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Novel integration options of concentrating solar thermal technology with fossil-fuelled and CO₂ capture processes

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Abstract

Concentrating solar thermal (CST) technology has been commercially proven in utility-scale power plants that have been in operation since the 1980’s. CST uses reflecting surfaces to focus solar energy onto collectors, generating extreme heat than can be used for a variety of purposes. The current focus of CST is large-scale electrical power generation. However, new applications, such as solar fuels, are quickly gaining momentum. One key shortcoming of CST technology is its sensitivity to disruptions in sunlight availability over time. CST systems require either thermal energy storage or backup systems to operate during heavy cloud periods or at night. On the other hand, fossil-based energy systems have high availability and reliability, but they generate substantial CO₂ emissions compared to equivalent CST processes.

A novel solution would combine the benefits of CST technology and of fossil-fueled energy systems. Such a solar-fossil hybrid system would guarantee energy availability in the absence of sunlight or stored solar energy. The addition of carbon capture to these systems could reduce their carbon intensity to almost zero. This paper introduces three important solar-fossil hybrid energy systems: 1) Integrated Solar Combined Cycle (ISCC), 2) Solar-assisted post-combustion capture (SAPCAP), and 3) Solar gasification with CO₂ capture. These novel concepts have great potential to overcome the inherent limitations of their component technologies and to achieve superior greenhouse gas mitigation techno-economic performance in large-scale applications.

The paper describes the features of the three solar-fossil hybrid systems described earlier, discusses its advantages and disadvantages, and provides examples of applications. The goal of this manuscript is to introduce experts in the CCS and CST fields to the opportunities of integration between these technologies and their potential benefits.

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1. Introduction

Currently, the bulk of the world’s energy is supplied by fossil fuels. Their abundance, coupled with high energy densities and low prices, contributed to their almost absolute dominance throughout the 20th century. In the past decade, however, there has been a rapid and sustained growth in demand for cleaner energy sources. Societal expectations going forward are that greenhouse gas (GHG) emissions associated with energy production must be substantially reduced. Global concerns over climate change have prompted a renewed interest in clean technologies such as carbon capture and storage (CCS) and renewable energy.

Renewable energy includes wind, biomass, and solar sources. Wind power is among the most mature renewable technologies whereas many biomass and solar technologies are still under development. Solar energy has gained tremendous popularity worldwide in the past decade, mostly in the form of Photovoltaic (PV) technology for power generation. However, a less-known solar technology called Concentrating Solar Thermal (CST) offers substantial advantages over solar PV and other renewable energies in terms of potential GHG mitigation options. For instance, CST enables the production of not only power, but heat/steam, and chemicals such as hydrogen/syngas. Although biomass can also be used to produce these, it requires a physical feedstock that must be cultivated, watered, transported, and processed prior to its use. Biomass energy also produces air emissions and by-products. CST does not have any of these features as it relies on photons as a source of nearly unlimited energy. In many respects, CST is in fact more similar to CCS than to other renewable energy technologies.

While the currently-prevailing attitude among proponents of CCS and CST technologies may be to regard them as mutually exclusive, an alternative perspective is to consider them as complementary to each other. This view is supported by a variety of reasons. First, one of the drawbacks of CCS is that it increases fossil fuel intensity, as additional energy is required to capture the CO₂ produced by the original fossil-fueled process. Second, the CO₂ captured via CCS must be compressed, transported, and stored underground, adding to its cost and complexity. CST is inherently fossil fuel-neutral and generates no by-products, but it is highly susceptible to disruptions in sunlight availability over time. Third, CST is highly land-intensive, whereas the land intensity of CCS technology is lower on a per tonne of CO₂ mitigated basis.

The above reasons highlight the chief advantages of combining CST and CCS to overcome each technology’s shortcomings. Solar-fossil hybrid systems would combine the benefits of each technology and guarantee clean energy availability in the absence of sunlight or stored solar energy in a variety of large-scale applications. This paper introduces three important solar-fossil hybrid energy systems: 1) Integrated Solar Combined Cycle (ISCC), 2) Solar-assisted post-combustion capture, and 3) Solar gasification with CO₂ capture. These novel concepts have great potential to overcome the inherent limitations of their component technologies and to yield better GHG mitigation technoeconomic performance in large-scale applications.

