

SOLAR-ASSISTED CO₂ CAPTURE WITH AMINE AND AMMONIA-BASED CHEMICAL ABSORPTION A Comparative Study

by

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Intensive energy penalty caused by CO₂ separation process is a critical obstacle for retrofitting power plant with carbon capture technology. Therefore, the concept of utilizing solar energy to assist solvent regeneration for post-combustion carbon capture power plant is proposed recently as a promising pathway to compensate the efficiency reduction derived from CO₂ capture process. However, the feasibility of solar-assisted post-combustion technologies largely depends on the types of CO₂ absorbent, categories of solar thermal collectors, areas of solar field, and the integration of thermal energy storage system. Therefore, this paper conducts a comparative analysis on monoethanolamine-based and NH₃-based solar-assisted post-combustion power plants employing two types of solar collectors, i.e. the vacuum tube and the parabolic through collector, with climate data of Tianjin City, China. Levelized costs of electricity and cost of CO₂ removed are comparatively studied for both solar-assisted post-combustion configurations. Results show that the proposed solar-assisted post-combustion configurations are economically viable when the price of vacuum tube is lower than 86.64 \$/m² and 117.29 \$/m² for the monoethanolamine-based and NH₃-based solar-assisted post-combustion power plant, respectively. Meanwhile, the price of parabolic through collector should be less than 111.12 \$/m² for the monoethanolamine-based and 114.51 \$/m² for the NH₃-based solar-assisted post-combustion power plant. It is indicated that employing the vacuum tube for chilled NH₃-based solar-assisted post-combustion power plant offers a promising approach to reduce the energy penalty with attractive economic performance.

Key words: solar energy, amine absorption, ammonia absorption,
post combustion, carbon capture

Introduction

Carbon capture and storage is identified as a key technology to mitigate climate change. Currently, there are several carbon capture technologies available for CO₂ separation from industrial flue gas, which can be divided into three types: the oxyfuel-combustion, the pre-combustion and the post-combustion capture [1, 2]. Among above technologies, the

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chemical based post-combustion carbon capture (PCC) has its advantage as it can be added to existing power plants with minimum modification providing that there is enough space to be available [3]. Regarding chemical absorbent, monoethanolamine (MEA) method is commonly accepted as the most mature solvent for post-combustion capture [4, 5], which is capable of achieving high CO₂ capture efficiency as well as obtaining high concentration of CO₂ stream for sequestration [6].

However, despite that the MEA-based capture process is promising to remove massive CO₂ emissions from power plants, it is a quite costly option with CO₂ reduction cost ranging from 40 to 70 \$/tCO₂ [7]. Therefore, ammonia (NH₃) aqueous solution has been proposed and investigated recently as an alternative chemical absorbent. Commercially, the involved process is named as chilled ammonia process (CAP). Compared to the conventional MEA-based chemical absorption, the advantages of NH₃-based solvent include its lower absorbent cost, lower regeneration temperature, less solvent regeneration energy consumption, advanced anti-degradation ability, and thermodynamic properties that allowing for lower desorption pressure [8]. However, further analysis should be carried out to study its technical and economic feasibility.

To compensate for the loss of efficiency caused by CO₂ capture, renewable energy is proposed to be implemented as parts of the energy infrastructure to offer heat source for solvent regeneration in the near future. In general, regenerate temperatures for NH₃-based process and MEA-based processes are approximately 80-90 °C and 110-120 °C respectively [9, 10]. Therefore, solar thermal energy is a promising heat source for solvent regeneration. Therefore, recently, increasing numbers of studies have been carried out focusing on the feasibility of PCC utilizing solar thermal energy to regenerate CO₂ solvent.

The MEA-based chemical adsorption

Amines have been used for CO₂ capture since 1930's. Among amine-based solvent, MEA is the most commonly used solvent to absorb CO₂ from industrial gas mixtures, which is regarded as the leading technology for post-combustion capture process and also well understood for large-scale application [11]. However, the main disadvantages of the MEA process origin from the great amount of heat demand by extracting steam from steam turbines, which would lead to considerable efficiency decrease for the power plant. Many efforts have been put to investigate the integration options between the steam cycle of the power plant and the carbon capture process by means of system optimization. Previous researches have shown that the steam extraction will cause a significant decrease of power output which leads to an efficiency penalty around 9-12% by lower heating value [12]. An optimization study on a MEA-based CO₂ capture system of a 600 MW_e bituminous power plant reveals that the re-boiler energy consumption is able to decrease from 3.9 GJ/tCO₂ to the minimum 3.0 GJ/tCO₂ when the MEA solution is at 40 wt.% [13]. Researches on the performance of different alkanolamines for large-scale PCC system (375-450 MW) show that with the CO₂ capture efficiency between 89% and 96%, the CO₂ emissions can be reduced from 807.4 kg/MWh to 89.5 kg/MWh with 30% MEA-based capture process. However, it comes at the cost of 16.6% reduction of overall thermal efficiency [14]. A comparison between the vapor recompression, multi-pressure stripping and the simple stripping of a MEA-based CO₂ capture system was analyzed via ASPENPLUS. Results demonstrate that the multi-pressure stripping can reduce the equivalent work by 3-11% while the vapor recompression offers no reduction benefits. Furthermore, depending on [15], at optimized conditions, the maximum CO₂ absorption capacity is up to 1.19 mol CO₂/kg solvent. Regarding the economic performance, the costs of

electricity rise sharply by 42-66% due to both of the efficiency penalty and additional costs, while the costs of CO₂ removed (COR) are within the range of 30 to 50 \$/tCO₂ [12].

