Utilizing Solar Thermal Energy for Post-Combustion CO₂ Capture

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Abstract: Post-combustion amine absorption and stripping can remove 90% of the CO₂ from power plant flue gas, but systems can reduce electrical output by approximately 30% due to energy requirements for stripping CO₂ from solvent and CO₂ compression. The CO₂ capture energy penalty can be reduced while developing renewable energy technologies by meeting CO₂ capture energy requirements with a solar thermal energy system, particularly when electricity demand and prices are the highest. This study presents an initial review of solar thermal technologies for supplying CO₂ capture energy, with a focus on high temperature systems. Parabolic troughs and central receivers are technically able to provide energy for CO₂ capture. However, the solar system's capital costs would be roughly half that of the base coal-fired plant with CO₂ capture, and high electricity prices are required to offset the costs of operating the solar thermal system. For high temperature solar thermal systems, direct electricity generation is likely a more efficient way to use solar energy to replace output lost to CO₂ capture energy. However, low temperature solar thermal systems might integrate better with solvent stripping equipment, and more rigorous analysis is required to definitively assess the feasibility of using solar energy for CO₂ capture.

Key words: Carbon capture, carbon dioxide, solar thermal, climate change, electric power.

1. Introduction

1.1 Carbon Dioxide Capture and Sequestration for Climate Change Mitigation

Scientific consensus asserts that climate change is progressing at an alarming rate and that anthropogenic carbon dioxide (CO₂) emissions from fossil fuel burning are the primary contributor. Coal-fired power plants alone emit over one third of anthropogenic CO₂, making them a primary target for emissions reduction efforts [1]. Eliminating coal from the electricity sector might be a plausible long-term strategy, but the prevalence and longevity of coal-fired power plants will likely allow coal to remain a vital part of United States and world electricity generation for several

decades. Coal is also an abundant, politically secure, and relatively inexpensive fuel, making it attractive in spite of the harmful effects of flue gas emissions. Therefore, carbon dioxide capture and sequestration (CCS) is appealing technology because it could allow coal use without the negative environmental impacts of CO₂ emissions.

Comparative assessments of CO₂ capture technology consistently point to post-combustion capture with amine absorption and stripping as one leading CO₂ capture technology, especially in the near-term because of industrial experience and its availability for retrofit to current plants [2, 3]. Fig. 1 displays a simplified diagram of the amine absorption and stripping process integrated into a coal-fired power plant. After burning coal in the boiler to produce steam, the resulting flue gas passes through other pollution controls before entering the CO₂ absorber column. In

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Fig. 1 CO₂ compression and solvent stripping are the primary contributors to the energy requirement of CO₂ capture at a coal-fired power plant integrated with post-combustion absorption/stripping.

the absorber column, flue gas flows counter currently with an aqueous amine solvent that reacts with and absorbs CO₂. The solvent loaded with CO₂, termed “rich” solvent, then flows through a heat exchanger to the stripper column, where it is heated in order to reverse the CO₂-amine reaction and liberate nearly pure CO₂. The “lean” solvent then cycles back to the absorber to restart the process, while CO₂ is compressed to pressures suitable for efficient pipeline transport and subsequent storage.

Systems can be designed to efficiently remove around 90% of the CO₂ from incoming flue gas; however, they are capital intensive, and process energy requirements can reduce net plant output by 11-40% relative to output without CO₂ capture [3-6]. This energy requirement is primarily attributed to work for CO₂ compression and heat to raise CO₂-rich solvent to temperatures required to liberate CO₂. Energy is supplied by steam extracted from the power cycle to drive a CO₂ compression train and heat solvent. Typical designs use a reboiler (not shown) to exchange heat between steam and solvent. An alternate configuration would extract steam solely for solvent stripping and use electrical energy to drive the CO₂ compression train.

1.2 Using Solar Thermal Energy for CO₂ Capture Energy

When steam extraction from the power cycle

provides the energy requirement for CO₂ capture, the resulting decrease in power plant output reduces available capacity on the electric grid and potential electricity sales at the power plant. One proposed method to reduce or eliminate steam extraction would use a solar thermal energy system to meet steam requirements when solar energy is available [7]. Since high electricity demand and prices correspond fairly well to daytime hours when solar energy is available, using a solar thermal system for CO₂ capture energy requirements could allow plant operators to increase electrical output when electricity is most valuable [8]. High CO₂ removal rates could be maintained with power plant output near the base plant capacity without CO₂ capture. If a thermal storage system is implemented, high plant output could even be sustained during time periods without sufficient sunlight to operate solar collection systems.

