Solar Energy and Thermal Storage for CO_2 Emissions Reductions for Coal Power

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Abstract: This study evaluates the size and cost of a solar aided feedwater heating (SAFWH) system necessary to reduce the emissions of a new coal-fired power plant to 1,400 pounds of carbon dioxide per megawatt-hour of gross electricity (1,400 lb CO_2/MWh_g) produced by the plant. An Aspen Plus Model was used to determine the efficiency improvements which could be achieved through SAFWH and these results were used to size parabolic trough Concentrating Solar Power (CSP) Systems for three different steam conditions ranging from supercritical to advanced, ultra-supercritical. Thermal energy storage was included in the system to ensure 20–24 hours of the operation per day. Two geographic locations were evaluated in order to evaluate the effects of high and low solar resources. The combined costs of the solar field and the thermal storage system ranged from $30 to $70 million for a next-generation, advanced ultra-supercritical plant to between $119 and $276 million for a supercritical plant. The ranges in costs reflect a difference in solar resource quality at the two locations. More broadly, the results illustrate how increased power plant efficiency can dramatically reduce the size and cost of an SAFWH system required to meet an emissions limit of 1,400 lb CO_2/MWh_g.

Keywords: Coal, solar, CSP, thermal storage, molten salt, parabolic trough, feedwater heating, CO_2 emissions, supercritical, ultra-supercritical

1 Introduction

The Environmental Protection Agency (EPA) regulates greenhouse gas (GHG) emissions from electricity generating units (EGUs) of a certain size under the clean air act (CAA). Newly constructed power plants are regulated under section 111(a)

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of the CAA and in October of 2015, the EPA promulgated a rule which set the emissions standard for newly constructed or modified coal-fired EGUs at 1,400 pounds of carbon dioxide per megawatt-hour on a gross-output basis (lb CO_2/MWh_g) [1]. This standard is based on new coal-fired EGUs implementing some level of carbon capture and storage (CCS) as the "best system of emission reduction" (BSER) [2]. While this rule is currently under legal challenge, it remains the current emissions standard [3, 4].

While the EPA has defined CCS as the current BSER for coal-fired EGUs, it remains that CCS may not be realistic for some subsets of geographical locations in the continental United States (U.S.). The reasons for this vary from geology or other conditions which make the location unsuitable for the storage of CO_2 to the lack of proximity to infrastructure which could transport the CO_2 to a location where it could be properly sequestered or utilized. This paper investigates scenarios in which a newly constructed coal-fired EGU could meet the current CO_2 emissions limit through a combination of high efficiency operation and the integration of renewable energy in the form of solar thermal energy. In the scenario investigated, parabolic trough solar panels provide renewable thermal energy that displaces steam produced from coal which is being used to heat feedwater being sent to the boiler in a pulverized coal (PC) power plant. Displacing the use of this steam increases the efficiency of the unit.

The concept of solar aided feedwater heating (SAFWH) systems to integrate solar thermal power into fossil-energy generating units is not a new concept. It has been demonstrated at one coal-fired EGU in Colorado (prior to the retirement of that unit), was explored at length in the literature, and offered as a service by engineering, procurement, and construction (EPC) vendors [5–14]. These systems are generally designed to either (a) boost the electrical output of the EGU during the day or (b) reduce fossil fuel consumption [14]. Both of these configurations utilize the heat generated from a parabolic trough concentrating solar power (CSP) to provide thermal energy in the boiler feedwater heater (FWH) instead of using steam generated by the combustion of fossil fuels that has been extracted from the power cycle.

The approach utilized in this work is novel in that it examines the cost of deploying solar energy to meet an emissions limit for a coal EGU utilizing a thermal energy storage (TES) to allow this emissions limit to be met for the entire day (i.e. even when the sun isn't shining). The range in deployment costs in different areas of the U.S. is explored by determining the cost differential at two distinct geographic locations. Lastly, the opportunity presented by higher efficiency steam cycles to reduce costs is also explored, illustrating how improving basic power plant efficiency can reduce the cost of meeting these emissions targets with a SAFHW system.

2 Methodology

This work evaluates what amount of solar thermal energy would be required for a 550 $MW_{e\text{-}net}$ coal-fired EGU to comply with the current NSPS for CO_2 emissions.

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Three different PC plant performance levels are evaluated in order to evaluate the impact of power plant efficiency on the solar thermal energy requirements for compliance. These solar energy requirements were then used to determine an order of magnitude cost of such a solar energy system in two different geographical locations: West Virginia (WV) and a generic location in the American Southwest (SW). These locations were chosen based on the presumed interest in building new coal-fired EGUs (WV) and a location with a very good solar resource (SW).

