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THE ECONOMIC POTENTIAL AND TECHNICAL FEASIBILITY OF HYBRIDIZING COAL POWER PLANTS WITH MOLTEN SALT PARABOLIC TROUGHS

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ABSTRACT

When a coal-fired power plant is considered for closure, arguments are commonly made about the loss of jobs and unrealized investments. Facing this pressure, governments are reluctant to enact enforceable emission standards, and these plants continue to emit pollutants into the atmosphere. As the equipment ages, the plants may retire, but in their lifetime they will cause irreversible environmental damage. This report presents a method to mediate this damage, create jobs, maintain the efficiency of the turbine, and maintain or increase the capacity factor of the plant.

Solar parabolic troughs using molten salt technology are scalable and can meet the steam conditions of a standard Rankine cycle coal-fired power plant. A marriage of these technologies allows the parabolic trough field to be installed without new power generation equipment. The turbine, generator, and transmission equipment are already in place, and when compared to a standalone concentrated solar power (CSP) plant, can be amortized over a greater number of operational hours without the use of very large amounts of thermal storage. That allows for a reduction in capital investment compared to a greenfield CSP plant, and reduces the levelized cost of energy (LCOE) from the solar contribution to well below current US Department of Energy SunShot targets.

Coal-fired plant operators note that they typically cannot operate at partial power output without reducing the efficiency of their turbine accordingly. So, while a photovoltaic hybridization can take advantage of existing transmission infrastructure, it will require that the coal-fired system reduces its output and will consequently reduce the efficiency of the coal cycle. If we have to burn coal, we should do it in the most efficient way possible. Hybridizing with a molten salt parabolic trough installation makes use of the same turbine as the coal-fired system, which maintains the overall efficiency of the turbine at its design point and optimal load. With this model, the coal plant can operate at full power, reduce overall usage of coal while maintaining or even increasing employment opportunities, and reduce CO2 emissions.

INTRODUCTION

This paper examines the cost reduction potential of utilizing parabolic troughs as a hybrid heat source for existing coal-fired power plants. Such a model is feasible with technology that is commercially available today, such as SkyFuel's SkyTrough® using molten salt as the heat transfer fluid. By hybridizing the parabolic trough plant with an existing power generation system, many of the capital costs can be eliminated when compared to a standalone, "greenfield" parabolic trough power plant. Components of the power block are already installed and are amortized over near-continuous operation, a smaller 2-tank molten salt storage system can be used, permitting is substantially complete, and transmission infrastructure is in place.

The study documented herein examines a comparison of these two systems in both the United States and China, and found a potential for reduction in LCOE of up to 22% compared to a greenfield CSP installation. With today's technology and favorable solar conditions, parabolic troughs can be economically hybridized into exiting power plants. At least 70 coal-fired power plants in the United States can be considered for immediate hybridization, and the market in China is immense due to declining capacity factors for coal-fired plants. Between these two countries, the potential for parabolic trough hybridization is on the scale of many gigawatts, and can have a measurable impact on global greenhouse gas emissions. While the technology is available for this hybridization today, support for demonstration sites is lacking. And because the installed base of coal-fired power plants is ageing, it is important to hybridize them today, while the owners can still reap financial returns and take the most advantage of their parabolic trough system.

NOMENCLATURE

BOP	Balance of Plant
CSP	Concentrating Solar Power
DNI	Direct Normal Irradiance
EIA	Energy Information Administration
EPA	Environmental Protection Agency
GHG	Greenhouse Gas
HTF	Heat Transfer Fluid

IRR	Internal Rate of Return
ITC	Investment Tax Credit
LCOE	Levelized Cost of Energy
NREL	National Renewable Energy Laboratory
O&M	Operations & Maintenance
PPA	Power Purchase Agreement
SAM	System Advisor Model
SCA	Solar Collector Assembly
SGS	Steam Generation System
TMY	Typical Meteorological Year

COAL FIRED POWER PLANTS TODAY

Sunk Cost, Employment, and Existing Capacity

Existing coal-fired power plants represent a large and long term investment in many parts of the world, accounting for 41 percent of global electricity generation in 2014 [1]. In the US, a new coal plant construction would cost $3,250 per kW of capacity, or about $1.6 billion for a 500MW facility [2]. Existing plants in the US employ about 90 people in a 500MW facility [3]. These factors lead to labor- and cost-intensive efforts to keep existing facilities operating, even in the face of increasing governmental regulation. For example, between 2010 and 2015, coal plants in the US spent $33 billion on the installation of emission control systems [4]. Coal-fired generation currently accounts for 33% of utility scale power in the US [5] and represented 63% of the electric capacity in China in 2013 [6].

Capacity Factor

Aside from the nameplate capacity of existing coal-fired generation, it is important to consider the effective capacity factor of these plants, defined as the fraction of actual generated electricity to the maximum possible generated electricity in the same timeframe. For coal plants, the maximum rate is usually assumed to be 24-hour generation at full generator capacity.