2. Steam Requirements for CO₂ Capture

2.1 Figures and Tables

The steam requirements for CO₂ capture vary depending on the design of the CO₂ capture system and the base power plant. The CO₂ capture system shown in Fig. 1 is a base case process configuration that uses one absorber and stripper where no material or energy flow (flue gas, solvent, CO₂, steam) enters or leaves at more than one location of each component.

Monoethanolamine (MEA) is a baseline solvent for this process. In order to limit thermal degradation of the MEA solvent, stripping temperatures are limited to about 120 degrees Celsius (°C), so typical designs use saturated steam at temperatures slightly above 120 °C for solvent stripping [3]. If steam must first drive CO₂ compressors, higher temperature and pressure superheated steam is required for the let-down turbine. When extracting power cycle steam for CO₂ capture energy requirements, a typical design extracts roughly 50% of the steam flow from between the intermediate and low pressure turbine sections [9].

A detailed plant design analysis by Trimeric, Corp. considers a base case MEA absorption/stripping system installed at a 500 megawatt gross electrical output (MW_e) coal-fired power plant (453 MW_e net output without CO₂ capture) [10]. Superheated steam is extracted at 945 kilopascals (kPa) and 355 °C to drive the CO₂ compression train with a turbine, where it expands to 446 kPa and 281 °C before being desuperheated to provide saturated steam at 446 kPa (148 °C) for solvent stripping [10]. The stripping heat duty is 500 megawatts of thermal energy (MW_t) and requires nearly 764,000 kilograms per hour (kg/hr) of steam [10]. Using the reported CO₂ recovery per hour, the energy requirement for CO₂ capture is 4.34 GJ/tCO₂.

Energy and mass flows and resulting steam requirements could vary with amine solvent choice regardless of the process configuration. Many amines and amine blends are being evaluated for CO₂ capture, and their unique properties will ultimately determine stripping conditions and the resulting steam requirements [3]. For instance, concentrated piperazine (PZ) has demonstrated thermal stability up to 150 °C; a system using this solvent would likely be designed to operate at higher temperatures and pressures and thus require higher temperature saturated steam [11].

Alternative configurations or operating schemes in the stripping section could drastically change steam requirements. Operating the stripper at multiple pressures in different column sections or at vacuum

pressures would change the optimal thermodynamic and mass transfer conditions and resulting steam requirements. Complex configurations such as the double matrix stripper (Fig. 2) could require heat input at multiple temperatures and pressures, as could a process that uses multiple flash tanks to strip CO₂ instead of a simple stripper column (Fig. 3) [12, 13]. One study finds that a three-stage flash tank configuration is more efficient than a simple stripper when heat input is a variable temperature energy source, which might be the case with solar thermal energy systems [13].

Steam requirements for CO₂ capture must be compatible with the base power plant configuration, which ultimately determines the available conditions for steam extraction. Different facilities might use different steam turbine combinations, so they might have different steam conditions at the intermediate pressure-low pressure (IP/LP) crossover pipe. Depending on the steam turbine configuration, there might or might not be flexibility in steam conditions available for CO₂ capture systems [14]. If the CO₂ compression train is electric motor-driven rather than steam turbine-driven, required steam temperatures and pressures are much lower. However, such a configuration could only use solar thermal energy for solvent stripping; there would still be a significant reduction in net power plant output for CO₂ compression.

3. Solar Thermal Energy Technologies

This section briefly describes several available solar thermal technologies and discusses their potential to meet some or all of the energy requirements for CO₂ capture.

3.1 Low Temperature/Efficiency Systems

Solar thermal technologies that concentrate solar energy mildly or not at all include flat plate collectors (FPC), evacuated tube collectors (ETC), and compound parabolic collectors (CPC). FPCs can achieve stagnation temperatures above 200 °C but

Fig. 2 A double-matrix stripper splits the rich solvent feed to two strippers operating at different pressures [12].

Fig. 3 A three stage flash configuration uses flash tanks at descending pressure. A single preheater is shown, but more could be installed between flash sections [13].

only operate efficiently up to about 100 °C. ETCs can reach operating temperatures up to 200 °C, and CPCs can reach 300 °C, but costs are higher than FPCs [15]. FPCs could be used for solvent stripping only at below-average regeneration temperatures, but ETCs and CPCs can easily achieve steam conditions required for solvent stripping [15].

