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A review of potential routes to zero and negative emission technologies via the integration of renewable energies with CO_2 capture processes

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ABSTRACT

This paper broadly reviews the integration of different renewable energy sources including solar, bioenergy, wind, and geothermal energy with CO_2 capture processes and evaluates the possible contribution to achieve net-zero or negative CO_2 emissions. Each renewable energy integration option possesses advantage points, which may help reducing the CO_2 capture cost and potentially realize the net-zero or negative emission ambitions. In power sector, renewable energy integration encounters a number of challenges such as high upfront investment, large fluctuation in the CO_2 capture rate, and electricity cost. Nonetheless, those drawbacks can be minimized by flexible designs that would optimize renewable energy contribution with steam extraction to improve power plant efficiency and install on/off function to exploit low electricity price periods and to alleviate the effect of the intermittent nature of those renewable energy options. Although, many integration scenarios have been proposed in literature, there is a lack of consideration with recently advanced CO_2 capture technologies in the hard-to-abate emission sectors such as heavy industries and heavy transport. Renewable energy integration may also bring a promising revenue to advance the ambitious goal of direct air capture (DAC) technologies due to the flexibility in location and operation modes, nevertheless, it draws a little attention. In this analysis, the advantages and disadvantages of each renewable energy source when it is integrated into a CO_2 capture process are discussed and thereby potential research directions are identified. It is emphasized that renewable energy integration could autonomize carbon capture retrofits to provide convenience to power/industrial plant operators and/or to realize the ambitions of installing independent and scalable DAC systems on inexpensive land or in vicinity of the CO_2 storage/utilisation sites.

1. Introduction

It is widely recognized that anthropogenic CO_2 emissions is a main contributor to the rapid increase in atmospheric CO_2 concentration, which is directly linked to the global warming and climate change (Canadell et al., 2007). By 2019, CO_2 concentration in the atmosphere reached 36.4 billion tonnes per year and was projected to raise further, although, in 2020 when the world economy was seriously impacted by COVID-19 pandemic that caused a temporary drop in CO_2 emissions (Xu et al., 2020; Wang et al., 2020; Liu et al., 2020). However, the global economic activities have returned to the business as usual, where the reduction in carbon emissions during the pandemic will not have a positive impact in the long term (Ray et al., 2022). The rapid surge in industrial and transport activities have caused a great increase in atmospheric CO_2 concentration, which has reached a record value of 419 ppm in Feb 2022 (Jordán et al.). To mitigate the environmental impact, CO_2 emissions must be reduced, and the United Nations (UN) has set an ambitious goal to reach a global net-zero emission by mid-century (Horowitz, 2016; UN, 2015). The UN have recently called on countries to push more efforts and approaches to achieve this goal (UN, 2021). Global emissions reduction is not a responsibility of a single country or economic sector, rather, it requires a synergic effort with the participation of multiple countries, sectors and pathways. Renewable energy utilization, CO_2 capture and storage, and more technology innovation for a better fuel and electricity efficiency have been considered as important gadgets that have critical roles in implementing approaches and pathways to achieve net-zero emission goal. Therefore, their

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Nomenclature

BECCS	bioenergy coupled with CCS
CCS	Carbon capture and storage
CCFCV	CO_2 capture fuel cell vehicle
CEI	Carbon emission intensity
CHP	Combined heat and power
COA	Cost of the CO_2 avoidance
CSP	Concentrated solar power
DAC	Direct air capture
EGS	Enhanced geothermal system
EOR	Enhanced oil recovery
ETC	Evacuated tube collector
FPC	Flat plate collectors
GA-PCC	Geothermal-assisted PCC
GAPG	geothermal-assisted power generation
HFC	Heliostat field collector
HHV	High heating value
HSA	Hot sedimentary aquifer
LCOE	Levelized cost of electricity
LFR	Linear Fresnel reflectors
LHV	Low heating value
MEA	Monoethanolamine
MOF	Metal-organic framework
NGCC	Natural gas combined cycle
PCC	Post-combustion carbon capture
PSA	Pressure swing adsorption
PTC	Parabolic trough collector
PTSA	pressure/temperature swing adsorption
PV/T	Photovoltaic/thermal
SA-PCC	Solar-assisted PCC
SCF	Solar collector field
SP-PCC	Solar-powered PCC
So-St	solar-stripper
SOFC	Solid oxide fuel cell
STE	Solar thermal energy
TCR	Total capital requirement
TES	Thermal energy storage
TLF	Thermal load-fraction
TSA	Temperature swing adsorption
TVSA	Temperature/vacuum swing adsorption
VSA	Vacuum swing adsorption

integrated technologies would offer a great opportunity to realize the net-zero ambition target.

Fossil fuel consumption accounts for about 90% of the total global CO_2 emissions, in which fossil fuel-fired power plants are considered to be the major source of CO_2 emissions (Olivier et al., 2012). While burning fossil fuels for energy production cannot be stopped in the foreseeable future because of the ever-increasing industrial activities and energy demand, CO_2 capture and storage (CCS) technologies may

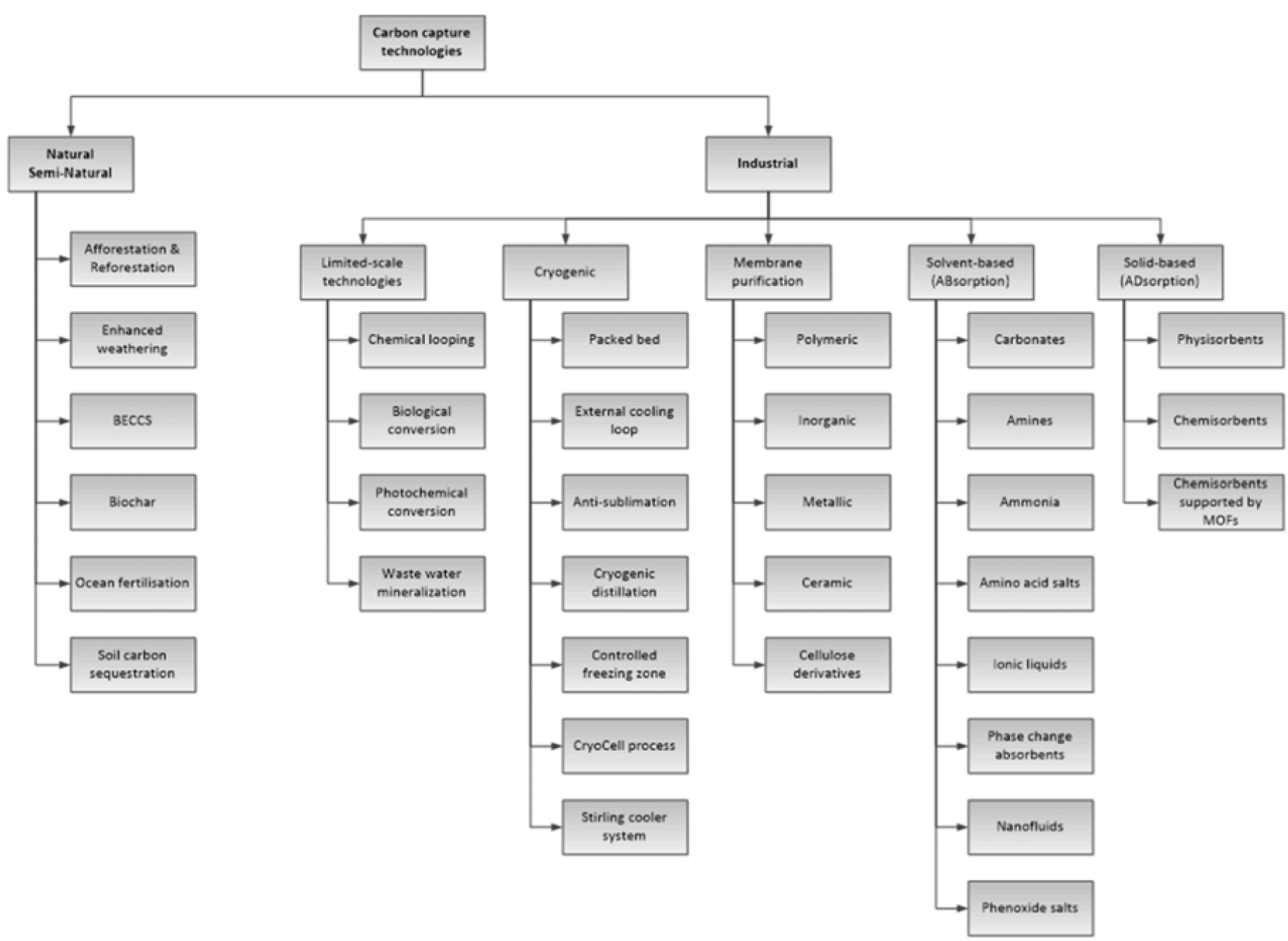


Fig. 1. An overview of leading carbon capture technologies categorized by scale and operation principles.

provide an excellent option to continue utilizing fossil fuels, but in a more clean and sustainable approach. Many efforts have been proposed to reduce CO_2 emissions in which CCS has been considered to be the most viable technological option for CO_2 reduction accountable for an estimation of 19% of the total CO_2 reduction measures by 2050 (Taylor, 2010).

Generally, the nature itself has the resilience of combatting the accumulation of atmospheric CO_2 to a limited extent via the plant photosynthesis, inherent carbon mineralization in rocks, and natural ocean uptake mechanisms that have worked over millions of years to maintain the carbon cycle balance. Nevertheless, as the unprecedented anthropogenic CO_2 emissions disrupted this balance, engineering solutions must interact to restore carbon cycle balance again. Categorized by scale and robustness, some of these carbon capture solutions resemble natural routes but at a more intensive pace, while others propose innovative engineering solutions at an industrial scale (Albritton, 2022). Fig. 1 presents an overview of leading engineering solutions in each category. In power sector, the scale and intensity of CO_2 emissions are relatively large where many of these capture technologies are incompatible and/or uneconomic. Nevertheless, apart from limited-scale and/or early-stage technologies, some engineering solutions such as solvent-based absorption have reached a high level of maturity and have already been deployed at commercial scale CCS projects around the world.