2.1 *Coal-Fired Power Plant Performance*

The three different PC plant performance levels evaluated represent (1) the current state-of-the-art (SOA) in the United States, (2) the "cutting edge" of current coal-fired performance (based on the highest reported efficiency plant in the world (A-USC - CE)), and (3) the projected performance of a next generation, advanced ultra-supercritical (A-USC - NG) power plant. These represent the performance that can easily be achieved by a new, supercritical pulverized coal power plant (SC PC) in the U.S., the highest demonstrated performance of a new PC plant with current advanced ultra-supercritical (A-USC) technology, and the potential future performance which can be achieved in the next five to ten years with continued research and development (R&D). Table 1 summarizes the performance and basis for the performance of these three options.

2.2 *Solar Feedwater Heating Systems*

Two separate types of CSP systems were evaluated: SkyFuel's SkyTrough (ST) collector and SkyFuel's SkyTrough DSP (ST-DSP) collector [17, 18]. Both systems use parabolic trough collectors and are current commercial offerings from SkyFuel, but the ST represents a slightly more mature technology that has been deployed at multiple sites throughout the U.S. and internationally [15]. The ST-DSP is able to achieve higher temperatures through the use of molten salt – as opposed to mineral oil – as a working fluid and has lower projected costs than the current SOA.

Table 1 Coal-fired power plant performance levels.

Identifier	Heat rate (Btu/kWh-g)	Efficiency (HHV)	Technology status	Steam cycle	Basis
SC-PC - SOA	7,950	40.7%	State of the Art	Supercritical	NETL Baseline Study [23]
A-USC - CE	7,465	43.9%	Cutting Edge	A-USC	Trianel Lunen [24, 25]
A-USC - NG	7,270	45.3%	Future Deployments	A-USC	EPRI A-USC [26]

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Table 2 Parabolic trough technologies.

	SkyTrough [17]	**SkyTrough DSP [18]**
Technology Status	Commercial	Commercial
Working Fluid	Mineral Oil	Molten Salt
Maximum Outlet Temperature (F)	739	932
Thermal Efficiency	73.7%	71.0%
Rated Output at 1000 W/m^2 DNI (kWh$_{th}$)	483	692
Solar Collector Assembly (SCA) Size (m^2)	656	975
Installed Cost (\$/m^2) [27]	230	212
Largest Deployment (m^2) [21]	28,864	104

In terms of thermal performance, however, the technologies are similar, resulting in the similar collector area requirements shown in the results. Table 2 summarizes the difference between the two CSP technologies, including the size of a single Solar Collector Assembly (SCA). The cost data provided in Table 2 reflects installed costs for the CSP system, but excludes TES. These costs are explored in more detail below.

2.3 System Design

The SAFWH integrates solar thermal energy into a Rankine cycle coal-fired plant by using solar heat to preheat water used in the steam cycle. This water would normally be heated using steam that is extracted from the power cycle prior to the intermediate and low-pressure steam turbines. The use of solar heat allows this steam to be used for power generation and results in both a greater amount of electricity being produced by the power plant and an increase in power plant efficiency.

The design of the CSP and thermal storage systems has been well characterized in the literature for both standalone power generation and integration with fossil energy systems [5–8, 12, 14, 22–26]. Systems using mineral oil as a heat transfer fluid (HTF), shown in Figure 1, vary slightly from those which use a molten salt HTF (Figure 2), as in the latter the molten salt is both the HTF and storage medium, thereby affecting a reduction in cost. In contrast, the mineral oil system requires a system of heat exchanges to heat up the storage medium, incurring additional costs and reduced storage temperatures due to both the reduced operating temperature of the HTF and heat exchanger approach temperature [22]. The use of molten salt as an HTF is not without challenges, but the potential for cost reductions has driven the market in that direction.

The CSP system in this study is designed to use high temperature heat from the parabolic troughs to heat up the storage medium for nighttime feedwater heating,