In the US, the average capacity factor of coal plants fell from 67% in 2005 to 55% in 2015, primarily due to low natural gas fuel prices driving the use of that technology as a first-service for electric demand [7].

In China, the capacity factor of coal-fired capacity fell from 60.4% in 2011 to 49.4% in 2015, but was driven primarily by the continued construction of new coal-fired capacity (84GW in 2015) despite of an overall declining use of coal to meet electricity demand [1] . Analysis indicates that the transfer of authority for coal power plant permit approvals from the National Government to Regional Governments has driven this trend, explaining why there is a discrepancy between new plant construction and overall reduced electricity use [8].

The trend of reduced utilization of coal-fired power is reflected in other parts of the world as well, as shown in Figure 1 [1]. Under good solar conditions, the under-utilization of these existing plants represents an opportunity for hybridization with solar thermal technology, increasing capacity factors without increasing coal use.

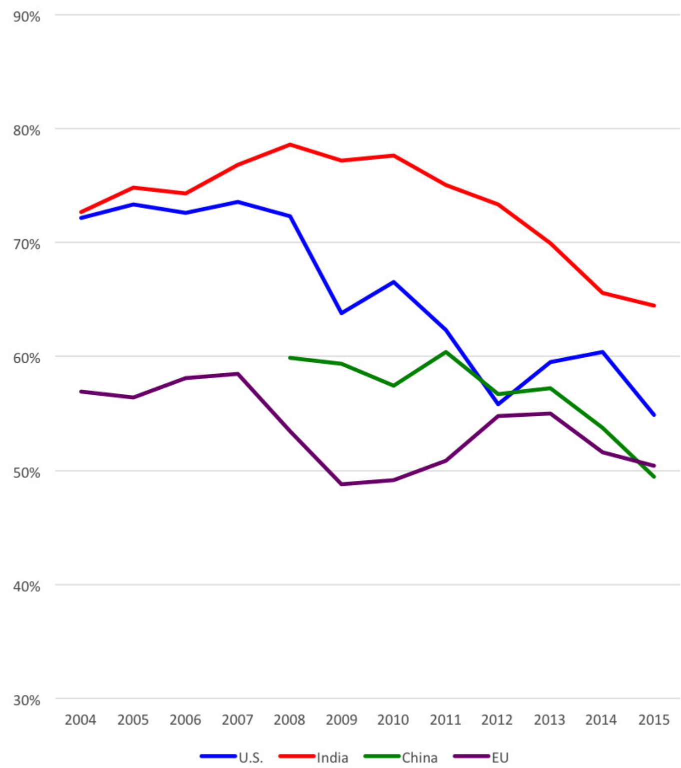

Figure 1: Coal Power Plant Capacity Factor in the U.S., India, China, and E.U.

New Installations, Cancellations, and Closures

In the US, from 2003 to 2015 there were 23GW of coal-fired capacity installed, but 54GW retired [1]. According to the US Energy Information Administration, 83% of existing coal plants in the US are 30 years old or older and there are only 6 proposed coal generators in the pipeline [9]. The trend of slow to no coal plant construction and retirement of older plants is expected to continue, with the Annual Energy Outlook 2015 predicting 40GW of total coal retirements between 2013 and 2040 [10].

In China, 297GW of coal-fired capacity was installed between 2010 and 2015, while a proposed 164GW was cancelled [1]. It is likely that the Central Government of China will continue to push cancellations and closures of coal plants, but the scale of coal projects in the pipeline (approximately 246GW) makes it likely that many new plants will still be constructed.

Environmental Considerations

Coal-fired electricity generation and its related industry is still the single largest contributor to GHG emissions, accounting for 44% of emissions worldwide [11]. Environmental Protection Agency regulations in the electricity generation sector have focused heavily on coal, including a conclusion that all new units built in the US should use Carbon Capture and Storage technology as best practice for emission reduction [12]. Coal also has the highest contribution of CO_2 per kWh of energy generated of common fossil fuels, at approximately 2.1 lbs. per kWh as compared to 1.2 lbs. per kWh for natural gas and 1.6 lbs. per kWh for fuel oil [13].

PARABOLIC TROUGH HYBRIDIZATION TECHNOLOGY

The market and technical conditions of the coal-fired electricity generation industry today provide an opportunity for a solution that combines the economic needs of plant owners and operators with global environmental needs - hybridization with CSP parabolic trough technology.

CSP Trough Overview

A parabolic trough is a line-focus solar concentrator technology that coverts sunlight into thermal energy. The thermal energy is converted via a heat transfer fluid (HTF) that subsequently generates steam. This steam may be used in a process application, or may power a standard Rankine cycle power block. Current, commercially-available parabolic troughs can be highly efficient, scalable, low cost, and easy to assemble in both small and large installations [14]. This report uses SkyFuel's SkyTrough product as an example of the current state-of-the-art, due to its myriad hybrid installations, demonstrated high-temperature operation, and scalability.