The energy requirement for CO₂ capture at a commercial-scale power plant is very large, so reducing capital cost and land area will likely be a primary design goal for a solar thermal system being used for CO₂ capture. An exceptionally large solar field might create labor and maintenance logistics issues and increase costs for pumping heat transfer fluid and/or steam. Meeting environmental impact permitting requirements might also become more difficult as the solar field size grows.

Fig. 4 plots the required aperture area of a solar field

Fig. 4 Due to large energy requirements for CO₂ capture (500 MWt in this example), solar technology efficiency must be high to reduce the required aperture area for the solar thermal collector.

for solar to thermal efficiencies from 10%-90% if the plant is sized for a heat requirement of 500 MW_t and the average daytime direct normal solar insolation for Ward county in the west Texas panhandle — 561 watts per square meter (W/m²) [16-18]. Area requirements increase substantially as efficiency decreases.

Designing for less solar insolation would require a larger collector area to meet the same energy requirement. However, even if sizing for peak insolation of around 900 W/m² and assuming 90% efficiency, aperture area must be greater than 0.6 km². For reference, the largest parabolic trough Solar Electric Generating System (SEGS) installed at Harper Lake, California is 0.484 square kilometers (km²) and produces 80 MW_e. The potential effect of thermal storage on solar field size is not considered, but thermal storage may be used to justify larger aperture area or to store excess energy if actual insolation is greater than design insolation. Excess solar energy above CO₂ capture requirements could be used for other power cycle heat requirements, but additional components would be required.

Actual efficiency and energy output of a particular technology at a given time depends on instantaneous solar insolation and the difference in temperature of the heat transfer fluid and ambient air [15]. Though CPCs and ETCs can produce temperatures required for solvent stripping and have higher efficiencies than FPCs, large area requirements might still become a practical limitation. Nevertheless, CPC and ETC systems designed specifically for CO₂ capture process conditions could be promising if the benefits of improved plant integration outweigh the costs of aperture area.

3.2 High Temperature/Efficiency Systems

The rest of this study focuses on solar thermal technologies that reach higher temperatures and have higher efficiencies across a wide range of ambient temperatures. They are prioritized under the assumption that smaller system size with high temperature/efficiency systems is preferred to the potential process integration benefits of a low temperature/efficiency system used solely for solvent stripping. However, further analysis is required to validate this assumption.

Three high temperature/efficiency technologies, parabolic dish, power tower, and parabolic trough, are

being considered for solar-to-electric energy conversion. These technologies are compared in the context of electricity generation and evaluated for their applicability to meet CO₂ capture steam requirements. Table 1 summarizes representative cost and performance parameters for each technology when used for electricity generation. These quantities, especially efficiency and costs, are highly dependent on market conditions and analytical assumptions such as power plant capacity factor¹ and the use of thermal storage. Actual values will be site and design specific.

3.2.1 Parabolic Dish

Focusing mirrors and two-axis sun tracking allow parabolic dish systems to achieve operating temperatures over 1,500 °C [19]. High temperatures allow efficient use of a heat engine, with demonstrated solar to electric efficiencies over 30% [20]. Dish systems only require water for mirror washing, so total water consumption is much lower than solar thermal technologies that have

Table 1 The three candidate high temperature solar thermal systems are compared in a electricity context using representative literature values² [19, 24, 26, 27].³

Parameter	Parabolic dish	Central receiver	Parabolic trough
Heat transfer fluid	Helium or hydrogen	Molten nitrate salt	Heat transfer oil (VP-1)
Heat transfer fluid Temperature (°C)	over 1500	600	390
Annual solar to electric efficiency (%)	20	14	13
Capital cost (\$/kW _e) ⁴	*	6,650	2,740
Operating cost (\$/MWh _e) ⁷	*	39	20
Levelized cost of electricity (\$/MWh _e)	390	117	108
Water consumption ⁵ (gal/MWh _e)	20	~750	760-920

¹ The capacity factor is the ratio of actual power plant output in a year to the maximum possible output if the plant operated at its full rated capacity throughout the year.

² All monetary quantities in this report are shown in 2002 U.S. dollars.

³ MWh = megawatt-hour, gal = gallons.