The NH₃-based chemical absorption

Although NH₃-based post-combustion CO₂ capture is less well understood, it is promising because NH₃ is low-cost and the requirement of energy grade for reboiler heating might be lower than that of amine-based methods. In addition, the desorption can be operated at high pressure which is beneficial for the following transportation stage. Several studies investigated the performance of aqueous NH₃ absorption for CO₂ separation. For instance, an experimental result indicates that the CO₂ removal rate can reach 98.4% by NH₃-based absorption process using a spray column [16]. Based on the techno-economic analysis, COR of chilled NH₃ process (53 \$/tCO₂) is lower than that of the MEA process (61 \$/tCO₂) for a 600 MWe pulverized coal combustion power stations with PCC technologies [4]. Experimental researches comparatively studied CO₂ capture with NH₃ and MEA-based solvents [17, 18], indicating that NH₃-based solvent might achieve higher CO₂ removal rate and absorption capacity than MEA-based solvent. Similarly, experimental results from [19] indicates that NH₃-based CO₂ capture might consume less energy than the MEA-based process.

Solar-assisted post-combustion carbon capture

It is promising to integrate solar energy for chemical solvent regeneration, because the temperature supply range of available solar thermal collectors (STC) can cover the regeneration temperature of MEA and NH₃ solvents [20]. Therefore, there were a few studies concern the feasibility of integrating solar field with carbon capture power plant in recent years. It is indicated that the cost of electricity (COE) and COR might be sensitive to several factors including types of STC, climate conditions, CO₂ capture rate as well as capital costs of solar collectors, *etc.* In comparison with PCC power plant, SPCC system is competitive regarding COE and COR only when the price of solar collectors are lower than a certain value [9]. Mokhtar *et al.* [10] assessed the techno-economic feasibility on a SPCC with Fresnel solar collector, indicating that the economically viable price of solar collectors is about 100 \$/m² based on current retail electricity price in New South Wales. In general, SPCC performances better with the increase of solar load-fraction, electricity price and the decreasing of solar collector costs [8]. Furthermore, a technical and economic analysis and optimization on a 660 MWe SPCC power plant were conducted taking Sydney, Townsville, and Melbourne as the geographical reference. Five types of solar collectors including evacuated tube solar collectors (ETC), flat plate collectors, compound parabolic collectors, parabolic through collectors (PTC), and linear Fresnel collectors were comparative analyzed. Results indicated that Sydney, Townsville, and Melbourne have different optimal solar fractions (SF) at 0.35, 0.23, and 0.17, respectively, while the integration of ETC performs best among all the options [21].

Integrating solar energy into PCC systems is quite a new concept, thus there are insufficient studies investigating the feasibility of different configurations. The objective of this study is to parallel analyze the performance of MEA-based and chilled NH₃-based SPCC system for a pulverized power plant. The climate data of Tianjin city is utilized for the design of solar field, and two kinds of solar collectors are utilized *i.e.* PTC and vacuum tube (VT). Levelized costs of electricity (LCOE) and COR are comparatively analyzed to evaluate the performance of MEA and NH₃-based capture process when introducing solar thermal energy to heat reboiler. Results should provide guidance in terms of the implementation of different SPCC options.

System description

Figures 1(a) and 1(b) depicts the sketch of MEA-based and chilled NH₃-based CO₂ capture power plant systems integrated with solar collectors. Both systems consist of a coal-fired power plant, a CO₂ capture system and a solar field.

The MEA-based CO₂ capture approach

The MEA-based capture technology is a standard MEA-based absorption process as presented in fig. 1(a) [22]. Flue gas is directed into the absorber after being treated, in which CO₂ is chemically absorbed into the MEA-based solvent. Then the clean flue gas emits to atmosphere from the top of absorber after going through a water scrubber. There is a rich and lean solvent cross heat exchanger connecting absorber and stripper. After passing through the cross-flow heat exchanger, the rich solvent is pumped into the stripper and finally regenerated in reboiler. Finally, the lean solvent is recycled to the absorber after passing through the cross-flow heat exchanger for another absorption cycle. The released CO₂ is finally compressed for transportation or further utilization.

The NH₃-based CO₂ capture approach

Different aqueous NH₃ capture methods have been put forward as alternatives to MEA-based method. The CAP technology is one of leading technology described in [23, 24]. The feature of CAP lies in that the capture of CO₂ should be completed at relatively low temperature ranging from 0-20 °C. As can be seen from fig. 1(b), flue gas at 60 °C enters a direct contact cooler to be chilled to around 30 °C and then passes through a chilled water heat exchanger to make sure that the temperature is decreased to about 10 °C before entering the absorber. In the absorber, CO₂ in the flue gas is absorbed into the lean solvent and the rich solvent leaves from the bottom part of absorber. Similar to MEA-based process, the rich solvent is then sent into the stripper to be regenerated and the clean flue gas emit to atmosphere from the top of absorber. To complicate the next capture cycle, the lean solvent needs to be cooled to around 10 °C through a cross-flow heat exchanger and a chilled water heat exchanger. However, it is worth noting that there might be significant escape of NH₃ vapor together with the flue gas from the absorber. Therefore, a water treatment system is necessary in order to recover the slipped NH₃. Consequently, the NH₃ should be further regenerated in the NH₃ stripper and finally returned back to the absorber for another cycle.

Solar assisted SPCC systems

As described in figs. 1(a) and 1(b), for both SPCC systems, the thermal energy demand for reboiler heating could be provided by solar thermal energy or steam from turbines. Regarding to solar thermal systems, thermal oil is used as heat transfer fluid to avoid high pressure of STC. When the solar irradiation is abundant, the thermal oil heats up and transfers thermal energy into the thermal energy storage (TES) system, which finally heats steam for solvent regeneration. However, when the amount of solar energy reaching the solar collectors is insufficient, steam extraction from the steam turbine cycle would be utilized to regenerate solvent in reboiler. In this study, the TES is employed to store additional heat to make better use of the installed solar collectors. There is significant variation in solar irradiation condition and ambient temperature in different seasons. Therefore, the solar field is designed according to monthly climate data of a typical full year. In addition, the TES is designed to supply energy for limited hours considering the variation of solar irradiations.