Molten Salt Heat Transfer Fluid

Parabolic troughs are versatile and can use many HTFs, typically determined by the required process temperature. Applications vary from low-grade residential heating to power generation at a temperature of about 585°C. Above that limit, radiative heat loss from the receiver overwhelms thermal production, and the system's efficiency suffers significantly [15]. However, collectors such as the SkyTrough have been demonstrated with molten salt HTF and can provide reliable steam at temperatures matching traditional coal-Rankine cycle superheated steam (~550°C) [16].

Reaching this temperature is important for coal augmentation. Figure 2 depicts a typical arrangement for hybridization at the main steam header using molten salt as the solar HTF. Figure 3 presents a hybrid arrangement using a lower-temperature oil-based HTF with a maximum operating temperature of 400°C. Hybridization at 400°C implements the parabolic trough system as a preheater, which increases the necessary components and limits the amount of solar heat that can be added to the system.

While a typical coal-fired boiler can be turned down at least 10% without a significant drop in efficiency and up to 30% with an acceptable drop in efficiency [17], the economizer can only be hybridized to a plant capacity of about 4% [18]. Thus, steam injection into the main header provides the potential for an order of magnitude greater addition of solar heat. The potential for significant reduction in coal emissions via hybridization with CSP is contingent upon the ability of the solar block to inject steam into the main header at existing process conditions (>500°C), and that is contingent upon the parabolic trough's capacity to use molten salt as the HTF.