⁴ Costs of parabolic dish technology are uncertain due to technological immaturity.

⁵ The reference indicates that an additional 8 gal/MWh is required for central receiver and parabolic trough systems but does not specify whether this water is consumed or withdrawn and returned to its source.

significant cooling water requirements to condense steam that has passed through a turbine. The largest demonstrated dish/stirling engine is a 25 kilowatt (kW_e) system by Stirling Energy Systems; larger capacities could be achieved by installing an array of several dishes [20]. Though highly efficient, parabolic dish technology is less mature than other efficient solar thermal technologies, so cost and reliability are uncertain and could slow deployment in the short term.

Though high temperatures are achieved at the absorber surface of a parabolic dish, these systems are not currently designed to store or transport thermal energy for use in steam generation. Parabolic dish systems are tailored for electricity generation; thus, they do not appear suitable for meeting the heat requirements of solvent stripping in a CO₂ capture system.

3.2.2 Central Receiver (Power Tower)

Central receiver systems, also known as “power towers,” use a field of heliostat mirrors with two-axis sun tracking to focus sunlight onto one central receiver at the top of a tower structure. High efficiency and concentration ratios allow operating temperatures up to 1,500 °C for some working fluids; however, better heat transfer and smaller receivers are possible using molten nitrate salt at 600 °C to generate steam for a Rankine cycle [19]. High receiver working fluid temperatures allow for more efficient operation of thermal cycles and large-scale thermal storage systems [19]. Though high efficiencies could eventually lead to low operating costs, power towers are currently relatively expensive to install and operate [21, 22].

The 10 MW_e SOLAR ONE power tower was demonstrated in California in the 1980s using steam as a heat transfer fluid, and the plant has more recently been rebuilt as SOLAR TWO to utilize a molten salt heat transfer fluid with a two-tank molten salt thermal storage system [23]. Future plants are expected to be on the scale of hundreds of MW_e, on the order of that required to provide CO₂ capture energy [23].

Heat transfer fluid temperatures in a central receiver system can meet or exceed those required for steam used in the CO₂ capture process, whether the steam is

used to drive the CO₂ compression train or strictly for solvent stripping. Thermal storage could allow increased control over the use of solar-based energy for CO₂ capture, allowing plant operators to assure that solar energy is utilized at the most economically desirable time periods, such as when electricity prices are high.

Another downside of all Rankine cycle-based solar power generation systems is the large cooling water requirement, especially given that sites with high solar insolation often have low water availability [24]. However, when using solar thermal energy for CO₂ capture processes, steam exits the CO₂ capture system from the reboiler as condensate that can be returned to the steam generator in the solar thermal energy system. Thus, there is no water requirement associated with steam cooling and condensation as with a solar-to-electric facility; water consumption is restricted to mirror washing and process makeup water.

3.2.3 Parabolic Trough

Trough technology uses rows of long parabolic mirrors with single-axis tracking to focus solar energy and heat a working fluid such as VP-1 heat transfer oil to temperatures in the vicinity of 390 °C [25]. As with power towers, heat in the solar collector working fluid must be exchanged with water to generate steam. Though temperatures and efficiencies might not be as high as those experienced with central receiver technology, parabolic troughs are still relatively efficient systems that can similarly be coupled with thermal storage [25]. When used to produce steam for Rankine cycle-based electricity generation, lower operating temperatures slightly increase water consumption relative to that of power towers due to less efficient heat transfer in the condenser [24]. However, as indicated in Section 3.2.2, water requirements are far less when using parabolic troughs for CO₂ capture.

Parabolic troughs generate heat at high enough temperatures to produce superheated steam to drive CO₂ compression, though heat transfer driving forces might be relatively small and thus require a great deal

of heat exchange surface. Troughs can easily achieve temperatures suitable for producing saturated steam used in solvent stripping.

In addition, nine parabolic trough SEGS facilities ranging from 13.8 MW_e to 80 MW_e in size were installed in California in the 1980s and early 1990s and remain in operation today, making parabolic trough technology the most mature and low-cost high efficiency solar thermal system that can be implemented at the scale necessary for CO₂ capture [25].

3.2.4 Thermal Storage

Installing a thermal storage system can allow solar-based energy to be used at night or when insufficient sunlight is available during the day, such as during periods of dense cloud cover. Installing thermal storage and oversizing the solar collection system could increase power plant capacity factor and markedly improve plant economics [25]. Central receivers and parabolic troughs operate at high enough temperatures for efficient thermal storage.