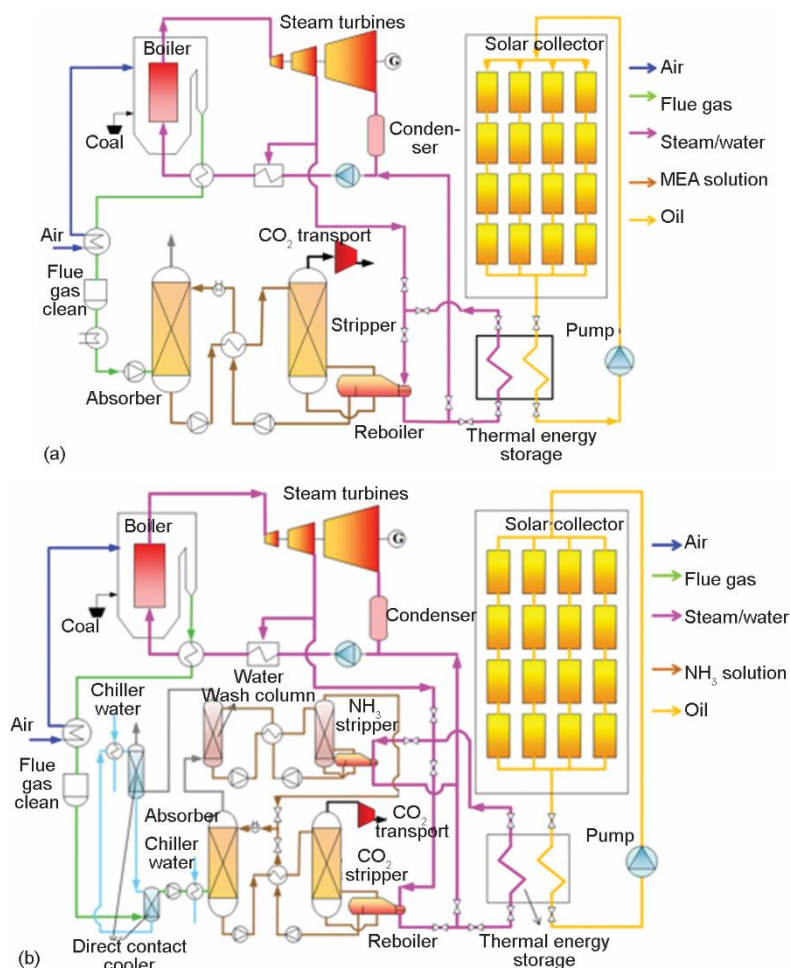


Figure 1. System sketches of (a) MEA-based and (b) NH₃-based SPCC systems

Methodology and input data

Power plant and carbon capture system

In this study, different configurations are based on a supercritical pulverized coal fired power plant (PC) with net power output of 550 MW_e as described in [23, 24]. Table 1 summarizes the operation parameters of the reference PC, MEA-based capture PC, and NH₃-based capture PC. The nominal net outputs for all the power plants is maintained at 550 MW_e through increasing the quantity of steam to offset the output penalty imposed by CO₂ capture facilities. The net outputs of the reference PC, MEA-based capture PC, and NH₃-based capture PC are 550.1 MW_e, 546.0 MW_e, and 558.7 MW_e, respectively, all of which are approximately 550 MW_e and correspondingly obtaining the efficiencies, HHV [%], of 39.1%, 27.2%, and 27.9%, respectively. The CO₂ capture rate is assumed at 90% when integrated PCC systems with solvent concentration at 14.4 wt.% for NH₃-based solvent and 30 wt.% for MEA-based solvent. Regarding to NH₃-based carbon capture system, the slipped NH₃ from the water scrubber is restricted to 10 ppm. Costs input data are summarized in tab. 2. It should

be noted that the capital costs of NH₃-based CO₂ capture system are greater than that of the MEA-based system because it requires a larger steam turbine.

Table 1. Power plant parameters (MW_e)

Parameter	PC without carbon capture	MEA-based capture power plant	NH ₃ -based capture power plant
Gross power output (MW _e)	580.2	827.6	827.6
Net power output (MW _e)	550.1	546.0	558.7
Steam load for carbon capture (MW _e)	N.A	164	112
Auxiliary electrical load	30.1	119	156
Plant efficiency, HHV [%]	39.1	27.2	27.9
The CO ₂ capture rate [%]	0	90	90

Table 2. Involved Economic parameters

Parameter	PC	MEA-based PCC	NH ₃ -based PCC	References
Project life [years]	25	25	25	[10, 25]
Construction time [years]	1	1	1	[25, 26]
Operation time [h per years]	8016	8016	8016	[25]
Interest rate [%]	6	6	6	[10, 25]
Coal price [\$ per ton]	95 (60-130)	95 (60-130)	95 (60-130)	[23]
Salvage value [% of capital cost]	0	0	0	[25]
O&M cost [% of capital cost]	4	4	4	[25]
Power plant				
Capital cost of PC [M\$]	881.1	1166.2	1169.0	[23, 24]
Capital cost of carbon capture [M\$]	N.A	393.9	483.0	[23, 24]
Carbon capture system				
The MEA cost [\$ per kg]	N.A	2.361	N.A	[23, 24]
Ammonia cost [\$ per kg]	N.A	N.A	0.483	[23, 24]
Cost for CO ₂ transportation and storage [\$ per t]	N.A	3.75	3.75	[24, 24]

Climate data and solar field

Determining the detailed climate data is essential for feasibility studies [9]. Tianjin city is selected which is located in the area with relatively abundant solar energy in China. Figure 2 presented the average monthly direct normal insolation (DNI), sunshine hours and ambient temperature [27]. Specifically, the value of annual average DNI, sunshine hours and ambient temperature in Tianjin city are 5.58 kWh/m² per day, 7.05 hour sper day, and 13.9 °C. The locally available STE and the solar collector area (SCA) and the volume of phase change material (VPCM) are designed and further analyzed in terms of the economic performance.