To effectively abate the emissions from coal-fired power plants, three different CO_2 capture concepts have been proposed: pre-combustion carbon capture, oxy-fuel combustion, and post-combustion carbon capture (PCC). In this context, PCC has been recognized as the most versatile option due to its possibility to retrofit to the existing fleet of fossil fuel-fired power plants without major disruptions (IPCC, 2005). In fact, adopting CCS strategy is likely to be the only option that allows the continuation of fossil fuel consumption, but at low or near-zero emission level. Among CO_2 capture technologies, the absorption of CO_2 into aqueous solutions such as amines (e.g. ethanolamine, diethanolamine and amine blends) has relatively demonstrated competitive advantages for CO_2 capture (Lee et al., 2009; Abu-Zahra et al., 2007c; Abu-Zahra et al., 2007a; Adeosun et al., 2013). Numerous studies have been conducted to demonstrate the feasibility of this technology at large/-commercial scale (Abu-Zahra et al., 2007c; Idem et al., 2005; Artanto et al., 2012; Abu-Zahra et al., 2013). The application of this technology, however, is impeded by high energy requirement for the solvent regeneration, which causes a hefty energy penalty on the power production and a significant increase in electricity cost. To reduce the cost and enhance the effectiveness of this CO_2 capture process, many efforts focused on finding more efficient and cost-effective methods to capture CO_2 from the flue gas. In last decade, rigorous work to improve solvents' thermo-physical properties (Nookuea et al., 2016), process integration (Liu et al., 2018), or HEN optimization (Khalilpour and Abbas, 2011) has been proposed. Moreover, process intensification concepts such as rotating packed bed (Wang et al., 2015) and rotating liquid sheet contactor (Mehdipour et al., 2021) were also considered as potential avenues to improve the energy performance of the PCC. Yet, the global investment and public interest in PCC technologies have been relatively trivial.

Recently, under the extensive stress to integrate more renewable technology options in various power systems, the CO_2 capture process has also been considered for integration with renewable energy to lessen the energy penalty on power plants. Ideally, solvent-based absorption is capable of removing CO_2 completely from the flue gas of power plants and other industries, however, removal efficiency is usually recommended at a range of 85–95% due to economic considerations (Brandl et al., 2021). The remaining of CO_2 amount is emitted to the atmosphere, which, together with CO_2 emanated from mobile and other hard-to-abate sources will continue to increase atmospheric CO_2 concentration. Therefore, to achieve net-zero emission target, not only the implementation of carbon capture from large stationary sources is essential, but also negative-emission technologies such as direct air capture (DAC) and bioenergy coupled with CCS (BECCS) would still be very significant gadgets (Jiang et al., 2019; Gough and Upham, 2011; Bui et al., 2017; Sanz-Pérez et al., 2016). However, DAC is even more energy-intensive process because of the relatively diluted CO_2 concentration in the atmosphere, and thus it requires a sustainable energy supply option to ensure its potential contribution in achieving net-zero or negative emission. Thus, the CO_2 capture technologies, if integrated with renewable energy options, may offer a viable approach to reach neutral or even negative emission targets (IEA, 2011; Platform, 2012; Bui et al., 2018a; Carapellucci et al., 2015).

The major drawback of the renewable energy sources is mostly related to their intermittent supply and low power density (Safdarnejad et al., 2015). It will be more effective to integrate renewable energy with conventional energy generation processes, particularly in a context that simultaneously considers increasing the renewable energy share and reducing carbon footprint. The integration of renewable energy options with CO_2 capture technologies could mitigate the impact of energy penalty and enhance the sustainability of the capture process. Renewable energy sources may directly supply energy for CO_2 capture process and/or offset part of the energy that a power plant endures for CO_2 capture process (Parvareh et al., 2014).

As demonstrated in Fig. 1, a variety of CO_2 capture technology options including thermochemical, electrochemical, photochemical, thermophysical, and biological routes can be integrated with different forms of renewable energy sources. Each capture technology is in a different stage of development, and each offers unique characteristics, benefits, and also challenges. Of numerous articles available in open literature, this study mostly highlights on key review articles summarizing the latest state-of-the-art integration options around the globe. Most of carbon capture routes are well-recognized and, therefore, this article only lists these technologies, but reviews the renewable integration pathways in more detail. Every attempt is made here to cite the majority of articles that have appeared in the literature on this topic, although inevitably, space constraints preclude an all-inclusive compilation. Interested readers can gain entry into the specialized literature starting from the selected articles cited below and expand further to any particular technology of interest.

Most of published review papers on renewable energy integration in CO_2 capture processes focused on solar energy integration with coal-fired power plants, while other possible renewable energy integration options have mostly been overlooked. Moreover, as the attention to the CO_2 emissions is extending to the hard-to-abate heavy industries (i.e. cement, steel, aluminum, and chemicals industries) and heavy-duty transport (i.e. road trucks, shipping, and aviation), more innovative renewable integration routes are being sought. In this context, negative emission technologies such as DAC can play a critical role to balance the overall CO_2 emissions and bring it closer to net-zero target. Thus, smarter and cheaper renewable integration methods are critical to enhance the sustainability and increase public awareness and acceptance of these technologies.

This review therefore broadly discusses all types of renewable energies including solar thermal/PV, biomass, wind, and geothermal energy integrated with the most mature and marketable CO_2 capture technologies. In comparing different renewable integration routes with carbon capture processes, the objective of this review is to provide pathways for readers in selecting renewable integration scenarios that would maximize the renewable contribution toward net-zero emission initiatives and be more suitable to locally available renewable energy options.

2. Solar energy integration with CO_2 capture processes

There is a profound argument that solar photovoltaic (PV) systems may prevail in terms of providing direct electricity to the grid rather to serve the auxiliary equipment or steam production for the solvent regeneration in the PCC (Breyer et al., 2017). Moreover, the deployment of a large-scale PV system to assist in carbon capture process would also necessitate a well-designed electric storage option (e.g. batteries) to buffer power supply and provide adequate energy in non-solar or night hours. Today, the market of lithium-ion battery (LIB) energy storage systems is exponentially growing in many industrial and transport applications because of rapid technology breakthroughs improving their capacity, efficiency, and lifespan (Rouhi et al., 2021; Olabi et al., 2022). However, the cost of LIB is mostly driven by appealing markets such as electric vehicles and smart grid applications (Wang et al., 2021). Currently, it is difficult for an energy-intensive process with a poor market drive such as carbon capture to economically compete with other LIB markets. Hence, given the low power density and conversion efficiency of the PV systems, the complex power supply-demand relation, and the cost/reliability of electric storage options (e.g. batteries), solar thermal technologies could relatively be more attractive option.

Solar thermal energy is the most appealing renewable energy source for carbon capture and has been extensively studied in the literatures (Kumar et al., 2019; Sharma et al., 2017; Parvareh et al., 2016; Saghafifar and Gabra, 2020). Several review papers have been published on the integration pathways of solar energy in coal-fired power plants coupled with PCC. In 2010, a preliminary review on the feasibility and implications of solar energy integration for CO_2 capture was done by Cohen et al. (Cohen et al., 2010). In 2014, several configurations for the integration of solar thermal energy to offset the energy penalty of a power plant due to the application of PCC was reviewed by Parvareh et al. (Parvareh et al., 2014). Those configurations include: (1) the production of steam from solar thermal energy for full/partial steam supply for the PCC reboiler, (2) a solar hybridization in which solar thermal energy is used to preheat the feed water of a power plant or to generate high temperature/pressure steam to inject into the turbine circuit or the boiler of the power plant, and (3) an integration of solar thermal energy with PCC-retrofitted power plant where solar thermal energy is used to produce steam for the PCC reboiler and to generate power for PCC auxiliary loads. In a more comprehensive study, Manaf et al. (Manaf et al., 2016) thoroughly investigated the modelling, design and optimization of this process integration and operation for the trinity (power plant retrofitted with PCC and solar-thermal plant) that would lead to significant reductions in the CO_2 capture energy penalty. The solar collector structure and type are usually determined by the required temperature output. There are two main categories of solar collectors: stationary and tracking collectors. Tracking collectors are also sub-categorized into single axis and two-axes tracking systems which often used for larger scale applications that require a much higher heat input. Fig. 2 presents a categorization of available solar thermal collectors based on their sun tracking motion.

Stationary solar collectors such as flat plate collectors (FPC) and evacuated tube collectors (ETC) relatively have poorer energy conversion rate (concentration ratio is 1:1) and would require massive land area for effective solar penetration in the power system efficiency. High-temp technologies (e.g. Fresnel and heliostat) are more expensive and the temperature range is usually above the PCC solvent regeneration temperature range, which are mostly suitable to produce high-enthalpy steam to be mixed with high pressure steam of the power plant (Wang et al., 2016; Wang et al., 2017c). The main route of solar thermal integration with carbon capture technologies is either via the solvent-based absorption or solid-based adsorption. Other possible integration routes are also possible, but due to limited scale or techno-economic barriers have had less attractive applications.

Recently, adsorbent based CO_2 capture technology has proved to be an advanced and promising option to reduce energy consumption (Quang et al., 2016a; Lee and Park, 2015; Younas et al., 2016; Sun et al., 2015; Quang et al., 2016b; Quang et al., 2015; Zhang et al., 2019; Azmi and Aziz, 2019). Although, the calculated regeneration heat for a polyethyleneimine/silica adsorbent can be as low as 2.4 GJ/t_{CO2} compared to 3.9 GJ/t_{CO2} for a typical aqueous ethanolamine system (Lee and Park, 2015; Quang et al., 2013), more reduction could be achieved if the integration with solar thermal energy can effectively reduce the

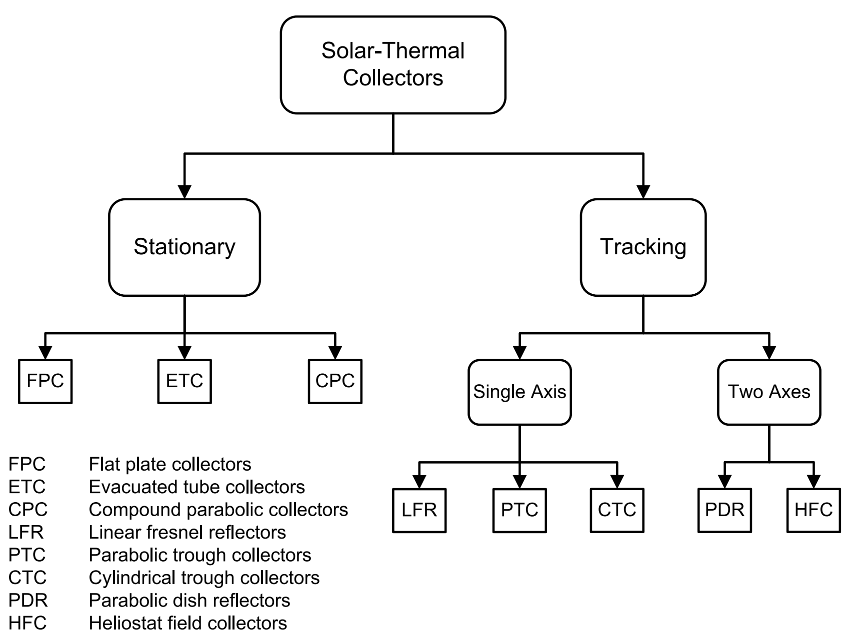


Fig. 2. Categorization of various solar-thermal collectors based on their sun tracking motion.

bleeding of thermal steam from the power plant steam cycle. Several studies have proposed the integration of solar thermal energy into adsorbent-based CO_2 capture process (Zhao et al., 2018; Zhao et al., 2019), but no comprehensive review has been made in this regard. The following subsections provide information on the technical and economic feasibility of potential solar thermal integration technologies for both absorbent/adsorbent based and complete the review for other possible carbon capture technology routes, accordingly.