The most mature thermal storage system uses two tanks, one at high temperature and the other at low temperature [25]. Stored heat is utilized by exchanging heat from the storage media in the high temperature tank with water/steam for process requirements and then sending the cooled storage media to the low temperature storage tank. Another thermal storage option known as a thermocline system stores energy in a solid media held in a single tank [28]. By regulating the flow of high temperature fluid in and out of the top of the tank and low temperature fluid in and out of the bottom, thermal energy can be added and withdrawn from the storage system on demand [28]. The elimination of one tank in the thermal storage system can greatly reduce capital costs [25].

A two-tank thermal storage system using a molten nitrate salt storage medium has been successfully demonstrated at the SOLAR TWO facility, so this technology is considered a near-term large scale storage solution [23]. Thermocline systems are in comparatively early stages of development but show promise [25].

Since the purpose of using solar energy for CO₂ capture is to reduce turbine steam extraction and increase power plant output, adding thermal storage to the solar energy system would add additional control over power plant output. Storing the quantity of energy required for CO₂ capture on a scale of hours would require a storage system on the order of thousands of MWh_t. While demonstrated systems such as that at SOLAR TWO are only on the scale of hundreds of MWh_t, substantially larger storage systems are under discussion [21, 29].

4. Integrating Solar Thermal Systems with CO₂ Capture

In order to provide heat for the CO₂ capture process when solar thermal energy is unavailable or insufficient to meet CO₂ capture energy requirements, a facility would likely be designed to utilize turbine steam extraction as well. Fig. 5 shows a process configuration in the case where steam generated using solar energy is used for CO₂ compression as well as solvent stripping. A facility could be designed for solar-only operation of solvent stripping and CO₂ compression, but the plant operator would have to be prepared to pay any CO₂ emissions costs when current or stored solar energy is inadequate to operate CO₂ capture systems at full-load. If the CO₂ capture system has the option of using extracted steam, solar steam, or a combination of the two, effective control systems are required to maintain safe and efficient operation of the solar thermal system and the power cycle. Though this study primarily discusses the use of solar thermal energy for the entire heating requirement of CO₂ capture, size and capital cost of the solar thermal energy system could be reduced by designing to meet only a fraction of the total energy requirement for CO₂ capture.

Solar thermal energy is primarily discussed here as a technology used to generate steam for use in the CO₂ capture process. Though CO₂ compressors must be mechanically driven either by a steam turbine or an electric motor, solvent stripping merely requires heat.

5. Analysis of a Nominal Facility Using Solar Energy for CO₂ Capture

This section uses performance and economic parameters from various sources in the literature to make preliminary estimates of the size and cost of a solar thermal system used to supply CO₂ capture energy requirements. The costs of operating CO₂ capture using extracted steam and solar steam are then estimated to allow discussion of power plant economics in the context of electricity dispatch. Detailed process simulation with time-varying inputs is outside the scope of this analysis but should be completed to conclusively assess solar thermal technology for CO₂ capture.

5.1 Nominal System Configuration

The analysis considers the same 500 MW_e gross output coal-fired power plant mentioned in Section 2 to maintain consistency between CO₂ capture energy requirements, steam conditions, and the integration of power and CO₂ capture systems. Without CO₂ capture, the net power output after auxiliary electricity requirements is 453 MW_e. The CO₂ capture system uses a 7 molal (30% by weight) MEA solvent and is configured as shown in .

The solar thermal facility uses parabolic trough technology to supply steam for CO₂ compression and solvent stripping. Parabolic trough technology is chosen because troughs are currently the most mature and least cost of high efficiency solar thermal systems. The solar system is sized to supply the entire energy requirement for CO₂ compression and solvent stripping, 500 MW_t, when receiving a site's average solar insolation of 561 W/m². Though it might be difficult for a parabolic trough system using synthetic oil to efficiently produce steam at conditions necessary to drive the CO₂ compression train (945 kPa/355 °C), this baseline analysis assumes that steam conditions can be met.

A steam-generating solar thermal system for both CO₂ compression and solvent stripping is considered instead of a direct exchange configuration for solvent

stripping. The energy requirement of the CO₂ capture system as reported in the Trimeric study is 35% of the gross power plant output (38% of the net output without CO₂ capture), which is on the relatively high end of estimated CO₂ capture energy requirements [3]. Thus, analyzing a solar thermal system that provides energy for both CO₂ compression and solvent stripping at this facility should provide a relatively conservative estimate of the total size and cost of the system.

