial detriment to the plant. The result is expensive power block equipment, already permitted and connected to the grid, that sits unused for the majority of its valuable lifetime at the expense of the plant owners and operators.

This problem will not be remedied through a shifting policy from the Chinese government. As recently as January of 2017, China announced the cancellation of over 100 coal plants, in pursuit of its own goal of limiting total coal capacity in the country to 1100 GW by 2020 (3). As the United States has pushed to remove itself from the Paris Agreement, leaving China as the leading nation to achieve the largest CO_2 reductions, political and environmental pressures against coal continue to build in that nation.

CSP hybridization provides a solution for increasing plant capacity factor without increasing coal use. It utilizes existing infrastructure to provide value to the plant owner from a sunk investment, and gives value to grid operators to add clean, renewable energy to the mix without the investment required for a greenfield plant. While CSP hybridization would not necessarily result in a further decrease in the use of coal at that location, it would provide a competitive advantage over a standalone coal plant as the Chinese government continues to move away from coal as a fuel source, and would result in reduced coal use nationwide. CSP hybridization with coal solves an emerging and difficult problem in the Chinese energy industry while creating an economically viable market for plant owners and CSP developers alike.

Potential Market Selection Methodology

To determine the market size for CSP hybridization in China, the Global Coal Plant Tracker from CoalSwarm was used (4), which contains location information, plant name, owner/operator information, turbine capacity, operating status, build year, combustion type, heat rate, and capacity factor for coal-fired power plants worldwide. The list was filtered for operating power plants in China, which resulted in a list of approximately 1000 plants.

Much of China does not have a suitable solar resource to support a cost-effective concentrated solar power system. Using annual average Direct Normal Irradiance (DNI) data from the Global Solar Atlas (5), the Google Earth Pro desktop application was used to plot the GPS locations of all Chinese coal-fired power plants. Polygons were then derived, enclosing areas of China with a DNI average value greater than 3.5 $kWh/m^2/day$, and the coal-fired sites were reduced to only those falling within the high-DNI regions. A screenshot of the DNI map inside the Google Earth application is included in Fig. 1 for reference. While a large land area of China meets this DNI restriction, high DNI typically occurs in the least populated areas of the country, where a small fraction of power plants reside and where power transmission infrastructure does not exist.