The amount of harvested solar thermal energy is dependent on several factors, including solar irradiation, incidence angle and ambient temperature. In this study, the collected solar thermal energy is estimated based on eqs. (1) and (2) [9, 20]. Table 3 lists the main physical parameters for PTC and VT:

$$Q_s = \eta_{0b} K_b(\theta) G_b + \eta_{0d} G_d - a_1(T_m - T_a) - a_2(T_m - T_a)^2 \quad (1)$$

$$K_b(\theta) = 1 - b_0 \left[\frac{1}{\cos(\theta)} - 1 \right] \quad \theta \leq 60 \quad (2)$$

where η_{0b} and η_{0d} are the optical efficiency of DNI and diffuse irradiance, respectively, G_b – the DNI, G_d – the diffuse irradiance, a_1 and a_2 – the constant and the temperature dependent part of the overall heat loss coefficient, respectively, T_m – the average temperature of solar collector, T_a – the ambient temperature, θ – the incidence angle, K_b – the modifier for incidence angle, and b_0 – the characteristic parameter in the angle of incidence modifier.

Table 3. Efficiency parameters for VT and PTC [9, 20]

Items	η_{0b}	η_{0d}	a_1	a_2	b_0
The VT collector	0.8	0.72	1.5	0.01	0.01
Concentrating collector	0.75	0.08	0.50	0.00	0.10

With the development of advanced material, it is proved that the temperature of VT is able to reach 200 °C [28]. Therefore, both VT representing the non-concentrating collector and PTC representing the concentrating collector are comparatively examined in this study. The economic data input for PCM and STC is listed in tab. 4.

Techno-economic analysis

Solar assisted scheme

The area of solar collector determines the required volume of PCM and SF, which in consequence have an effect on the efficiency of the power plant steam cycle. For the sake of analysis, two area boundaries, the 1st boundary area and the 2nd boundary area, are defined to distinguish the implementation volume of the TES. In details, when the area of solar collectors is under a threshold value, all the solar thermal energy is utilized for solvent regeneration, thus no spare heat is left to be stored. Therefore, we defined this solar area as the 1st boundary area, indicating that there is no requirement to integrate the heat storage system. However, when the solar field area is over a threshold value, the collected solar energy is greater than the reboiler energy demand during the daytime, thus the spared energy can be stored. Under

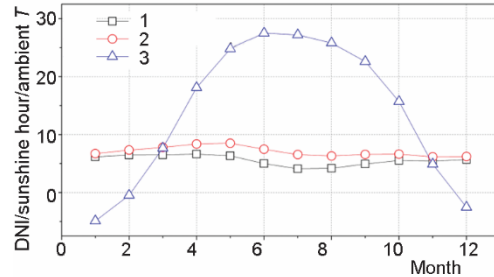


Figure 2. Climate conditions in Tianjin city; 1 – DNI, 2 – sunshine hour, 3 – ambient temperature

Table 4. Economic data input for PCM and STC [9]

Thermal storage material type	Erythritol
Density of energy storage material [kJkg ⁻¹]	339.8
Cost of energy storage material [\$ per kg]	3.5
Cost of PTC [\$ per m ²]	185 (120-250)
Cost of VT [\$ per m ²]	130 (70-200)

this condition, the increased area of the collector is useless if there is no TES. Therefore, we defined this collector area as the 2nd boundary area.

Table 5. The list of the SF/collector area/VPCM of six coupling schemes

Description		CH1-W/O	CH2-W/O	CH3-W	CH4-W	CH5-W	CH6-W
MEA-based-VT	SF [%]	22.70	29.40	39.15	50.03	75.00	100.00
	SCA [km ²]	2.33	4.01	4.01	5.13	7.69	10.41
	VPCM [kt]	NA	NA	16.37	27.20	52.05	76.93
MEA-based-PTC	SF [%]	24.92	29.40	39.59	50.00	75.01	100.00
	SCA [km ²]	2.04	3.24	3.24	4.09	6.14	8.28
	VPCM [kt]	NA	NA	14.60	24.96	49.85	74.72
NH ₃ -based-VT	SF [%]	23.48	29.40	36.70	50.05	75.01	100.00
	SCA [km ²]	1.23	1.93	1.93	2.63	3.94	5.33
	VPCM [kt]	NA	NA	8.97	18.04	34.99	51.95
NH ₃ -based-PTC	SF [%]	24.93	29.40	39.27	49.98	75.01	100.00
	SCA [km ²]	1.34	2.11	2.11	2.69	4.04	5.45
	VPCM [kt]	NA	NA	9.73	17.01	34.00	51.81

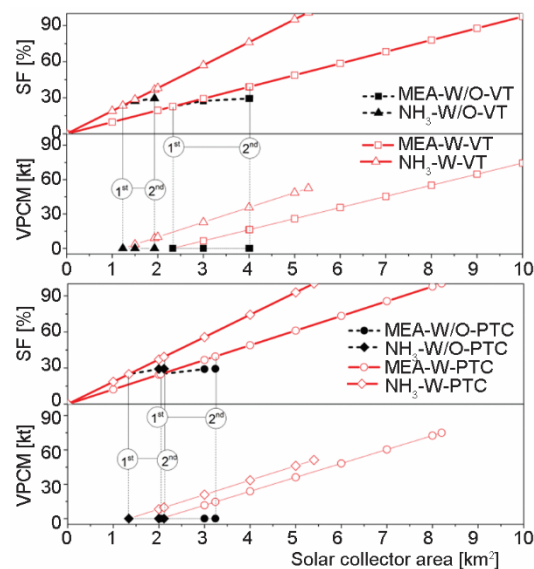


Figure 3. Variation of the SF and the VPC with the changes of SCA

LCOE and CO₂ emissions [12, 25], which is an important index to the evaluate different carbon reduction measures:

Figure 3 displays the variation of the SF and the volume of the PCM (VPCM) with the variation of SCA with the 1st and 2nd boundary area marked in the figure. To achieve the same SF, more SCA and VPCM are required for the MEA-based SPCC because of the higher energy requirement for CO₂ regeneration. According to the coupling principle of the SPCC and local weather conditions, six coupling schemes (CH1-CH6) with different SF, namely from 22.70% to 100%, are calculated and listed in tab. 5. In details, Scheme 1 and Scheme 2 are without TES while schemes from CH3 to CH6 are coupled with TES.