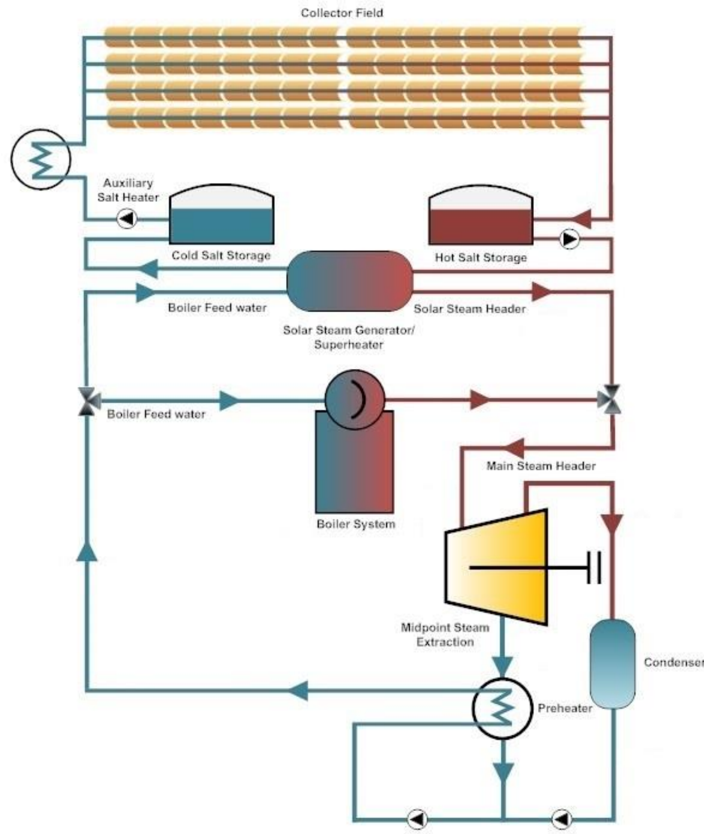

Figure 2: Hybridization using a Molten Salt HTF

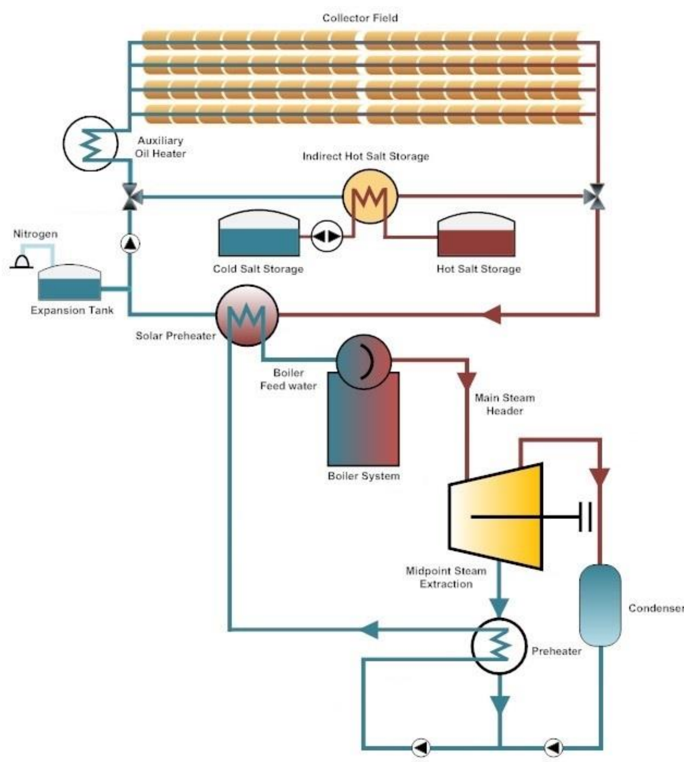

Figure 3: Hybridization using an oil-based HTF

However, molten salt HTF brings several challenges. Blends that can reach the temperature required for hybridization typically freeze at or above 200°C [15] requiring innovative methods for freeze protection and freeze recovery. Nitrate salts are corrosive oxidizers, and they radiate more heat during standby periods than lower-temperature HTFs. While these are challenges, they can be addressed with proper research and development. These factors highlight the importance of fielding demonstrated equipment when hybridizing coal power plants.

Steam Generation and Thermal Storage

Aside from the challenges presented above, hybridizing power sources of any two types is challenging, especially when one source relies on a variable resource (i.e., the sun). When hybridizing power sources, the steam generation must be ramped down from the prime source and up from the secondary source at equivalent rates, and vice versa. In the case of molten salt trough hybridization, the solar generation is decoupled from the power generation through the use of thermal storage. As a result, transient effects such as intermittent cloud cover can be accommodated during operation, such that the turbine supply is maintained at a fairly consistent flow rate. In the case of a molten salt steam generator, care must be taken to prevent the system from freezing. Options to achieve this include draining the system after shutdown, circulation of salt or hot feedwater during non-operating hours, or use of freeze protection methods such as heat race and impedance heating. Independent of the freeze protection method chosen, the temperature of the SGS must be ramped to its operational temperature during morning start-up. During this ramp period, steam is rejected until conditions match those of the existing steam line.

To maintain a consistent and predictable rate of steam generation from the solar block, a minimal amount of storage is required (2-3 hours). This storage acts as a thermal mass to inhibit freezing in the system, level any transients, and provide sufficient thermal energy for startup and shutdown.

One of the key benefits of the hybrid system compared to a greenfield CSP plant, however, is the ability to maintain energy output throughout the evening *without* very large amounts of storage (typically 8 hours or greater in a greenfield plant). The power block and transmission infrastructure have a high capacity factor and are amortized over many hours of operation via the use of coal-based steam. Storage is only used to ensure stable operation of the solar field, and can be minimized in size compared to a greenfield rival. Thus, capital expense is minimized, and the solar addition maintains an even lower cost of generation.

ADVANTAGES OF HYBRIDIZATION

Utilization of Existing Infrastructure

The primary benefit of hybridizing CSP troughs with existing coal-fired generators is the increased utilization of previously installed equipment. The costs of the feed water system, steam turbine, transmission equipment, carbon abatement, and interconnect with the grid are large investments that can be considered sunk costs in the hybrid scenario. In addition, the cost of the solar field, solar steam generation system, and associated mechanical and electrical equipment is not significantly different between the hybrid and greenfield solar plant scenarios.

There are multiple benefits of utilizing existing plant infrastructure as well. A hybrid plant would take advantage of existing permitting to operate on the national grid, reducing the permitting requirements compared to a greenfield scenario. The plant O&M, employees, and other management considerations are established and functional.

Importantly, the hybrid scenario requires the plant to continue to operate primarily as a coal-fired generation source. If environmental regulations or excessively low capacity factors make this option uneconomical, the addition of solar would not be possible.

Age, Capacity, Land Use, and Operating Conditions

When considering a coal plant for hybridization, several key factors must be taken into account. First, the operating conditions of the plant must match with the temperature range of molten salt trough technology. The plant must also be young enough that the solar system capital cost can be amortized over a long enough period to maximize the return on investment (approximately 25 years). As many coal plants in the US operate longer than their original planned lifetimes (15GW of coal capacity in the US is 60 years old or older) [9] plants currently 35 years old or younger were determined to be sufficiently new for this study. The boiler size must be large enough so that turndown rates used for the solar contribution are between 10% and 30%, but small enough that the solar addition still makes an appreciable contribution to capacity factors. There must be available land for the construction of the solar field, and the solar conditions at the site must be of sufficient quality to keep the solar field to a reasonable size.

When considering an actual plant for hybridization, there are regulatory, economic, and social considerations as well. Primarily, the solar portion of the plant extends the total operating time of the coal fired source without increasing coal fuel use, in effect increasing the capacity factor of the resource. If the plant is already operating near 100% utilization, or excessively low utilization, the solar addition would not be able to operate often enough to provide an economic benefit. While operation of the solar hybrid portion of the plant would reduce the pollution emitted per watt generated, if a plant cannot operate under current environmental regulations, the solar addition would not prevent the plant's shutdown.

