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Can Hybrid Solar-Fossil Power Plants Mitigate CO_2 at Lower Cost than PV or CSP?

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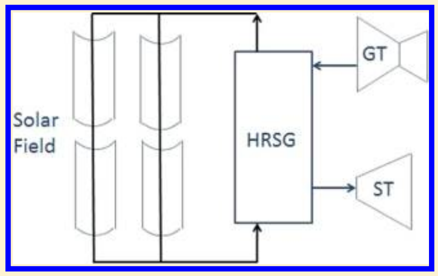
Ⓢ *Supporting Information*

ABSTRACT: Fifteen of the United States and several nations require a portion of their electricity come from solar energy. We perform an engineering-economic analysis of hybridizing concentrating solar thermal power with fossil fuel in an Integrated Solar Combined Cycle (ISCC) generator. We construct a thermodynamic model of an ISCC plant in order to examine how much solar and fossil electricity is produced and how such a power plant would operate, given hourly solar resource data and hourly electricity prices. We find that the solar portion of an ISCC power plant has a lower levelized cost of electricity than stand-alone solar power plants given strong solar resource in the US southwest and market conditions that allow the capacity factor of the solar portion of the power plant to be above 21%. From a local government perspective, current federal subsidies distort the levelized cost of electricity such that photovoltaic electricity is slightly less expensive than the solar electricity produced by the ISCC. However, if the cost of variability and additional transmission lines needed for stand-alone solar power plants are taken into account, the solar portion of an ISCC power plant may be more cost-effective.



■ INTRODUCTION

Many governments around the world provide incentives for solar energy. Of the 29 US states that have renewable portfolio standards (RPS), 15 have solar provisions.[1] Given the specific solar requirements states have invoked and the broader emphasis on solar energy, we seek to determine the cost effectiveness of hybridized solar/thermal systems compared to other solar technologies that comply with the requirements, specifically solar photovoltaics (PV) and concentrated solar thermal power (CSP).

Integrated Solar Combined Cycle Technology. Integrated Solar Combined Cycles (ISCC) are natural gas combined cycle (NGCC) power plants hybridized with solar thermal energy to boost the output of the heat recovery steam generator. The principal advantage to hybridization for solar power is the ability to directly offset fossil fuel energy without having to pay for a power block or transmission lines dedicated to solar energy. The solar field is made up of parabolic troughs, which have mirrors that reflect solar rays onto an evacuated glass tube carrying heat transfer fluid (HTF),[2] designed to absorb solar energy. The power block is essentially the components at the center of typical thermal based power plants: boiler, heat exchangers, steam turbine, condenser, etc. The power block of a stand-alone CSP plant is an appreciable investment, accounting for approximately 40% to 50% of the capital costs.[3,4] Assuming that the capacity factor of stand-alone CSP plants is around 25%, sharing a power block with a fossil fuel power plant significantly increases its utilization. Additionally, since maintenance personnel are already on hand to monitor and maintain the power block, maintenance costs assigned to the solar portion are reduced relative to stand-alone solar plants.[5] Figure 1 shows an illustration of the concept.

We assume the plant in which we would integrate solar thermal energy would have "duct firing" capability. NGCC plants with duct firing capability have an oversized steam turbine in which the full capacity may be utilized only by directly heating steam with a natural gas burner. This direct heating takes place in the HRSG (no. 3 in Figure 1 below). Because duct firing utilizes direct heating (Rankine cycle) instead of a combined cycle, using duct firing lowers the overall efficiency of the plant. However, the duct firing is utilized only when grid prices are high and the marginal benefit of increased MWh production outweighs the slightly higher marginal cost per MWh caused by duct firing.

With ISCC capability, solar energy is used to reduce the quantity of natural gas used in duct firing or to add generation without the energy penalty of duct firing. When solar resources are high, the combined cycle can run at full capacity with a lower heat rate than base-load without duct firing (Table 1). Replacing natural gas duct firing with solar energy is an advantage for combined cycle plants because the marginal costs are lower than other NGCC plants. Therefore, as demand increases, an ISCC plant will be dispatched before a NGCC plant.