5.2 Cost and Size of Solar Thermal System

Calculations are made for a solar system without thermal storage and one with 6 hours (3,000 MWh_t) of thermal storage. The chosen thermal storage system is a two-tank design using molten nitrate salt as a storage medium. Though other technologies could achieve lower costs, this technology is chosen for its relative maturity. In order to allow design output of the solar thermal system during all operating hours, the collector field increases in size when thermal storage is added.

Solar-to-thermal efficiency is calculated using component efficiencies for a near-term facility reported in a Sargent & Lundy (S&L) report for the National Renewable Energy Laboratory (NREL) [21]. Efficiencies account for solar field optical efficiency, receiver thermal losses, piping thermal losses, storage thermal losses (if applicable), and electric load of the solar thermal facility. Since the solar thermal system is not being used for electricity generation, efficiency of the Rankine cycle is not included. The resulting aperture areas are larger than the combined aperture area of all existing California SEGS facilities (2.08 km²), especially when the collection system is oversized for thermal storage [25]. However, the scale would be similar to a solar-to-electric facility designed for several hundred MW_e.

Capital costs are also determined using values reported by S&L for a near-term trough facility. Costs calculations include the solar collection system, its support structure, heat collection elements, mirrors, and the thermal storage system (if applicable). Capital

costs are very high considering that the total cost of a 500 MW_e coal-fired power plant with post-combustion CO₂ capture is on the order of \$1,500 million [6]. The thermal storage system is a relatively small component of total capital cost, but oversizing solar collection systems for maximum utilization of thermal storage adds significant cost.

To maintain consistency, operating and maintenance (O&M) costs are also determined using the S&L report. Since S&L provides values that incorporate conversion of solar thermal energy to electricity with a Rankine cycle turbine-generator, the solar-to-thermal efficiency in Table 2 is calculated by scaling S&L quantities by the turbine efficiency used in the S&L analysis.

The values presented here are primarily intended to place order-of-magnitude estimates on the cost and size of a solar thermal energy system being used for CO₂ capture energy requirements. A detailed plant design study would account for diurnal and seasonal variations in solar insolation in order to choose system size based on plant performance, economic, and environmental tradeoffs. However, such an analysis is outside the scope of this work.

5.3 Operating Costs in an Electricity Market Context

Table 3 contains estimates of operating costs at the nominal power plant under several operating conditions: (1) when steam extraction is used exclusively for CO₂ capture energy requirements; when solar thermal energy is used for CO₂ capture energy requirements (2) with thermal storage and (3) without thermal storage; and (4) when the CO₂ capture system is bypassed completely. Bypassing the CO₂ capture system implies that the CO₂ emissions rate at the power plant returns to its value without a CO₂ capture system.

When using solar energy for CO₂ capture or bypassing the CO₂ capture system, no steam is extracted prior to the low pressure turbine. Auxiliary loads of the CO₂ capture system are ignored because they are small compared to the energy requirement for CO₂ compression and solvent stripping, so plant output

Table 2 A parabolic trough solar thermal system to supply CO₂ capture energy for a 500 MW_e gross power plant will be very large and costly to install and operate [21].

Parameter	No storage	6 hours storage
Solar to thermal efficiency (%)	40.8	40.4
Approximate aperture area (km ²)	2.19	3.38
Total solar system capital cost (millions)	\$839	\$1,381
Collector/structure/heat collection elements/mirrors (millions)	\$839	\$1,300
Thermal storage system (millions)	\$0	\$81
Solar system operating cost (\$/MWh) ⁶	13.9	10.4

is assumed to return to 453 MW_e, the net output without CO₂ capture. In practice, the bypass scenario might have residual energy requirements of the CO₂ capture system if solvent circulation is maintained and components are kept hot to prepare for rapid resumption of the CO₂ capture process.