2.1. Solar thermal technologies for amine solvent-based CO_2 capture process

Aqueous solvent-based CO_2 capture has been extensively investigated and considered as the most mature technology option. CO_2 capture technology based on amine solvents is usually associated with extensive energy consumption, amine degradation, corrosion, and loss with exhaust gases; hence, many studies have been conducted to address these issues and offer novel amines with greater thermophysical properties or novel CO_2 capture methods to reduce energy consumption (Yu et al., 2012; El Hadri et al., 2017; Asif et al., 2018; Anwar et al., 2018; Wu et al., 2014; Song et al., 2018; Alonso et al., 2014). Several commercial scale plants have been deployed in the last decade i.e. SaskPower Boundary Dam and Petra Nova plants (Oko et al., 2017; Vega et al., 2020). SaskPower Boundary Dam (Estevan, Canada) was launched in 2014 targeting to capture 90% CO_2 emitted from 120 MW coal-fired power plant. Petra Nova plant (Texas, USA) with ability to capture 92.4% CO_2 from 240 MW coal-fired power plant operated two years later (2016). The common point of these two commercial plants is the combination of CO_2 capture with CO_2 utilization via enhanced oil recovery (EOR) mechanism (Vega et al., 2020). In many regions, EOR is unfeasible option and, hence, the deployment at large scale faces fierce problem to justify the investment. The integration of solar thermal energy with an aqueous amine-based CO_2 capture plant has proved the potential reduction of CO_2 emissions due to the low-carbon intensity of solar technologies and is expected to lower energy penalty for retrofitted power plant (Cohen et al., 2010; Parvareh et al., 2014; Liu et al., 2017; Zhao et al., 2015).

Li et al. evaluated the technical feasibility of two med-temperature solar technologies (PTC and ETC) integrated directly with CO_2 capture system for three geographic locations (Alice Spring in Australia, Denver in United States, and Beijing in China) with diverge climatic conditions (Li et al., 2012). Their study indicated that the PTC could collect almost double the solar thermal energy (STE) compared to the ETC (Table 1). The maximum amount of obtainable STE for PTC compared to ETC was calculated at 1505/808 kWh/m^2/year in Alice Spring, 950/458 kWh/m^2/year in Denver, and 519/250 kWh/m^2/year in Beijing, respectively (Li et al., 2012). The amount of STE collected in a year is greatly linked to the daily solar intensity and sunshine time; with the higher radiance and longer sunshine time, Alice Spring can almost collect triple the amount of STE as in Beijing, regardless of the deployed solar thermal technologies. Due to higher solar concentration ratio, parabolic trough collector (PTC) required less aperture area accounts for almost half of that required by ETC in both cases with and without thermal energy storage (TES). Compared to the reference power plant coupled with CO_2 capture process, the assistance of solar thermal energy can significantly improve the power plant capacity and its electrical conversion efficiency, particularly when reasonable thermal energy storage (TES) system is added (Li et al., 2012). Even though, the STE amount collected in Denver and Beijing are lower than Alice Spring, the addition of PTC system created a maximum efficiency improvement of 18% compared to the reference power plant with CO_2 capture in Denver, which helped the power plant to reach the highest electrical efficiency of 41%. Whereas, the ETC system is found to be more efficient and suitable for Beijing conditions with the higher improvement and helped the power plant reach the highest electrical efficiency of 42%. Both solar technologies did not show significant differences in the improvement of the power plant efficiency in Alice Spring in which the highest plant efficiency reached <39%. Obviously, the direct integration of med-temperature solar systems with an amine-based CO_2 process is technically viable. A study reported by Bravo et al. demonstrated that the integration of PTC system to natural gas combined cycle (NGCC) power plant with CO_2 capture increases the plant performance and lessens the detrimental impact on MEA-based CO_2 capture system (Bravo et al., 2020). The annual electricity generation improved 1.6% by using STE for low pressure steam heating. Cau et al. showed that the integration of concentrating solar system such as linear Fresnel reflectors (LFR) with ultra-super critical steam power plant with CO_2 capture can offset part of the energy penalty due to the CO_2 capture (Cau et al., 2014). The concentrating solar as in LFR system proved to be more efficient as it produces and supplies superheated steam to the power plant.

Table 1
Ratio of maximum solar thermal energy collected, solar collection area, and cost of solar collection area required by solar trough to vacuum tube in different locations (Li et al., 2012).

Location	Alice Spring	Denver	Beijing	Average
Yearly STE collected per km^2	1.86	2.07	2.08	2.00
Solar collection area required for 6 h operation (without TES)	0.56	0.61	0.43	0.53
Solar collection area required for 6 h operation (with TES)	0.54	0.61	0.43	0.52
Cost of solar collection area required for 6 h operation (without TES)	0.79	0.87	0.61	0.76
Cost of solar collection area required for 6 h operation (with TES)	0.77	0.86	0.61	0.75

Previous studies indicated that the integration of solar energy with CO_2 capture is technically feasible, however, economic data including total capital requirement (TCR), levelized cost of electricity (LCOE), and the cost of the CO_2 avoidance (COA) are the key factors for the solar integration consideration. Li et al. (Li et al., 2012) proved that locations with higher STE would have lower TCR, COE, and COA and they would be significantly improved when the STE collection technologies are also equipped with TES systems. Alice Spring with maximum STE collection (1,505 kWh/m^2/year by PTC and 808 kWh/m^2/year by ETC, respectively) relatively has the lowest TCR, COE, and CO_2 capture cost value, but these values are still higher than the reference case of power plant coupled with CO_2 capture without solar energy integration by 7.1, 1.4, and 9.6%, respectively. While for the worst-case scenario (Beijing), the TCR, COE, and CO_2 capture cost reached 101.0, 65.0, and 179.0% higher than the reference scenario. These results were calculated based on unit price of 185 and 130 USD/m^2 for PTC and ETC, respectively. This implies that TCR, COE, and CO_2 capture cost can reach lower levels if the system was built in regions with long sunshine and high solar radiation together with the reduction in the price of the STE collectors. According to Li et al. (Li et al., 2012), the LCOE and CO_2 capture cost can only be lower than the reference case when the solar system built in Alice Spring reaches the price of <150 USD/m^2 for PTCs and <90 USD/m^2 for ETCs, respectively. The similar effect of solar field price was also found when a concentrating solar system (e.g. LFR) is integrated with an ultra-super critical steam power plant having CO_2 capture process (i.e. MEA-based absorption) (Cau et al., 2014). Thereby, solar energy was used to produce intermediate pressure superheated steam to be mixed with the high-pressure turbine outlet steam. The obtained results showed that the LCOE was lower than that of the reference scenario without solar integration in case the solar field costs lower than 146–153 USD/m^2. For any specific location, the cost of solar field plays an utmost important role and the solar integration with CO_2 capture process becomes economically viable only when the solar field price reaches a certain low level.

Because of high upfront investment of most solar-assisted energy options, the scale of solar share (solar fraction) in those hybrid systems is often optimized with the help of various government legislative support schemes. Without government incentive programs such as renewable subsidies, carbon price, or renewable energy certificates, the economic feasibility of solar-assisted carbon capture projects are in doubt (Qadir et al., 2015). Moreover, irrespective of the solar fraction value in those solar-assisted carbon capture systems, the process sustainability is also undermined because the steam extraction from the power plant to the capture process would still rely on fossil-fuel firing, which would inherently impact the life cycle analysis of these capture processes. More recently, Milani and co-workers proposed a novel concept in solar thermal integration to autonomize carbon capture process. In their methodology, the CO_2-rich solvent exiting the absorber was directly pumped into a scalable solar collector field (SCF) to run through solar collector receiver tubes. Instead of generating steam in the SCF, the rich solvent can directly absorb solar heat and instantaneously release the CO_2 gas. At the end of each tube segment, the gas/vapor can be vented-out and the remaining liquid solvent is consequently being regenerated in the next segment/s (Milani et al., 2020b; Milani et al., 2021b; Nelson et al., 2021). In this configuration, it was anticipated that the typical desorption unit in the PCC including the complex stripper and the reboiler can be eliminated, and the rich solvent is directly regenerated in a so-called "solar-stripper" (So-St) network (Fig. 3). The key advantage of this novel concept not only in eliminating the conventional and costly desorption unit, but will also cease steam bleeding from the power cycle and make the capture process completely independent from the power plant. As a result, the notion of solar-assisted PCC (SA-PCC) was elevated to a new frontier of "solar-powered" PCC (SP-PCC) (Milani et al., 2021c). This self-sufficient carbon capture process at almost net-zero carbon footprint would significantly benefit from the cost reduction as a result of the desorption unit (i.e. stripper and reboiler) elimination. However, this configuration would require a substantial SCF installation over a large land area because of low solar energy density. Yet, the economics of this proposal is substantially higher than the conventional PCC, unless more process and/or material innovation can favorably revert the economics of the SP-PCC (Milani et al., 2021a; Milani et al., 2022).

2.2. Integration of solar energy into solid adsorbent-based CO_2 capture process

Industrial applications of gas separation and purification using adsorption materials has a long history beginning with air drying and air separation for oxygen production. Compared to other carbon capture techniques, adsorption processes offer many potential advantages such as lower energy and temperature for regeneration, greater capacity, and ease of handling. In the past few years, several research teams have been involved in the development of new solid sorbents for CO_2 capture from flue gas seeking superior performance and desired economics (Samanta et al., 2012). A variety of promising sorbents such as activated carbonaceous materials, microporous/mesoporous silica or zeolites, carbonates, and polymeric resins loaded with or without nitrogen functionality have been studied. The performance characteristics of the solid sorbents are assessed in terms of various attributes, such as their equilibrium adsorption capacity, selectivity, regeneration, multicycle durability, and adsorption/desorption kinetics. In this context, the potential of metal-organic frameworks (MOFs) and their derivatives are extensively studied to determine whether these novel materials can provide a better CO_2 adsorption capacity under low CO_2 partial pressure (Aniruddha et al., 2020; Ben-Mansour et al., 2016; Prasetya et al., 2020). In these extensive studies, not only the physiochemical properties of these materials are investigated, but also their optimized shapes and operation mechanisms are scrutinized (Fig. 4) (Sinha et al., 2017). In this subsection, we only review studies that focus on the integration of the adsorption systems with solar thermal energy systems.