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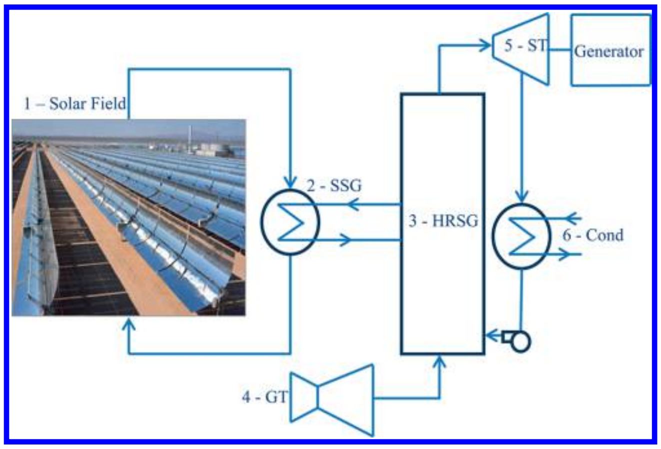

Figure 1. Diagram of an ISCC plant, after Flagsol:[6] 1. parabolic trough solar field;[7] 2. solar steam generator (SSG); 3. heat recovery steam generator (HRSG); 4. gas turbine and generator (GT); 5. steam turbine (ST) and generator; 6. condenser. Solar thermal energy is integrated into the HRSG. Heat transfer fluid (HTF) is heated in the solar field by parabolic trough-shaped mirrors. Hot HTF is then used to make steam in a heat exchanger before the steam returns to the HRSG. Use of natural gas to directly heat steam, also known as duct firing, occurs in the HRSG.

Table 1. Efficiency and MW Output Comparison of Victorville 2 CEC Application and Constructed Thermodynamic Model Used for This Paper

	base load		duct firing		solar and duct firing	
	efficiency (LHV/HHV)	MW	efficiency (LHV/HHV)	MW	efficiency (LHV/HHV)	MW
CEC application for certification	55.2/49.7%	463	52.6/47.4%	563	58.8/53.0%	563
constructed model	54.9/49.4%	463	52.9/47.7%	567	59.2/53.3%	564

Development of ISCC Plants. The concept of hybridizing solar thermal power plants was first used in 1986 in some of the Solar Electric Generating System (SEGS) plants.[8] However, these were not combined cycle power plants but Rankine cycle plants with parallel natural gas boilers.

Hybrid solar thermal with NGCC's has become more mature. Plants have been constructed in Italy, Iran, Morocco, and Algeria with solar capacities of 5 MW, 17 MW, 20 MW, and 25 MW, respectively.[9−12] Florida Power and Light retrofitted one of its NGCC plants in 2010 to make the equivalent of a 75 MW solar plant.[13]General Electric recently bought an interest in eSolar and is developing an ISCC plant in Turkey. ISCC plants are being developed in the U.S., India, Mexico, and Egypt.[14−17]

WorleyParsons prepared a comprehensive set of reports in 2009 on ISCC technology for the Electric Power Research Institute (EPRI).[5] The reports allowed us to make design decisions for the ISCC plant model and to validate our model's efficiency and costs. EPRI divided the research into solar augmentation for NGCC or for coal plants. The present paper focuses on integration with natural gas plants because we believe that relatively low natural gas prices due to shale gas combined with stricter EPA rules will cause NGCC plants to dominate future development.

METHODS

Selection of Solar Technology. We elected to model parabolic trough plants without storage because the technology is relatively mature and performance and cost data are available. Power tower technology may be preferable to parabolic troughs because the thermal medium used in a power tower can reach higher temperatures, thus increasing steam cycle efficiency. However, the modeling of power towers is far more difficult and uncertain with the larger vendors (BrightSource, Solar-Reserve, and eSolar) all having unique designs with uncertain costs.