The cost of producing solar thermal energy from Table 2 is converted to a cost of producing electrical energy by multiplying the cost in \$/MWh_t by the ratio of total thermal load at the solar plant to the increase in electrical output at the power plant (500 MW_t/(453-281)MW_e). The resulting quantity represents the cost of operating the solar thermal system per megawatt-hour of regained electrical output. Calculated values are actually larger than the S&L-quoted O&M costs for solar-to-electric production, suggesting that using a solar thermal system to supply CO₂ capture energy and regain power plant output is less efficient than simply using the solar thermal system to generate electricity. If a solar system produces high temperature/pressure steam, the steam might be better used for electricity generation than CO₂ capture heat, partly because of heat losses when exchanging thermal energy from the solar system to the amine solvent. Low temperature solar thermal systems designed specifically to provide stripping heat might actually improve operating economics from a process efficiency standpoint.

Operating costs not attributed to the solar energy system are calculated using a methodology described

⁶ Solar system operating costs include staff, administration, maintenance, and mirror washing.

Table 3 Operating economics are displayed for several CO₂ capture operating configurations in order to demonstrate the electricity market implications of using solar energy for CO₂ capture.

	Turbine extraction	Solar energy without storage	Solar energy with storage	Bypass CO ₂ capture
Output (MW _e)	281	453	453	453
solar system operating cost (\$/MWh _e)	n/a	40.6	30.1	n/a
\$50/tCO₂				
Non-solar operating costs (\$/MWh _e)	61.7	48.0	48.0	79.3
Total operating costs (\$/MWh _e)	61.7	88.6	78.1	79.3
Minimum electricity price for profitability (\$/MWh _e)	n/a	132	105	108
\$100/tCO₂				
Non-solar operating costs (\$/MWh _e)	70.0	56.3	56.3	130.8
Total operating costs (\$/MWh _e)	70.0	96.9	86.4	131
Minimum electricity price for profitability (\$/MWh _e)	n/a	141	113	230

in previous work for a coal price of \$1.5 dollars per million British thermal units (MMBTU) and CO₂ prices of \$50 per metric ton of CO₂ (tCO₂) and \$100/tCO₂ [31, 32]. Power plant heat rate and CO₂ emissions rate without CO₂ capture are assumed typical of coal-fired power plants in the Electric Reliability Council of Texas (ERCOT) electric grid. The calculation includes costs of fuel, CO₂, and other base plant O&M costs. Non-solar operating costs also include additional costs of CO₂ capture including those of MEA makeup, solvent reclaiming, degradation product disposal, water consumption, CO₂ transport and storage, labor, administration, and maintenance [32].

In a competitive electricity market such as ERCOT, power plants submit offer curves of marginal electricity cost vs. production (\$/MWh_e vs. MW_e) and are generally dispatched in order from low to high cost until electricity demand is met. The market price for electricity at any instant is typically set to the offer cost of the last and most expensive plant dispatched at that time, termed the marginal generating facility. Any plants supplying electricity at a lower cost earn operating profits. In a perfectly competitive electricity market, plants would submit bids that reflect their marginal cost of electricity production; capital costs are not generally incorporated into electricity dispatch decisions. Market inefficiencies and additional power plant and electric grid constraints limit the practicality of ideal economic behavior, but a first-order analysis

can assume that electricity dispatch is determined solely by power plant operating costs.

Comparing total operating costs under the four operating conditions and two CO₂ prices indicates the value of solar thermal energy for CO₂ capture in the context of electricity dispatch. Though the sunlight is free of cost, converting it to thermal energy for use in CO₂ capture systems is not, especially when accounting for the amount of solar thermal energy necessary to increase power plant electrical output. When using solar energy for CO₂ capture, operating costs are lower with thermal storage because higher solar system capacity factors reduce startup/shutdown costs and spread fixed operating costs over a longer operating period. However, operating costs in either case are significantly greater than when using steam extraction to meet CO₂ capture energy requirements.

Though operating costs are higher, a power plant might choose to operate CO₂ capture using solar thermal energy rather than steam extraction if added costs are offset by greater electricity sales when power output increases from 281 MW_e to 453 MW_e. Assuming that the output at this particular power plant has a negligible effect on electricity price, a minimum electricity price can be determined above which operating profits are greater when using solar energy for CO₂ capture. In the CO₂ capture bypass scenario, the minimum electricity price for profitability is the price where electricity sales from increased power output

offset the additional costs of CO₂ emissions.