Using the US Energy Information Administration's 2015 EIA-860 form report and filtering by coal generation, 300-600MWe generator size, and built in 1980 or later, there are currently 73 plants in the US that fit these selection criteria [9]. In China, there are 6.6GW of recent completed coal plants in the solar-rich Gansu province alone [1]. With much of the construction moved to rural areas of China to curb emissions and smog concerns in large cities and the capacity factor of coal plants falling below 50%, China has a very large potential for hybridization. Northern Gansu is one of the provinces that was identified as a candidate area based on the volume of coal plants, high solar radiation, and existing transmission infrastructure. Additional provinces that should be considered include Inner Mongolia, Xinjiang and Qinghai.

Power Purchase Agreements

Power Purchase Agreements, the agreed price per delivered kWh of electricity between the plant owners and energy buyers, for solar thermal power plants are typically higher than for conventional power generation. Two recent CSP installations in the US, Solana and Ivanpah, yielded PPA rates of 14 and 18 cents/kWh, respectively [19], higher than the US average electricity price of 10.4 cents/kWh [20]. In a hybrid scenario, the energy delivered by the solar system could be tracked and paid for at this higher rate, both increasing plant economic return and incentivizing maximum use of the solar portion of the system. From a technical perspective, the energy delivered is traceable through the combination of measurement of thermal output of the solar steam generation system via inlet and outlet temperatures and flow rates, and the continuous turbine efficiency measurement, commonly taken in existing power plants.

From a permitting and legal perspective, challenges include agreement on the solar portion PPA price, ability to ensure accuracy of reported solar contribution, and willingness from utilities and buyers to invest in the extra work required to track these values. In the US, these agreements are done on a case-by-case basis and would require negotiation to determine project feasibility. In China, the government recently announced a feed-in-tariff for solar thermal projects under their demonstration program of approximately $0.17/kWh [21]. This could be used as a baseline for hybrid plants constructed in China. In both countries, however, government guidance on hybrid power purchase agreements is lacking, and must be addressed to streamline the installation of these plants at a large scale.

COST & PERFORMANCE MODELING

Methodology and Inputs

Hybridizing a coal plant is technically feasible and beneficial environmentally, but in order to investigate the economics of a hybrid plant, an analysis was performed to evaluate the following characteristics:

- Size of hybrid and greenfield plants;
- Cost reductions available to the plants;
- Overall LCOE; and
- Evaluation of the normalized LCOE between hybrid and greenfield plants.

The costs presented in this analysis do not include the savings associated with the coal displaced, carbon credits, and other incentives. This analysis will show that the hybrid plants are feasible in both the US and Chinese markets and are more economical compared to greenfield plants. For the US market, the impact of the changing Investment Tax Credit (ITC) was also evaluated on the feasibility of the hybrid plants.

In order to determine the size of the hybrid plant to use a basis for the cost and performance analysis, a few representative coal plant cases were selected. As previously explained, the case selection criteria used in selecting the representative plants is based on existing coal plants that are:

- in operation and not scheduled for decommissioning;
- built after 1980;
- 300MWe to 600MWe in turbine size;
- solar resource of Direct Normal Irradiance (DNI) above 6.0 kWh/m2/day; and
- have usable land adjacent that would be suitable for the addition of the solar field, 2-tank thermal storage and steam generator system.

Note that these criteria are representative only, and were used to identify sample sites. The actual number of plants available for hybridization may include many more, based on site-specific economic analyses.

Table 1 presents some of the characteristics of the three coal plants selected for this case study. This table also includes data from NREL's NSRDB Viewer [22] for the US coal plants with respect to their rating for solar-augmentation potential and maximum trough plant size based on estimated available area. Figure 4 presents a comparison of the mean monthly DNI for the three case sites based on the Typical Meteorological Year (TMY) weather files that were used for the analysis. All three sites have a similar annual DNI profile and also reflect seasonal changes.

Table 1: Case Study Coal Plant Characteristics

	Cholla	Tolk	Jiuquan
Location	Joseph City, AZ	Muleshoe, TX	Gansu, China
Turbine Size (MW)	414	535	300
Year Built	1981	1985	2011
Average DNI (kWh/m2/day)	7.23	7.06	6.25
NREL Solar-Augment Potential	Excellent	Good	(1)
NREL Max. Estimated Trough Capacity (MWe)	54	84.4	(1)

Notes:
(1) Not included in the NREL NSRDB Data Viewer. Data limited to continental US locations only.

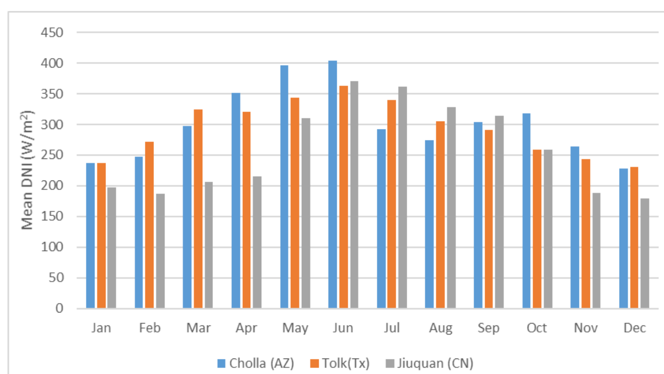

Figure 4: Comparison of Monthly Mean DNI for Case Study Locations

Based on the existing coal plant turbine sizes and maintaining about a 10% turndown of the existing boiler, a nameplate rating of 40MWe was chosen for sizing the hybrid solar plants. The same size was also used for the greenfield plants for cost and production comparison purposes. As a result, the only parameters that were varied for the greenfield plants were solar multiple, hours of thermal storage and cost differences (discussed subsequently). In both the hybrid and greenfield cases, a molten salt parabolic trough with storage was selected.