Design of the ISCC Plant and Thermodynamic Model. It was necessary to build a thermodynamic model to calculate marginal fuel costs, solar electric generation, and fossil electric generation as the solar resource varied. The EPRI reports[5] provided a basic understanding of the design and operation of an ISCC plant. However, to design the thermodynamic model, we extracted technical data from the Victorville 2 Hybrid Power Project Application for Certification for the California Energy Commission (CEC).[18] The application gives three different heat balances: base-load, duct-firing, and duct-firing with solar. A heat balance reveals the gas and steam flows at each major part of the power plant steam cycle. It also shows the temperature, pressure, and energy content of the fluids.

In agreement with the recommendation of the EPRI reports, the solar steam was injected into the high pressure steam drum for the Victorville 2 Hybrid Power Project permit application. The thermodynamic properties of the steam and gas were given for most points in the heat balance diagrams, and we constructed a complete thermodynamic model using MATLAB and Cantera software.[19] A detailed description of the construction, use, and assumptions of the thermodynamic model is available in the Supporting Information (SI) on page S10.

The validation results of our thermodynamic model are shown in Table 1.

To ensure that assumptions were not adjusted solely to meet the data points in Table 1, we devised a method to separate the contributions of the solar and fossil electricity.

Computing the Renewable Fraction. In order to receive renewable energy credits, the CEC requires that hybrid plants "...submit with its application ... a proposal for an appropriate method to measure the renewable fraction of the facility's generation".[20]

The thermodynamic model allows us to determine the renewable portion at varying solar and duct-firing loads. The method we use to find the renewable electricity is straightforward: if we add heat from the CSP unit to a fixed amount of gas input, the difference in power produced is solar. For example, at base load, the combined cycle uses about 140000 pounds per hour (3180 MMBTU/h) of gas and produces approximately 460 MW. When 145 thermal MW of solar energy are sent to the power block with the same gas input, the output of the plant increases to approximately 510 MW. The difference, 50 MW, is the solar electricity produced. Similarly, one of the three heat balances submitted to the CEC for the Victorville 2 Hybrid Power Project used 20000 pounds per hour (454 MMBTU/h) of natural gas for duct firing and 145 thermal MW of solar energy to produce approximately 560 MW. If the solar energy was removed, and we used the same amount of gas for duct firing, only 510 MW of electricity would

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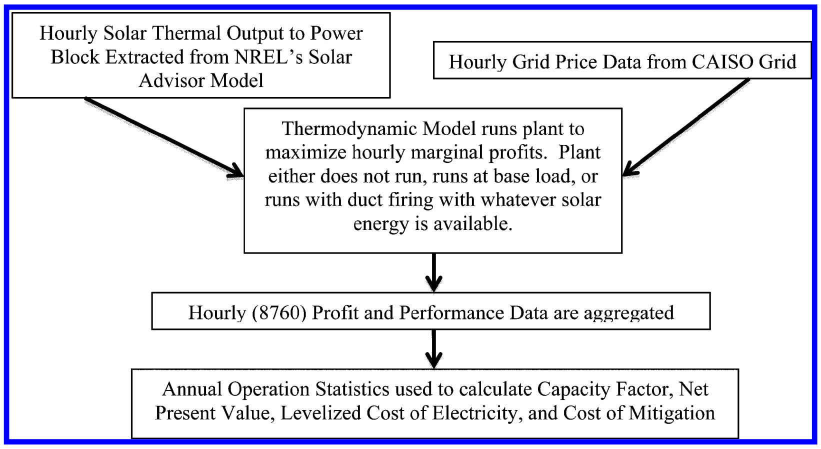

Figure 2. Block diagram of economic model.

be produced. Constructing the thermodynamic model allowed us to perform this calculation (SI page S5).