The potential for integrating solar thermal energy into an adsorbent-based CO_2 capture process has been investigated by Zhao et al. (Zhao et al., 2018). Low-grade solar thermal energy can be used for adsorbent regeneration in a pressure/temperature swing adsorption process (SOL-PTSA) as shown in Fig. 5. Typical adsorbents including zeolite and

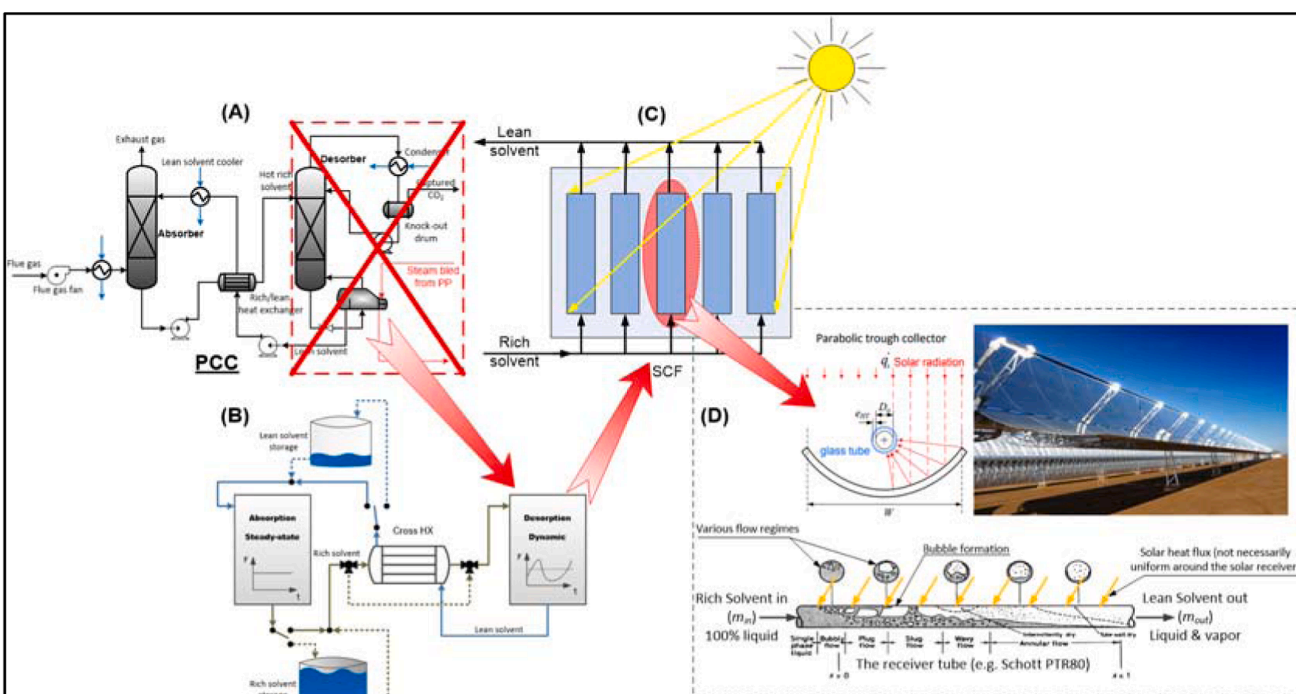


Fig. 3. (A) Eliminating the conventional desorption unit from the conventional PCC to regenerate the rich solvent dynamically and buffering the process by solvent storage tanks (B). The rich solvent is directly regenerated in the SCF (C) where the solvent goes through the solar receiver tubes of the parabolic trough collectors and the heat transfer is optimized via regulating the flow regime in the receiver as a function of solvent velocity and solar heat availability (D).

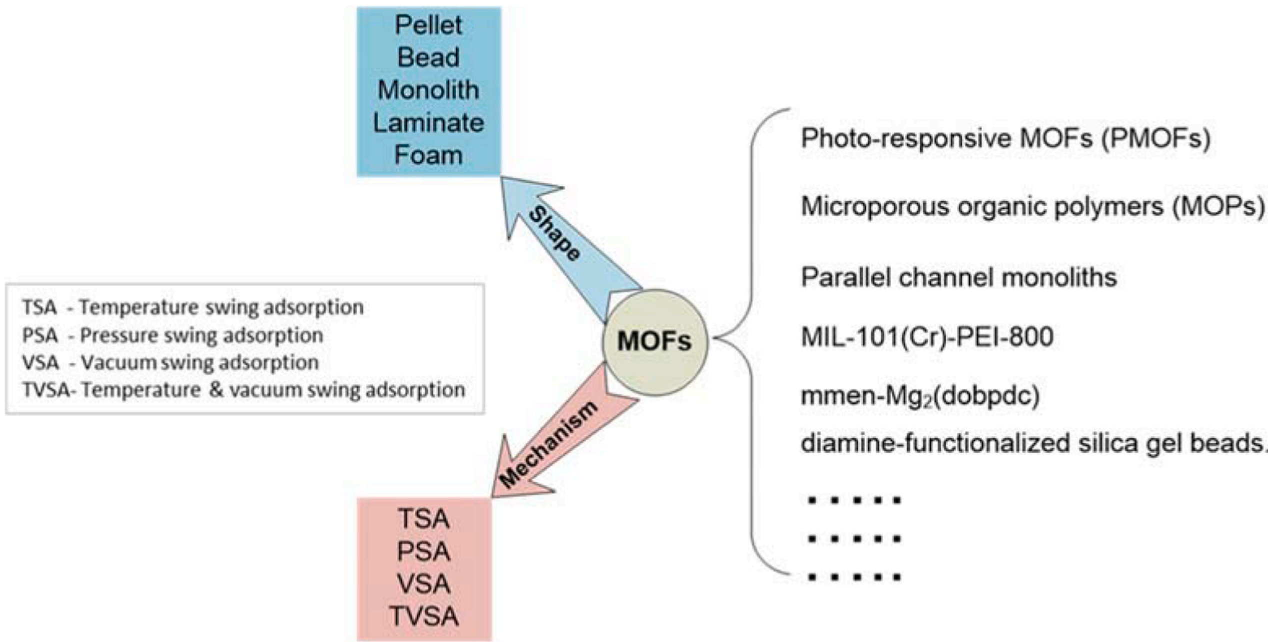
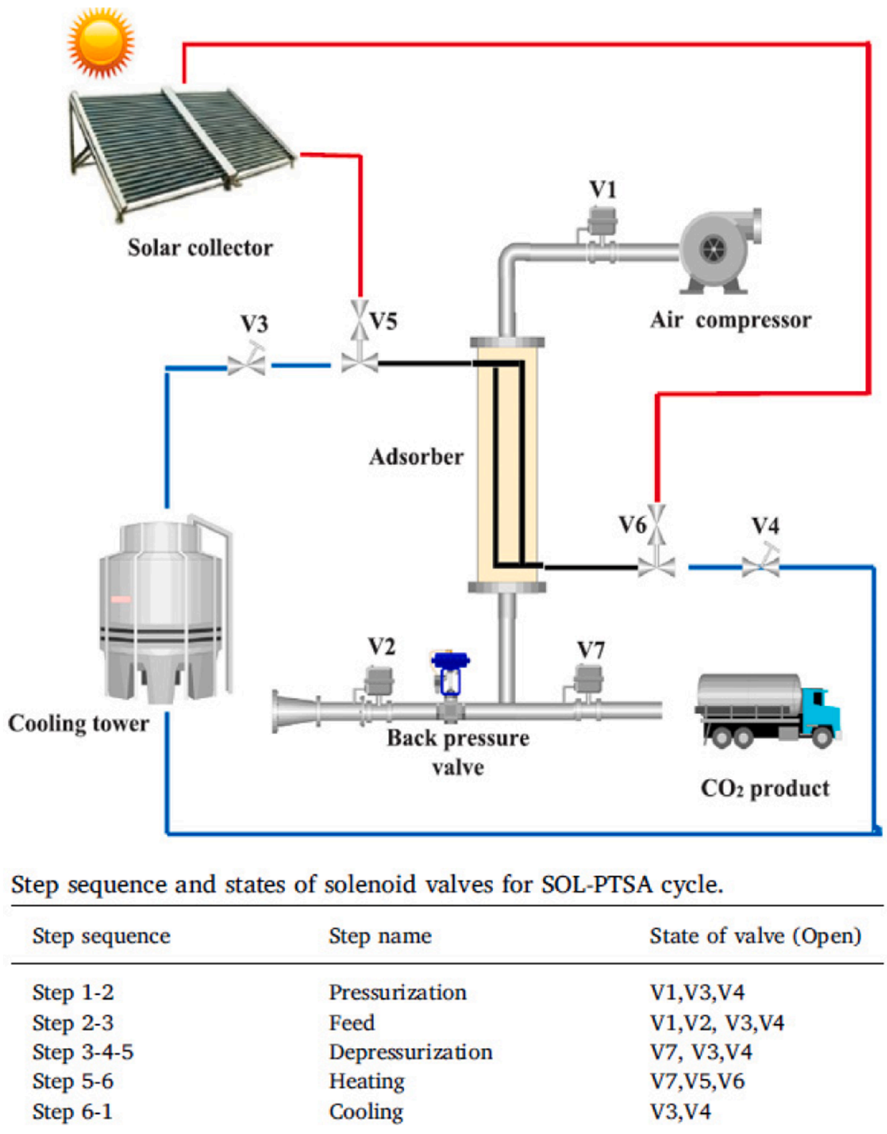


Fig. 4. A list of potential MOFs derivatives (right) and their shapes and operation mechanisms (left).

chemical adsorbent (i.e. APDES-NFC-FD, which is synthesized from nanofibrillated cellulose and 3-aminopropylemehtyldiethoxysilane) were assessed for their technical suitability in terms of sensible and latent heat requirement. The CO_2 adsorption capacity was estimated to be ~176 mg/g (~4 mol/kg), ~127 mg/g (~2.9 mol/kg), and ~74 mg/g (~1.7 mol/kg) at the pressure of 1 bar for zeolite 13X, zeolite 5A, and APDES-NFC-FD, respectively. The energy consumption of SOL-PTSA system was found in the range of 0.6–2.0 GJ/t_{CO2} for three adsorbents including zeolite 13X, zeolite A, and chemical adsorbent with a second-law efficiencies range from 9.18 to 26.89%. Based on the thermodynamic analysis, two major energy loads for the process operation, i.e. thermal energy for adsorbent regeneration and electric power for auxiliary system, were recognized. Both major energy loads can be efficiently supplied by solar energy in an integrated option as proposed in Fig. 6 where both non-concentrating and concentrating solar collectors can provide thermal energy for adsorbent regeneration and the photovoltaic system can provide electric power for auxiliary systems. More recently, Shen et al. (Shen et al., 2022) studied a solar-driven adsorption-based carbon capture system using a an integrated solar photovoltaic/thermal (PV/T) to form a new solar cascade utilization-based hybrid system. They argued that PV/T hybrid system can relatively provide a better solar exergy efficiency, but for an optimal CO_2 partial pressure. Further increasing the CO_2 partial pressure may exceed the capacity of the system resulting in lower exergy efficiency and longer regeneration times. In this case the system capacity (the overall size) must be increased to be able to capture from different CO_2 concentration sources.