The paper covers the features of the three solar-fossil hybrid systems described earlier, discusses its advantages and disadvantages, and provides examples of applications. The goal of this study is to introduce experts in each of the CCS and CST fields to the opportunities of integration between these technologies and their potential benefits. The paper includes a succinct outline of CST technology, followed by an in-depth discussion of each of the three fossil-solar hybrid concepts. References to extensive literature sources are given for further reading.

2. Concentrating solar thermal technology overview

Concentrating solar thermal technology uses reflecting surfaces (e.g., mirrors) to focus incident solar radiation onto appropriately designed collectors where solar heat is gathered. The collected solar heat then undergoes an energy conversion step to produce one or more of: steam, electricity, chemicals, or hot water. Since no fossil fuel is required, the energy produced is carbon-free. There are four main CST technologies: parabolic troughs, linear Fresnel, towers, and parabolic dishes (depicted in Figure 1).
Trough systems consist of long rows of semi-curved mirrors that focus the solar energy lengthwise onto an absorber tube through which a heat transfer fluid flows. These systems feature a one-axis sun tracking mechanism, thus both the reflectors and the absorber tubes follow the trajectory of the sun throughout the day. By concentrating solar energy over a small area, very high temperatures (up to 400 °C) are achieved. The solar heat is used to produce superheated steam in a heat exchanger. The steam drives a turbine-generator assembly, generating electricity. Parabolic troughs are the most mature CST technology, having been commercially proven since the 1980’s. Current trough CST power plants have sizes ranging from 50 MW to 75 MW (net) [1].

Linear Fresnel technology uses multiple parallel long rows of flat mirrors to focus sunlight onto a fixed receiver. Its simpler design leads to lower costs than parabolic troughs (flat vs. curved mirrors) and is less land intensive than troughs. The efficiency and maximum achievable temperatures of Fresnel CST systems are lower than those of parabolic troughs. Linear Fresnel is an emerging technology that has yet to see a utility-scale commercial plant.

Solar towers consist of a large field of small, flat, sun-tracking mirrors called heliostats, surrounding a centrally located tower. The sunlight is reflected onto a single point located high above ground, heating a transfer medium contained within the towers. Thus, temperatures in excess of 700°C are achieved. Commercial tower power plants of sizes up to 20 MW are currently in operation [2]. The high temperature operation leads to higher thermal efficiencies and enables the use of phase-changing materials as heat transfer fluids and temporary heat storage medium.

Solar dishes consist of a parabolic-shaped dish made of flat mirror pieces or a reflective membrane, similar in design to a satellite dish. The dish and the receiver both track the sun’s movement using a dual-axis system. The focused solar energy is directed to a centrally-mounted receiver, yielding temperatures in excess of 800 °C. Current dish designs generate electricity using Stirling engines instead of producing steam to drive a turbine. They are compact in size, with commercial units currently limited to 25 kW [3]. The only known commercial power plant is 1.5 MW [4]. By virtue of their geometry, dishes have the highest thermal efficiency of all CST systems.

An increasingly important add-on to CST plants is a thermal energy storage (TES) system. TES allows CST plants to operate after sunset or during extended cloudy periods, approximating baseload operation. TES is based on collecting excess heat from an oversized solar collector array throughout the day and releasing the stored heat into the steam cycle after sunset or during peak hours. State-of-the-art TES systems use molten salts to provide up to 7 hours of additional power generation for a 50 MW parabolic trough facility [2]. The current trend is to develop higher temperature TES based on phase-change materials, to reduce its added cost and increase efficiency.

3. Integrated solar combined cycle

Stand-alone CST power plants require TES to achieve dispatchable operation. This adds to the capital and power costs due to the oversized solar field required and the cost of the TES system itself. An attractive alternative to thermal energy storage is the integration of a CST steam generation system to the steam cycle of a fossil-fired power station. This solar-fossil hybrid concept is called integrated solar combined cycle (ISCC), and is illustrated in Figure
A CST system is employed to generate steam, which is then fed to the heat recovery steam generator (HRSG) of the power plant. The operations of the fossil power plant are largely unchanged, although an oversized steam turbine is required. This is so that whenever solar energy is available, the turbine can accommodate the extra steam generated in the solar steam generator, thus generating power without burning extra fuel. ISCC is currently the most cost-effective way of producing power via CST, because the fossil plant and the CST system share a steam turbine and cooling equipment, resulting in substantial savings over stand-alone CST power plants.