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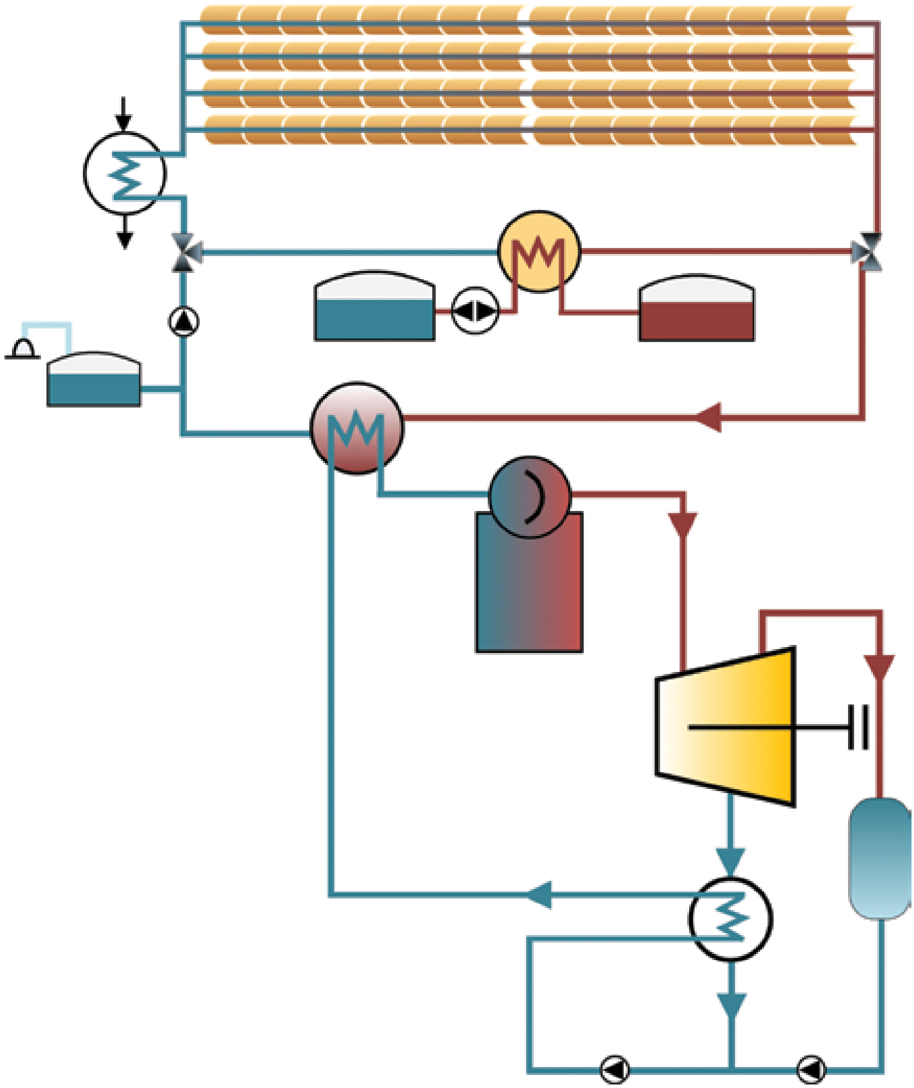

Figure 1 Solar aided feedwater heating system with mineral oil heat transfer fluid.

then to heat up successive stages of lower temperature feedwater. This is done until the efficiency (and therefore emissions) target is met. The primary difference in the approach utilized in this work is that the system is specifically designed to meet an emissions limit for a coal EGU for an entire day (i.e. even when the sun isn't shining). Full day (24 hour) emissions compliance is achieved by using 12 hours of TES, which in turn should enable the power plant to overperform on emissions

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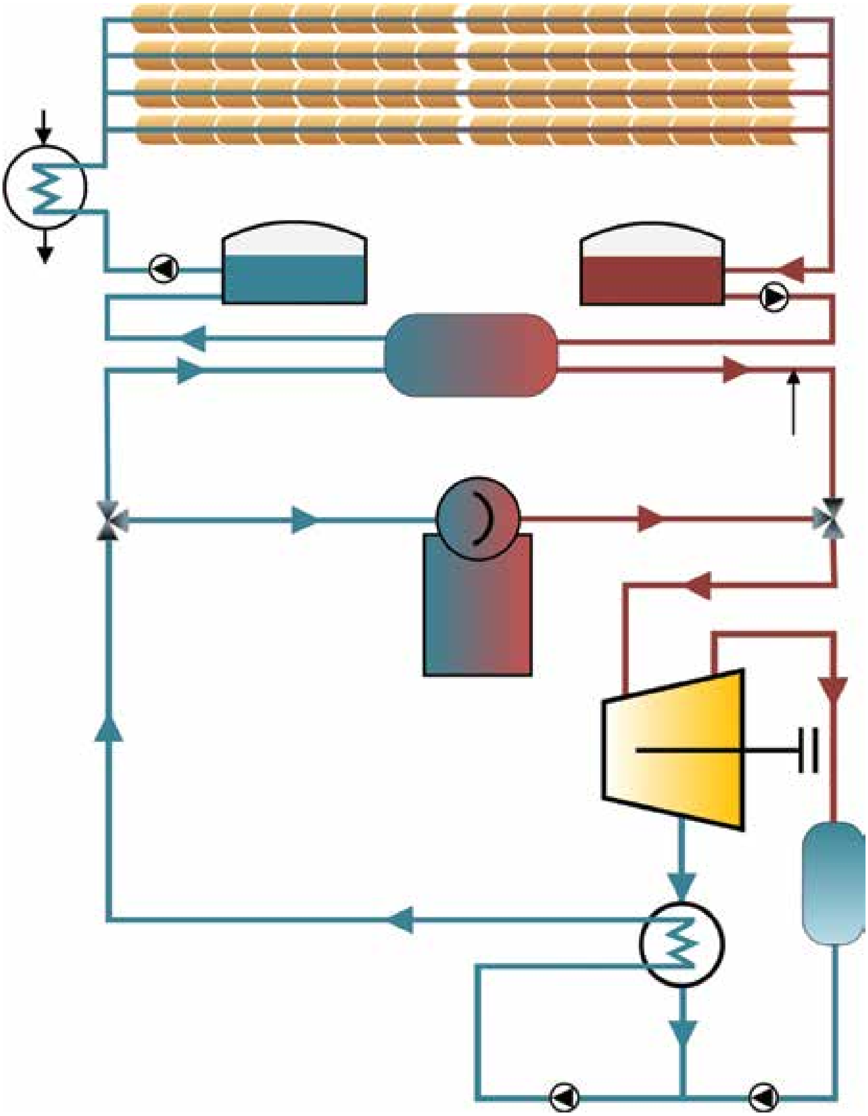