The utilization of solar thermal energy for the adsorbent regeneration in PTSA process was further studied with techno-economic evaluation by Zhao et al. (Zhao et al., 2019). An 800 MW_e supercritical coal-fired power plant was used as a base–case scenario. In this study, the meteorological data of Melbourne, Australia was used for solar thermal energy calculation and zeolite 13X was selected as a solid adsorbent. The integrated system was designed in a way that the heat for sorbent regeneration can be supplied by either solar thermal energy or by steam extraction from the power plant turbines. However, the size of the SCF was devised in light of the annual mean meteorological conditions to meet the heat demand without steam bleeding from the turbines of the power plant. The integrated system showed an improvement in carbon emission intensity (CEI) reported as 95.59 g/kWh at a desorption temperature of 95 °C in SOL-PTSA process equipped with ETCs; approximately 2 g/kWh lower than that for a traditional PTSA system. In contrast to the CEI, the LCOE and CO_2 capture cost were found to be higher in the integrated scenarios. As in the case of SOL-PTSA process equipped with ETCs, the LCOE and CO_2 capture cost were at 68.95 USD/MWh and 28.38 USD/t_{CO2}, which are higher than the reference case with CO_2 capture reported at 49.48 USD/MWh and 25.28 USD/t_{CO2}, respectively. To lower the LCOE and CO_2 capture cost, the adsorbent cost and solar collector price should therefore be reduced. Noticeably, the LCOE in an integrated system using ETCs can be lower than that of the reference system with CO_2 capture if the SCF cost is reduced to < 46.08 USD/m^2. Similarly, CO_2 capture cost in this system can reach a level lower than the reference system as the SCF cost is reduced to below 47.73 USD/m^2. This reveals that the choice of the solar thermal collector technology is a very important factor. Overall, the utilization of ETCs can attain lower LCOE and CO_2 capture cost compared to FPCs because it has relatively higher efficiency and therefore less SCF area.

Generally, the integration of solar energy into an adsorbent based CO_2 capture processes has relatively showed economic benefit as shown in Table 2 with lower CO_2 capture cost (28–50 USD/t_{CO2}), LCOE (68–75 USD/MWh), and CEI (92–95 g/kWh) in comparison with solar energy integrated with aqueous amine-based CO_2 capture processes (COA: 45–65 USD/t_{CO2}, LCOE: 70–117 USD/MWh, and CEI: 94–145 g/kWh) (Zhao et al., 2019; Qadir et al., 2013; Li et al., 2012; Wang et al., 2017c; Wang et al., 2016; Cau et al., 2014). Plausibly, the LCOE for both options are still greater than the reference case without CO_2 capture, ~43 USA/kWh (Abu-Zahra et al., 2007b). The solar-assisted CO_2 capture cost can be lower than the reference power plant without CO_2 capture only when the SCF cost are reduced to a certain level or when the CO_2 capture and storage activities obtain a substantial legislature support through designated incentive programs. Despite potential reduction in the cost of CO_2 capture, only few adsorbents (two zeolites: 13X and 5A and one chemical adsorbent: amine-functionalized cellulose) have been investigated in this pressure-temperature swing adsorption process integrated with solar energy. To date, there has been great advancement in solid adsorbent-based CO_2 capture technologies in which the cost of CO_2 capture could be significantly reduced (Lockwood, 2017; Jiang et al., 2019). Zhou et al. claimed that CO_2 capture using amine-functionalized adsorbent in a TVSA process can reach a CO_2 capture cost as low as



Step sequence	Step name	State of valve (Open)
Step 1-2	Pressurization	V1,V3,V4
Step 2-3	Feed	V1,V2, V3,V4
Step 3-4-5	Depressurization	V7, V3,V4
Step 5-6	Heating	V7,V5,V6
Step 6-1	Cooling	V3,V4

Fig. 5. A system sketch of SOL-PTSA process (adapted from(Zhao et al., 2018)).

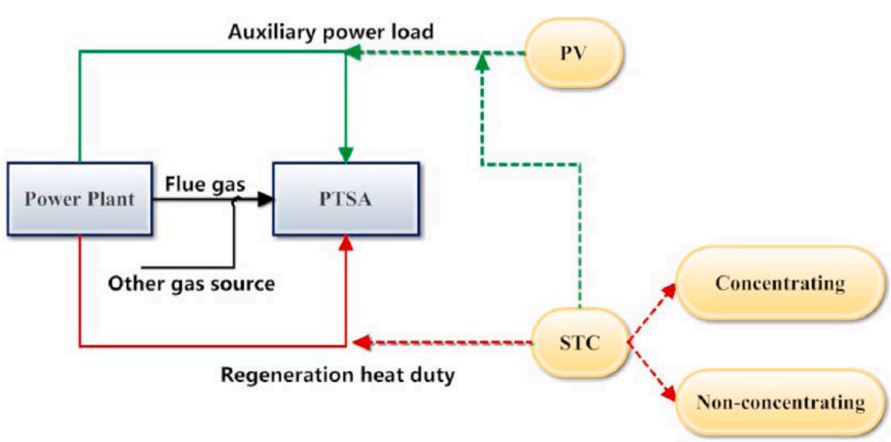


Fig. 6. Options of solar energy utilization in a pressure/temperature swing adsorption (PTSA) process for CO_2 capture (Zhao et al., 2018).

29.68 USD/t_{CO2} (Zhou et al., 2019). In another study, it was indicated that the PSA process can reduce the cost of CO_2 capture to below 30 USD/t_{CO2} if the adsorbent reaches the working capacity of 4.3 mol/kg and the CO_2/N_2 selectivity of 150 (Ho et al., 2008). Therefore, it would be very interesting when the solar energy integration with CO_2 capture technology is considered in recent advanced processes, particularly with

Table 2
Economic comparison of power plants coupled with solar energy-integrated, amine solvent-based and adsorbent-based CO_2 post combustion capture.

No	Power plant capacity (MWe)	Integration scenario	Capture Technology	Solar collectors	Location	CEI (g/kWh)	LCOE (USD/MWh)	CO_2 capture cost (USD/t_{CO2})	Ref.
1	800	Solar-assisted adsorbent regeneration	Zeolite 13X	LFC; ETC	Melbourne	92–95	68–75	28–50	(Zhao et al., 2019)
2	660	Solar-assisted reboiler heating	MEA	FPC; LFC; CPC; ETC; PTC	Sydney; Melbourne; Townsville	94.1	–	–	(Qadir et al., 2013)
3	520	Solar-assisted reboiler heating	MEA	PTC; ETC	Alice Springs; Beijing; Denver	145	~70	~45	(Li et al., 2012)
4	300	Solar-assisted reboiler heating	MEA	PTC	Hohhot	–	117	62	(Wang et al., 2017c)
5	300	Solar-assisted reboiler heating	MEA	PTC; ETC	Alice Springs	–	99–101	–	(Wang et al., 2016)
6	672	Solar-assisted solvent regeneration	MEA	LFC	Cagliari	103.5	–	–	(Cau et al., 2014)
7	300	Solar Organic Rankine Cycle for solvent regeneration	MEA	PTC	Western China	102	99	49.4	(Zhao et al., 2015)

more effective solid adsorbents.

2.3. Integration of solar energy into other carbon capture technologies

CO_2 capture by a calcium looping process is another popular case that has been considered for integration with solar energy. The major difference of calcium looping compared to other capture processes is related to its high operation temperature. CO_2 capture bases on the carbonation reaction between CaO and CO_2 occurs in the carbonator at ~650–670 °C and sorbent regeneration bases on the thermal decomposition of $CaCO_3$ occurred in the calciner at ~850–950 °C (Dean et al., 2011). Calcination is an endothermic process (178 kJ/mol) that required an external energy supply. The advantage of the solar integrating process is the potential for both renewable energy storage and CO_2 capture, which has been explored in several prior works (Matthews and Lipiński, 2012; Zhang and Liu, 2014; Tregambi et al., 2015; Zhai et al., 2016). Thermodynamic analyses revealed that over 45 MJ of solar energy per mole of CO_2 captured is required for the input CO_2 concentration of 300 ppm without heat recovery. When the heat from gas stream is recovered, the required solar energy could reach as low as 207 kJ/mole of the CO_2 captured (Matthews and Lipiński, 2012). Since the temperature required for calciner ≥850 °C, concentrated solar power (CSP) such as HFC systems are more likely suitable for the integration with calcium looping process (Tregambi et al., 2015). Zhai et al. proposed two integration scenarios in which solar energy directly supplied heat to calciner for sorbent regeneration or to the power plant (Zhai et al., 2016). Thermodynamic analyses suggested that even the former scenario slightly reduces in power efficiency penalty, the latter scenario poses to be better off in consideration of other parameters such as heat and mass transfer and technical design for calciner. To deal with the intermittent nature of solar energy, an adsorbent storage has been discussed by Tregambi et al. as a promising way for the capture system works without delay during nighttime (Tregambi et al., 2015). In their work, Tregambi et al. considered a 100MW coal-fired power plant with calcium looping CO_2 capture which powered by a HFC solar system (Tregambi et al., 2015). It was estimated that the system would require nearly 2200 m^3 of storage for both $CaCO_2$ and CaO to have a continuous 24 h operation. A critical issue of calcium looping carbon capture is the loss of CaO adsorption capacity over cyclic operation. To improve the performance of the calcium looping capture rate integrated with CSP, Di Lauro et al. (Di Lauro et al., 2021) tried to operate at lower carbonation temperature, pre-calcination, and replacing limestone with dolomite sorbent. Their experimental study showed the use of dolomite in the place of limestone can improve the system performance after 20 cycles. Thermochemical energy storage and carbon capture performance improved from 28.1 to 37.1% and 15.3–18.7% with limestone, to 61.5% and 36.7% with dolomite, respectively. Undoubtedly, calcium looping has a great potential contribution to CO_2 reduction by mean of both CO_2 capture and solar energy storage, however, it may need higher investment and more demonstration at large or commercial scale (Ortiz et al., 2021).

