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Technical Report
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Abstract

Concentrating Solar Power (CSP) systems utilize solar thermal energy for the generation of electric power. This attribute makes it relatively easy to integrate CSP systems with fossil-fired power plants. The “solar-augment” of fossil power plants offers a lower cost and lower risk alternative to stand-alone solar plant construction. This study ranked the potential to add solar thermal energy to coal-fired and natural gas combined cycle (NGCC) plants found throughout 16 states in the southeast and southwest United States. Each generating unit was ranked in six categories to create a qualitative overall score of *Excellent*, *Good,* or *Fair*. Plants ranking below fair or failing to pass other criteria were scored *Not Considered*. Separate analysis was performed for parabolic trough and power tower technologies due to the difference in the steam temperatures that each can generate. The study found a potential for over 11 GWe of parabolic trough and over 21 GWe of power tower capacity. Power towers offer more capacity and higher quality integration due to the greater steam temperatures that can be achieved. The best sites were in the sunny southwest, but each of the sixteen states had at least one site that ranked *Good* for augmentation.

Background

In 2009, coal and natural gas provided 2/3 of the nation’s electricity [1]. These fuels are domestic and relatively inexpensive, yet they represent finite energy sources that come with environmental liabilities. Transitioning to a lower carbon and renewable energy future will require technical advances and time to integrate and adapt current systems to new generation sources such as wind and solar. Of the wind and solar technologies, CSP is unique in its ability to integrate with existing fossil generation systems. Such integration offers a low-risk opportunity to meet renewable energy targets while promoting deployment and speeding the learning-curve growth that helps drive down the cost of new technologies.

CSP differs from photovoltaic solar power in that CSP uses the sun’s heat to drive a thermal power cycle. This reliance on thermal energy means CSP plants can be backed up with natural gas and can supply steam to augment fossil-fired power plants. Such hybridization can allow for more reliable and lower cost application of solar power. In 2009, the Electric Power Research Institute (EPRI) completed studies examining the best ways to integrate CSP steam into coal-fired and NGCC power plants [2, 3]. In this work, EPRI developed models that predicted the performance of augmenting coal- or natural gas-fired power plants with steam from CSP equipment. NREL assisted by providing data on solar resource and the amount of thermal energy that can be supplied by parabolic trough and power tower (also known as central receiver) CSP technologies.

Solar-augment of a fossil power plant offers several advantages to the developer. These advantages include:

- Pre-existing steam power block, electrical substation, and other ancillary equipment,
- Pre-existing transmission and grid interconnect,
- Adjacent land for solar field may already be owned by the utility,

- Location next to an existing power plant likely minimizes environmental and view-shed concerns,
- Solar variability is mitigated by fossil fuel use.

These features combine to lower the cost and risk associated with the solar project, and also may shorten project development timelines. As risk is reduced, indirect costs associated with financing costs and project contingencies may also decrease.

In this follow-on study, EPRI and NREL surveyed the fossil power plants across sixteen US states to determine their solar-augment potential. This report documents the solar capacity and energy, as well as air emission reductions, that could be achieved by augmenting these existing and planned fossil power stations.

Objectives

The goal of this study is to rank fossil-fired power plants for their suitability to incorporate the addition of solar thermal energy. This ranking provides guidance to utilities regarding the feasibility of integrating solar thermal energy into their existing fleet and allows analysts to estimate the contribution such hybrid plants might make to the nation’s electricity supply. The work was carried out through the following steps:

1. Identified all operating, under construction, and planned pulverized coal and NGCC power plants in regions of the United States known to have good solar resource as defined by their direct normal insolation (DNI). The study region included the western states of California (CA), Arizona (AZ), Nevada (NV), New Mexico (NM), Utah (UT), Colorado (CO), Texas (TX), and Oklahoma (OK), as well as eastern states of Florida (FL), Alabama (AL), Georgia (GA), Louisiana (LA), Mississippi (MS), North Carolina (NC), South Carolina (SC), and Tennessee (TN).
2. Created a qualitative ranking of solar-augment potential for each power plant. Ranking was based on augmenting the unit(s) at each power station with the highest potential for solar integration. Augment potential was evaluated for both parabolic troughs and power tower CSP technologies. Linear Fresnel systems would also be good candidates for this application, but performance models were not as well developed as for troughs.
3. Summarized total solar energy provided and emissions reduced by incorporating solar thermal energy into the ranked power plants. Categorized potential by plant ranking, geography, age, and other criteria as appropriate.
4. Estimated the benefit to the solar industry and utility sector of deploying CSP systems for solar-augmented plants. Benefits were based on investment, manufacturing scale, and operational learning.
5. Incorporated the ranked database of the plants into NREL’s Solar Power Prospector webtool.

Ranking Criteria

Six criteria were chosen for ranking the solar-augment potential of existing fossil power plants. These criteria include:

- age of the fossil plant,
- average capacity factor of the fossil plant,
- DNI resource available at the plant site,
- amount of available land surrounding the existing plant,
- topography of that land, and
- solar-use efficiency that could be expected if the plant were augmented with a solar field.

A methodology was developed that weighted the importance of these criteria on the overall solar-augment potential of the plant and each criterion was assigned a range of scores. From this, a numeric score and qualitative ranking of all existing fossil plants was calculated to determine those with the highest potential for solar integration. Table 1 shows the weights and ranges assigned to the criteria, followed by a discussion of each criterion and the overall scoring methodology.

Table 1. Ranking Criteria

	Age of Plant (years)	Capacity Factor (%)	Annual Average DNI (kWh/m^2/day)	Amount of Land Available (acres/fossil plant MW)	Topography of the Land (% slope)	Solar Use Efficiency (%)
Score/ Weighting	**5%**	**20%**	**35%**	**15%**	**15%**	**10%**
Not Considered	> 30	< 15	< 4	< 0.05	> 5	--
1	16-30	--	4-5	0.05-0.2	3-5	< 30
2	--	15-50	5-6	0.2-0.35	--	30-32
3	11-15	--	6-6.5	0.35-0.5	1.5-3	32-35
4	--	--	6.5-7	0.5-0.65	--	35-38
5	0-10	≥ 50	≥ 7	≥ 0.65	≤ 1.5	≥ 38

Age of Plant

The age of the plant is calculated based on the plant's in-service date. For plants that are under construction or under development, the age of the plant is considered to be zero. Plants that have been built more recently receive a higher score because it is expected that they will have a longer operating life, increasing the likelihood that the solar plant will be able to operate throughout its expected life. Plants that are older than 30 years (built before 1980) are not considered based on the assumption that these plants will be closer to retirement and likely have less sophisticated controls than the newer plants, which may make incorporating the control logic of the solar field integration more difficult. In addition, emissions controls may be limited at these older plants, potentially jeopardizing the long-term operation of these plants. Overall, the age of the plant is given a 5% weighting as it is only a minor consideration compared to other plant characteristics.

Capacity Factor

The capacity factor of the plant indicates how frequently the plant operates. Based on EPRI's standard definitions, a plant with a capacity factor greater than 50% is considered a baseload plant, between 20% and 50% is considered intermediate, and less than 20% is considered peaking. Because solar augmentation can occur only when the fossil plant is operating, a plant with a low capacity factor is undesirable. The infrequent operation of a plant with a low capacity factor will result in significantly reduced megawatt-hours attributed to solar, which in turn raises the cost of solar-generated electricity as there are fewer hours over which to reclaim capital costs. However, it is possible that the operation of some peaking plants could correlate well with solar resource availability if the peaking units are operated on the hottest, sunniest days to meet air-conditioning loads. Baseload plants are most preferable and, therefore, plants with a capacity factor of 50% or greater receive a top score. Intermediate and higher capacity peaking plants with a capacity factor between 15% and 50% receive low points, but are still considered because there is some potential for solar operation. Plants with a capacity factor below 15% are not considered further. Due to the strong effect that capacity factor will have on annual megawatt-hours generated and plant economics, it is given the second highest weighting at 20%.