Figure 2 Solar aided feedwater heating system with molten salt heat transfer fluid.

compliance during peak summer months with more than 12 hours of daylight per day and meet emissions when operating in shoulder or winter months. The amount of heat provided to the FWH has been optimized, such that the CSP array is no bigger than required to provide sufficient energy for the SAFWH and charging the TES.

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2.4 Performance Impacts of Reduced Extraction Steam for Boiler Feedwater Heating

This study used a next generation, A-USC power plant design as its basis [18]. The plant utilizes a series of nine heat exchangers for boiler feedwater heating. Six of the nine boiler FWHs use extraction steam (steam extracted from the steam cycle) as their heat source. AspenPlus was used to model the performance of this power plant design and the impacts of supplanting extraction steam with solar heat was determined by reducing the steam flows to each of the six FWHs to zero in order to determine how much additional power would be generated by the steam turbine.

2.5 Solar Energy & Storage Requirements for NSPS Compliance

The solar energy system is designed to provide enough energy for the power plant to be compliant with the NSPS for CO_2 emissions. During daylight operation, this occurs by providing enough heat to both charge the thermal storage battery and heat the boiler feedwater. During nighttime operation, heat is taken from the thermal storage battery in order to sufficiently heat the FW to achieve the required efficiency increase.

The solar energy system was designed using the annual average Direct Normal Irradiance (DNI) of each location to determine the size of the solar array. Energy storage was sized at twelve hours of storage with an assumed thermal loss rate of 3% overnight, based on a nominal 2.5% rate of thermal losses at the commercial, concentrating solar facility, Andasol-3, over a shorter, 7.5 hour timeframe of energy storage [25]. This system is projected to over-perform during summer months, when average daily DNI is higher (in part due to longer days) and performs sufficiently in spring and fall months, when 12 hours or more of daylight exists. Winter performance may be reduced, requiring total plant output reductions or the addition of more storage to maintain NSPS compliance. Making the determination on the performance required for NSPS compliance, however, is beyond the scope of this work.

2.6 System Cost Methodology

This work evaluates the installed cost of integrating an SAFWH system into a Rankine cycle coal-fired power plant. The SAFWH system design consists of parabolic trough solar collectors, which provide solar energy, the heat transfer fluid system, and TES. The final "installed" cost of each of these component systems for the ST case is reported by IRENA and these costs reflect the entire subsystem cost in 2015 dollars [22]. In contrast, while the ST-DSP system is commercially offered by SkyFuel, to the knowledge of the authors, no current deployments exist. Consequently, no cost data existed for two of the ST-DEP component subsystems – the collectors and the HTF – and it was necessary to utilize cost projections for these components as they were the only cost data available.

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The installed costs of the ST and ST-DSP are \$230 per square meter (\$230/m^2) of reflective area and \$212/m^2, respectively [22]. The ST-DSP cost was developed by starting at the \$230/m^2 based on the use of similar materials, then modifying that price based on assumed cost savings associated with the use of molten salt for the HTF. This is reported to result in a 40% reduction in the amount of HTF over mineral oil, which represents 34% of the \$52/m^2 total cost reduction IRENA reports as possible through technology improvements and learning by doing [22]. Molten salt thermal energy storage was priced at \$42/kWh_{th} for the mineral oil-based ST and \$26/kWh_{th} for the molten salt HTF-based ST-DSP. The \$26/kWh_{th} cost is in line with other cost projections reported by NREL for the ST-DSP [26].