Indicators used for system evaluation

In this study, LCOE and the cost of COR are used as evaluation indicators [26]. The calculation of LCOE is based on eq. (3). The COR is the combination between

$$\text{LCOE} = \frac{\sum[(\text{investment}_t + \text{MEA}_t + \text{fuel}_t + \text{O\&M}_t + D_t)(1+r)^{-t}]}{\sum[\text{electricity}_t(1+r)^{-t}]} \quad (3)$$

where investment_t is the present value of investment costs, MEA_t and Fuel_t – the present value of MEA and fuel costs, respectively, $\text{O\&M}_t$ – the cost for operation and maintenance, D_t – the costs for decommissioning, and electricity_t – the amount of electricity output:

$$\text{COR} = \frac{(\text{LCOE}_{\text{cap}} - \text{LCOE}_{\text{ref}})\text{electricity}_t}{\text{CO}_{2,\text{ref}} - \text{CO}_{2,\text{cap}}} \quad (4)$$

where $\text{CO}_{2,\text{ref}}$ denotes CO₂ emissions of the reference PC without carbon capture, and $\text{CO}_{2,\text{cap}}$ denotes CO₂ emissions from carbon capture power plants.

Other assumptions

Several assumptions are made for tech-economic assessment:

- the climate data used for all systems are based on Tianjin city,
- the minimum DNI for operation of solar collector is, indicating that the STC is in use only when the hourly DNI is larger than 200 W/m² [10],
- the reboiler temperature for MEA-based and NH₃-based solvent regeneration is approximately 120 °C and 80 °C, respectively [22, 23] Accordingly, the solar collector temperature for MEA-based and NH₃-based carbon capture systems are set at 140 °C and 100 °C,
- it is assumed a linear interpolation between CO₂ capture load and the power output penalty [29],
- a month of maintenance period is assumed every year for all systems [30]. Therefore, the plant operation is 8016 hours in this paper, and
- carbon tax and subsidies for solar energy and carbon capture are not considered [26].

Results

The solar field can operate with or without thermal energy storage system. In general, the system configuration is simpler for the option without TES. However, when thermal storage system is integrated, more heat demand of reboiler can be provided by STE. Therefore, systems with TES perform better in terms of LCOE and COR compared with systems without TES, especially when the area of the solar field is over the 2nd area boundary value

Figure 4 shows the increase trend of LCOE and COR with the growth of the solar field area. As shown, the value of 1st boundary area is 2.32 km² and the 2nd boundary area is 4.01 km² for the MEA-based SPCC power plant with VT as the designed solar collector. While when the PTC is implemented as the solar collector, the 1st and 2nd boundary value is 2.03 km² and 3.24 km², respectively, because the heat efficiency of PTC is higher than that of VT. Similarly, for the NH₃-based SPCC power plant, the boundary areas are 1.23 km², and 1.92 km² when applying VT, while when applying the PTC, the boundary areas are 1.34 km², and 2.11 km², respectively. Regarding SPCC power plant, the additional investment for solar collectors and thermal storage systems lead to considerable increase in the total capital cost. Therefore, the total investment of the solar field system has significant impacts on the value of LCOE and COR. When solar thermal storage system is employed, both SF and VPCM increase linearly with the increase of SCA, thus cause a slight growth of LCOE and COR. However, if thermal storage system is not integrated, the SF remains at 29.40% after the solar

field area expanding to the 2nd boundary area. Therefore, the thermal storage system is necessary when the solar field area is over the 2nd boundary area.

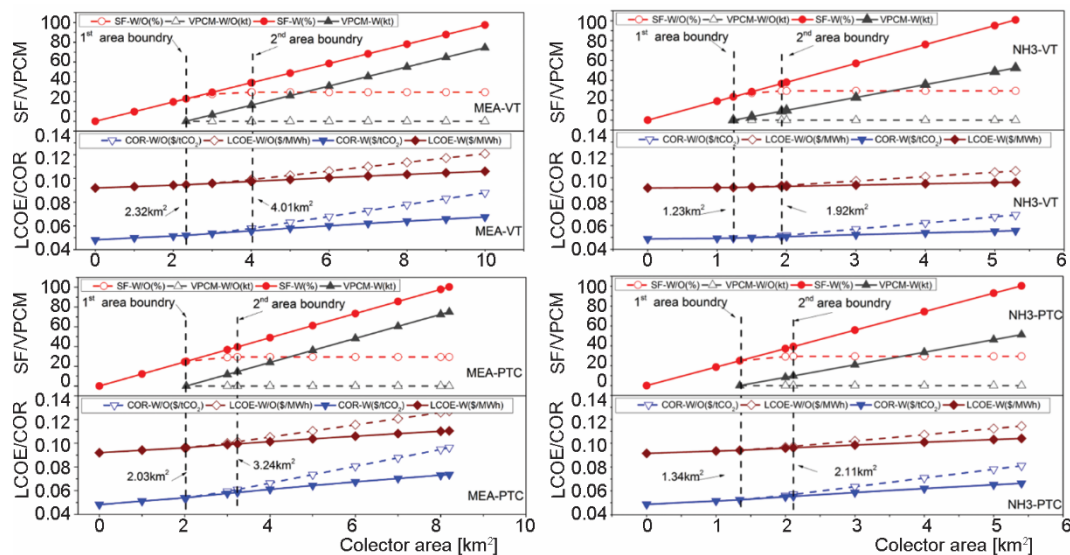


Figure 4. The LCOE and COR with the change of solar area

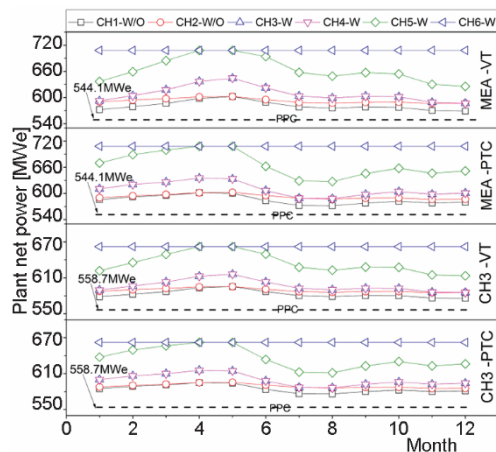


Figure 5. Monthly net power with different types of STC assisted into the power plant

Figure 5 presents the calculated results of monthly net power output for the mentioned six schemes based on different types of solar collector and chemical absorbent with a capture rate at 90%. As can be seen, for all combinations, the net power output of the SPCC power plants is higher than that of the conventional carbon capture plant owing to the integration of solar thermal energy.