Oxy-fuel combustion, which uses pure oxygen instead of air to facilitate CO_2 removal, is another interesting case of renewable energy integration. This system generates pure CO_2 that is ready for storage and utilization, however, it requires large energy input for air separation unit to produce oxygen. Son et al. proposed the integration of a supercritical CO_2 oxy-fuel combustion with solar energy as shown in Fig. 7 (Son et al., 2019). Supercritical CO_2 oxy-fuel combustion is an oxy-fuel combustion in a closed loop system which uses the CO_2 as a working fluid. Their calculation suggested that the integrated system can operate more efficient than the system with solar energy system working independently. Integrated system helps reduce fuel consumption by 17–38% compared to the conventional separated system. Moreover, the intermittency caused by solar energy can be eliminated via heat distribution. Son et al. believed that this system can achieve almost zero emission, however, this concept would require more validation and rigorous techno-economic scrutiny (Son et al., 2019).

3. Biomass energy integration

3.1. Bioenergy with CO_2 capture

Bioenergy can be produced from a variety of biomass sources such as forests, agricultural and livestock residues, energy crops, and municipal solid wastes. Through different processes, biomass can be directly converted to electricity, heat, or fuels. Bioenergy is deemed as a renewable energy source that has a very significant role in the transition to a decarbonized economy (Edenhofer et al., 2011; Sanchez et al., 2015; Canadell and Schulze, 2014). Bioenergy itself is a neutral emission energy source. Plants or organisms absorb atmospheric CO_2 through photosynthesis process that converts sunlight into chemical energy (McKendry, 2002). The chemical energy is stored in the form of carbohydrates and the heat is released when biomass or its derivatives are burned (Bajwa et al., 2018). Conversely, the combination of bioenergy process with CCS (BECCS) takes one step further and offers a promising avenue to achieve energy production at ultimately net negative emission, because the CCS process captures and stores the CO_2 gas that has already been removed from the atmosphere via biomass stock (Daggash et al., 2019). A schematic illustration of CO_2 cycle in a BECCS process is illustrated in Fig. 8. The CO_2 from bioenergy production may follow one of two selective routes: either the neutral or negative pathway. In

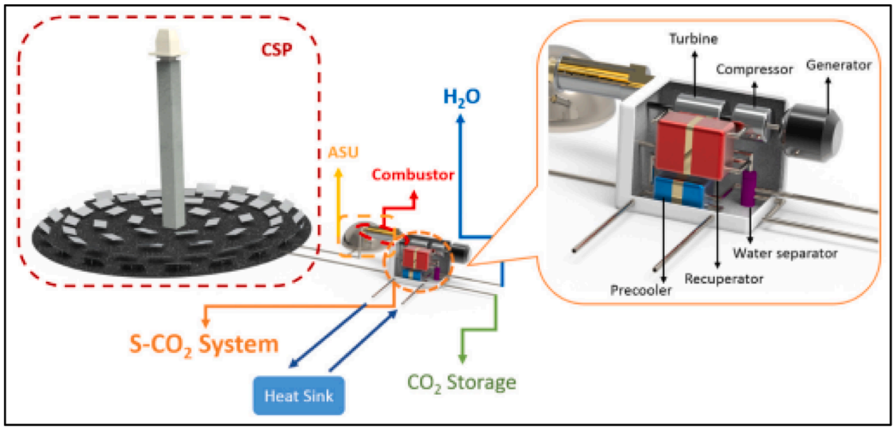


Fig. 7. A schematic illustration of a supercritical CO_2 oxy-fuel combustion integrated with concentrated solar power (CSP) system (Son et al., 2019).

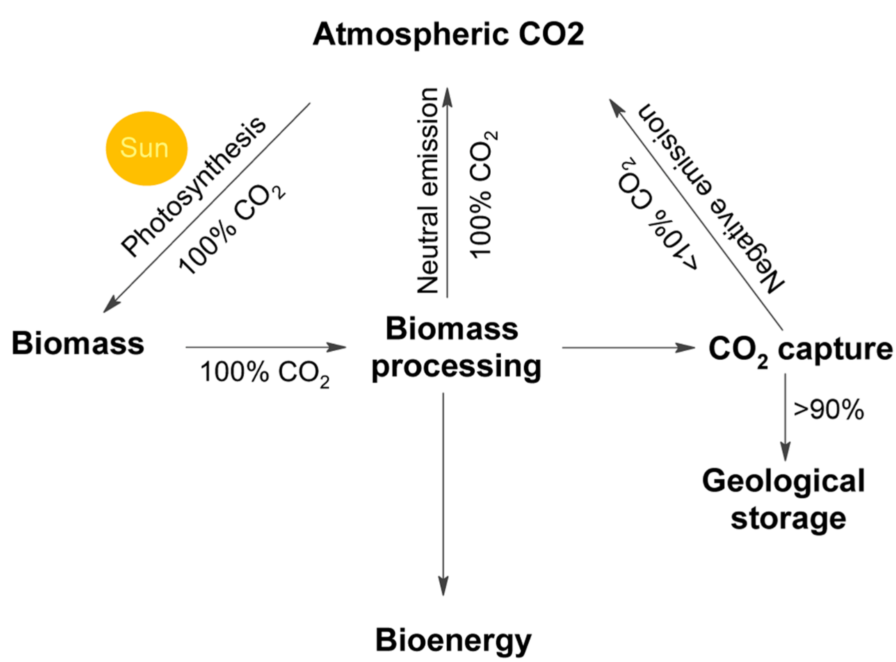


Fig. 8. Schematic illustration of CO_2 cycle in a BECCS process.

neutral pathway, almost 100% of the CO_2 absorbed from atmosphere is re-emitted when biomass is burned. The 100% neutral path, however, can only be achieved, if the emission related to biomass collection, processing, and transportation is negligible, in fact, this is a very challenging target to reach. Meanwhile, the negative pathway contributes a net negative emission because of the CO_2 removal and permanent storage via the complementary CCS mechanism. This could be a cost-effective carbon-negative option for energy production and therefore it may induce lesser burden on the environment compared to fossil-fuel fired power generation. Of course, the total environmental impact and the degree of net emission from bioenergy production depends on a number of parameters such as technology readiness level related to both bioenergy and CCS (Bui et al., 2018b; Kemper, 2015), the feedstock issues related to the biomass resources, incentive policy framework, and social perception (Fridahl and Lehtveer, 2018). In comparison with coal, biomass has often a poorer high heating value (HHV) mostly because of higher moisture content. The economic viability of biomass utilization must be closely linked to the local availability and sustainability of the raw materials. The key attributes of the supply chain are the quantity, distribution, cost, and physio-chemical characteristics of the biomass. As biomass feedstocks diverge greatly in composition and form, all of these attributes must be carefully considered when matching the feedstock with the relevant conversion technology. To this end, moisture and the mineral content would be the key parameters in the evaluation of biomass quality and/or quantity which lead to the foremost engineering decisions (Milani et al., 2020a).

To improve the performance of a BECCS process, it would require more advanced technology assessment for both bioenergy and CCS processes. It is suggested that the energy efficiency can be improved by enhancing waste heat recovery from a biomass co-firing system for the regeneration of high performance solvents (low heat duty) for CO_2 capture (Bui et al., 2017). By combining high performance solvent regeneration with the waste heat recovery, the BECCS process could achieve an efficiency of 38% HHV, compared to efficiencies from 26 to 35% of current coal-fired power plants (Bui et al., 2018b). The carbon neutrality of bioenergy also depends very much on the type of biomass and the method and the extent that biomass is being produced (Pour et al., 2017; Pour et al., 2018; Kraxner et al., 2013; Hughes et al., 2012). The rapid development of energy crops and the land use may significantly influence food production, forests management, and the overall ecosystems. Pang et al. revealed that the development of BECCS technology may have adverse effect on the ecosystem; it could be a trade-off between the carbon reduction benefits and the ecological cost when adding the CCS to the biomass power plant (Pang et al., 2017). Obviously, the deployment of BECCS should be considered under an inextricable link in food-water-energy-climate nexus; however, this is only one of few methods that could effectively contribute to the negative emissions (Kemper, 2015). The BECCS process and its potential contribution in atmospheric CO_2 removal have been reviewed in several papers (Gough and Upham, 2011; Kemper, 2015), but a review on the direct utilization of bioenergy in the form of thermal energy for a CO_2 capture process is rarely reflected in literature. Therefore, in the next subsection, the exploitation of biomass to supply the required thermal energy for CO_2 capture process and its potential contribution to reduce CO_2 emission and cost is compared with other integration scenarios.

3.2. The techno-economics of bioenergy utilization in CO_2 capture process

It is well-established that bleeding steam for a CO_2 capture process causes a great impact on the efficiency of a fossil-fuel fired power plant, thus, the utilization of external renewable energy to heat the reboiler and power other auxiliary units are of a great interest. Along with renewable energy sources, the use of biomass to heat the reboiler is very interesting because of its carbon-neutral nature and possibly continuous supply. The concept of using biomass to produce steam for CO_2 capture was first proposed by Mathisen et al. (Mathisen et al., 2011). A schematic illustration of this concept is exhibited in Fig. 9. In the conventional case (Fig. 9-a), steam for CO_2 capture is extracted from the power plant, while in the proposed concept (Fig. 9-b), the biomass is utilized to produce steam and the CO_2 generated from both the gas-fired power plant and the bioenergy plant are captured by a solvent-based CO_2 capture plant. Steam was produced by burning wood chips and CO_2 capture from bioenergy plant can then result in negative CO_2 emissions. This concept is found to be technically feasible, but the economics is compatible only when the biomass cost is low and CO_2 quota cost is high. The estimated investment cost increased about 45% when the steam was provided by burning wood chips (528 million Euros in 2008) compared to the steam extraction (364 million Euros) (Mathisen et al., 2011). Meanwhile, the estimated operation cost even increased by 3.6 folds; 76 million €/year to produce steam from biomass compared to 21 million €/year to extract the steam from a gas-fired power plant. The cost of electricity may vary with the CO_2 quota and biomass price. In general, the use of bioenergy would be more competitive if the CO_2 quota price increases and biomass price decreases. More options for bioenergy utilization in NGCC power plant retrofitted with CO_2 capture were investigated by Carapellucci et al. (Carapellucci et al., 2016). A biomass fired boiler operates at high pressure (80 bar) to produce superheated steam (540 °C) expandable into a back-pressure turbine, helps increase net power output by 4% compared to the case that the steam for CO_2 capture is bled from the gas-fired power plant itself. Such design would also be effective in coal-fired power plant with a net power efficiency of 34.1%, in a case that steam is supplied from a discrete biomass boiler, compared to 33.1% in a case that steam is directly bled from the power plant (Carapellucci et al., 2015). The combination of steam production from biomass burning with steam extraction from the power plant also improves the plant efficiency. Of course, the power plant improvement usually followed by an increase in the investment cost; to improve 4% in net power output, the cost of CO_2 capture retrofit reached 860.5 USD/kW (steam from the biomass burning boiler operates at high pressure) in comparison with 746.9 USD/kW in the case of steam extraction from the power plant (Carapellucci et al., 2016). The levelized cost of electricity and the cost of CO_2 capture are sensitive parameters that vary substantially with the price of biomass and natural gas; however, they have the opportunity (at lower biomass and gas prices) to be lower than the cost resulted from direct steam extraction from the power cycle.