Because of the significant role TES plays in the system being evaluated, a sensitivity analysis was performed investigating the impact of higher thermal storage costs. A TES cost of \$75/kWh_{th} was used for the ST case, based on the default cost in NREL's System Advisor Model (SAM) reported by NREL in 2015. [28] In the ST-DSP case, a value of \$59/kWh_{th} reflected the \$16/kWh_{th} reduction in cost reported by IRENA in moving from mineral oil to molten salt as an HTF.

System integration costs, such as the cost of additional piping, pumps, increased heat exchanger costs for the FHWs, and other ancillary costs, are expected to be very plant specific and were beyond the scope of this screening assessment.

3 Results

3.1 Efficiency Impacts of Reducing Steam Extraction for Boiler Feedwater Heating

Table 3 describes the impacts of displacing extraction steam to the FWHs in terms of additional turbine output (in horsepower (hp)), electricity generated (kilowatts electricity (kW_e)), and percentage increase in total plant output. The feedwater inlet and outlet temperatures into the FWHs are also presented. As shown, replacing the extraction steam that goes to the low temperature feedwater heaters – FWHs

Table 3 Efficiency impacts of displacing extraction steam.

FHW	HP increase (hp)	Turbine output increase (kW_e)	% Increase in gross output	Heat duty (MMBtu)	FW temperature (F)	
					Inlet	Outlet
1	2,059	1,535	0.2%	109.30	89	124
2	2,630	1,961	0.2%	118.89	124	162
3	11,579	8,634	1.1%	204.46	162	227
7	46,081	34,363	4.3%	512.39	401	462
8	115,962	86,473	10.8%	447.64	462	562
9	136,006	101,420	12.7%	447.60	562	641

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1-3 – has a minimal impact on total plant output, increasing it by 12,131 kW_e, or 1.5 percent. Displacing the extraction steam sent to the high temperature BFWHs has a much more pronounced impact on plant output, increasing output by 222,255 kW_e, or almost 28 percent. It is also worth noting that replacing any of the three high temperature feedwater heaters – FWHs 7-9 – increases output more than replacing all three of the low temperature heaters.

3.2 *Solar Thermal Energy Requirement*

The solar energy requirement required for each PC plant configuration to meet an emissions standard of 1,400 lb CO_2/MWh_g was determined by iteratively calculating the efficiency improvement and associated reduction in heat rate required to meet the emissions limit. Table 4 describes these results, showing that an SOA PC plant would require an efficiency improvement of 13.5 percent over the base performance, while the A-USC-CE would require half as much of an increase (6.3 percent) and the A-USC-NG only a quarter of the increase (3.4 percent).

The calculated efficiency improvement was then used in conjunction with the Aspen Plus modeling results to determine how much extraction steam would need to be displaced by solar energy. Parabolic trough solar panels have an operational temperature range that is optimal for displacing extraction steam in the highest temperature FWHs, numbers eight and nine, which also have the highest potential for improving power plant efficiency. The storage requirement is based on a need to provide auxiliary energy for an average of twelve hours per day and allow for a three percent energy loss over the storage period.

The system size required to displace an appropriate level of extraction steam and charge molten salt thermal storage (used to replace the solar-related heat during operation in the dark hours) is shown in Table 5, which describes the total area of solar panels, and Table 6, which provides the number of SCAs and TES capacity required for operation. A plant located in West Virginia would require between 247 and 1,447 SCAs for a next-generation A-USC plant and current SOA supercritical plant, respectively. A plant in the American Southwest would require between

Table 4 Efficiency requirements for CO_2 NSPS compliance.

	Heat rate (Btu/kWh-g)	**Efficiency (HHV)**	**Emissions (lb CO_2/MWh-g)**	**Efficiency increase required for compliance**
SC-PC - SOA	7,950	40.7%	1,619	13.5%
A-USC - CE	7,465	43.9%	1,495	6.3%
A-USC - NG	7,270	45.3%	1,449	3.4%
Compliant Plant	7,246	47.1%	1,400	n/a

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Table 5 Solar panel area by location and panel type.

	Panel area (m²)			
	West virginia		Southwest	
Case	**ST**	**ST-DSP**	**ST**	**ST-DSP**
SC-PC - SOA	949,232	963,300	443,456	449,475
A-USC – CE	436,896	438,750	204,016	204,750
A-USC – NG	240,752	240,825	112,832	113,100

Table 6 Solar module and thermal storage requirements for a 550 MW_e plant.