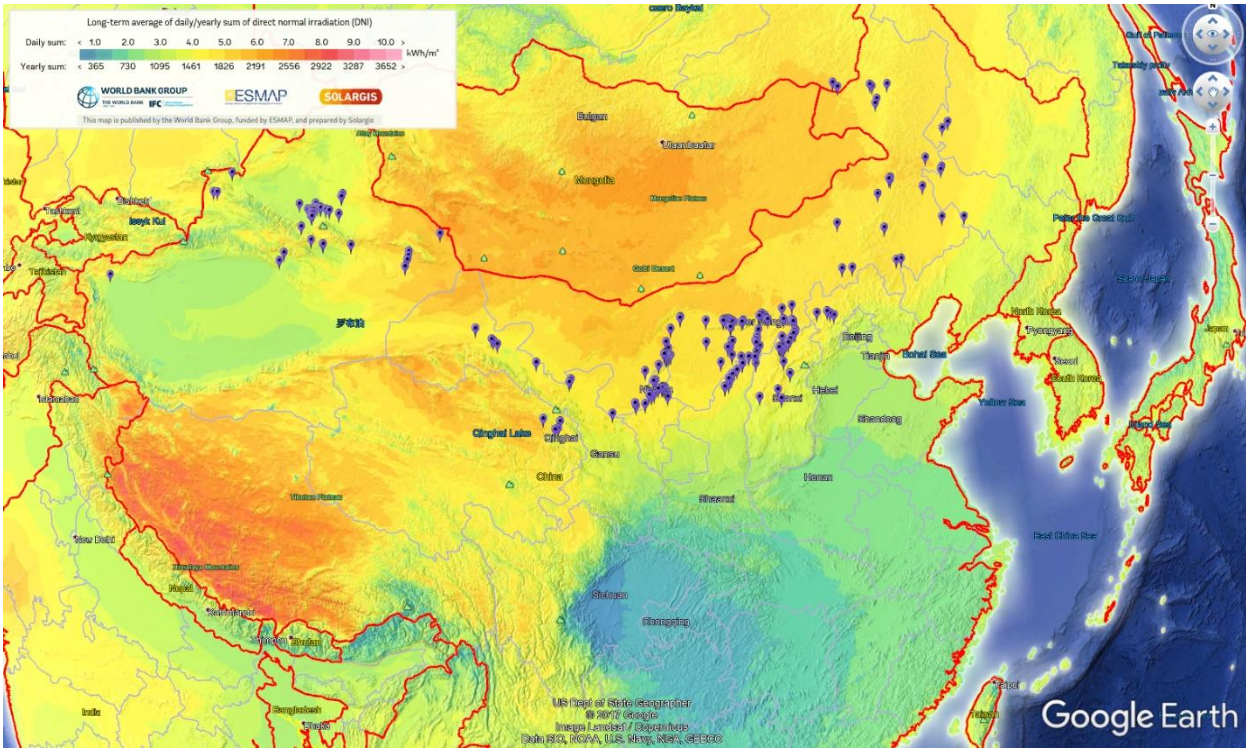

FIGURE 1: World DNI Map in Google Earth, with Plant Locations for Potential CSP Hybridization

The latitude and longitude of each plant from the initial reduced list was evaluated to determine if it was inside the DNI polygon utilizing a user-defined script in a spreadsheet application. This list of potential plants contained 189 candidates (also shown in Fig. 1) with 181 GW of turbine capacity. Since some of the 189 sites reside in populated or mountainous regions where land is not available, the list was further reduced to 146 sites with some available land. The available land size for each of the 146 sites was evaluated and referenced to a land-area-based CSP capacity, assuming two hours of thermal storage. A maximum hybridization fraction of 20% was assumed in order to maintain boiler efficiency, and the minimum of land area and capacity fraction was taken as the potential for hybridization at that site. As a result, 15.8 GW of CSP addition was identified in this market, significantly more than the total global operating CSP capacity (6).

OVERVIEW OF PARABOLIC TROUGH TECHNOLOGY UTILIZING MOLTEN SALT

The market identified above is available immediately and is feasible for CSP hybridization, but only with technology that can reach the main steam conditions of steam Rankine power plants. In hybrid scenarios, especially where the turbine and coal boiler already exist, it is not feasible to inject lower-temperature solar steam at a midway point of the boiler. The boiler would be unbalanced, with a higher mass flow rate at the discharge than at the inlet. Lower-temperature heat can be used in the boiler preheater effectively, but preheaters typically can only be hybridized to account for about 3% of a plant's total thermal power requirement. If the boiler system is turned down as a whole, rather than in select components, it can be hybridized by up to 20% of the plant's thermal power load with minimal impact on boiler efficiency. In the case of China, where coal-fired power plants are already running at half capacity and boiler efficiencies may already be low, solar steam may be injected into the turbine at even greater fractions. Therefore, assuming a 20% maximum boiler turndown with matched main steam conditions versus a 3% lower-temperature preheater hybridization, lower-temperature systems only open a market that is 1/3 the size identified above.

Traditionally, the sub-critical Rankine cycle operates in the 550°C range, which can be matched by conventional CSP technologies operating with either molten salts or direct steam. Other heat transfer mediums are being researched, but have not yet been demonstrated commercially. While both molten salt and direct steam can match the steam conditions of a coal-fired power plant, only molten salt offers the advantage of low-cost thermal storage, which is important for generation during peak demand periods, stabilization of cloud transients, and extended hours of operation. Fig. 1 presents hybridization options utilizing (a) a lower temperature oil-based system, and (b) a high temperature molten-salt-based system. In the salt system, the storage system does not require heat exchangers, and steam is injected directly into the turbine inlet. The coal-fired boiler and solar steam generator are decoupled, which allows for the boiler to be turned down up to 20% with minimal impact on efficiency. In the oil-based system, the feedwater is preheated by the CSP system, which offers up to 3% hybridization with the coal-fired plant.