Some of the advantages of ISCC include: 1) CST can be fitted to existing or new fossil-fired power plants without disrupting operations, degrading performance, or requiring extensive modifications, 2) ISCC can increase the generating capacity of existing plants, or decrease their fossil fuel consumption, 3) No energy storage is required, 4) ISCC can supply lower-GHG power to the grid without requiring new transmission infrastructure, and 5) ISCC decreases the CO₂ intensity of the existing power plant without the efficiency penalties associated with CCS. Its main disadvantage is that the maximum contribution of CST power to the total fossil plant output is generally limited, whether by the spare capacity of the steam cycle (in retrofits) or land availability. Thus, the carbon intensity reductions attainable by ISCC are lower than those potentially achievable by CCS technologies.

ISCC is a relatively new concept. Recently, however, a few trough-based ISCC installations are being developed. The first ISCC to become operational, located in Morocco consists of a 450 MW NGCC plant and a 20 MW trough-based CST system, supplying steam at 400°C. A second plant in Algeria, featuring a 130 MW NGCC and a 20 MW trough-based CST field is under construction and anticipated to be completed by August, 2010. The U.S. is anticipated to be home to the world’s largest ISCC plant, a 75 MW trough field integrated with an existing 3,800 MW NGCC, among the largest fossil fuel plants in the country, to be completed later in 2010 [6]. A few smaller ISCC installations have been proposed, including a demonstration unit in Medicine Hat, in Alberta, Canada [7].

Currently, ISCC technology is only being applied to NGCC plants without CO₂ capture. However, coal-fired plants are also good candidates for ISCC implementation. A 4 MW demonstration plant in Colorado increases the output of an existing 53-year-old coal fired plant has been in operation since April, 2010, using parabolic trough technology [8]. IGCC coal plants may be better candidates for ISCC integration, as their operational flexibility would allow them to cope with any fluctuations in the CST-produced supply of steam to the steam cycle better than PC coal plants would.

In our view, although it is not a perfect solution, ISCC combines the key GHG benefits of CST technology with the operational advantages of fossil-fired combined cycle plants and their high availability. Concerning ISCC with CCS; in principle, a CST steam system could be incorporated to a fossil power plant with capture. The key benefit would be GHG emissions reductions approximating 100%, where roughly 90% of the carbon is captured via CCS and the remainder is offset by adding a CST steam system equivalent to the power production without capture. This solution would incorporate the advantages of each technology although with high costs. A potentially lower-cost alternative scheme for CCS and CST integration will be discussed next.
4. Solar-assisted post-combustion capture

One of the major drawbacks of post-combustion CO₂ capture is its large energy demands, usually in the form of steam, required to regenerate the CO₂-bearing solvent. For this reason, most power plant designs featuring post-combustion capture rely on bleeding off steam from the fossil plant’s steam cycle to supply the energy demands of the CO₂ reboiler. This approach has undesirable consequences, because it leads to substantial thermal efficiency losses, typically of 7-13 percentage points [9]. Hence, more fuel must be burned to generate the same amount of electricity as in a non-capture plant and more CO₂ must be captured, compressed, and transported. The efficiency penalty due to post-combustion capture leads to higher electricity costs, especially in gas-fired power plants, whose economics are highly sensitive to fluctuations in fuel costs.

Figure 3 shows a block diagram of a CST steam generation plant attached to a fossil power plant with post-combustion CO₂ capture. This novel concept, called solar-assisted post-combustion CO₂ capture (SAPCAP) is similar to ISCC, except that the steam is directed to the CO₂ stripper reboiler instead of to the steam turbine. In SAPCAP, solar-generated steam offsets steam extracted from the plant’s HRSG, thus reducing the efficiency losses normally associated with CO₂ capture. If the energy demands of the solvent reboiler were fully supplied by the CST plant, the efficiency penalty of CO₂ capture would approximate zero. SAPCAP thus offers the potential to overcome one of the main disadvantages of implementing post-combustion carbon capture in fossil-fired power plants.