	Number of parabolic trough SCAs				Thermal storage (MWh_{th})	
	West virginia		Southwest			
Case	**ST**	**ST-DSP**	**ST**	**ST-DSP**	**ST**	**ST-DSP**
SC-PC - SOA	1,447	988	676	461	1,268	1,249
A-USC – CE	666	450	311	210	583	568
A-USC – NG	367	247	172	116	319	312

116 and 676 SCAs for next-generation A-USC and SOA plants, respectively. Plants in either location would require between 312 and 1,249 megawatt-hours of thermal (MWh_{th}) energy storage in order to heat feedwater during evening hours and maintain low-emission operation.

3.3 Solar Panel and Thermal Storage Capital Cost

The purchase, site preparation, and installation of a CSP array for boiler feedwater heating would cost anywhere from \$47 million to \$223 million for a site in West Virginia for a next generation, advanced ultra-supercritical power plant and an SOA supercritical powerplant, respectively. A similarly constructed system in the Southwest would cost less than half of that, or \$22 million to \$104 million, which directly relates to the improved solar resource in that region. Thermal energy storage costs range from \$8 million and \$53 million for a next generation A-USC plant and SOA supercritical plant, respectively. These results are presented in Table 7 and Figure 3.

The combined installed costs of the CSP and TES are detailed in Table 8 and Figure 4. Costs for a plant constructed in West Virginia range from \$55 million for a next generation A-USC plant to \$276 million for a SOA supercritical plant. Combined costs for a similar plant in the Southwest range from \$30 million to \$158 million.

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Table 7 Solar module and thermal storage costs for a 550 MW_e plant.

Case	Parabolic trough installed cost (millions $)				Thermal storage cost (millions $)	
	West virginia		Southwest			
	ST	ST-DSP	ST	ST-DSP	ST	ST-DSP
SC-PC - SOA	$223.1	$185.9	$104.2	$86.7	$53.3	$32.5
A-USC – CE	$102.7	$84.7	$47.9	$39.5	$24.5	$14.8
A-USC – NG	$56.6	$46.5	$26.5	$21.8	$13.4	$8.1

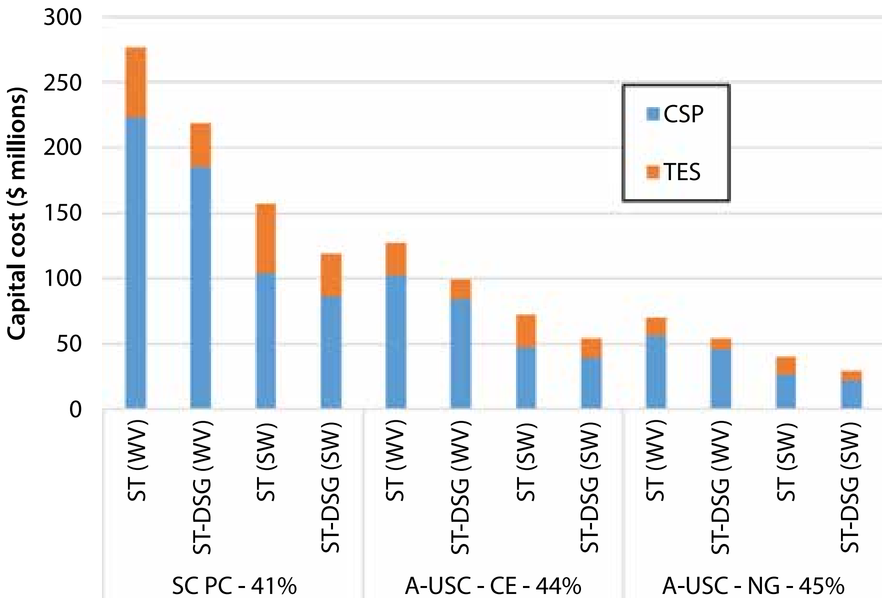

Figure 3 Concentrating solar power and thermal energy storage installed cost breakdown.

Table 8 Total installed solar module and thermal storage costs for a 550 MW_e plant.

Case	Installed cost of solar field and TES (millions $)			
	West virginia		Southwest	
	ST	ST-DSP	ST	ST-DSP
SC-PC - SOA	$276.3	$218.4	$157.5	$119.2
A-USC – CE	$127.1	$99.4	$72.4	$54.3
A-USC – NG	$70.0	$54.6	$39.9	$29.9

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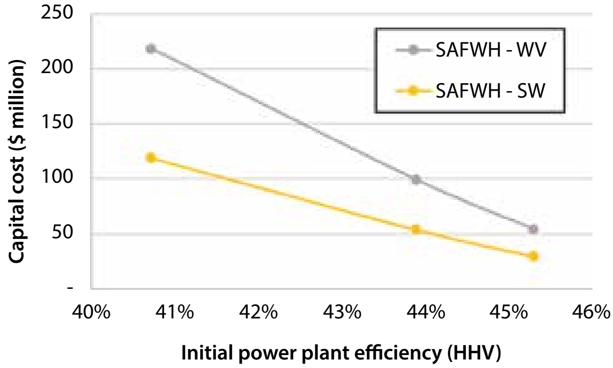

Figure 4 Installed costs of the SAFWH system.