The cost and performance analysis was performed using NREL's System Advisor Model (SAM)[23] using the CSP physical trough model with a PPA (single owner) financial model. SkyFuel's SkyTrough was selected from SAM's default library as well as the PTR-70 receiver. Since molten salt is being used as the solar field HTF, the properties of the receiver were modified to account for the higher temperature coatings. These parameters included the absorptance, emittance and heat loss values. For the SkyTrough, the incidence angle modifier coefficients were modified to reflect the 70mm receiver. Some of the other SAM parameters that were modified were the temperatures, cycle efficiency, and pressure; each to be consistent with a molten salt plant configuration.

From a parametric analysis, a hybrid configuration was selected using a solar multiple of 1.6 and 3 hours of storage. This yields a solar field configuration of 64 loops with 6 SCAs per loop. A larger field size was selected for the greenfield plants because greater thermal storage is desired for utility-scale solar power plants in order to maximize the annual hours of operation. Using parametric analysis, a greenfield configuration was selected using a solar multiple of 2.2 and 8 hours of storage in order to increase the capacity factor and minimize the LCOE. This yields a solar field configuration of 88 loops with 6 SCAs per loop.

Most of the current SAM cost defaults are based on previous cost studies performed by NREL and indexed for inflation [24]. The solar field costs were updated based on a recent cost study performed by NREL [25] and with SkyFuel's most up-to-date cost estimates for the SkyTrough technology. The SAM cost model was selected as a conservative and common basis for the cost analysis presented.

For the cost analysis, SAM default costs were used except as follows:

- The Storage costs were reduced by 60% based on the molten salt being shared between the Storage system and the HTF system; therefore, the cost would be closer to the cost estimate used for a Molten Salt Power Tower [25].
- For the hybrid case, the Power plant costs were reduced from \$1150/kWe to \$390/kWe to reflect that most of the costs associated with the Power plant are in existing equipment and only the steam generator system with associated piping and valves would be added. This was based on the costs for a Molten Salt Power Tower Power plant [25]. A detailed look at this reduction is provided in Annex A.
- In addition to reducing the power block cost, the balance of plant cost was removed for the hybrid cases. The basis for this is that this is part of the existing infrastructure from the coal plant. This reduction is presented in detail in Annex A.
- For the hybrid case, the fixed O&M costs were reduced by 30% to reflect the O&M costs associated with the addition of the solar field and equipment but not include O&M for existing equipment. This value is in addition to the existing plant O&M budget.
- For the China cases, costs were lowered by 25% to reflect the cost savings for the use of a local supply chain and lower labor costs.

The following sections will discuss the results of the cost and performance models that were generated for each of the three representative locations. Comparisons will also be made between the hybrid and greenfield plant configurations.

Case: United States

The plants that were selected in the United States for this study are Cholla Power Station in Joseph City, AZ and Tolk Power Station in Muleshoe, TX. The following results show the expected electrical generation and associated LCOE value of the solar portion of the plant. For this study and for comparison purposes, the LCOE of the hybrid and greenfield plant configurations were normalized using the LCOE of the Tolk greenfield plant and shown as a percentage. In addition to determining economic feasibility, the impact of varying ITC rates was also investigated based on the current legislation [26]. The analysis shows that there is a rising cost associated with ITC reductions, and there is a 21.9% LCOE reduction for the hybrid plant over a greenfield plant when the ITC is in place.

Table 2 presents a comparison of the plant configurations, energy production, and normalized LCOE percentage. The greenfield plant uses a different configuration in order to decrease the LCOE. The normalized LCOE for these cases was done using a 30% ITC.

Table 2: US Solar Plant Comparison

	Solar Multiple (SM)	Solar field area (m^2)	# Loops	# SCAs/ loop	Storage Hours	Annual Energy - Net (MWhe)	Normalized LCOE
USA Tolk Hybrid	1.6	251904	64	6	3	108707	78%
USA Cholla Hybrid	1.6	251904	64	6	3	112650	76%
USA Tolk Greenfield	2.2	346368	88	6	8	152673	100%
USA Cholla Greenfield	2.2	346368	88	6	8	157830	97%

Figure 5 presents the after-tax IRR of the four plants. The IRR was calculated for each case using a fixed PPA of 14₵/kWh, a 25-year analysis period and a 30% ITC. As a result, the hybrid plants yield IRRs of 26-32%, while greenfield plants range from 16-21%. Of the cases studied and with the financial inputs chosen, the Cholla hybrid plant presented the lowest LCOE and highest IRR.