Electricity price thresholds when using solar thermal energy for CO₂ capture are relatively high; average 2008 electricity price in the ERCOT grid was \$63.3/MWh_e, though with no CO₂ price [33]. If a CO₂ price is imposed on the electricity market, electricity prices should increase by the emissions costs of marginal generating facilities. The emissions rates of coal- and gas-fired facilities are approximately 1 tCO₂/MWh_e and 0.5 tCO₂/MWh_e, respectively, so one might expect average electricity prices to increase by \$25-\$50/MWh_e at \$50/tCO₂ and \$50-\$100/MWh_e at \$100/tCO₂, if coal- or gas-fueled plants set electricity prices. With these CO₂ costs added to electricity prices, there might be a significant amount of time when operation is more profitable when using solar energy for CO₂ capture; however, operating time will be limited by available sunlight and thermal storage capacity.

At \$50/tCO₂, the minimum price to use solar energy for CO₂ capture is near that of the minimum price required to justify bypassing the CO₂ capture system entirely. Though operating economics are similar, there is little to no capital cost associated with designing a facility that could bypass the CO₂ capture system; maintenance and operability requirements will likely require a bypass option anyway. Furthermore, bypassing CO₂ capture is not constrained by solar resources. Slightly better operating economics with a solar thermal system relative to CO₂ capture bypass are unlikely to offset the high capital costs of a solar thermal energy system.

At high CO₂ prices, using solar thermal energy to maintain high CO₂ removal has significantly better operating economics than bypassing the CO₂ capture system. However, detailed economic analysis is required to assess whether the additional operating profits can justify installation of the solar thermal energy system.

6. Conclusions

This study presents a preliminary review of the feasibility and implications of using solar thermal

technologies to meet CO₂ capture energy requirements.

Heat requirements for the CO₂ capture system will vary substantially with base power plant and CO₂ capture system design. Superheated steam above 900 kPa/350 °C might be required if using solar steam to drive CO₂ compressors, but lower temperature saturated steam (120-150 °C) can be used for solvent stripping.

Low temperature, low efficiency solar thermal technologies could provide heat for solvent stripping, but high temperature, high efficiency systems are primarily considered because they can also supply steam to drive CO₂ compression with smaller system size (land area). Parabolic dish technology is primarily a solar-to-electric system with limited energy storage capability; thus, it is unsuitable for meeting CO₂ capture heat requirements. Central receivers (power towers) and parabolic troughs are technically feasible for supplying heat to the CO₂ capture system, especially when coupled with thermal storage to increase capacity factor and improve plant economics. Temperature constraints might limit parabolic troughs' ability to supply superheated steam for CO₂ compression, but technological maturity and relative low cost make them the best near-term option among high temperature/efficiency systems.

Given a 500 MW_e gross coal-fired power plant using a 7 m MEA-based CO₂ capture system, a parabolic trough facility supplying all energy required for CO₂ compression and solvent stripping would require a total aperture area on the order of 2 km² or more if sized for an average insolation of 561 W/m². For comparison, the cumulative area of all existing SEGS facilities in California is 2.08 km². Without thermal storage, a system would require capital costs on the order of half the cost of the base power plant with CO₂ capture, and system cost and area grows substantially if the collector field is oversized for thermal storage.

Using solar thermal energy for CO₂ capture instead of steam extraction allows increased power plant output but at the increased cost of operating the solar thermal system. Electricity prices on the order

of \$100/MWh_e are required for additional electricity sales to offset the costs of operating the solar thermal system. Prices in this regime might be common with substantial CO₂ prices, but availability of sunlight and thermal storage capacity will further restrict the use of solar thermal systems. At CO₂ prices around \$50/tCO₂, bypassing the CO₂ capture system at high electricity prices is likely to be more economical than using solar energy for CO₂ capture because operating costs are similar but with little to no capital cost. High CO₂ prices shift operating economics in favor of using solar energy over bypassing CO₂ capture, but improved operating profits are unlikely to offset the capital cost of the solar thermal system.

It might be more efficient for a high temperature, high efficiency solar thermal system to generate electricity directly than to provide heat for CO₂ capture in order to increase power plant output. However, low temperature solar thermal systems used solely for stripping heat have the potential for more seamless integration with the CO₂ capture process and should be a primary focus of future work.

Using solar thermal energy for CO₂ capture appears technically feasible, but significant capital and operating cost reductions are required to offer an economic improvement over steam extraction. A more realistic approach might use solar energy for just a fraction of the stripping heat requirement. However, size and cost calculations reported here are preliminary; detailed plant design analysis and dynamic simulation is required for an accurate assessment of the technical and economic feasibility of using solar energy to meet CO₂ capture energy requirements.

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