Annual Average DNI

The solar resource at the plant site, measured as annual average DNI, will significantly affect the performance of the solar-augmented fossil plant. A high average DNI will produce more steam for augmenting the plant, increasing the number of megawatt-hours attributed to solar and reducing fossil fuel consumption. Top points are given to a solar resource of 7 kWh/m^2/day and greater, with points dropping incrementally down to a resource of 4 kWh/m^2/day. Plants in a location with a DNI less than 4 kWh/m^2/day are not considered further. Because the solar resource has such a significant effect on the plant performance and economics, it is given the highest weighting at 35%.

Amount of Land Available

The amount of land available surrounding the existing fossil plant affects the size of the solar field that can be built, which in turn affects the amount of solar steam and solar-generated electricity produced. Previous work has shown that existing fossil plants can accept a design-point maximum of between 10% and 20% of their total plant output from solar steam before reaching equipment or other design limitations. Because the amount of solar steam a plant can accept will vary based on the plant's capacity, the amount of available land criterion is calculated as acres per fossil plant megawatt. For example, based on the assumption that 1 MWe of solar requires 5 acres of land, a 100 MW plant could accept up to 10 to 20 MWe of solar generation, which would require 50 to 100 acres of land or 0.5 to 1 acres per fossil plant megawatt. The ability to produce a high percentage of the plant output from solar results in larger offsets of fossil fuel consumption and plant emissions. Maximum points are given to a plant with enough land available to produce roughly 13% or greater of plant output from solar, or greater than 0.65 acres per fossil plant megawatt. Plants with land available for less than 1% plant output from solar, or less than 0.05 acres per fossil plant megawatt, are not considered further. Although larger field sizes will benefit somewhat from economies of scale, other economic drivers likely have a greater effect. Therefore, an intermediate weighting of 15% is given to this criterion.

Topography of the Land

The topography of the land surrounding the plant affects the ease of installation of the solar field as well as its performance. Generally, land with less than 3% slope is preferred for concentrating solar technologies. Ground slopes greater than 3% require extensive grading for parabolic trough installations, and while the power tower technology is less sensitive to the need for flat land, it is easier to install on a slope of less than 3%. Plants with a slope greater than 3% will require significant regrading, which can notably affect the cost of installation and, therefore, the overall plant economics. For this study, any plant with surrounding land that has a slope greater than 5% is not considered, while low scores are given to those with a slope of 3% or greater. Plants with a slope of 1.5% or less are given maximum points. Because land topography can affect both plant performance and installation costs, it is given an intermediate weighting of 15%.

Solar Use Efficiency

Solar use efficiency is the measure of how many megawatts of solar electricity are generated per solar thermal megawatt integrated into the fossil plant. Solar-augmented plants can have solar-use efficiencies that exceed stand-alone solar plants; however, solar-use efficiency generally decreases with solar contribution. Particularly for troughs, higher percentages of solar integration have been shown to result in lower solar-use efficiencies due to the mismatch between the solar steam temperature and that of the fossil plant steam cycle at the point of integration, see Figure 1. This study seeks to maximize solar energy production, not solar-use efficiency. Plants are given a high score for solar-use efficiencies that exceed values for stand-alone solar plants, middling score for values comparable to stand-alone solar plants, and low score if solar-use efficiency is lower. No plants are eliminated from consideration based on their solar use efficiency. To avoid penalizing plants with large solar fields and higher percentages of solar integration, the solar use efficiency criterion is given an intermediate weighting of 10%.

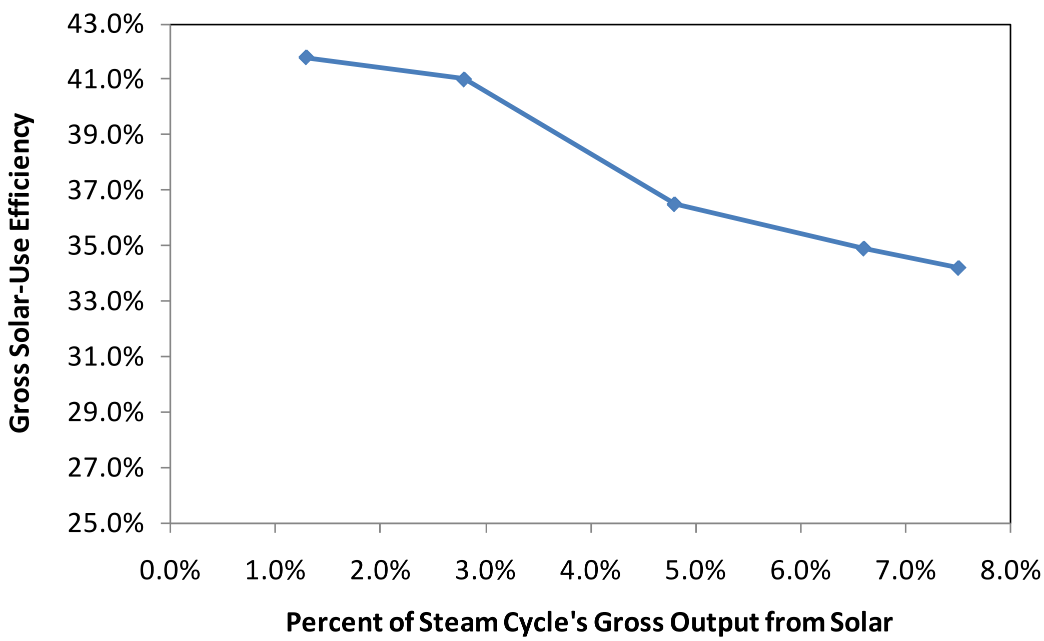

Figure 1. Solar-use efficiency generally falls with increasing solar contribution. This study seeks to maximize solar energy, which sometimes results in lower solar-use efficiency. Figure from EPRI [2].

Scoring Methodology

EPRI compiled data about the fossil plant size, in-service year, and capacity factor from the SNL database [4]. As data were entered into a scoring spreadsheet, each input was checked to see if it met the minimum acceptance criteria. If the age of the plant (calculated by subtracting the in-service year from the current year, 2010) or the capacity factor was below the minimum criteria the plant scored as *Not Considered* and no further analysis was performed. Those plant sites that passed this initial hurdle were analyzed by NREL to determine annual average DNI, topography of the land, and the amount of land available. The amount of land available on an acre-per-fossil-plant-megawatt was calculated by dividing the land amount provided by NREL by the fossil plant capacity. Sites not meeting minimum criteria for those parameters were also classified as *Not Considered*. The remaining sites were analyzed with EPRI's solar use performance models that were developed for an earlier project [2, 3] to determine solar-use efficiency and overall augment potential. As data were input into the spreadsheet, each site was scored based on the criteria described above. Figure 2 shows a sample of the scoring spreadsheet.

	A	B	C	D	E	F	G	H
1		Age of plant (years)	Capacity factor (%)	Annual Average DNI (kWh/m2/day)	Amount of land available (acres/fossil plant MW)	Topography of the land (% slope)	Solar use efficiency (%)	
2		>30 = NC, 16-30 = 1, 11-15 = 3, 0-10 = 5	<15 = NC, 15-50 = 2, >50 = 5	<4 = NC, >4 = 1, >5 = 2, >6 = 3, >6.5 = 4, >7 = 5	<0.05 = NC, <0.2 = 1, <0.35 = 2, <0.5 = 3, <0.65 = 4, >0.65= 5	>5 = NC, >3 = 1, >1.5 = 3, <1.5 = 5	<30 = 1, 30-32 = 2, 32-35 = 3, 35-38 = 4, >38 = 5	**TOTAL**
3		5%	20%	35%	15%	15%	10%	**100%**
4	A	3	5	3	2	3	3	**3.25**
5	B	Plant Too Old	5	3	2	3	3	**Not Considered**
6	C	3	Low Operation	3	2	3	3	**Not Considered**
7	D	3	5	DNI Too Low	2	3	3	**Not Considered**
8	E	3	5	3	2	Slope Too Steep	3	**Not Considered**
9	F	3	5	3	Not Enough Land	3	3	**Not Considered**
10	G	3	5	3	2	3	1	**3.05**
11	H							
12	I							

Figure 2. Scoring sheet with examples of "Not Considered" rankings.

