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# Energy efficient considerations on carbon dioxide capture: Solar thermal engineering (Part I)

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## Abstract

Representative carbon dioxide capture and storage (CCS) system of the post-combustion, no matter it employs adsorption, absorption or cryogenics separation technologies, commonly requires significant amounts of energy for the fundamental operation. Thus, energy consumption and related cost rise are primary challenges for the promotion of post-combustion technology. Solar thermal energy has already been widely used as an effective and clean energy source in industrial applications for drying, heating and even cooling since the last century. Various options of solar collector, such as flat plate type, evacuate tube type, and parabolic trough type, facilitate a comprehensive energy supply in different energy quality grades.

In this paper, a technological framework for the energy efficiency in post-combustion $CO_2$ capture is briefly presented for a connection between the energy demand of a CCS system and the energy supply of solar thermal engineering. The match performance between solar thermal utilization systems and CCS system is discussed in terms of energy form of the demand side (CCS), energy grades of supply sides (solar collector), and possible dynamic adjustment.

*Keywords:* post-combustion; CCS; solar energy; renewable energy

## 1. Introduction

The atmospheric concentration of the greenhouse gas (GHG), which was believed to be the largest contribution to global warming and climate change, has increased since 1750 due to human activity. In 2011, the concentration of $CO_2$, was 391ppm and exceeded the pre-industrial levels by about 40% [1]. Electric-power generation still remains the single largest source of $CO_2$ emissions, emitting as much $CO_2$ as the rest of the industrial sector combined [2]. Chemical absorption method which employs monoethanolamine (MEA) or related amines is considered the most matured near-term technology

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solution of post-combustion $CO_2$ capture for flue gases. However, MEA system integrated with power plant commonly causes a 15-20% steam reduction for an energy penalty to $CO_2$ regeneration [3]. The thermal energy required for the stripper and power for cycle pumps and the corresponding high capture cost became main barriers to technology development.

## 2. Solar thermal utilization in CCS

### 2.1. Technological framework

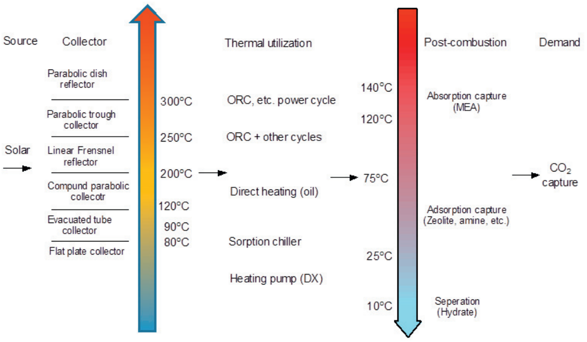


Fig. 1. Technological framework for solar thermal utilization in CCS

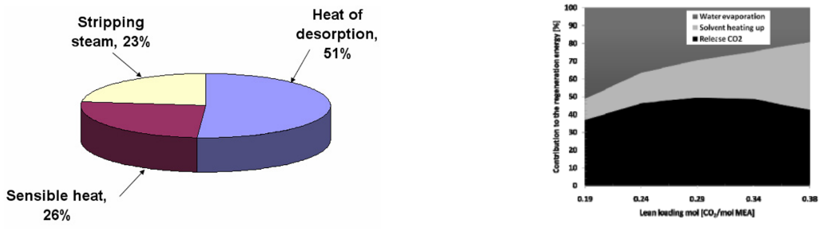
A brief technological framework between solar thermal source and post-combustion $CO_2$ capture is shown in Fig 1. Using various patterns of solar collector, thermal energy from solar can be supplied in a temperature range from 80°C to more than 300°C. As for the demand side, four typical conventional post-combustion systems are considered. The regeneration temperature for the conventional MEA absorption capture is 120°C to 140°C and regeneration temperature for $NH_3$ method is relatively lower (80-100°C). For the adsorption system, the regeneration temperature, as summarized in reference [4], is as low as the environmental temperature. For hydrate separation, 0.6°C is a conventional operating temperature, but the temperature can be raised with possible additive, such as Tetrabutyl ammonium bromide (TBAB).

The content of the framework mainly focuses on the potential technological solution between supply and demand as shown in the middle part of Fig 1. Several options, such as solar thermal driven ORC system, solar thermal direct heating, even solar thermal driven cooling system, were presented for the energy supply in different grades.

The technological framework is discussed in terms of the energy form of the demand side, the energy grade on the supply side, and possible adjustment for the match performance. Several representative technologies and corresponding systems and key issues in design are presented in the second part of this two-part study.