Beside the steam supply for the purpose of solvent regeneration, excessive steam could be further expanded in the turbines to generate power for compressors and fans operation. Khorshidi et al. have considered to supply both steam (for the boiler) and electricity (for compressors) for MEA-based CO_2 capture process from a bioenergy plant using wood chips, and the excessive generated electricity was sold out to the grid (Khorshidi et al., 2014). The bioenergy utilization slightly reduced the cost of the electricity by 2% as a result of capturing CO_2 from the coal-fired power plant only, but it increased the electricity cost by 20% when CO_2 from both coal-fired power plant and bioenergy plant were captured at a rate of 90%. Higher cost in this case is due to higher CO_2 amount emitted from burning biomass (0.1149 t_{CO2}/GJ) compared to black coal (0.0851 t_{CO2}/GJ). Both bioenergy utilization scenarios produced less net CO_2 emission than the case without bioenergy utilization; 0.08 t_{CO2}/MWh and −0.95 t_{CO2}/MWh for capturing CO_2 from coal-fired power plant only, and from both coal-fired and bioenergy plants, respectively. The net CO_2 emission is the CO_2 amount emitted from coal firing only, which considers biomass as a carbon neutral source. The use of combined heat and power (CHP) units can be more economic than the use of auxiliary boilers. Even though, capturing CO_2 from both coal-fired power plant and biomass auxiliary units would generate negative CO_2 emissions, although, a great deal of design flexibility should be considered to minimize the risk of biomass shortage. According to the analysis conducted by Khorshidi et al., a design that only captures CO_2 from coal-fired power plant while using bioenergy for auxiliary units could be more attractive than other configurations because it has the least cost of electricity over a large range of fuels, biomass, and carbon prices (Khorshidi et al., 2015). Moreover, such design allows one to temporarily switch between coal and biomass options to encounter the possible biomass unavailability.

Generally, CO_2 capture process powered by bioenergy has been considered as a promising avenue to accelerate the deployment of CCS technology in heavy industries such as cement (Ali et al., 2019) and pulp

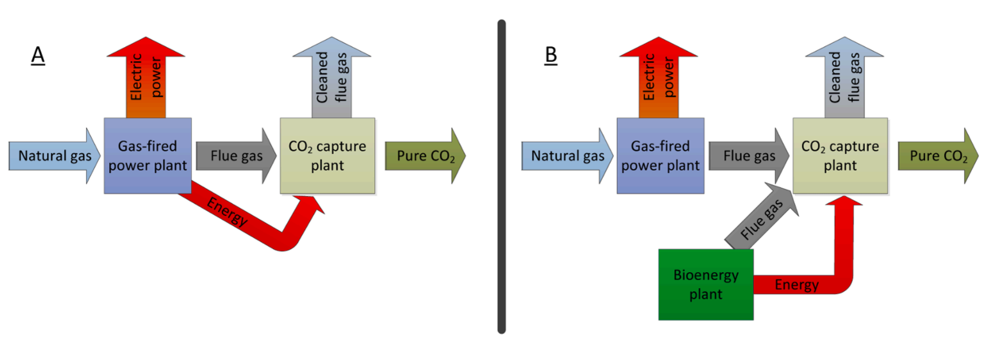


Fig. 9. A schematic illustration of a conventional gas-fired power plant with CO2 capture (A) and the proposed concept that use biomass for steam generation for the CO2 capture plant (B) (Adapted from (Mathisen et al., 2011)).

(Kuparinen et al., 2019; Haugen et al., 2019). Norcem's cement plant (Brevik, Norway) can use waste heat to power the CO_2 capture plant, but the use of waste heat only enables to capture 30% of the total emitted CO_2. In this case-study, biomass has been used as a supplementary fuel to produce enough steam for the CO_2 capture plant to achieve the 90% CO_2 capture target. The results showed that the biomass produced steam with very high cost (33–38 €/tonne) in comparison with coal (11.7–12.2 €/tonne) and natural gas (9.5–9.9 €/tonne) (Ali et al., 2018). The high cost mainly originates from the high price of biomass following by availability, transportation, and storage. Evidently, the use of biomass to supply thermal energy for a CO_2 capture plant is technically feasible, however for economic aspects, it requires a flexible availability and cost-effective biomass resources. To reduce the price, the use of municipal solid waste as a cheap biomass resource can also be taken into account. Currently, the global municipal solid waste generation is estimated to be 1.3 billion tonnes annually and projected to reach 4 billion tonnes annually by 2100 (Hoornweg and Bhada-Tata, 2012). This amount of solid waste, if not properly managed and discharged, may cause adverse impact on the environment. A promising way for solid waste management is to convert it into energy. By 2015, it is estimated that about 765 incineration waste-to-energy plants are operating worldwide and consuming 83 million tonnes of solid waste annually (UNEP, 2015). This is an evidence that municipal solid waste could be used as a potential cheap biomass resource with large supply quantity that could be utilized as a renewable energy source for CO_2 capture.

4. Wind energy integration

Wind is one of the fastest growing sustainable energy sources that technologists, investors, and policy makers have considered wind energy as a key technology option for emission reduction (Denny and Malley, 2006; Samal and Tripathy, 2019). However, as other renewable energy sources, wind power supply is intermittent and has small capacity factor compared to thermal power generation; one megawatt (MW) of wind power unit cannot replace a 1 MW thermal power unit (Safdarnejad et al., 2015; Kang et al., 2011). Therefore, wind energy should be integrated with thermal power options to develop a reliable power generation system and at low-carbon footprint. The wind integration may offer opportunities to mitigate the disadvantages associated with both CO_2 capture and renewable energy. Indeed, the proposal of such integration must be considered with the co-location of renewable energy sources and thermal energy generation plants.

Kang et al. proposed an approach for the optimal operation of the integration model in a combined coal-CCS-gas-wind energy system (Fig. 10. Overall process model showing the integration of wind energy in the coal-CCS-gas-wind energy systemFig. 10), including a coal-fired power plant, CO_2 capture unit, auxiliary natural gas combustion turbine, heat recovery steam generator, which provide heat to the CO_2 capture unit, and wind power facility (Kang et al., 2011). The CO_2 capture unit is based on aqueous ethanolamine solvent. Heat for the CO_2 capture process is supplied by the heat recovery from the steam generator and by electric power from wind power via the possible heat conversion. Decision variables such as the operation of gas turbine, the conversion of wind power to heat during the time of low electricity price, and the rich solvent storage play significant roles in the viability of the integrated energy system. In the optimization mode, decision variables such as natural gas turbine operation, CO_2 rich solvent storage, and time to convert wind power to heat are optimized to maximize the operating profit. Accordingly, the operating economics of the energy system could be improved by ~20% in the optimization mode. The amine solvent storage does not only allow exploiting the low-price electricity by postponing the most energy-intensive step of the CO_2 capture process, but also mitigating the variability of wind power. This requires the flexibility in the CO_2 capture unit operation with on/off function during low/high electricity prices (Delarue et al., 2012; Van der Wijk et al., 2014). Recent studies demonstrated the importance of the temporally flexible on/off operation of the CO_2 capture unit on the increased profits and wind power integration (Bruce et al., 2014). Using electricity prices and wind data from the eastern region of the USA, Bandyopadhyay and Patino-Echeverri indicated that the integration of wind power into a thermal power plant with amine-based CO_2 capture can be more effective than other alternatives for reducing CO_2 emission from an existing coal-fired power plant (Bandyopadhyay and Patiño-Echeverri, 2014). The LCOE of wind-coal hybrid system is in the range of 86.4–107.7 USD/MWh with annual average CO_2 capture rates of 85%, which is comparable to the LCOE of NGCC power plant (85.9–111.7 USD/MWh) with 90% CO_2 capture rate and lower than the LCOE of integrated gasification combined cycle power plant (111.8

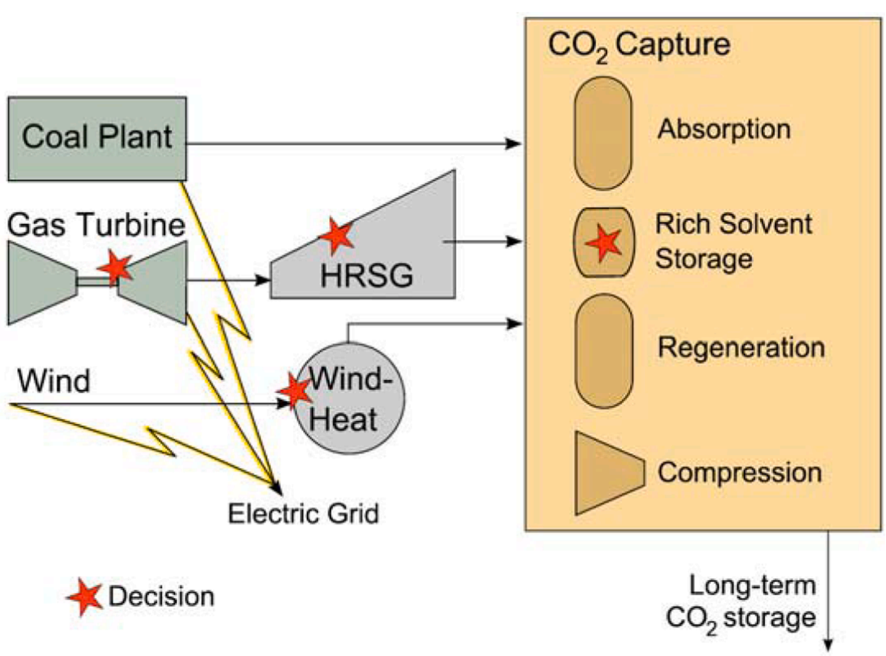


Fig. 10. Overall process model showing the integration of wind energy in the coal-CCS-gas-wind energy system (Kang et al., 2011).