Estimating Solar-Augment Potential

Each plant was first screened as a full plant and then evaluated on a unit basis. On the plant level, the in-service year of the newest unit of the plant and the highest capacity factor between 2009 and 2010 was used for the screening. All plants that passed the minimum criteria of newer than 30 years and greater than 15% capacity factor were submitted to NREL for land and solar resource analysis.

Analysis for the physical location, topography, and average annual solar DNI value for each considered power plant was conducted at NREL using ArcMap Geographic Information System (GIS) software. The analysis was conducted using the following primary steps:

- Verify the latitude and longitude for each proposed location.
- Analyze the topography for each location and filter results based on usable land requirements.
- Calculate the average solar DNI for the plants that meet the usable land requirements.

Proposed plant locations (latitude/longitude) were cross referenced to ensure geographic precision and the verified geographic coordinates were analyzed for the land use criteria. The analysis was performed initially using a 3.25-km radius to ensure inclusion of all available raster grid cells. A 3-km radius was selected based on previous EPRI studies that indicated solar fields located further from the plant power block have significantly higher capital cost, greater thermal losses and higher auxiliary loads associated with pumping fluid long distances. The land filtering techniques eliminated developed land, wetlands, open water, impervious surfaces (i.e. included buildings and structures, roadways, etc.), and areas with percent slope greater than 5% [12]. Filtered results from the 3.25 km radius were then reduced to the desired 3-km radius by converting the raster to vector format and clipping with the more precisely defined radius. The contiguous area was then calculated for those areas that remained. Only land parcels of 10 acres or larger were retained for final consideration in the solar-augment modeling process.

In order to determine the solar resource for each location the filtered parcels were spatially joined to the average solar DNI data. The statistics for each region were calculated to provide the average annual DNI for all parcels within the 3 km radius, and the final average was used as the proposed plant solar DNI value. Additional statistics included average slope of the region, average contiguous land parcel size, as well as minimum and maximum contiguous land parcel sizes.

All plants that passed these initial criteria were then further evaluated on the unit level. For the coal plants, each steam turbine was evaluated as a separate unit. For the NGCC plants, the units were broken into combinations of combustion turbines and steam turbines. This was done as logically as possible based on the unit sizes and in-service years of the individual steam and combustion turbines and should provide a representative NGCC unit value for the plants. Each steam turbine and combustion turbine combination was then given a unique, representative name to be used throughout the analysis; however, these are not names that are necessarily used by the plants.

A key criterion for a NGCC plant to accept solar steam is spare capacity in its steam turbines to accept additional steam without backing off the combustion turbines. The NGCC plants were evaluated in a few different ways to determine if there was sufficient steam turbine capacity. The EIA 860 database was consulted to determine if the plants had duct burners or not. Typically, if a NGCC has a duct burner, there is extra capacity in the steam turbine when the duct burners are not firing, assuming that the plant does not operate as a cogeneration unit that generates steam not used in the steam turbine. The EIA 860 database and the SNL database were consulted to try to determine if a unit was a cogeneration unit or not. Duct burner manufacturers were also consulted to learn where they had installed duct burners, though their response rate was low. Finally, the ratio of the combustion turbine capacity to the steam turbine capacity was analyzed, with the assumption that a typical combined cycle plant without extra steam turbine capacity has a 2:1 ratio of combustion turbine to steam turbine capacity. Based on this collection of data, each NGCC was analyzed to determine if it likely had sufficient extra steam turbine capacity for solar augmentation. Those that did not were not analyzed further. For 68 units, mostly in the planning stage, ratio information was not available. These plants were identified as plants that need more information before further analysis can be conducted. For coal plants, the EPRI model assumes that coal-firing will be reduced in order to accommodate the solar steam. Excess capacity in the steam turbine is not necessary.

Plants were evaluated on a unit level in the same way that they were screened on a full plant scale, except that the individual unit's in-service year and capacity factor were used when available. For plants with multiple units, each unit was initially screened with the assumption that it could use all of the land available surrounding the plant. However, in the modeling, the full amount of land available was divided among the units. For all plant locations, only the single largest contiguous land parcel was used. In some cases, it could be that two or more separate parcels could be used to add more solar to a plant, but such a piecemeal configuration could increase costs and was not used in this analysis.

Solar-Augment Integration

Units that passed all age, capacity factor, land availability, topography, and DNI screening criteria were then evaluated in models developed by EPRI to determine the solar-augment potential [2, 3]. EPRI developed detailed performance models using the process simulation software IPSEPro to examine a variety of integration points and solar steam conditions. While a more detailed analysis would be required before any specific project is undertaken, the modeling tool does provide an estimate of the solar-use efficiency and annual solar output of a given plant based on its general design, the amount of solar integration assumed and the solar resource available at its location.

Each unit was evaluated for both parabolic trough and power tower integration. The solar steam conditions (Table 2) are selected to match the typical steam pressure conditions expected in the fossil power plant at the point of integration. Boiler feedwater is extracted from the fossil plant's Rankine cycle and routed through a heat exchanger, where it is heated by the heat transfer fluid (HTF) coming from the solar field before being returned to the fossil plant's steam cycle at a location that depends on the steam conditions (Figure 3). The EPRI model was developed for oil-HTF trough and molten-salt-HTF power tower systems and assumes a heat exchanger bank is used to generate the specified steam. Similar performance results can be expected for other working fluids, such as steam, if the same temperatures and pressures of integrated steam are achieved. However, the cost and land usage of these direct steam generation designs may differ from the assumptions used here.

Table 2. Steam conditions and integration points for solar-augment.

Solar Technology	Fossil Technology	Preferred Integration point	Solar Steam Conditions
Parabolic Trough	Coal	Before superheaters	165 bar, 371 °C
	NGCC	Before superheaters	110 bar, 371 °C
Power Tower	Coal	After final superheater	165 bar, 538 °C
	NGCC	After final superheater	110 bar, 538 °C

The maximum amount of solar integration possible was determined for each unit, either based on the size of the plant and limits determined in earlier EPRI studies or the amount of land available. Limits imposed by the fossil plant included the duct firing capacity for NGCC units and the steam pressure limits on coal plants. For plants that were not limited by the amount of land available, the field was sized with a solar multiple of 1.2 over the maximum amount of solar thermal input the plant could accept. (A solar multiple of 1.0 provides the exact amount of solar thermal energy required when running at a specified design-point insolation.) While a solar multiple greater than one results in defocusing some mirrors during peak periods of solar resource, it results in more hours when the plant operates near full solar capacity. For plants with a limited amount of land, it was assumed that the newest units would receive the maximum augmentation based on the maximum solar field achievable. Power tower plants were limited to a maximum tower height of 300 meters based on input from Sandia National Laboratory and NREL. For sites with multiple units, it was assumed that one central receiver could provide solar input to multiple units if the tower was within the 300 meter limitation. For these plants, annual solar output is reported as a single output for all units fed by the tower. In cases where there were multiple units and enough land, it was assumed that more than one tower could be built on the same plant site to supply the multiple units. However, it was assumed that only one tower would feed an individual unit.