Table 9 Molten salt storage cost fraction and sensitivity analysis.

Storage as percentage of total cost				High cost storage sensitivity			
West virginia		Southwest		West virginia		Southwest	
ST	ST-DSP	ST	ST-DSP	ST	ST-DSP	ST	ST-DSP
19%	15%	34%	27%	34%	34%	60%	62%

The move to higher efficiency power cycles results in significantly smaller solar feedwater heating systems and associated thermal storage requirements. This, in turn, substantially reduces system costs; compared to implementing the system on an SOA supercritical plant, the system for a "cutting edge" A-USC would cost 54 percent less, a savings of between $119 million and $149 million for WV and the SW, respectively. The CSP and TES system for a next generation A-USC would cost 75 percent less than a system for an SOA SC PC, a savings of between $164 million and $206 million for the SW and WV, respectively.

Molten salt TES plays a critical role in the ability to successfully integrate solar feedwater heating into a coal-fired power plant, both to smooth out operational transients and to achieve NSPS compliance for CO_2 emissions. Reference costs for molten salt storage varied significantly, from $26/kWh$_{th}$ to $75/kWh$_{th}$ [22, 28]. A sensitivity analysis was performed to determine how this impacted total system cost, as well as the portion of the total system cost associated with thermal storage.

Tables 9 and 10 describe the results of this sensitivity analysis. Molten salt energy storage goes from constituting 15 to 19 percent of the combined system cost for a plant located in West Virginia to 34 percent at the higher installed costs reported by NREL. Storage constitutes a larger portion of the combined system costs for plants located in the Southwest, from 27 to 34 percent, as less SCAs are

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Table 10 Total installed solar module and thermal storage costs at higher storage cost.

	Installed cost of solar field and TES (millions $)			
	West virginia		Southwest	
Case	ST	ST-DSP	ST	ST-DSP
SC-PC - SOA	$318.2	$259.6	$199.34	$160.4
A-USC - CE	$146.4	$118.2	$91.64	$73.0
A-USC - NG	$80.5	$64.9	$50.45	$40.2

required owing to the better solar resource. At the higher cost figure for storage, this increases to roughly 60 percent of the combined system cost. The updated combined system costs are presented in Figure 9, where the minimum cost has increased to $40 million for a next generation A-USC in the Southwest to a maximum of $318 million for an SOA supercritical plant in West Virginia. These represent overall cost increases of 34 percent and 15 percent, respectively.

4 Discussion

4.1 *Comparing the Cost of Solar Integrated FWH with CCS*

NETL has reported that an SOA supercritical PC plant equipped with a post-combustion CCS system could achieve an emissions level of 1,400 lb CO_2/MWh_g by capturing 16% of the CO_2 produced by the facility [29]. Implementing such a system would increase the total overnight cost by $295 million dollars (in 2011 dollars), from $1.379 to $1.674 billion [29]. This is an equivalent of $314 million in 2015 dollars.

Based on the analysis performed here, implementing CSP FHW and TES as a means to improve plant efficiency could be a lower cost pathway to NSPS CO_2 compliance for a new, supercritical PC in certain locations with good solar resources. The costs for implementing such a system would range from $99 million to $276 million for a WV location, assuming the use of technologies commercially available now, the cutting-edge A-USC and SOA SC plants, respectively. These costs are reduced by roughly 54 percent for a system constructed in the Southwest.

This assessment is by no means conclusive, but a more detailed analysis is warranted into cost basis for the solar and thermal storage systems, the integration and ancillary equipment costs, and the performance impacts of reducing steam extraction for FWH, particularly for the current SOA plants.

4.2 *Impacts of Improved Power Plant Efficiency*

One of the striking findings of this analysis is the impact that improved power plant efficiency can have on the size and cost of the CSP and TES system. As

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described above, the cost of achieving an emissions level of 1,400 lb CO_2/MWh_g decreases by 54 percent if it is implemented on a coal-fired power plant with a higher heating value (HHV) efficiency of 43.9% - our cutting-edge A-USC plant – compared to a state-of-the-art supercritical PC plant operating at 40.7% efficiency. The cost reductions are even more stark when efficiency is increased further. This translates into savings of between $119 million and $149 million for WV and the SW, respectively.