Figure 5: Summary of After-Tax IRR for US Cases

In the US, the ITC rates are scheduled to drop over the next 10 years. Although the current schedule does not include the removal of the ITC completely for utility-scale solar, that case has been included nonetheless. Figure 6 presents the reduction of the ITC on the LCOE of greenfield and hybrid power plants. The same solar field configurations, shown in Table 2, were maintained for the hybrid and greenfield cases and the LCOE was normalized using the LCOE of the Tolk greenfield plant with an ITC of 0%. Figure 6 presents a comparative reduction in LCOE of the hybrid plant in the range of 22% with respect to the greenfield plant, regardless of ITC.

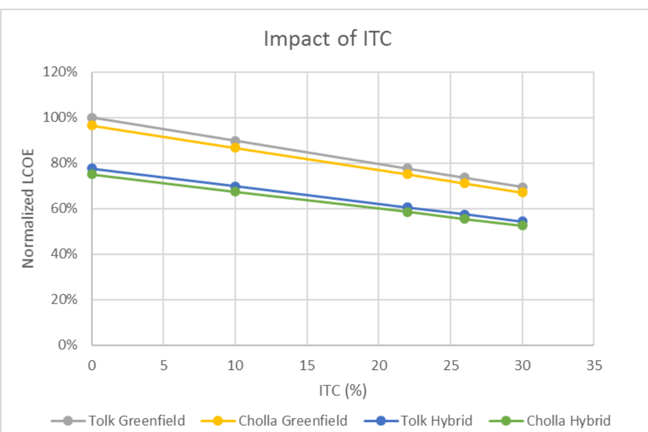

Figure 6: Impact of ITC

Cost reduction trends in parabolic trough installations counteract the ITC reduction, and provide for economically feasible installations in the future as well. As a result, the relative cost savings of a hybrid plant over a greenfield plant using parabolic trough technology is anticipated to continue.

Case: China

The plant selected for study in China is the Guodian Jiuquan Power station in the Gansu Province. In addition to the case selection criteria, this choice was based on transmission availability. For this study and comparison purposes, the LCOE of the hybrid plant was normalized using the LCOE of the of the greenfield plant. This results present a hybrid plant with a 19% reduction in LCOE compared a greenfield plant.

Table 3 presents a comparison of the plant configurations, their energy production, and their normalized LCOE values. The hybrid plant configuration is identical to that which was used for the US cases. The greenfield plant implemented an optimized configuration in order to increase the capacity factor and minimize the LCOE. This greenfield plant optimized with increased storage compared to the US greenfield cases due to the lower DNI.

Table 3: China Solar Plant Comparison

	Solar Multiple (SM)	Solar field area (m^2)	# Loops	# SCAs/ loop	Storage Hours	Annual Energy - Net (MWhe)	Normalized LCOE
Hybrid	1.6	251904	64	6	3	84847.6	81%
Greenfield	2.5	393600	100	6	12	139763.9	100%

Figure 7 presents the after-tax IRR of the two plants. The IRR for each case was calculated using a fixed PPA of 17¢/kWh (equivalent to China's current feed-in tariff rate), and a 25-year analysis period. The hybrid plant yielded an IRR of 20%, while the greenfield plant returned 12%. Again, the hybrid plant presented the lower LCOE and higher IRR.

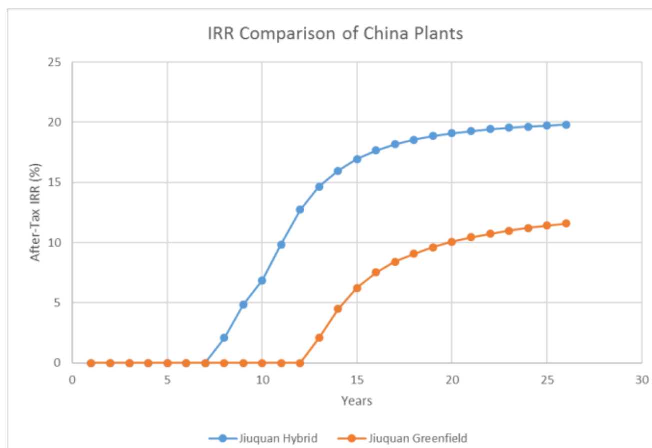

Figure 7: Summary of After-tax IRR for China Cases

CONCLUSION

Coal-fired power plants are the primary source of electricity generation worldwide. The sunk capital cost, existing infrastructure, and existing jobs at these plants have driven owners to make significant investments in keeping the plants operational. As coal is the primary contributor to global GHG emissions and is less able to meet environmental regulations than other fossil fuel sources, the continued use of these plants under normal operating conditions represents a challenge for meeting global climate goals.