Once the maximum solar field was determined, NREL's System Advisor Model (SAM, https://www.nrel.gov/analysis/sam/) was run for the solar field size and plant location to determine the hourly thermal megawatt output of the field for a full year. These data were input into the EPRI model and the annual megawatt-hour output due to solar and the solar use efficiency were calculated. For NGCC plants, the EPRI model is based on solar steam integration into the high pressure stage of the heat recovery steam generator. The coal plant integration assumes that the solar steam is integrated with the main steam flow after the boiler and either before or after the superheater, depending on the solar technology used. The solar-use efficiency result for each unit was input to the database scoring spreadsheet as the final piece in the ranking criteria. Each unit was analyzed for maximum solar input based on either the land available or the plant size. It has been found that for solar-augmented plants, especially those using parabolic troughs, increased solar input can result in decreased solar-use efficiency. As a result, for the plants that did not have a land limitation, solar-use efficiency may be lower than those that had a reduced amount of solar input. However, these plants will have a higher annual solar output.

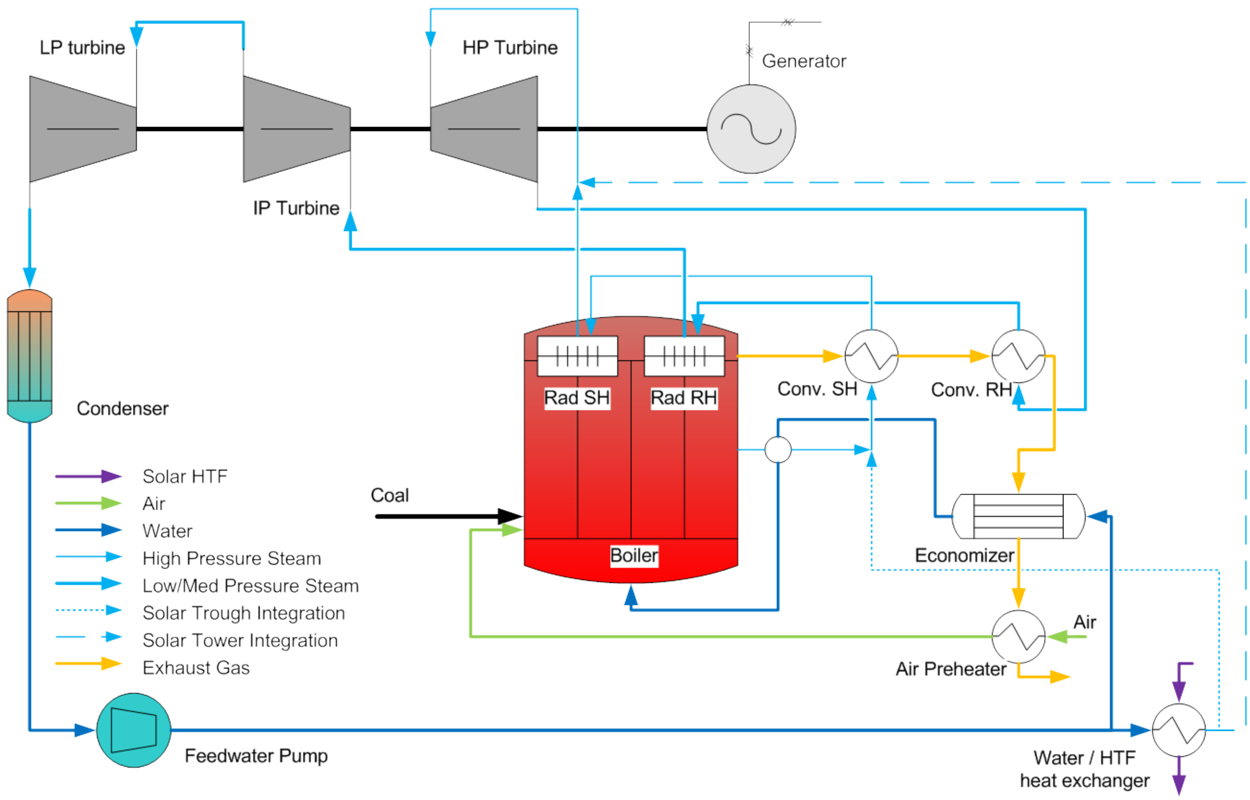

Figure 3. Simplified schematic of solar steam integration into a coal plant. SH = superheater; RH = reheater.

Rating the Plants

Once the plants were fully scored, they were ranked based on total score and assigned a rating of *Excellent, Good, Fair,* and *Not Considered*. Ratings were assigned on a 5-point scale where a score of 4-5 is *Excellent*, a score of 3-4 is *Good*, and a score of 2-3 is *Fair*. Plants and units that did not qualify for a complete evaluation are listed as *Not Considered* with an explanation of which criterion the plant failed. A handful of plants passed the initial hurdle but scored less than 2 in the ratings. Although they were evaluated, they were ultimately placed in the *Not Considered* category. A few plants were dropped for other reasons such as insufficient information on duct firing or extra steam turbine capacity.

Results and Discussion

It is important to note that the augment potential was calculated separately for parabolic troughs and power towers; thus, cumulative numbers for the two technologies should be considered individually and not added together. Technically, power towers offer a better option for augmentation because they can achieve higher steam temperatures than troughs and, therefore, have greater opportunity for integration with the fossil plant. From a project perspective, this technical advantage may be countered by the greater maturity and lower risk associated with the use of parabolic trough solar fields.

Capacity-Based Results

Table 3 displays the cumulative coal and NGCC nameplate capacity for the 16 states in the study. The numbers include existing, under construction, and planned facilities and combine for a total fossil-generation capacity of approximately 353 GW. For comparison, total nameplate capacity for all sources in the U.S. is 1122 GW [1]. Also shown are the augment potentials in MWe for both parabolic trough and power tower CSP technologies. The total augment potential for troughs comes to approximately 11 GWe, while towers offer the ability to achieve over 21 GWe. The augment potential for troughs represents roughly 3.2% of fossil capacity and for power towers corresponds to 6.1% of total fossil capacity. Figure 4 shows the cumulative augment potential for the two different CSP technologies in graphical form. This format highlights the greater potential and higher-quality potential capable with the power tower technology. All the *Excellent* sites are in the southwest, but every state has at least one *Good* site.

Table 3. Nameplate Fossil-Fired Capacity and Solar-Augment Potential by State

			Parabolic Trough (MWe)				Power Tower (MWe)			
State	Coal Capacity (MW)	NGCC Capacity (MW)	Excellent	Good	Fair	Total	Excellent	Good	Fair	Total
AL	12,620	13,020	-	45	723	767	-	49	918	967
AZ	6,760	15,570	849	253	-	1,102	1,794	97	-	1,890
CA	220	32,880	166	339	360	866	191	702	112	1,006
CO	6,120	4,290	-	173	283	456	-	953	167	1,120
FL	10,760	33,370	-	615	415	1,030	-	1,298	464	1,762
GA	17,300	9,590	-	131	523	654	-	609	701	1,310
LA	3,800	10,310	-	76	420	496	-	484	401	885
MS	2,920	7,680	-	18	363	381	-	215	438	653
NC	14,100	5,650	-	-	242	242	-	191	505	696
NM	5,880	1,780	19	322	-	341	105	502	-	607
NV	3,420	7,280	396	154	-	549	553	418	-	971
OK	5,720	10,320	-	111	698	809	-	511	1,150	1,661
SC	6,800	3,470	-	205	121	326	-	457	119	576
TN	9,990	1,840	-	40	-	40	-	45	-	45
TX	26,840	54,960	-	740	2,103	2,843	-	4,453	2,008	6,461
UT	5,090	2,570	-	328	13	341	-	1,031	-	1,031
	138,340	214,580	1,430	3,550	6,264	11,244	2,643	12,015	6,982	21,640
	Percentage relative to total fossil capacity =					3.2%				6.1%