SAPCAP features a number of advantages. First, CST systems can feasibly produce steam at the conditions required in the reboiler. Second, the efficiency and economics of CST steam are superior to those of CST electricity, and may improve the economics of CCS. Third, the steam supply to the reboiler is always guaranteed, as steam extraction from the steam turbine is always an option. Fourth, the fraction of steam produced by the solar system can be customised to best match the solar resource and operational requirements of the plant. Finally, unlike ISCC, SAPCAP can be implemented in other fossil-fired applications, such as hydrogen plants. Some disadvantages of SAPCAP include its increased land requirements, added capital costs, and increased operational complexity.

The basic SAPCAP concept presented in Figure 1 can be improved in a number of ways. The most immediate would be the addition of TES, which would increase the availability of solar steam to the process. Another potential improvement would be to eliminate the solar steam generator and use the solar heat transfer fluid to heat the solvent in the reboiler directly. If this concept is taken one step further, the solvent may be used as the heat transfer fluid in the solar field, field effectively acting as an alternative to the reboiler when sufficient solar energy is available. However, the heat transfer properties of the solvent and its impact on the solar equipment (maintenance, operability) must be evaluated in further detail. If TES were to be added, the solvent from the stripper could simply exchange...
heat with the stored heat transfer fluid, with improved thermal efficiency. This scheme would be an ideal match for solar towers, which can use molten salts as heat transfer and storage agents.

The merit of the improved SAPCAP alternatives is squarely derived from the higher integration between the CST system and the solvent regeneration process. This would result in a higher proportion of the energy demands of the latter being provided by solar energy, reducing steam extraction from the steam turbine and requiring less equipment, while potentially improving the economics of SAPCAP. The greater integration, nevertheless, leads to a tradeoff with complexity, which in turn must be assessed against the controllability and operability of the entire plant. Thus, the cost-benefit advantages of deeper integration must be established on a project-by-project basis.

Although promising, SAPCAP is an immature technology concept that is currently under evaluation. AITF in Canada will conduct a techno-economic study of SAPCAP vs. amine-based post-combustion capture applied to NGCC and supercritical PC power plants. The results will identify and quantify the differences between both approaches. From a feasibility perspective, however, both SAPCAP core processes have been commercially proven, so the remaining issues are limited to integration, engineering, and process control, which are substantially less challenging than developing a new technology concept from a paper or bench scale.

5. Solar gasification with CO₂ capture

An emerging application of CST technology is the conversion of solar energy into chemical fuels. Solar fuels include synthetic gas (syngas) and H₂. Solar fuel production via CST offers an attractive method for storing solar energy, in addition to providing an alternative to fossil fuel-based hydrogen production. There are three major routes for solar fuel production using CST technology: 1) Electrochemical – solar electricity is used to power electrolyzers, 2) Photo-chemical/-biological – uses direct photon energy in photochemical and photobiological reactions, and 3) Thermochemical – high-temperature solar heat powering endothermic reactions. Thermochemical processes are currently the most researched processes.

The leading thermochemical processes involve water splitting and decarbonisation of fossil fuels. Although water-splitting processes are desirable due to their negligible carbon intensity, solar decarbonisation processes offer a more immediate route to the production of low-carbon H₂ and syngas, by virtue of their relative lower complexity and maturity level. Decarbonisation methods rely on more familiar processes, such as cracking, reforming, and gasification of fossil feedstocks, using solar energy at lower temperatures than water splitting processes.

Solar gasification of carbonaceous materials has been under development for the past two decades. Recent advances in CST systems have made it possible to reliably achieve the high temperatures required to drive the endothermic reactions associated with gasification. Solar gasification processes use steam to turn fuels such as coal or petroleum coke into a syngas with an ultra-low CO₂ content, as illustrated in Figure 4. Depending on its intended use, the syngas can be steam-shifted to H₂ via the water-gas shift reaction, generating CO₂ which can then be removed via pre-combustion capture and the H₂-rich gas further purified in a PSA (pressure swing adsorption unit).