In the US, coal power plant use in the national energy mix is declining, plants are aging, and the low cost of natural gas is driving the industry away from coal as a first choice to meet demand. However, even with the declining installation of coal-fired power plants, the existing installed capacity and expected lifetime contribute significantly to global GHG emissions. In China, a disconnect between coal power plant permit approvals and actual electricity demand in the country is also driving down capacity factors.

CSP technology utilizing parabolic troughs and a molten salt HTF provide the ability to generate steam at operating conditions equal to that of many common coal-fired plants. In this configuration, the steam is injected into the main steam header, as opposed to providing feed water heating only, and allows for hybridization up to 30% of the nameplate capacity of the existing plant. As a result, molten salt hybridization allows for greater CSP grid penetration than oil-based technology.

The key benefit of hybridization is realized in the increased utilization of existing coal plant capital equipment, transmission infrastructure, and existing permitting. It represents a significant investment reduction compared to greenfield CSP plants, and the increased electricity generated is renewable. The types of coal plants considered for hybridization must meet specific requirements, such as turbine capacity, age, existing environmental controls, operating conditions, current capacity factors, and land availability. The US market potential for hybridization includes at least 70 coal plants ideal for hybridization. The Chinese market is much larger, as coal power plants are still being built in GW scale in spite of significant governmental regulations on emissions and a steady rise in national electricity demand. The economic potential of these plants is increased by the opportunity to receive increased revenues for renewable energy realized through hybrid PPAs.

Hybridization of coal-fired power plants is a lower cost investment than a comparative greenfield CSP plant. Through the use of SAM and a conservative cost model, representative hybrid CSP plants showed LCOE reductions of up to 22% when compared to optimized greenfield solar plants.

There is a huge worldwide potential for hybridization of existing coal and CSP parabolic trough technologies, on the scale of gigawatts. At least 70 coal-fired power plants in the United States should be considered, and the social, economic, governmental, and environmental factors involved all support a successful execution of this type of project. The technology required exists today. Demonstration-scale plants should be initiated immediately, taking advantage of the 20% cost savings over greenfield alternatives, and utilizing existing facilities before they age any further.

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ANNEX A

POWER BLOCK COST COMPARISON

As previously mentioned, the SAM default costs for the hybrid power block and balance of plant were reduced on the basis that this equipment already exists from the coal plant. As part of developing the SAM parabolic trough cost model [24], an interactive spreadsheet was created for users to look at detailed costs used to generate the cost metrics. The NREL spreadsheet combines the power block and balance of plant costs in this model. As a result, the default metrics are $1150/kWe and $120/kWe, respectively. Below is the section for power block and balance of plant reflecting representative costs for a 40MWe power block.

Item	Sample Greenfield Cost	Sample Hybid Cost
Steam Turbine Generator Island	$ 16,470,297	$ -
Solar Steam Generator Equipment	$ 3,667,571	$ 3,667,571
Cooling Systems	$ 2,559,685	$ -
Condensate System	$ 527,375	$ -
Feedwater System	$ 2,229,897	$ 445,979
Auxiliary Cooling Water System	$ 716,737	$ -
Steam Piping, Insulation, Valves, & Fittings	$ 2,346,655	$ 703,997
Fuel Gas Handling & Metering System	$ 192,317	$ -
Water Treatment System	$ 1,250,897	$ 250,179
Power Distribution Systems	$ 7,193,189	$ 1,438,638
Back-up Power Systems	$ 216,357	$ 64,907
Instrumentation & Controls System	$ 2,062,623	$ 1,031,312
Fire Protection System	$ 1,738,866	$ 869,433
Foundations & Support Structures	$ 2,824,655	$ 1,045,122
Buildings	$ 1,415,667	$ 707,833
BOP Mechanical Systems	$ 2,529,745	$ 2,529,745
BOP Electrical Systems	$ 2,847,359	$ 2,847,359
	$ 50,789,892	**$ 15,602,076**
Cost per kWe	$ 1,270	$ 390

The sample greenfield plant reflects the complete cost since it represents construction of a new solar power plant. The sample hybrid costs reflect the cost or cost reductions related to adding a solar power plant to an existing coal power plant. Due to the existing systems from the coal power plant, the costs for the steam turbine generator, condensate system, cooling systems, and fuel handling & metering systems were removed. Since the majority of the change to the coal power block is the addition of the solar steam generator, the remaining costs were maintained or reduced to reflect integration to the existing system. There are some costs that remain that are associated with the addition of the solar field. These include the following:

- The water treatment system will need to be modified to account for the additional water and quality needed to cleaning the solar field.
- The power distribution system will need to be modified to account for the power needs in the solar field as well as the additional instrumentation and controls.
- The fire protection system will need to be modified to account for the solar field power and controls.
- The full BOP mechanical and electrical costs were maintained to cover the integration of the SGS and solar field into the existing systems.

This reflects a conservative approach to the cost reductions in the power block and balance of plant that were implemented in the cost analysis.