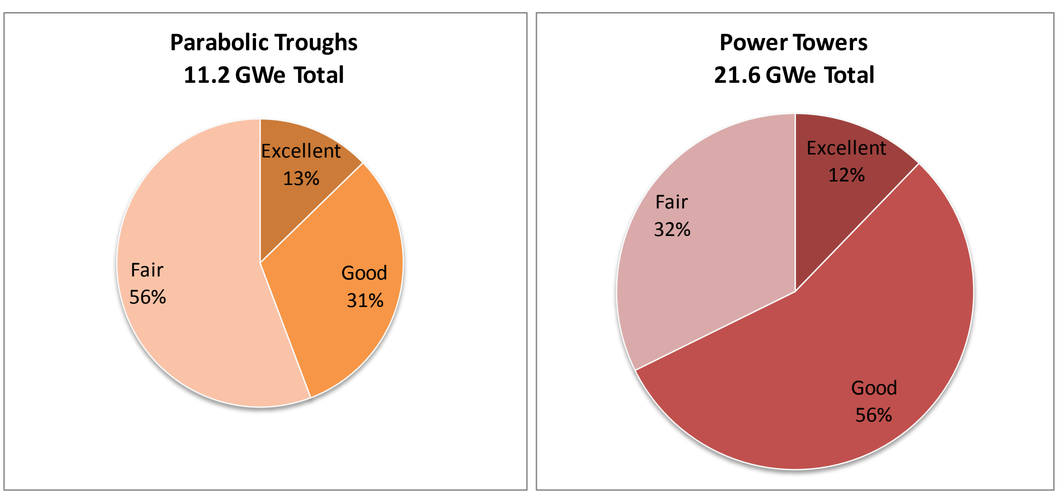

Figure 4. Augment potential in capacity (GWe) for either troughs (left) or power towers (right).

Energy-Based Results

Table 4 and Figure 5 display the results on the basis of total energy produced. Once again it is apparent that power towers provide greater options for augmentation, with slightly more than twice the total electricity production than is possible with parabolic troughs. The average capacity factor of the fossil systems in this study is approximately 46% for NGCC and 56% for coal generators. These values are almost twice that expected for the CSP technologies without storage. The corresponding solar contribution to total electricity generation is about one-third that stated above on a capacity basis. Troughs contribute about 1% to total annual energy generation, while power towers can contribute up to 2.2%. Adding thermal storage to the CSP system could increase their contribution, but this option was not included in the study. One primary benefit of solar-augment projects is their lower project risk and adding thermal storage would negate some of that advantage.

Table 4. Fossil-Fired Electricity Generation and Solar-Augment Potential by State

			Parabolic Trough (MWhe/yr)				Power Tower (MWhe/yr)			
State	Coal (MWhe/yr)	NGCC (MWhe/yr)	Excellent	Good	Fair	Total	Excellent	Good	Fair	Total
AL	60,225,000	53,370,000	-	56,371	957,685	1,014,056	-	77,454	1,399,077	1,476,531
AZ	45,433,000	58,359,000	1,886,412	573,063	-	2,459,475	4,616,796	262,916	-	4,879,711
CA	1,600,000	189,886,000	392,558	624,209	605,522	1,622,289	519,194	1,500,123	197,589	2,216,906
CO	39,717,000	21,181,000	-	280,856	505,049	785,905	-	1,841,594	429,124	2,270,719
FL	55,587,000	160,378,000	-	897,681	615,040	1,512,722	-	2,094,672	712,369	2,807,040
GA	94,778,000	44,620,000	-	178,546	784,650	963,197	-	1,034,561	1,010,809	2,045,369
LA	25,242,000	38,264,000	-	97,932	605,441	703,373	-	732,134	666,936	1,399,070
MS	14,677,000	22,433,000	-	23,332	493,457	516,789	-	362,735	698,973	1,061,708
NC	70,905,000	30,094,000	-	-	318,136	318,136	-	299,961	766,319	1,066,280
NM	42,172,000	7,502,000	42,124	710,663	-	752,788	272,172	1,187,217	-	1,459,389
NV	21,340,000	40,361,000	883,838	307,079	-	1,190,918	1,439,584	910,608	-	2,350,192
OK	36,576,000	48,791,000	-	154,462	1,022,963	1,177,426	-	861,349	1,991,516	2,852,865
SC	33,055,000	13,782,000	-	295,896	164,602	460,498	-	715,880	191,485	907,365
TN	47,561,000	12,095,000	-	51,365	-	51,365	-	71,241	-	71,241
TX	182,256,000	262,224,000	-	1,107,929	3,287,412	4,395,341	-	7,611,358	3,469,448	11,080,806
UT	37,027,000	14,948,000	-	593,496	20,830	614,326	-	2,158,241	-	2,158,241
	808,151,000	1,018,288,000	3,204,932	5,952,882	9,380,788	18,538,603	6,847,746	21,722,044	11,533,644	40,103,433
					Percentage relative to total fossil-derived electricity =	1.0%				2.2%

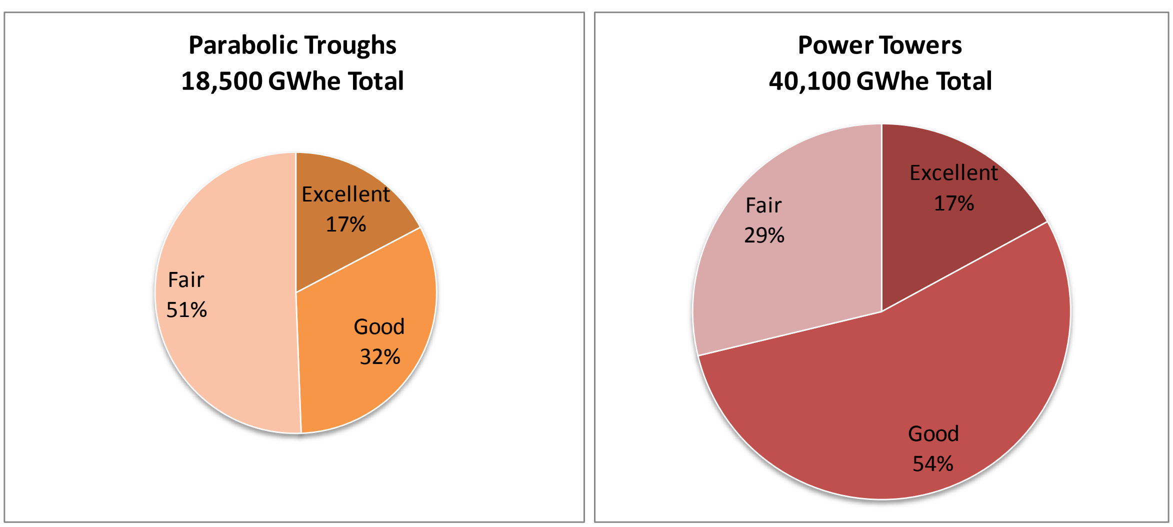

Figure 5. Augment potential in energy (GWhe) for either troughs (left) or power towers (right).

The solar-use efficiency (Figure 6) is calculated as the net electric energy attributed to solar divided by the solar thermal energy delivered to the power block. For comparison, the net thermodynamic conversion efficiency at design point for a solar-only trough or power tower system is approximately 33% or 37%, respectively. (This efficiency is calculated as the plant's net electric output divided by thermal energy delivered to the power block.) Although this was not a goal of the study, some of the best solar augment cases exceed the efficiency of the stand-alone solar plants. This study seeks to maximize solar contribution and, as shown in Figure 1, greater solar contribution often leads to lower solar-use efficiency.

As shown in Figure 7, the solar-use efficiency is slightly higher for NGCC plant augmentation than for coal plants. These different efficiencies result from what governed solar-augment capacity. EPRI limited NGCC plants by the duct burner or extra steam turbine capacity in the plant, while coal plants were limited by when turbine pressure limits were reached. Turbine pressure rises as one incorporates lower quality steam and seeks to offset the steam quality by increasing mass flow through the turbine to maintain plant output. This is most apparent for trough-based augments. Thus, the slightly higher solar-use efficiency in NGCC plants is an artifact of the lower solar fractions applied to the NGCC plants. EPRI's prior work indicates that solar-use efficiencies in coal plants can be higher than NGCC facilities when the integration is optimized for high solar-use efficiency rather than maximum solar output [2, 3].