### 2.2. Energy form of demand side

Taking MEA system as an example, the energy demands of the system are power and thermal energy. The power is used to drive a fan in the absorber, cycle pumps, and compressors. The thermal energy from the extraction steam is mainly for the reboiler. The simulated results of the MEA system in reference [5] show a breakdown of energy requirements in the reboiler: the thermal energy for desorption, stripping steam and sensible heat take 51%, 23% and 26%, respectively (Fig 2). With lean loading increases, although calculation conditions are different, the variation of these three sections in reference [5, 6] shows a similar trend. Furthermore, the total energy consumption for regeneration takes 62% of the entire amounts of energy consumption in the MEA system [5]. Actually, in addition to the energy consumption mentioned above, a large number energy is required to cool large volumes of flue gas before the flue gas comes into the absorber. It implied that cooling energy conversed from thermal energy or electricity, coolant (commonly water) are also necessary to the MEA system for a high-quality capture.



(a) (b)

Fig. 2. Regeneration energy: (a) breakdown; (b) variation contributions

For a MEA capture plant, the thermal energy requirement far exceeds the electrical input. The simulation result in reference [7] shows that the thermal duty of reboiler and power capacity of cycle pump is 602MW and 487 kW, respectively. The simulated results of available energy demands for compressor, pumps and reboiler are 5.56, 0.02 and 10.78 ($\times 10^6$ kJ/hr), respectively [8]. As for the total energy consumption, thermal energy requirement per ton $CO_2$ and power lost percentage due to extraction steam are conventional evaluated indexes. The range of thermal energy required is from 3 to 4.4 GJ/ton $CO_2$ for the common $CO_2$ capture method.

In addition to the thermal energy consumed by the stripper, electrical energy consumed by auxiliary equipments, such as flue gas blower and pumps, the compression train, steam consumed by the jet ejector all results in a loss of total power generation capacity [9]. Furthermore, some potential demands, which contain cooling energy for condensers, a large amount of water (sea water) and solvent, are necessary for a steady operation.

### *2.3. Energy grade of supply side*

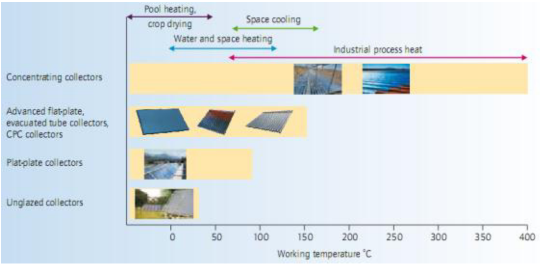


Fig. 3. Solar collectors and working temperatures for different applications [10]

Table 1. Solar collector performance [11]

| Collector type | Concentration ratio | Indicative temperature range (°C) |
|---|---|---|
| Flat plate | 1 | 30-80 |
| Evacuate tube | 1 | 50-200 |
| Compound parabolic | 1-15 | 60-300 |
| Linear Fresnel reflector | 10-40 | 60-250 |
| Parabolic trough | 10-85 | 60-400 |

Through various solar collectors, thermal energy from the solar source can be supplied in different energy grades. As shown in Fig.3, the range of working temperatures is commonly from 0 to 400°C for residential use and industrial application.

### *2.4. Dynamic adjustment for performance match*

Although it is commonly considered to be a steady value, heat duty of the regeneration process is affected by flue gas concentration, solvent temperature and some other fluctuating factors. Thus, regeneration process and other energy consumption elements show a dynamic performance, as some research results shown in Table 2. Moreover, the primary drawback of solar thermal energy is unsteady with dynamic climate conditions. Thermal storage device, such as a water tank and molten salt tank, are an efficient mean for a steady supply and widely used in existing demonstration projects of large-scale solar thermal plants. In addition, optimized control and system characteristics can perform a fine-adjustment between supply and demand.

Table 2. Researches on dynamic performance of supply and demand sides in CCS system

| Reference | Supply side (solar thermal energy) | Demand side (solvent regeneration ) |
|---|---|---|
| (Lawal et al. 2010) | - | Dynamic simulation, a dynamic variation in heat duty of reboiler |
| (Biliyok et al. 2012) | - | Simulation validated by test data, heat duty and intercooled solvent return temperature variation with time |
| (Li et al. 2012) | Optional thermal energy storage system is considered in the economic analysis of solar-assisted CCS system | - |
| (Qadir et al. 2013) | The thermal storage is used in the analysis system for a maximum of 15 full load hours | - |

## 3. Conclusion

In this study, a brief technological frame of solar thermal utilization for CCS was presented for the energy efficiency consideration. Through various solar collectors and solar thermal utilization system, power, heating and cooling energy can be provided to the CCS system for solvent pumps, heat duty of regeneration, and separation process. The working temperature of the solar collectors ranges from 0 to 400$^{o}$C, and working temperature of demand sides of CCS system can be covered through energy conversion and supply from the solar source. Dynamic adjustment for a performance match between supply and demand sides is necessary, as a performance decrease to the ideal solar-assisted CCS system would happen due to unsteady climate conditions and $CO_2$ sources.

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