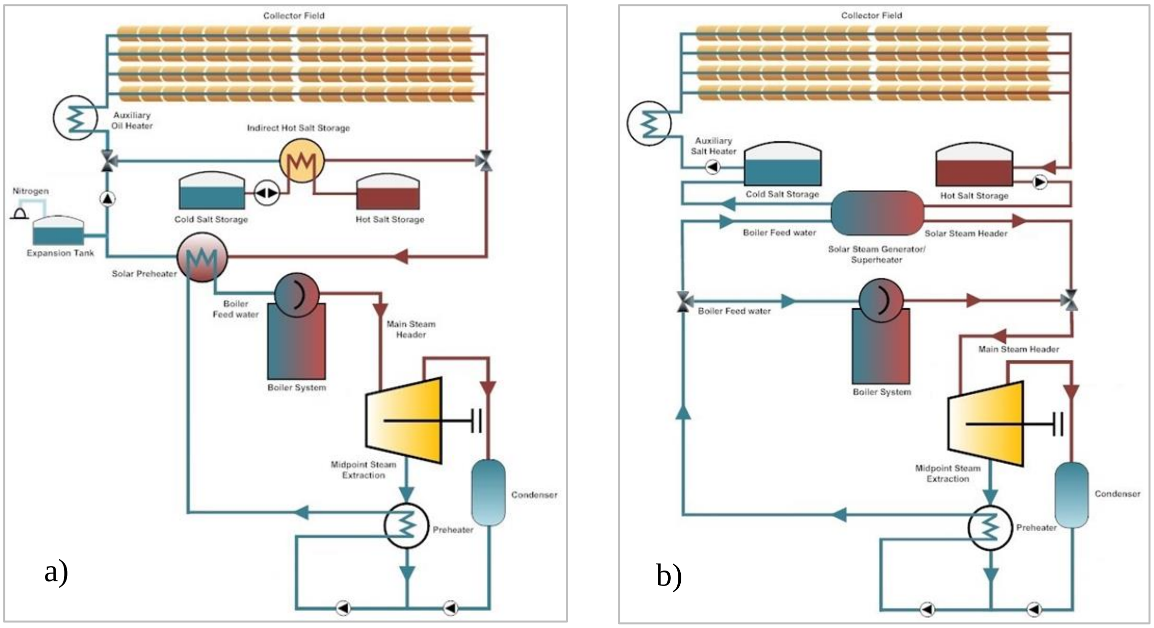

FIGURE 2: a) Low-Temperature (Oil-Based) Hybridization Schematic, Yielding 3% Total CSP Hybrid Addition, vs. b) High-Temperature (Molten-Salt-Based) Hybridization Schematic, Yielding 20% Total CSP Hybrid Addition

When a parabolic trough system is used as the CSP source, the solar field is easily scalable and does not require substantial site design work for varying thermal loads. In hybrid scenarios, it is typical to find that existing power plants have variations in hybrid thermal requirements and nearby land availability. With a parabolic trough system, these differences are straightforward to address, and do not require substantially varied system designs. They do, however, require that the parabolic trough system be highly efficient and designed specifically for use with high temperature working fluids, such as molten salts.

Salt-compatible parabolic trough systems are unique in that they must allow for electrical isolation of the receiver from the rest of the system. The receivers use impedance heating during fill and drain procedures, and in the rare case of a salt freeze event. The flexible piping connections at either end of the trough must be designed for molten salt compatibility, and all hot-side piping components must be constructed of stabilized stainless steel. The system must also be designed in a way that reduces heat loss through the receivers at night, with a high concentration ratio and high thermal efficiency.

Molten-salt-compatible parabolic troughs are available commercially, and offer the capability to meet a vast, untapped hybrid power market in China. The technical aspects of hybridization are straightforward, with minimal impact on the existing system's design or operation. This system provides a means to increase capacity factor, maintain or increase employment, and increase revenue at existing coal-fired power plants. To demonstrate the feasibility of this model, the following section describes in detail a few example sites in China, comparing a hybrid power scenario with construction of a "greenfield" CSP power plant.