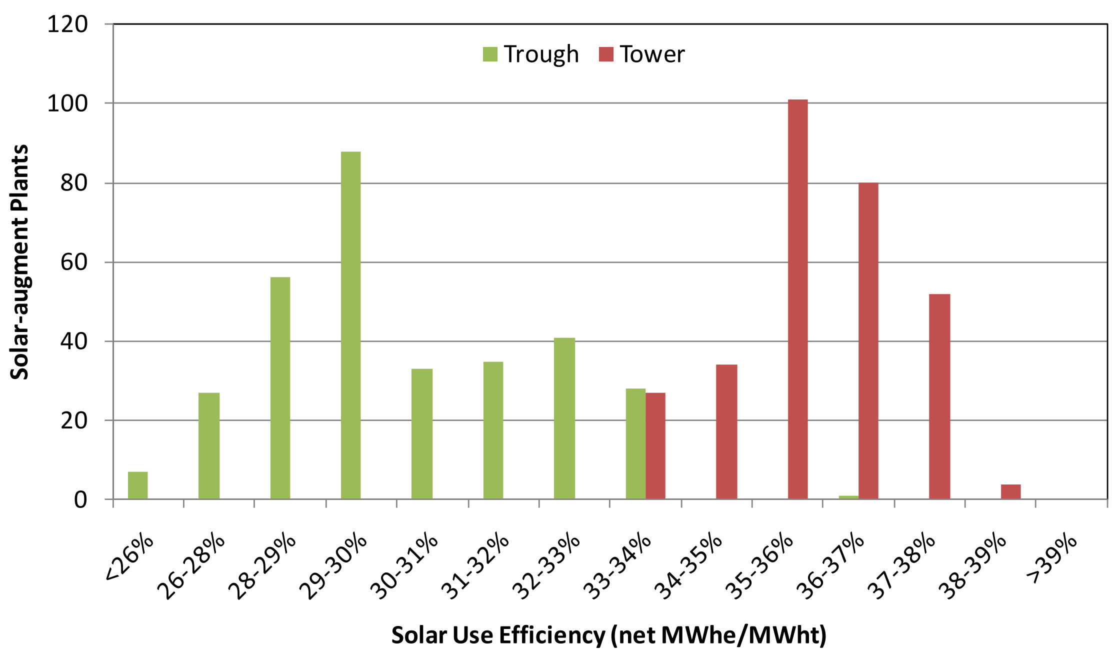

Figure 6. Higher temperatures allow power towers to have higher solar-use efficiencies compared to troughs.

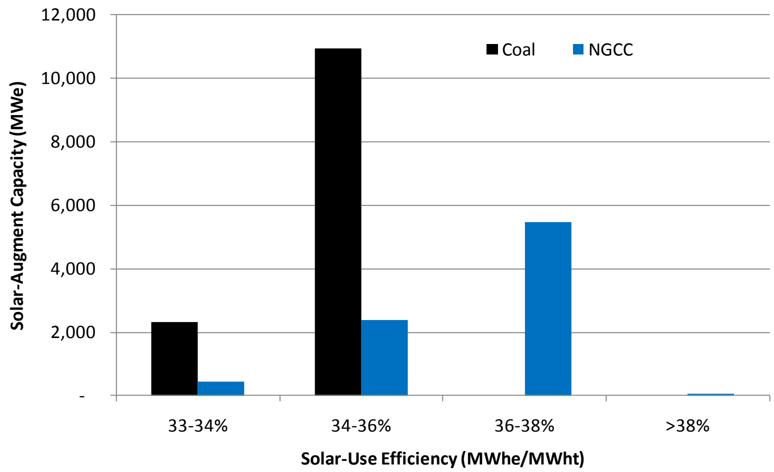

Figure 7. The higher solar-use efficiency for NGCC plants is an artifact of their typically lower solar-augment fraction due to limiting solar integration to the plant's duct firing or extra steam turbine capacity.

Emission Reductions

Solar-augment of fossil-fired power plants results in the reduction of air emissions associated with coal and natural gas combustion. The potential emission savings were quantified by examining the annual solar energy contribution in MWhe and assuming fuel consumption was diminished according to the reported heat rate for the facility in question. If heat rate was not reported, a value of 10,000 BTU/kWh for coal and 7,500 BTU/kWh for NGCC was used. Emission savings were calculated using EPA emission factors that are typically listed as pounds of pollutant per ton of coal or per standard cubic foot of natural gas [5]. Values were calculated for carbon dioxide (CO_2), sulfur dioxide (SO_2) and nitrogen oxides (NO_x). Other pollutants or by-products, for example, mercury and fly ash, could be calculated in a similar fashion but are not included in this report. The formula used for emissions reduction for each solar augment case took the form of:

Reduced air emissions =
(Solar Augment, kWhe/yr)(Heat rate, BTU/kWhe)*(CO2 emission factor, lb CO2/BTU)*(metric ton/2205 lb);*
(Solar Augment, kWhe/yr)(Heat rate, BTU/kWhe)/(heat value coal, BTU/lb)*(SO2 emission factor, lb SO2/ton coal)* (0.9072 metric ton/ton);*
(Solar Augment, kWhe/yr)(Heat rate, BTU/kWhe)/(heat value coal, BTU/lb)*(NOx emission factor, lb NOx/ton coal)*(0.9072 metric ton/ton).*

Similar expressions were used to evaluate the emissions from natural gas combustion. The emission factors and values used for coal and natural gas properties are shown in Table 5 below. Values representative of Powder River Basin subbituminous coal were used for all the pulverized coal plants in the western states and an Illinois Basin coal was selected to represent coal plants in the eastern states. Actual fuel source for the individual plants is not reported. It was assumed that all plants utilized low-NOx burners and coal units larger than 400 MW employed some form of SO_2 scrubbing. (According to the EPA, the average size of units with SO_2 scrubbers is slightly over 400 MW [11].) Because of these broad assumptions the estimated air emission savings should be considered rough approximations.

Table 5. Emission Factors and Fuel Properties used to Estimate Avoided Air Emissions

Parameter	Value	Units	Source / Comments
Coal heat value (western)	8,600	BTU / lb	Representative of Powder River Basin subbituminous coal
Coal heat value (eastern)	11,400	BTU / lb	Representative of Illinois Basin, high-sulfur coal
Coal CO_2 emission factor	210	lb CO_2 / MMBTU	http://www.eia.doe.gov/cneaf/coal/quarterly/co2_article/co2.html
Coal SO_2 emission factor (western)	4.6	lb SO_2 / ton	[5], assumes 0.6% sulfur coal and 80% scrubber control (Units smaller than 400 MW have no scrubber)
Coal SO_2 emission factor (eastern)	11	lb SO_2 / ton	[5], assumes 2.9% sulfur coal and 90% scrubber control (Units smaller than 400 MW have no scrubber)
Coal NOx emission factor	7.5	lb NO_2 / ton	[5], assumes low-NOx burners and subbituminous coal
NG heat value	1,000	BTU / SCF	Typical value for natural gas, SCF= standard cubic foot
NG CO_2 emission factor	0.12	lb CO_2 / SCF	[5]
NG SO_2 emission factor	0.6	lb SO_2 / 10^6 SCF	[5]
NG NOx emission factor	140	lb NO_2 / 10^6 SCF	[5], assumes low-NOx burners

The annual air emission reductions by state and in total are shown in Table 6. As before, the values shown assume solar-augmentation using either parabolic troughs or power towers. The total solar contribution for each approach (trough or tower) is provided along with the associated estimated air emission reductions. The trough case reduces CO_2 emissions by 11.5 million metric tons per year and the tower case provides an annual reduction of 30 million metric tons. A check of these total emission values is made by comparison with the emission footprint for the electric generation industry (by NERC region) published by the Leonardo Academy [6]. Average industry-wide emission factors for the five NERC regions relevant for this study are: 1.4 lb CO_2/kWh, 0.0039 lb SO_2/kWh, and 0.0020 lb NOx/kWh. Using these values yields avoided emission estimates for CO_2 and NOx that are 15% to 30% lower, which can be explained by nuclear and renewable power generators, as well as post-combustion NOx controls on some plants, lowering the industry-average emission factor. The industry-average estimate for SO_2 emissions is within 2%, but when nuclear and renewable generation are accounted for this suggests our estimated SO_2 savings maybe too low. That is, actual SO_2 savings may be greater than listed in Table 6.