The increase of the power output is proportional to the collector area and heat storage volume. Particularly, for a certain chemical absorption method, when the SF is set at the same value, the net power output is the same no matter what type of the STC is employed. However, because of the different thermal properties of the two types of collectors, their contributions to power generation are not uniform for each month. For example, the net power output is larger in August assisted by VT collectors than that of assisted by PTC collectors.

Figure 6. compares the performance of different SPCC power plant in terms of LCOE and COR. It is clear that the scheme of CH1 always has the lowest LCOE and COR no matter which kind of solar collector is applied. The SCA of the CH2 and CH3 is the same, with the difference lies in that no TES is involved for CH2. As demonstrated in fig.6, the LCOE and COR of CH3 are less than CH2, due to the price of the PCM is much lower than that of solar collectors. In addition, the employment of the PCM is capable to increase the SF

significantly. Consequently, the LCOE and COR show decrease trends when the SF of the system is set at the interval of the CH2 and the CH3.

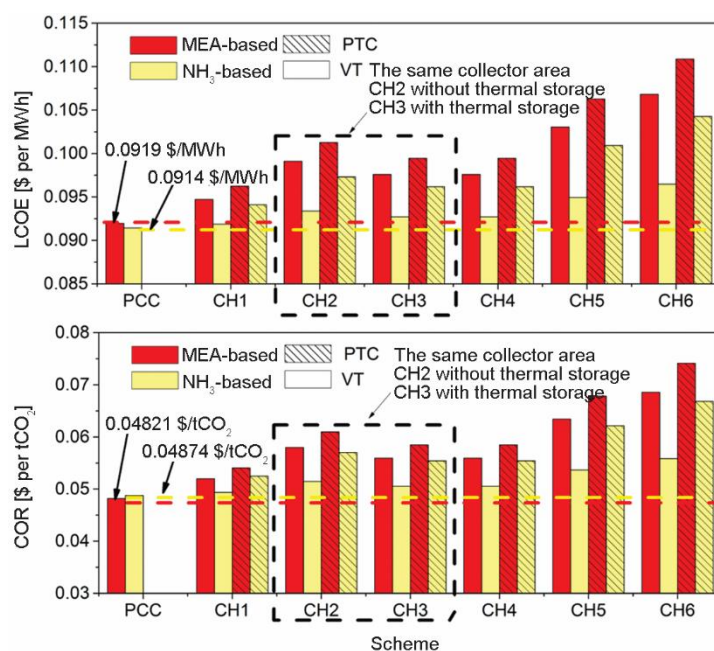


Figure 6. Comparison of LCOE and COR with different STC and VPCM

The LCOE of reference MEA-based and NH₃-based PCC power plant without solar energy is 0.0919 \$/MWh and 0.0914 \$/MWh. Meanwhile, the COR is 0.04821 \$/tCO₂ and 0.04874 \$/tCO₂, respectively. When solar thermal energy is involved, the LCOE and COR changes to various extent in terms of different absorption agent and types of STC.

In general, the LCOE and COR of SPCC power plant are greater than the reference PCC power plant. Growth rates of LCOE and COR directly depend on the price of the solar collector, which is to be further discussed in next section. It should be noted that, the scheme of NH₃-based SPCC power plant with VT performs best in terms LCOE and COR, which are nearly equal to the reference PCC power plant. Thus, VT solar collectors are more applicable to assist the NH₃-based capture process.

Discussions

Effect of STC price

Regarding to SPCC power plant, LCOE and COR are sensitive to the capital investment of solar collectors. Figure 7 indicates the trend of LCOE and COR with the variation of prices of PTC and VT. As expected, LCOE and COR decrease linearly with the drop of PTC and VT costs for both MEA-based SPCC power plant and NH₃-based SPCC power plant. Particularly, thermal storage is integrated when the area of solar field is over the 2nd boundary area. Therefore, the LCOE and COR increase more sharply when integrated TES system than the configurations without TES. Indeed, the employment of TES implies that larger areas of solar collectors are in need, thus the price of solar collector has a greater effect on the system than that without TES. The breakeven price for solar collectors is marked in fig. 7.