MODELING APPROACHES AND SITE EVALUATION

Example Site Selection

From the previously discussed list of 146 candidate sites, 6 representative plants were chosen in order to have diversity in geographic location, average DNI, and turbine size. Each of these sites were also reviewed in Google Earth to verify that there was suitable land for the solar field. In many cases, there was more than one power plant located at the same site. As a result, only one power plant was selected from the group for this case study. The basic plant information for each of the 6 representative plants is shown in Table 1. The maximum estimated trough capacity shown in the table is based on using a 20% hybridization of the turbine size and is averaged and/or rounded in order to get the three hybridization capacities of 65 MWe, 40 MWe and 30 MWe. The same solar field capacities were used for both the hybrid and greenfield solar plants. A comparison of the Monthly Mean DNI for each of the selected site locations is shown in Fig. 3 based on the Typical Meteorological Year (TMY) weather file for each site location. Seasonal and locational variations can be observed in the data.

	Zhangjiakou	Shanxi Yuguang	Tongliao	Huaneng M.G.	Huadian Turpan	Xinjiang G.
Location	Zhangjiakou, Hebei	Yulin, Shanxi	Tongliao, Inner Mongolia	Manzhouli, Inner Mongolia	Turpan, Xinjiang	Ejin_Qi, Xinjiang
Turbine Size (MW)	320	300	200	200	135	135
Year Built	1991	2012	1985	2009	2006	2011
Average DNI (kWh/m2/day)	4.66	4.04	4.29	4.89	3.77	4.22
Max. Estimated Trough Capacity (MWe)	65	65	40	40	30	30

TABLE 1: Characteristics of Selected Sites

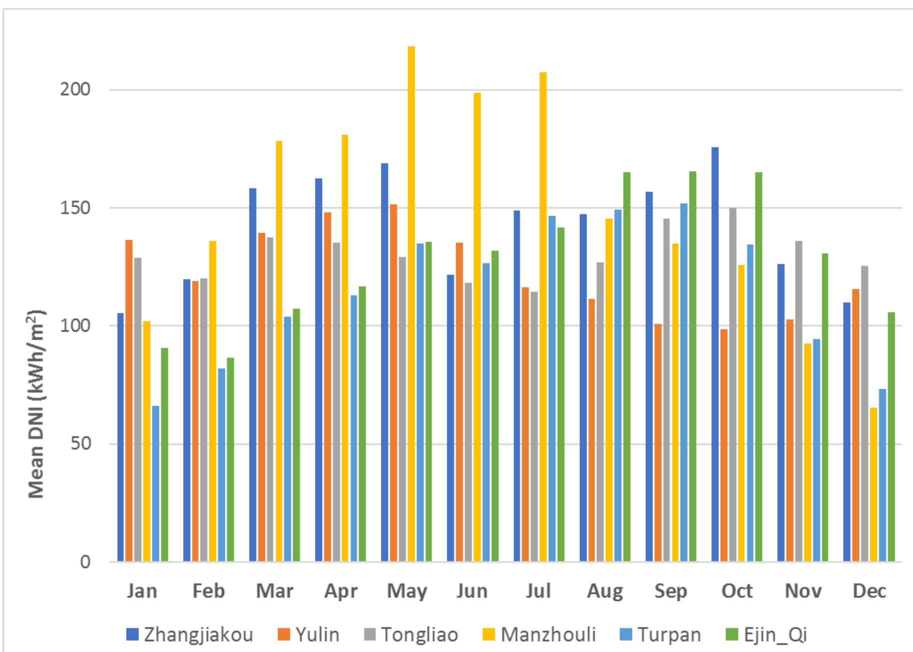

FIGURE 3: Comparison of Monthly Mean DNI for Selected Sites

Utilizing the System Advisor Model (SAM)

Plant Configuration & Optimization Methodology

In order to evaluate the economic feasibility of a hybrid plant over a greenfield plant, a cost and performance analysis was performed using NREL's System Advisor Model (SAM) (7). Since the same solar field capacity was used for both the hybrid and greenfield plants, the only parameters that were varied for the greenfield plants were solar multiple, hours of thermal storage, and cost differences of the power block (11). In both the hybrid and greenfield cases, a molten salt parabolic trough with direct thermal storage was selected. The solar fields were optimized using an East-West orientation in order to minimize the month-to-month electric production variation and maximize financial return in locations that are a significant distance from the equator.