Economic Model. With the ability to model output and efficiency with varying loads of solar thermal energy, with or without duct firing, an economic model can be constructed. This economic model simulates the behavior of a plant operator maximizing marginal profits. The simulations are needed to determine the private and public economics of the power plant. A capacity factor is needed to estimate the levelized cost of electricity (LCOE), and this capacity factor is determined by expected plant operation. A block diagram of the economic model is shown in Figure 2.

The amount of solar energy sent to the power block is determined by NREL's Solar Advisor Model (SI page S16). The grid price used is the median node price for each hour in the California Independent System Operator (CAISO) region in 2010 (SI page S2).[21] Every hour, one of three policies is followed: run at base-load, run with duct firing, or do not run at all. The policy that maximizes marginal profits is chosen for that hour. The economic model computes how the plant is operated (how many MWh are produced) given marginal gas prices and marginal electricity prices.

Parametric Study Varying Price of Gas and Electricity. We present our results as a parametric study varying the price of natural gas and electricity. Both the price of natural gas and the price of electricity are of importance to both the solar and fossil side of the power plant. In order to use the solar energy, the gas turbine of the power plant must be active. Without heat from the gas turbine, solar heat alone does not provide enough energy to keep the quality of the steam exiting the steam turbine above 0.9 (more information in the SI on page S7).

Natural gas price varied between \$2 to \$12 per MCF in the past decade.[22] The average price of electricity has varied significantly over the past decade in California.[23] Between 2005 and the recession of 2008, the average price varied from \$62/MWh to \$81/MWh. After the recession, the average wholesale price varied from \$37/MWh to \$40/MWh. Our sensitivity analysis varied the price of electricity from \$35/MWh to \$85/MWh. To vary the price of electricity for the parametric study, we multiply the observed hourly data by a constant to produce the desired average annual price.

RESULTS

Capacity Factor. The economic viability of the power plant is dependent on how many MWh are produced. Therefore, the first result we present, Table 2, is the capacity factor of the solar side and the overall capacity factor of the entire power plant.

Table 2. Capacity Factor of the ISCC Power Plant/Solar Portion of ISCC Power Plant (Location: Phoenix)

		average wholesale price of electricity [\$/MWh]					
		\$35	\$45	\$55	\$65	\$75	\$85
price of gas [\$/MCF]	2	87/22%	89/22%	89/22%	90/22%	90/22%	90/22%
	4	58/19%	80/21%	85/22%	87/22%	88/22%	89/22%
	6	16/8%	43/16%	67/20%	80/21%	84/21%	86/22%
	8	6/2%	15/7%	35/15%	55/19%	71/21%	79/21%
	10	4/1%	7/2%	14/7%	29/12%	45/17%	61/20%
	12	3/1%	4/1%	7/2%	14/6%	26/11%	39/15%

The capacity factor is defined as the number of MWh produced divided by the number of MWh that could have been produced if the plant ran at capacity for all 8760 h of the year. We assumed the plant would be constructed in Phoenix, Arizona. We also assumed an outage rate of 5% to account for the effect of planned and unplanned maintenance on MWh produced.

The capacity factor for the solar portion of the power plant is close to the observed ~25% capacity factor for CSP generators. Since the solar side of the plant can run only while the power block is available, the capacity factor is slightly lower due to an outage rate of 5% on the fossil side of the ISCC plant. Additionally, stand-alone CSP plants are expected to have a higher capacity factor because of a higher solar multiple (SI page S16).

The ISCC capability raises the capacity factor slightly (~2%) when compared to an NGCC plant under market conditions suitable for NGCC development. The boost to the capacity factor of the overall ISCC plant is limited because of the infrequency of solar energy. Also, the observed CAISO grid price remains too low in the mornings of the spring and early summer for the plant to run, even with solar energy lowering the marginal cost per MWh.

Economic Assumptions. The assumptions we used for the capital costs and maintenance are shown in Table 3.