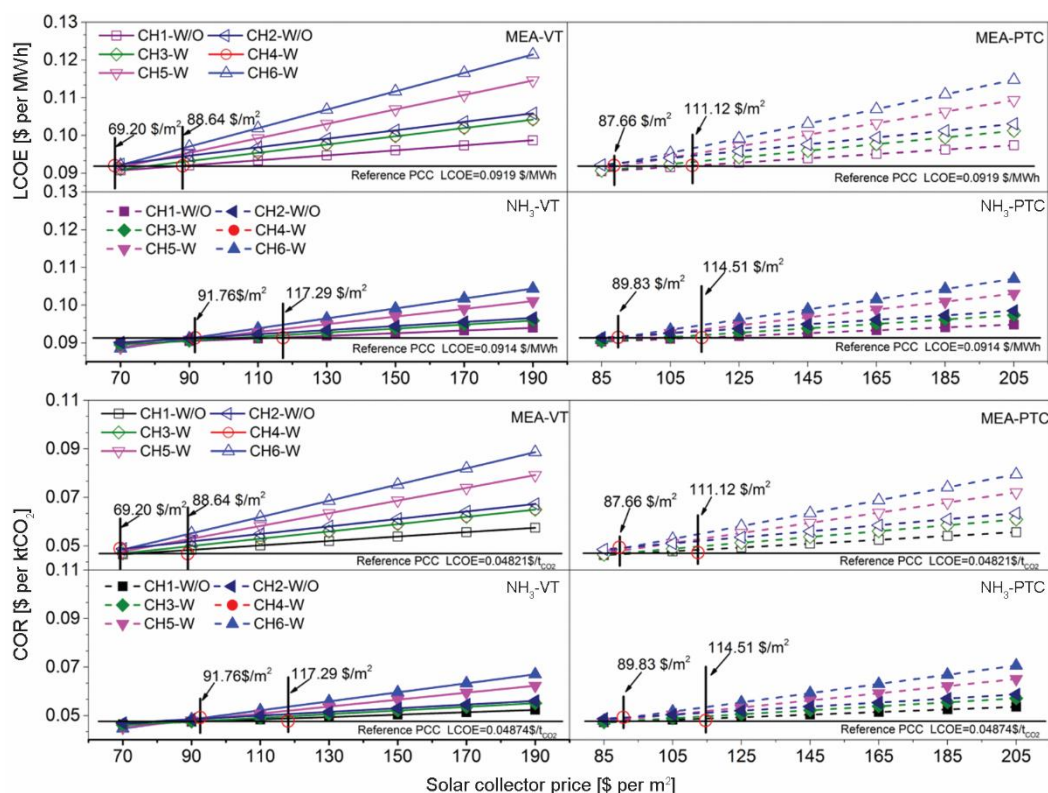


Figure 7. Effect of solar collector price

It should be noted that NH₃-based SPCC power plant performs better in terms of LCOE and COR than the configurations using MEA-based absorbent despite the types of collectors. In details, for the NH₃-based SPCC configurations employing VT, the breakeven prices for CH1 (the 1st boundary area with SF of 22.7%) and the CH6 (100% SF) are 117.29 \$/m², and 91.76 \$/m², respectively. While, for the MEA-based SPCC power plant, the breakeven prices for CH1 and CH6 are 88.64 \$/m², and 69.20 \$/m². Meantime, when the PTC is engaged, the breakeven prices for CH1 and CH6 are 111.12 \$/m² and 87.66 \$/m², for the MEA-based SPCC power plant. As for the NH₃-based SPCC power plant, the breakeven process lies on 114.51 \$/m² and 89.83 \$/m² for LCOA and COR, respectively. Apparently, based on the current prices of the VT (135 \$/m²) and PTC (180 \$/m²), the VT is more applicable for NH₃-based carbon capture system while PTC performs better for MEA-based SPCC power plant. Furthermore, allowable prices for VT assisted NH₃-based power plant is the highest among all the options, which indicates that it is a promising option to employ VT to assist NH₃-based SPCC power plant.

Effect of CO₂ recovery ratio

As seen in fig. 8, LCOE curves increase linearly with the increase of CO₂ recovery ratio (CRR) while COR shows an opposite trend when the CRR increases. The growth of CRR indicates that more CO₂ is captured, which in consequence leads to greater energy demand for reboiler heating. However, as the energy requirement for regeneration does not de-

crease linearly with the decline of the amount of CO₂ captured, the COR dropped exponentially with the increased of CRR. Taking scheme CH5 as an example which has SF of 75%, when the CRR increases from 30% to 90%, the LCOE increases by 23.82% to 0.1031 c\$/kWh and 23.58% to 0.1063 c\$/kWh for the MEA-based VT and MEA-based PTC power plant respectively. Meanwhile, the LCOE for NH₃-based VT and the NH₃-based PTC power plant show growth trends of 21.05% and 20.44%, respectively. However, there is a significant decrease of the COR for all configurations which is around 43%.