The advantages of solar gasification are multiple. First, the carbon-to-syngas yield is higher than in conventional gasification because the reaction energy is supplied by the sun instead of by partial oxidation of the fuel. Second, solar gasification does not necessitate an oxygen plant, for the above reason, which reduces capital costs. Third, solar air gasification yields syngas with an ultra-low CO₂ content. Fourth, all processes upstream and downstream of the solar gasifier are well-understood and many of the materials and equipment developed for conventional gasification can be applied with minimal modifications required.
The disadvantages of solar gasification include its high land intensity, as towers would be predominantly used. Also, while conventional gasification reactors operate at high pressure, pressurised solar gasification has not been proven or tested yet. Pressurised operation is desirable as it equals smaller equipment is needed and thus, lower costs, but most importantly, CO₂ can be recovered at high pressure, which is advantageous from a capture perspective. Finally, fluctuations in solar energy availability pose substantial operational challenges, as temperatures in excess of 1100 °C must be maintained for the reactions to proceed. To date, no TES system is capable of reaching the required temperature, so a backup, likely fossil-fired option would be required in large-scale applications.

Solar gasification is not yet a commercial technology. The most advanced project to date is a 500 kWth pilot unit at PSA in Spain. This project is a joint cooperation between Petróleos de Venezuela, the Eidgenössische Technische Hochschule in Zurich, and Spain’s Centro de Investigaciones Energéticas, Medio Ambientales y Tecnológicas (CIEMAT). The project, named SYNPET involves H₂ production by solar gasification of petcoke and vacuum residue from heavy oil refining in 3 phases over 6 years. In Phase I, a 5 kWth prototype underwent testing at Paul Scherrer Institute in Switzerland [11,12], the results of which formed the design basis for the optimised scaled-up reactor and ancillaries, built in Phase II [13] and shown in Fig. 5. Phase III includes the operation of the whole installation and a preliminary design of a 50 MW solar gasification plant to be located in Venezuela.
The experimental campaign was initiated in the second half of 2009. Its objective was to obtain operating experience and learn about the system behaviour (SCADA system monitors and controls about 850 process variables). Initial thermal test were carried out in February 2010. A maximum flux density of about 1.5 MW/m² was reached, amounting to a total absorbed power of 300 kW, which is somewhat far from the design level but achieved a reactor temperature of approximately 800 °C. Higher flux densities are being investigated to achieve power levels approaching the maximum load. Further test series will investigate the chemical behaviour of the whole installation. The second solar testing campaign is scheduled for September 2010 and will last 3 months. Its results will provide input to the pre-design of the gasification plant in Venezuela. The test data will be evaluated and compared with simulation tools to verify the calculations and to identify potential problems. The major components of a solar petcoke reforming plant will be analysed to assess their impact on the conceptual layout of the plant. For the upstream part of the gasification loop, the operation with different gaseous feedstocks (natural gas, weak gas, biogas, landfill gas), and concepts for gas cleaning and gas treatment will all be assessed.

From an integration perspective, the challenges for CCS implementation in solar gasification are modest. CO₂ removal can be easily achieved with existing pre-combustion technology, if the syngas is steam-shifted. Otherwise, any resulting carbon emissions from syngas burning can be mitigated using conventional post-combustion technology or even SAPCAP. Potential options for integrating solar and conventional gasification with CCS deserve further study, as a fossil-fired backup may be essential to make solar gasification commercially viable.

6. Conclusions

Fossil-fueled energy production processes featuring CCS are an essential intermediate step to a carbon-free world. CST-based energy production systems, due to their negligible GHG intensity and reliance on a practically inexhaustible source of energy are increasingly important elements of a long-term carbon mitigation solution. This paper proposes that hybrid solar-fossil systems combining both technologies, have great potential to overcome the latter’s shortcomings and exploit their unique advantages.

The three integration concepts presented here including ISCC, SAPCAP, and solar gasification have great potential to make a substantial contribution towards the goal of attaining significant GHG emissions reduction in the mid-term. ISCC is the most mature of these concepts and is ready for deployment, having been successfully proven on a large-scale already. Solar gasification has been proven on a pilot scale, and may be scaled up to a demonstration scale by 2012. SAPCAP is a novel paper concept that could be tested on a pilot scale with a relatively low effort, in a short timeframe, if enough support from industry and government was warranted by its techno-economic evaluation, currently underway.

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