Table 3. Capital Costs, Maintenance Costs, and Lifetime of Plant ($2010 USD)[a]

	NGCC[24,25]	solar thermal[24,25,3,5] (trough, no storage)	solar PV[24,25,26,27,28]	solar part of ISCC[5,3]
capital costs $/kW	1000 ± 100	5800 ± 500	4400 ± 1000	3900 ± 600
fixed maintenance costs $/kW-year	5.8 ± 1	65 ± 15	25 ± 10	30 ± 10
lifetime of plant (years)	25	25	20	25

[a]The cost estimate for PV is based on the cost per AC watt. Cost estimates for PV are frequently quoted in $/Watt$_{DC}$. To arrive at the cost per watt AC, we multiply the DC cost estimates by 1.15 for the AC to DC capacity difference. Therefore, the mid-value for capital costs for PV we garnered from studies was $3.8/W$_{DC}$.

To calculate the levelized cost of electricity and the net present value of the NGCC and ISCC plants, we used the economic assumptions shown in Table 4.

Table 4

parameter	comment
private discount rate	12%
social discount rate	3%
equity ratio	65%
fossil portion depreciation	straight line over lifetime of plant
renewable portion depreciation	accelerated over 5 years
federal tax rate	34%
state tax rate	4.2%
interest rate	5.8%
investment tax credit (renewable portion)	30%
location of power plant unless noted otherwise	Phoenix, AZ, U.S.

The solar portion of the ISCC cost estimate in Table 5 includes the components of the solar plant (solar field, solar boiler, and piping to connect power block to solar boiler). However, in addition to the solar components, we assumed in our economic analysis that the solar portion pays a commensurate amount for part of the capital costs of the power block. Additionally, we assume the plant does not receive any payments for regulation or spinning reserves. Costs for permitting or new transmission lines are not included in the capital cost estimates. For PV, we assumed a time period of two years from start of construction to commercial operation, and for all thermal based plants, we assumed three years. For PV, we assumed that the cells degraded at a rate of 1% per year.[29]

Levelized Cost of Electricity (LCOE). We computed the LCOE as described above and present the unsubsidized levelized cost of electricity using a 3% discount rate. Since this result is from the social perspective, no subsidies or taxes were included. The costs incurred include the capital costs, finance costs, and fixed and variable maintenance costs. More detailed LCOE information is documented in the SI on page S20.

We also used the same methods as used for the ISCC plant to calculate the LCOE of a PV and CSP plant in Phoenix, Arizona. The only exception to our method above is a reduced construction time for PV plants as mentioned above. The PV and CSP prices do not require a parametric study because the marginal costs of stand-alone solar plants are essentially zero. As long as the grid price is positive or the power purchase agreement has a fixed price for electricity, the solar plant may run whenever solar resources are available. The resulting LCOE for PV and CSP was $190/MWh and $210/MWh, respectively. Table 5 shows the unsubsidized LCOE for the solar portion of the ISCC power plant.

LCOE When Subsidies Are Included (State or Public Utilities Commission Perspective). Subsidies for renewable energy have a large effect on their net cost. From a Public Utilities Commission (PUC) perspective, these subsidies are granted by the federal government and may be considered "free money" for the term of the subsidy program. We again use a 3% discount rate but now take into account the investment tax credit and accelerated depreciation (i.e., difference in tax burden if standard depreciation was used). Table 5 shows the effect on LCOE when subsidies are included for the parametric study of an ISCC, PV, and CSP plants. We also calculated the subsidized LCOE for PV and CSP plants using the same methods and found that the midvalue was $110/MWh and $130/MWh, respectively.

A lower gas price and a higher electricity price reduces the levelized cost of electricity for the solar portion of the ISCC plant because it allows the capacity factor to increase. Table 5 shows that under the market conditions that a NGCC power plant would be built, the unsubsidized LCOE of the solar portion of solar energy is less than PV ($190/MWh) or CSP ($210/MWh).