Underpinning the effects of efficiency on system size and cost is the solar energy requirement for boiler FHWs in order to achieve the target plant efficiency. This analysis only evaluated the impacts of FW heating on the next-generation A-USC plant and scaled those results for the other performance levels. The findings here underscore the need for further analysis, including modeling the performance impacts of displacing extraction steam at lower efficiency plants. This may result in cost differences which are even more dramatic between the cases.

4.3 Additional Potential Benefits of Solar FWH and Thermal Storage Systems

This paper has been limited to evaluating the ability of CSP and TES to achieve a certain level of efficiency and CO_2 emissions. Integrating TES into a fossil energy power plant has several other potential benefits which have been explored in the literature. These include the potential to reduce the thermal impacts of ramping and startup/shutdown on equipment through the use of TES, as well as the potential to increase the output of the EGU during times of peak electricity prices [14]. These benefits should be considered in future work.

4.4 Environmental Concerns Surrounding Parabolic Trough CSP and Thermal Storage Systems

In evaluating new energy systems, caution must be taken to ensure one environmental concern is not being mitigated at the expense of creating a new concern. Deploying SAFWH on a coal-fired power plant has the benefit of reducing GHG emissions and other criteria pollutants through improved power plant efficiency; less coal needs to be burned at the plant in order to produce the same amount of electricity, thereby reducing combustion byproducts.

When examining the potential environmental concerns associated with the SAFWH subsystems, we find that the use of parabolic trough solar collectors limits the environmental impacts that might be associated with certain other solar energy systems. Specifically, unlike concentrating solar towers which have been shown to result in avian deaths, the parabolic trough system concentrates the sunlight on a pipe in the center of each SCA's aperture. Because the light is only being focused a short distance away, avian deaths have not been reported at power plants deploying these types of collectors [29]. These collectors are also rather simple in design

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and construction and, consequently, do not require some of the specialty materials utilized in photovoltaic solar panels.

One point of concern is the mineral oil that is used as an HTF in the ST systems. This oil is hazardous and a leak or spill could result in an environmental event. The recommended disposal of this oil is by re-processing spent or degraded oil, so, barring a spill, environmental concerns are relatively limited [11]. Another solution would be the use of molten salts as an HTF, as in the ST-DSG system, as these salts would revert to a solid phase in the event of a leak, limiting environmental exposure.

The molten salts used for both TES and as an HTF are rated as hazardous, but primarily in terms of fire hazard [30]. They are rated as Class I oxidizers and need to be kept away from other combustible materials which they could increase the burn rate of [30]. While this is the least hazardous class of oxidizers, any molten salt TES system would need to be deployed safely away from the coal handling and storage systems. As mentioned above, the benefit of using molten salts is that they revert to a solid phase at ambient temperatures, limiting the impact of leaks. These systems have been safely deployed without incident throughout the world.

5 Conclusions

This work has shown that a new, pulverized coal power plant has the potential to achieve NSPS compliance by integrating solar feedwater heating and TES. Such a system has the potential to be cost competitive with deploying CCS in certain locations with good solar resources, based on this analysis and current cost estimates of CCS, concentrating solar parabolic trough systems, and molten salt TES.

Additional analysis is warranted, as this screening assessment made several simplifying assumptions. These included the use of annual averages for daily DNI in the sizing of the solar field and thermal storage systems and the assumption that the performance improvements seen by modeling an A-USC power plant in AspenPlus would be representative for other power plant performance levels and this should be verified. Designing the system based on historic DNI data collected over one or more years for a specific proposed plant site would further improve the understanding of the design and size requirements of the renewable system.

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7 Nomenclature

A-USC	power plant utilizing steam in the advanced ultra-supercritical range
A-USC – CE	most efficient, "cutting edge" A-USC power plant performance
A-USC – NG	"next generation" A-USC power plant projected performance
BSER	"best system of emission reduction" for controlling power plant emissions
CCS	carbon capture and storage
CSP	parabolic trough concentrating solar power
EGU	electricity generating unit or power plant
FWH	feedwater heater for the power plant steam cycle
HTF	heat transfer fluid utilized in the CSP system
PC	pulverized coal power plant
SAFWH	solar aided feedwater heating system
SCA	solar collector array
SC PC	power plant utilizing steam in the advanced ultra-supercritical range
SOA	state-of-the-art
SC-PC - SOA	performance of the current, state-of-the-art PC plant
ST	SkyTrough CSP system utilizing mineral oil as an HTF
ST-DSP	SkyTrough CSP system utilizing molten salt as an HTF
TES	molten salt thermal energy storage

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