Figure 8 highlights the fact that solar-augment of coal plants yields much greater air emission savings than the augment of NGCC power plants. This is due to the greater emissions that result from coal combustion compared to natural gas use. If reduction of air emissions is the primary goal, solar-augment of coal plants is an effective pathway.

Table 6. Annual Air Emission Reductions Assuming Deployment of Parabolic Trough or Power Tower Systems to Augment Fossil Generators

	Parabolic Trough Augment				Power Tower Augment			
State	Solar Power Generation (MWhe)	CO2 avoided (metric ton)	SOx avoided (metric ton)	NOx avoided (metric ton)	Solar Power Generation (MWhe)	CO2 avoided (metric ton)	SOx avoided (metric ton)	NOx avoided (metric ton)
AL	1,014,000	549,000	1,200	700	1,477,000	819,000	3,400	1,100
AZ	2,459,000	1,237,000	800	1,800	4,880,000	3,189,000	3,800	5,600
CA	1,622,000	658,000	100	800	2,217,000	925,000	500	1,100
CO	786,000	544,000	900	1,000	2,271,000	1,884,000	3,800	3,700
FL	1,513,000	1,004,000	4,500	1,400	2,807,000	2,094,000	13,500	3,100
GA	963,000	748,000	1,500	1,100	2,045,000	1,655,000	3,800	2,500
LA	703,000	511,000	900	700	1,399,000	1,144,000	2,200	1,700
MS	517,000	289,000	300	400	1,062,000	759,000	1,200	1,100
NC	318,000	250,000	1,700	400	1,066,000	959,000	7,300	1,500
NM	753,000	526,000	700	1,000	1,459,000	1,169,000	2,200	2,200
NV	1,191,000	625,000	1,100	900	2,350,000	1,588,000	5,100	2,800
OK	1,177,000	727,000	800	1,200	2,853,000	2,238,000	3,300	4,200
SC	460,000	305,000	2,100	400	907,000	657,000	7,600	1,000
TN	51,000	21,000	-	-	71,000	29,000	-	-
TX	4,395,000	3,014,000	3,300	5,400	11,081,000	9,058,000	12,600	17,600
UT	614,000	486,000	500	900	2,158,000	1,903,000	2,300	3,900
	18,536,000	11,494,000	20,400	18,100	40,103,000	30,070,000	72,600	53,100

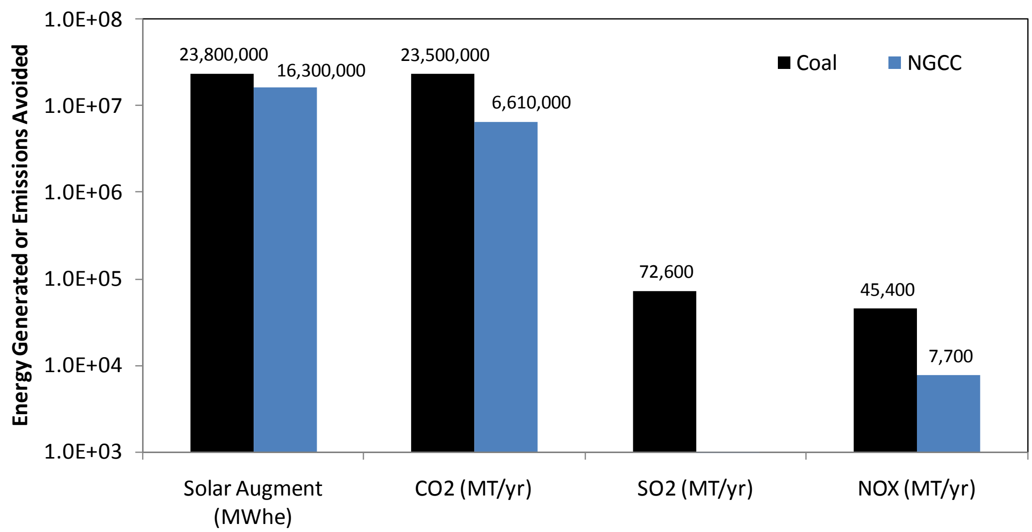

Figure 8. Greater air emissions savings are achieved by augmenting coal plants versus NGCC plants. Data for power tower augment shown. SO_2 emissions from NGCC are less than 33 MT/yr.

According to the US EPA, the average coal plant emitted 3.85 million metric tons of CO_2 in 2005; therefore, the estimated CO_2 savings of 30 million metric tons per year is roughly equivalent to elimination of 8 average-size coal power plants in the U.S. [10].

Deployment Impacts

Figure 9 shows the deployment of solar-augment systems by state for the parabolic trough and power tower cases. Texas displays the greatest potential due to its good solar resource and numerous fossil power plants. The sunny southwest holds the only states with opportunities that score *Excellent*, but every state has at least one application that ranks *Good*.