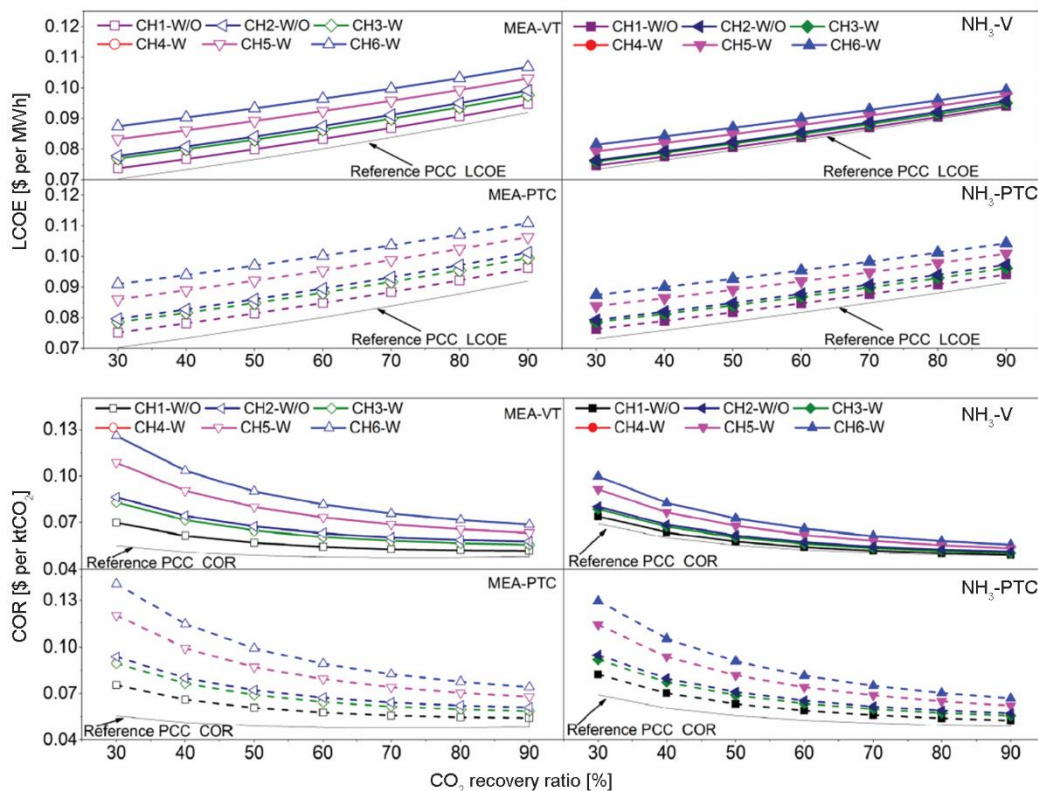


Figure 8. Effect of CRR

Effect of PCM price

As illustrates in fig. 9, both LCOE and COR show decline trend when the price of PCM decrease linearly. However, effects imposed by PCM price are less than the price of solar collector. In addition, the price of PCM has little impact on the LCOE and COR when a small volume is utilized. For instance, as the VPCM of CH3 is smaller than that of CH6, the change rates of the LCOE and COR of CH3 are smaller than that of CH6. It is worth noting that the LCOE and COR of the NH₃-based systems are always lower than that of the systems using MEA-based absorbent despite the types of solar collector. In terms of solar collectors, systems with VT for both MEA-based and NH₃-based power plants perform better than that of PTC assisted capture systems. From this point, the VT assisted NH₃-based- capture power plant is the most favorable among all the options.

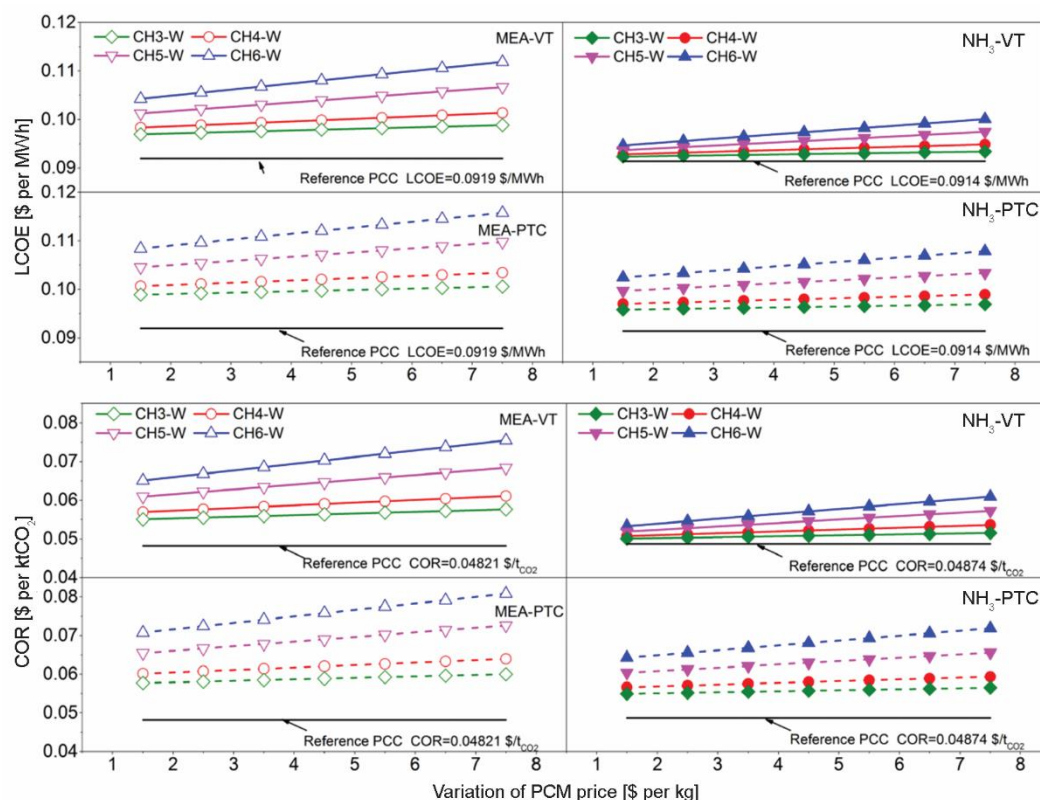


Figure 9. Effect of PCM price

Potential incentives

China has launched the carbon market since the end of 2017, by setting the carbon emissions allowance for the country's largest GHG emitters. Therefore, the carbon capture power plant could sell their extra carbon emission credits to get revenue. In general, the carbon trading prices in Beijing carbon market shows an increase trend recently with the highest carbon pricing over 12 \$/tCO₂ [31]. Moreover, there is regional solar thermal subsidies for solar heating in China to reduce the capital cost of solar field. It is implied that the SPCC systems are potentially feasible with support of policies. Therefore, detailed analysis should be further conducted to study the impacts of carbon tax, carbon market as well as relevant subsidies for renewables.

Conclusions

In this study, two configurations of solar assisted carbon capture systems (*i.e.* MEA-based carbon capture system and NH₃-based carbon capture system) are comparatively studied considering different types of solar collectors, the area of solar field, the integration of solar thermal storage as well as key economic and technical parameters. Based on the presented results, conclusions were drawn as follows.

- In general, employing solar thermal energy to assist solvent regeneration is able to improve the power efficiency effectively. However, when thermal storage is not integrated,

the SF will maintain at 29.40% when the area of the solar field is over the 2nd boundary area. Consequently, LCOE and COR for SPCC without TES system show much more sharp growth than that the system with TES.

- Regarding to economic performance, LCOE and COR are sensitive to the price of STC and PCM. Regarding to configurations with different absorption technology, the NH₃-based SPCC system is more competitive in terms of the LCOE and COR than that of MEA-based configurations despite the types of solar collectors. Meanwhile, the VT assisted capture power plant can achieve the lower LCOE and COR than that of PTC involved systems.
- The breakeven price of LCOE for VT assisted MEA-base and NH₃-based capture process is 88.64 \$/m² and 117.29 \$/m², respectively. While the breakeven prices of COR for the PTC are 111.12 \$/m² for the MEA-base and 114.51 \$/m² for the NH₃-based SPCC power plant.
- The NH₃-based SPCC power plant utilizing VT as the solar collectors can achieve the lowest LCOE and COR, which are nearly equal to the value of the reference PCC power plant. It is indicated that the employing VT to assist NH₃-based solvent regeneration offers a promising option to offset the energy penalty of capture process as well we obtain a reasonable LCOA and COR.

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