Federal subsidies change the balance of which solar technology is least expensive to local governments: PV is slightly less expensive than ISCC because the investment tax

Table 5. LCOE for Solar Portion of an ISCC Power Plant in Phoenix, AZ (Unsubsidized/Subsidized)[a]

		average wholesale price of electricity [$/MWh]					
		$35	$45	$55	$65	$75	$85
price of gas [$/MCF]	2	**$170**/120	**$170**/120	**$170**/120	**$170**/120	**$170**/120	**$170**/120
	4	$190/140	**$170**/130	**$170**/120	**$170**/120	**$170**/120	**$170**/120
	6	$500/370	$240/170	**$180**/130	**$170**/130	**$170**/120	**$170**/120
	8	$2000 +	$370/400	$270/200	$200/150	**$180**/130	**$170**/130
	10	$3000 +	$1800 +	$560/410	$310/230	$220/160	$190/140
	12	$3800 +	$3000 +	$1600 +	$590/430	$330/250	$250/230

[a]Bold font signifies a lower LCOE for the solar portion of the ISCC plant than for PV ($190/MWh) and stand-alone CSP plants ($210/MWh). All subsidized scenarios from the parametric study show the solar portion of the ISCC plant is more expensive than PV ($110/MWh) but not necessarily stand-alone CSP plants ($130/MWh).

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credit and accelerated depreciation favor the more capital intensive technology. Additionally, PV requires less time to construct. Therefore, the investment tax credit, which is higher for PV than for ISCC, can be claimed earlier when the plant is operational.

Effect of Location on ISCC Power Plant Economics. CSP technologies can harness only beam radiation, also known as direct normal insolation (DNI). Sunlight must be reflected in order to be concentrated onto a focal point, and only radiation that comes from the same angle can be manipulated this way. Nonconcentrating PV technologies are flat plate absorbers that can convert both DNI and diffuse radiation into electricity. For this reason, PV plants enhance their competitiveness relative to concentrating solar technologies in areas that experience more cloudy weather. Figure 3 shows the effect of varying solar resources on the cost of the solar portion of an ISCC plant or a PV plant.

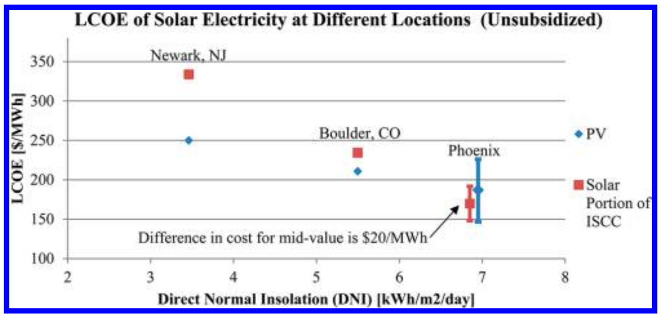

Figure 3. Effect of solar resource on the LCOE of PV and the solar portion of the ISCC plant. For Phoenix, we added the uncertainty of capital costs and maintenance costs as described in Table 5. For all ISCC data points, we assumed a gas price of $5/MCF and an average electricity price of $65/MWh. It should also be noted that solar plants for Newark, and Boulder, given their lower quality solar resources, would be designed in a way that would slightly lower the cost of electricity compared to what we show. Nevertheless, we show the difference to emphasize that ISCC would be at a disadvantage compared to PV for sites with weak DNI.

Net Present Value of ISCC from Private Perspective. From a private perspective, ISCC is more profitable than a traditional NGCC plant only with tax incentives and a solar renewable energy credit (SREC). Since the plant can only be more profitable with a SREC, we calculated what SREC value is needed to "break even" with a NGCC plant. Table 6 shows the results with the asterisks indicating scenarios where the NGCC plant's NPV is negative.

The SREC needed to have the same NPV as an NGCC plant is dependent on how much the solar energy increased revenue and decreased costs. With high electricity prices, the solar energy adds more revenue by increasing the capacity factor. In cases of high gas prices, the solar energy decreases more fuel costs. However, high gas prices may disallow the plant from running at the time solar resources are available and sometimes increase the SREC needed to break even.