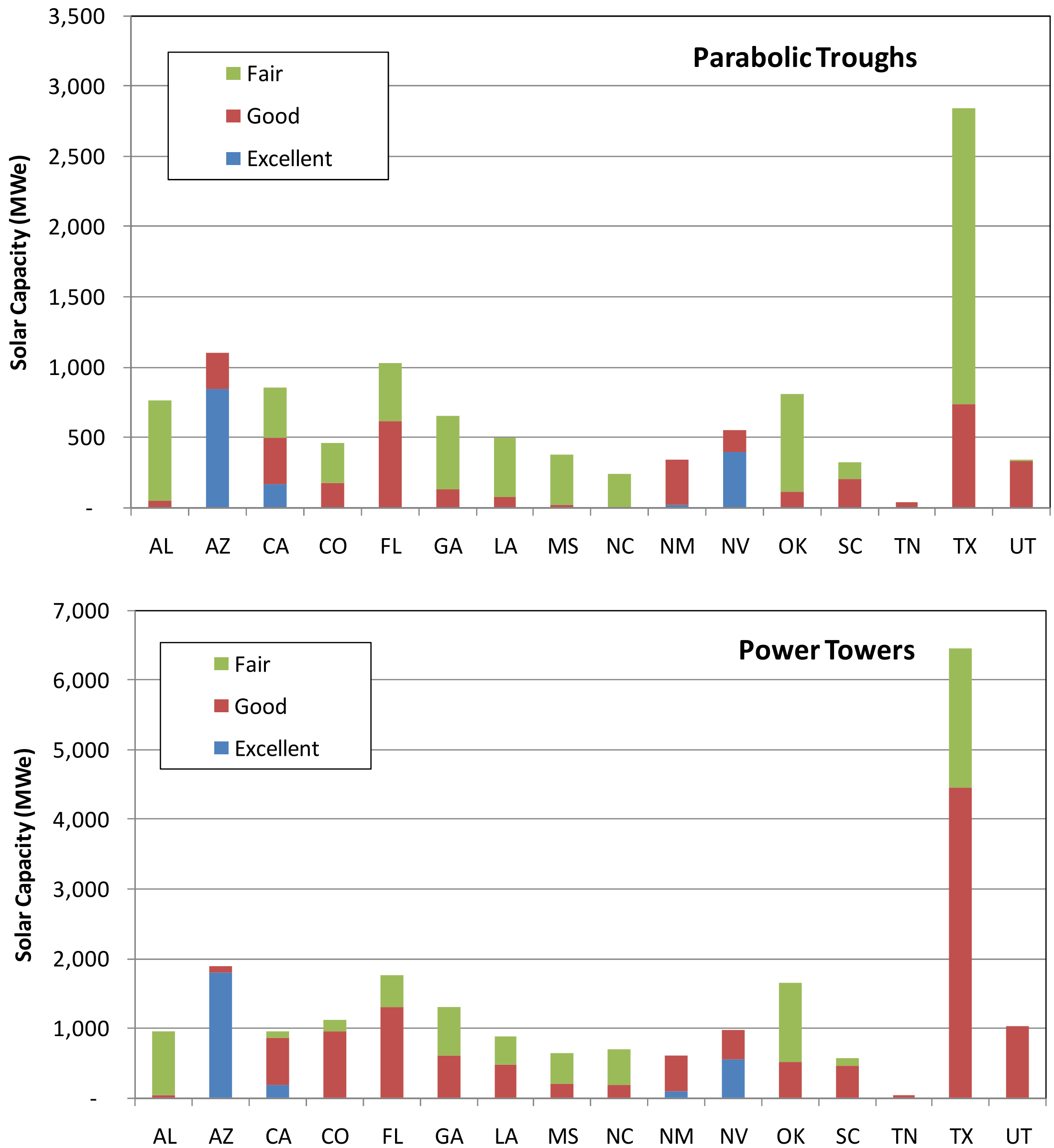

Figure 9. Solar-augment capacity by state for parabolic trough (top) and power tower (bottom) technologies. Note different y-axis scale.

The improvement of new technology cost with greater production volume is often tracked using a *progress ratio (PR)*, where:

$$\left(\frac{Cost2}{Cost1}\right) = (PR)^{(number\ of\ volume\ doublings)}$$

Assuming a progress ratio of 0.90, as suggested by [7], and accounting for world-wide parabolic trough capacity of ~2000 MW, the US solar-augment market alone could drive a 40% cost reduction in parabolic trough technology due to deployment, while taking advantage of the lower risk and cost associated with such projects.

At present there is only one 5-MW power tower demonstration in the US, although BrightSource's 370-MW Ivanpah project is under construction. The lower maturity of the technology and greater size of the solar-augment market means the opportunity for cost reductions in power towers is even greater than for troughs. Direct steam generation towers, such as offered by BrightSource, are ideally suited for solar-augment applications because steam is the desired final product. Steam towers are also simpler than molten salt designs, further reducing project risk.

It is worth mentioning that several developers are investigating direct steam generation troughs. The deployment of 500°C steam troughs would improve the economics of trough augment systems by elimination of the oil-to-steam heat exchanger bank and improve augment potential by providing higher temperature steam than is possible with current 390°C oil troughs.

If the full solar-augment capacity were developed, the estimated cost and land requirements are listed in Table 7. The trough field is assumed to require 5 acres per MW and the tower heliostat field is larger at 9 acre per MW. This power tower land area is based on values for large, single-tower designs. Modular tower designs promoted by some developers are reported to have a land use of roughly 50% smaller, i.e., comparable to the trough footprint. Investment costs are based on current estimated costs for parabolic trough and power tower systems minus the power block, but including costs for integration with the fossil plant. These are assumed to be approximately $4000/kW for troughs [8] and $3400/kW for steam towers [9]. As noted above, costs are expected to fall as deployment volume increases.

While this study seeks to identify the most favorable solar-augment sites, is does not address the specific economics of solar-augmentation. It is important to note that EPRI's latest analyses [2, 3] indicate solar-augment of fossil power stations is not cost-effective based purely on the cost of energy and using the current cost of parabolic trough and power tower hardware. However, the solar-augment option is believed to be less expensive and contain less project risk than a stand-alone solar plant. For utilities grappling with renewable portfolio standards, solar-augment of existing assets could be a valuable component to their renewable generation mix. Furthermore, aside from the ability to generate steam, the benefits of solar-augment projects are not tied to a specific technology. As CSP technology costs decrease, the solar-augment option is likely to be the first approach to achieve true cost parity with the traditional generation technologies.

Table 7. Estimated Solar Augment Capacity by State and the Associated Land and Investment Requirements

	Parabolic Trough Augment			Power Tower Augment		
State	Capacity (MWe)	Land (acres)	Investment ($M)	Capacity (MWe)	Land (acres)	Investment ($M)
AL	767	3,840	3,100	967	8,700	3,300
AZ	1,102	5,510	4,400	1,890	17,010	6,400
CA	856	4,280	3,400	967	8,700	3,300
CO	456	2,280	1,800	1,120	10,080	3,800
FL	1,030	5,150	4,100	1,762	15,860	6,000
GA	654	3,270	2,600	1,310	11,790	4,500
LA	496	2,480	2,000	885	7,960	3,000
MS	381	1,910	1,500	653	5,870	2,200
NC	242	1,210	1,000	696	6,260	2,400
NM	341	1,710	1,400	607	5,460	2,100
NV	549	2,750	2,200	971	8,740	3,300
OK	809	4,050	3,200	1,661	14,950	5,600
SC	326	1,630	1,300	576	5,190	2,000
TN	40	200	200	45	400	200
TX	2,843	14,210	11,400	6,461	58,150	22,000
UT	341	1,710	1,400	1,031	9,280	3,500
	11,235	56,190	45,000	21,601	194,400	73,600

Conclusions

Solar-augment of existing fossil power plants offers a lower cost and lower risk alternative to stand-alone solar plant construction. This study ranked the potential to add solar thermal energy to each of the coal-fired and natural gas combined cycle plants found throughout the 16 states representing the southern half of the United States. Each generating unit was ranked on a four-tiered scale ranging from *Excellent* to *Not Considered*. Separate analysis was performed for parabolic trough and power tower technologies due to the difference in the steam temperatures that each can generate. The study found a potential for over 11 GWe of parabolic trough and over 21 GWe of power tower capacity. Power towers offer more capacity and higher quality integration due to the greater steam temperatures that can be achieved. The best sites were in the sunny Southwest, but all states had at least one site that ranked *Good* for augmentation.

The study sought to maximize solar energy generation. Even so, the solar-use efficiency for the solar field sizes evaluated is comparable to stand-alone CSP plant designs. Smaller solar-augment fraction may yield higher solar-use efficiencies, if that is the dominant design criterion. The cost of technology deployment and project risk are lower than stand-alone CSP plants, suggesting that solar-augmentation is an attractive option for near-term deployment of solar power to meet renewable portfolio standards and reduce greenhouse gases and other air pollutants. These studies assume solar-augment to offset fuel usage at the fossil power stations. Accordingly, replacing fuel used for duct firing in NGCC plants will yield the best economics; however, the reduction of air emissions is much greater when coal plants are augmented.

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14. ABSTRACT *(Maximum 200 Words)*
Concentrating Solar Power (CSP) systems utilize solar thermal energy for the generation of electric power. This attribute makes it relatively easy to integrate CSP systems with fossil-fired power plants. The “solar-augment” of fossil power plants offers a lower cost and lower risk alternative to stand-alone solar plant construction. This study ranked the potential to add solar thermal energy to coal-fired and natural gas combined cycle (NGCC) plants found throughout 16 states in the southeast and southwest United States. Each generating unit was ranked in six categories to create an overall score ranging from Excellent to Not Considered. Separate analysis was performed for parabolic trough and power tower technologies due to the difference in the steam temperatures that each can generate. The study found a potential for over 11 GWe of parabolic trough and over 21 GWe of power tower capacity. Power towers offer more capacity and higher quality integration due to the greater steam temperatures that can be achieved. The best sites were in the sunny southwest, but all states had at least one site that ranked Good for augmentation.

15. SUBJECT TERMS
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