Each case used the CSP physical trough model with the PPA (single owner) financial model within SAM. For the solar field configuration, SkyFuel's SkyTrough DSP parabolic trough with an 80 mm molten salt receiver was modeled. This model was based on the known physical and optical properties of the parabolic trough and receiver, including the associated heat loss profile for the receiver. Additional parameters such as loop temperatures, loop flow rates, power cycle efficiency, and pressure were set to be consistent with a molten salt plant configuration. A configuration of 8 SCAs per loop was selected to achieve the required loop outlet temperature.

From a parametric analysis, a hybrid configuration was selected using a solar multiple of 2.0 and 3 to 3.5 hours of thermal storage. The size of each plant was based on optimizing the solar field and storage size to minimize the Levelized Cost of Energy (LCOE). Table 2 shows the selected sizes for each of the hybrid plants. As previously noted, the solar field capacity (equivalent turbine size) of the hybrid solar plants was based on 20% of the full coal plant capacity.

A parametric analysis was also performed to size the greenfield plants and is shown in Table 3. The larger solar field and thermal storage sizes were selected in order to maximize the annual hours of operation and reduce LCOE. The result of the parametric analysis was a solar multiple of 3.6 with 12 hours of thermal storage. In this configuration, the greenfield solar plant can operate in the baseload power generation mode, similar to a coal plant of the same size. Note that the LCOE reduction listed in Table 2 represents a comparison of the hybrid and greenfield power plants. In all cases, the hybrid plant resulted in a lower LCOE than the greenfield plant at the same location.

Case Name	Solar Multiple (SM)	Solar field area (m^2)	# Loops	# SCAs/ loop	Storage Hours	Equiv. Turbine Size (MW)	Annual Energy - Net (MWhe)	Capacity Factor	LCOE Reduction
Zhangjiakou Hybrid	2.0	577,200	74	8	3.5	65.0	124,762	22.0	10.1%
Shanxi Yuguang Hybrid	2.0	577,200	74	8	3.5	65.0	108,272	19.1	9.7%
Tongliao Hybrid	2.0	351,000	45	8	3	40.0	69,606	20.1	9.8%
Huaneng M.G. Hybrid	2.0	351,000	45	8	3	40.0	75,539	21.8	11.1%
Huadian Turpan Hybrid	2.0	265,200	34	8	3.5	30.0	42,416	16.3	7.9%
Xinjiang G. Hybrid	2.0	265,200	34	8	3.5	30.0	50,764	19.5	8.3%

TABLE 2: Hybrid Solar Plant Configurations

Case Name	Solar Multiple (SM)	Solar field area (m^2)	# Loops	# SCAs/ loop	Storage Hours	Equiv. Turbine Size (MW)	Annual Energy - Net (MWhe)	Capacity Factor
Zhangjiakou Greenfield	3.6	1,037,400	133	8	12	65.0	237,734	41.9
Shanxi Yuguang Greenfield	3.6	1,037,400	133	8	12	65.0	208,381	36.7
Tongliao Greenfield	3.6	631,800	81	8	12	40.0	135,600	39.1
Huaneng M.G. Greenfield	3.6	631,800	81	8	12	40.0	144,253	41.6
Huadian Turpan Greenfield	3.6	475,800	61	8	12	30.0	83,967	31.6
Xinjiang G. Greenfield	3.6	475,800	61	8	12	30.0	99,655	38.3

TABLE 3: Greenfield Solar Plant Configurations

Plant Cost Assumptions

The cost models used for both the hybrid and greenfield plants are based on previous cost studies performed by NREL for the US market (8) (9). These costs were reduced by 25% to account for the lower costs of local material and labor in China. Some financial values were adjusted based on China's lending rates and renewable tax incentive. A fixed PPA price of 17₵/ kWh was used, which is the current feed-in tariff rate for CSP projects (10). For the Hybrid plants, additional cost reductions were taken to account for the existing power block, balance of plant equipment, substation and transmission connection. Additionally, the hybrid plant is able to leverage the existing Operations & Maintenance (11) and reduced construction schedule, which represent further reductions. Other than the renewable tax incentive, no credits were included in the cost and financial model for displaced coal, carbon credits, or other incentives. For the hybrid plants, the electric generation from the coal portion of the plant was not considered in the cost calculations.