SREC markets have been set up in many of the states that have solar set-asides in their RPS. However, Nevada does not offer such a market.[30] The price of SRECs currently vary considerably and not all can be transferred across state lines. In 2011, the SREC in Pennsylvania was in the $10 to $20 per MWh range, while the SREC in New Jersey varied from $166 to $670 per MWh.[31] Aggressive solar mandates create upward pressure on demand and increase the price of a SREC if supply is not adequate. Conversely, some markets are oversupplied, for a variety of reasons, and the SREC price is suppressed.[32]

Cost of Mitigation (COM). We determine the cost of mitigating a tonne of CO_2 as

$$\text{Cost of Mitigation} = \frac{\$/\text{MWh}_{(\text{Renewable})} - \$/\text{MWh}_{(\text{Fossil})}}{\text{Tonnes } CO_2/\text{MWh}_{(\text{Fossil})} - \text{Tonnes } CO_2/\text{MWh}_{(\text{Renewable})}}$$

For the COM, we assume no subsidies and a discount rate of 3%. We present the COM in two ways.

In order to attempt to be consistent with the existing literature, we assume the cost of a new coal-fired power plant and its emissions as the baseline for costs and emissions of the fossil power plant. However, given that the solar plant may feed a grid which is heavily dependent on natural gas (California), we also estimate the COM if a NGCC plant was offset. Details of cost and carbon intensity of fossil fuel sources are available in the Supporting Information on page S7.

Table 7 shows that in situations where NGCC plants would be profitable, the cost of mitigation of the solar portion of the ISCC plant is lower than it would be for a PV power plant.

Cost Analysis if Including Variability, Transmission, and Other Costs. Fossil plants are needed to dampen the variable generation from renewable plants. Lueken et al. found that PV plants have variability costs of ~$11/MWh, and CSP plants have variability costs of approximately ~$5/MWh.[34] We assume the solar portion of the ISCC has the same variability costs as a stand-alone CSP plant and recalculate the cost of mitigation (COM) with these costs added in. The COM for the solar portion of the ISCC plant did not change the values of Table 7 given the number of significant figures we report. We conclude that adding variability costs for solar technologies strengthens the case for ISCC but does not change the "break points" of Table 7.

A significant cost that we have not accounted for in the cost of stand-alone power plants is transmission lines. Not enough

Table 6. SREC Needed To Have the Same NPV as an NGCC Plant (Location: Phoenix, AZ)[a]

		average wholesale price of electricity [$/MWh]					
		$35	$45	$55	$65	$75	$85
price of gas [$/MCF]	2	$50	$50	$50	$50	$50	$50
	4	$50*	$50	$50	$40	$40	$40
	6	$100*	$60*	$40	$40	$40	$30
	8	$180*	$100*	$60*	$40	$30	$30
	10	$270*	$180*	$110*	$70*	$40	$30
	12	$380*	$280*	$190*	$120*	$70*	$40

[a]Asterisks indicate that the NPV of NGCC plant is negative.

Table 7. Cost of Mitigation for Solar Portion of ISCC Plant in Phoenix, AZ[a]

		average wholesale price of electricity [$/MWh]					
		$35	$45	$55	$65	$75	$85
price of gas [$/MCF]	2	**$140/280**	**$130/280**	**$130/280**	**$130/280**	**$130/280**	**$130/280**
	4	$170/330	**$140/290**	**$140/290**	**$140/280**	**$130/280**	**$130/280**
	6	$530/940	$220/420	**$150/310**	**$140/290**	**$140/290**	**$140/280**
	8	$2400 +	$580/1000	$260/490	$170/340	**$150/300**	**$140/290**
	10	$4000 +	$2100 +	$610/1100	$300/560	$200/390	$160/320
	12	$4600 +	$3600 +	$1900 +	$640/1100	$340/610	$230/430

[a]If coal is offset/if NGCC is offset. [$/tonne CO_2 avoided]. Bold font signifies a lower COM for the solar portion of the ISCC plant compared to PV and CSP. The COM for PV and CSP if coal was offset $160 and $190/tonne of CO_2. The COM for PV and CSP if natural gas was offset is $350 and $380/tonne of CO_2. For gas plants, we accounted for upstream emission by assuming the plant emitted 500 g/kWh.[33]

solar plants have been built to estimate what the transmission cost of these distant generators would be. According to a LBNL meta-study, transmission lines for wind energy have had a median cost of $15/MWh.[35] In addition to the cost, permitting transmission lines are difficult, and the process is lengthy. From the Texas State Energy Conservation Office: "The greatest challenge facing the wind industry is that wind farms can be built more quickly than transmission lines. It can take a year to build a wind farm, but five to build the transmission lines needed to send power to cities".[36]

DISCUSSION

Fifteen states in the USA and a number of nations have mandates that require a portion of electricity be produced by solar energy. Although solar PV and CSP are the technologies most commonly used to meet these mandates, solar electricity from ISCC plants may be the most competitive way to produce electricity from solar energy in some regions. If the capacity factor of the plant is above 21%, ISCC may reduce costs relative to other solar options by ~$20/MWh. Another advantage to hybridization may be that it negates the need to build duplicate transmission lines, where permitting and construction is difficult and lengthy.

From a private developer's perspective, building an ISCC plant may increase the net present value only when solar renewable energy credits are available for ~$30 to $60 per MWh. This is true only if an investment tax credit of 30% is available as well as accelerated depreciation for the solar parts of the power plant as assumed in our model.

From a state or utility perspective in the U.S., the case for ISCC development is not clear-cut. With current federal subsidies mentioned above, PV is slightly lower in cost. Therefore, ISCC development would be warranted if other local costs, such as new transmission lines or the variability of PV, are appreciable (on page S19 of the SI we show that there are negligible criteria pollutant advantages conferred on the gas plant by the ISCC portion).

From a social perspective, the cost of mitigation for all solar energy options examined in this paper are far higher than other low carbon electricity options [37−40] If solar from an ISCC plant offsets a new coal fired power plant, the cost of mitigation would be ~$130/ton of CO_2 (~$160 for PV and ~$190 for CSP per ton of CO_2). Clearly, this number would be higher if the electricity offset had a lower carbon intensity than coal. If solar from ISCC is used to offset an NGCC plant, the COM increases to ~$280/ton of CO_2. Likewise, the COM for PV and CSP increases to ~$350 and ~$380/ton of CO_2, respectively. Because the cost of mitigation is so high, it is highly unlikely that a price on carbon alone would induce solar development. Failed attempts to price carbon by the U.S. Congress were estimated to have a price of $60/tonne of CO_2 by 2030.[41]

Where a solar set-aside is mandated, the most cost-effective solar option may be ISCC, in certain locations. Given the advantages noted above, governments should encourage the pathways necessary to allow for ISCC development: creating a permitting structure that clearly differentiates solar and fossil energy, creating a market for solar renewable energy credits, and ensuring that the market for those credits will be available for the duration of the project. We do not advocate ISCC as a cost-effective means of mitigating carbon. We also note the limited number of solar MWh the ISCC would produce and the infrequency of flat land colocated with fossil fuel power plants in the Southwest U.S. However, governments have shown through their solar set-asides that they desire solar electricity. In certain locations, ISCC would be a logical, practical way to build relatively cost-effective solar capacity that is one of the few renewable technologies that can be hybridized with a fossil fuel power plant.

ASSOCIATED CONTENT

Supporting Information

The solar ISCC thermodynamic model, electricity, natural gas and SREC price data, sensitivity analysis, assumptions for the cost of mitigation analysis, COM calculations with criteria pollutants, and the solar model. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

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