RESULTS & CONCLUSION

Each of the hybrid and greenfield plant configurations were analyzed with these cost and financial assumptions and the results recorded. Table 2 presents the annual electric production of each plant in addition to the reduction in LCOE from the greenfield plant to the hybrid plant, whereas Table 3 presents the annual electric production for the greenfield plants. In both cases, the annual electricity production presented only represents the solar contribution. The LCOE reduction varies from 7.9% to 11.1% demonstrating that hybridization of an existing coal plant is a cost-effective solution compared to a greenfield plant. Fig. 4 presents the correlation of the LCOE reduction to the average daily DNI and includes data from a previous study (11) in a region with higher average solar radiation. This figure demonstrates that the LCOE reduction for hybridization increases with an increase in average daily DNI.

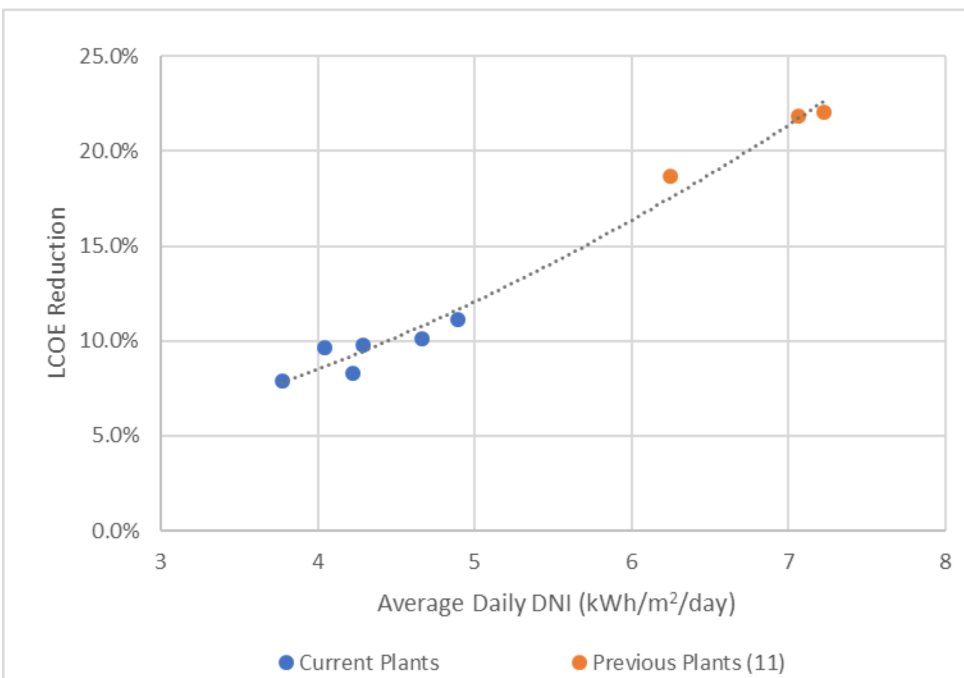

FIGURE 4: Comparison of LCOE Reduction to Average Daily DNI

The current market size for CSP hybridization with coal power plants in China is approaching 16 GW, and cost savings is clearly demonstrated over greenfield plant scenarios, even at lower DNI values. An economic incentive exists for plant owners to increase capacity factors on their existing equipment, and the government of China is driving the country toward increased renewable energy generation. CSP parabolic trough technology utilizing molten salt as a heat transfer fluid has been successfully demonstrated, allowing for direct compatibility with steam conditions at the turbine inlet at coal-based generation facilities. These factors lead the authors to conclude that hybridizing existing coal facilities in China with CSP trough technology should be immediately pursued by CSP technology providers, power plant owners, and government entities, and represents a shorter path to achieving economic sustainability of the solar thermal industry in China than greenfield plants alone.

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