USD/MWh) with 90% capture rate (Bandyopadhyay and Patiño-Echeverri, 2016). However, the financial and emission indexes of a wind and coal-fired power plant integration with CO_2 capture vary with the wind power proportion and the best performance of CO_2 emission mitigation can be attained at the wind power proportion of 0.48 (Huang et al., 2017).

Obviously, wind power should have a more noteworthy position in implementing negative emission strategies; yet, the attention to wind power for the field of CO_2 capture is still limited where only few publications were reported, probably due to the low energy intensity and the intermittent nature of wind power. The application of wind power requires a very flexible design with on/off switch functions to safeguard the intermittent supply and to categorize periods of high and/or low electricity price.

5. Geothermal energy integration

Geothermal energy is a consistent renewable energy source that retained in the earth's interior as heat (Barbier, 2002). The origin of this heat related to the physicochemical activities such as radioactive decay of minerals in the earth and the solar heat absorbed by the earth surface. Geothermal energy is an abundant source, but it is unevenly distributed and located deeply under the surface. There are, however, some areas where the hot sources are accessible by drilling. As seen in Fig. 11, when a hot source, e.g. magma bodies located near the surface is cooling down, they release the heat which is carried up to the sub-surface layer by geothermal fluids (Barbier, 2002). Rainwater, an essential geothermal fluid supplied from recharge area, comes into contact with the hot source (i.e. magma) and accumulates in aquifers (reservoirs) at high temperature and occasionally high pressure if the reservoirs are covered by impermeable rocks. Hot water can also go up to the surface via irregular fractions in the impermeable layer to form a hot springs or steam vents. By drilling through the impermeable caprock layer, the hot water can be extracted. Depending on the hydrogeological formation, this hot water at high temperatures can be obtained from the well. Generally, the fluid temperature increases from 11 to 30 °C for each 1000 m increment in depth (Kharseh et al., 2015). Extracted geothermal fluids can be utilized for electricity production, or direct/indirect use in a variety of industrial processes (Lund et al., 2011; Self et al., 2013). In a geothermal field, a continuous circulation of heat and fluid always occurs in which fluid is continuously supplied from the recharge area, enters the reservoir, receives heat from source and leaves the reservoir to discharge zone. When the geothermal fluid extraction combines with the reinjection, the geothermal heat can be considered as a renewable energy source.

Compared to other renewable energy sources, geothermal energy is counted as an ongoing supply energy option without intermittent nature as in the case of wind and solar energy. The most potential of geothermal energy is to be utilized for power generation, but, the electricity production usually has a low efficiency from 1 to 20% due to the significant heat loss while geothermal fluid travels long distances through the well and to the power station and therefore results in high costs (Zarrouk and Moon, 2014). The efficiency, however, can be improved if the fluid travel distance is reduced and geothermal energy is used together with other energy sources. To exploit this energy source efficiently, hybridizing geothermal energy with fossil fuel for electricity production has been investigated. Many studies have indicated that the hybridizing approach called geothermal-assisted power generation (GAPG) concept is a feasible method to reduce the cost of electricity production from both geothermal and fossil fuel energies. A very early study conducted by Khalifa et al. revealed that the GAPG concept can produce 60% more work if the temperature of geothermal fluid at 200 °C is used for feed water preheating (Khalifa et al., 1978). An early days technical and economic evaluation performed by White et al. showed that the GAPG concept applied in Arizona area to build a new hybrid plant can reduce the cost significantly; 18.3 USD/MWh compared to 19.3 USD/MWh in the comparative scenario of fossil-fuel only power plant (White and Goldstone, 1982). In another technical and economic assessment for an Australian case-study, Zhao et al. indicated that the advantage of this concept, however, can only be attained when a hybrid power plant is built in the vicinity of the geothermal site or the temperature of the fluid is proportionally higher if the well locating far away from the power plant (Zhou et al., 2014). The GAPG system operating in the booster mode produced 19% more power than the fossil-fuel only plant, but the increase in the power output is estimated to be reduced by about 48 kW per km if the geothermal source located far away from the power plant. Evidently, hybridizing geothermal energy with fossil fuel has proved to be beneficial to both geothermal energy and fossil fuel sources, which helps utilize these energy sources more efficiently and relatively lessens the CO_2 emissions.

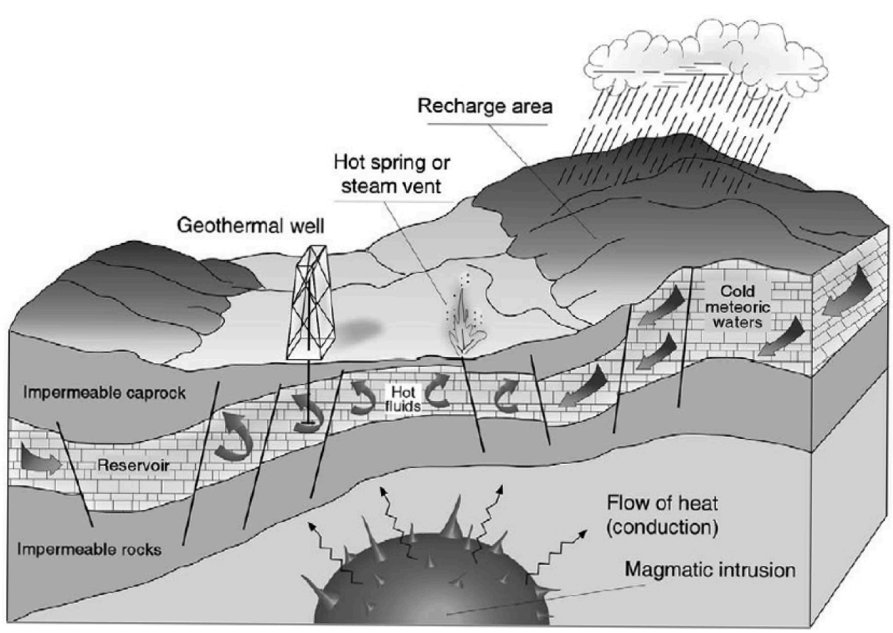


Fig. 11. A geothermal field with different elements: heat source, recharge area, reservoir, discharge area, and impermeable rock cover (Barbier, 2002).

Following the success of geothermal and fossil fuel hybridizing concept, the exploration of the geothermal energy for CO_2 capture from fossil-fuel fired power plant has also been proposed aiming for the geothermal energy to offset part/all the energy penalty of the carbon capture process and therefore enhancing the application of CCS. The geothermal energy can provide the required heat for the regeneration of the absorbent or adsorbent in the CO_2 capture process and thus reduce the energy penalty for the power plant. Since the low enthalpy of the geothermal fluid has the temperature below 150 °C, which sufficiently meets the requirement for solvent regeneration process in the CO_2 capture plant. In most cases, geothermal temperature approximately increases linearly with the depth of the well (Moses, 1961), and therefore, the lower temperature requirement for the solvent regeneration purpose may help to reduce the capital cost by avoiding deep well drilling. Accordingly, an integration system called a geothermal-assisted post combustion capture (GA-PCC) has been proposed by Wang et al. shown in Fig. 12 (Wang et al., 2017a). The integrated system utilized a medium-temperature geothermal energy to partially replace the energy requirement for MEA solvent regeneration in the CO_2 capture process. Hot geothermal fluid extracted from a production well went through a heat exchanger where thermal energy was transferred to the working fluid (saturated water) in CO_2 capture plant and then returned to the reservoir through another injection well. The working fluid can be combined with a low-pressure steam flow bled from the turbine of the power plant to meet the reboiler duty in the CO_2 capture plant. The coal-fired power plant with/without CO_2 capture (PCC) and the stand-alone geothermal power plant were taken as references to evaluate the efficiency of GA-PCC option. Two types of geothermal energy systems including enhanced geothermal system (EGS) (Olasolo et al., 2016) and hot sedimentary aquifer (HSA) (Bahadori et al., 2013) were selected to supply heat for the reboiler and a comparison was also made. The HSA comprises of permeable layers of fluid-bearing rocks. Hot fluid can flow through the porous rocks reaching the surface and can be directly used for heating and cooling purposes (Limberger et al., 2018). Meanwhile, EGS relates to a technical application to induce artificial fractures in the hot rocks which results in the reservoir creation (Lu, 2018). Compared to HSA, EGS has an advantage to access more abundant sources of the geothermal energy.

Technical analysis conducted by Wang and co-workers showed that in comparison with a PCC without geothermal integration, the fraction of thermal energy for amine regeneration replaced by geothermal energy (Thermal load-fraction, TLF) is 85.4% and 72.1% in EGS and HSA integration scenarios, resulting in the improvement of the net plant average low heating value (LHV) efficiency by 5.56% an 4.42%, respectively (Wang et al., 2017a). The higher TLF in the EGS scenario could be attributed to the higher thermal flow supplied by EGS integration system. This improvement resulted from the partial replacement of steam extraction so that more steam can contribute to the electricity production. Economically, a coal-fired power plant associated with CO_2 capture required almost more than double capital cost compared to the one without CO_2 capture. The integration with geothermal energy required even more capital cost but resulted in an overall lower LCOE in both EGS and HSA integration scenarios. The geothermal integration concept poses even more benefits when the coal price is higher. The LCOE in PCC would only be lower than that in GA-PCC if the coal price drops below 30 USD/tonne which is far below the current market price. The investment cost in EGS integration is a little lower than that in HSA scenario and thus results in a proportionally lower electricity cost. The electricity cost in the GA-PCC concept, however, significantly sensitive to the drilling price; its increment must be less than 10 and 20% for HSA and EGS integration scenarios, respectively, to keep it lower than that in PCC reference case (Wang et al., 2017a).

GA-PCC shows a better performance with 30.2% in the net plant average LHV efficiency in comparison with a solar–assisted post combustion CO_2 capture (SA-PCC) with thermal energy storage (TES) 29.51% and without TES 28.95% in NSW, Australia (Wang et al., 2017b). The efficiency, however, can vary from region to region due to the change in the solar intensity as well as the temperature of geothermal energy. Moving to Yangbajing, China, the net plant average LHV efficiency for GA-PCC (30.21%) is a little higher than that for

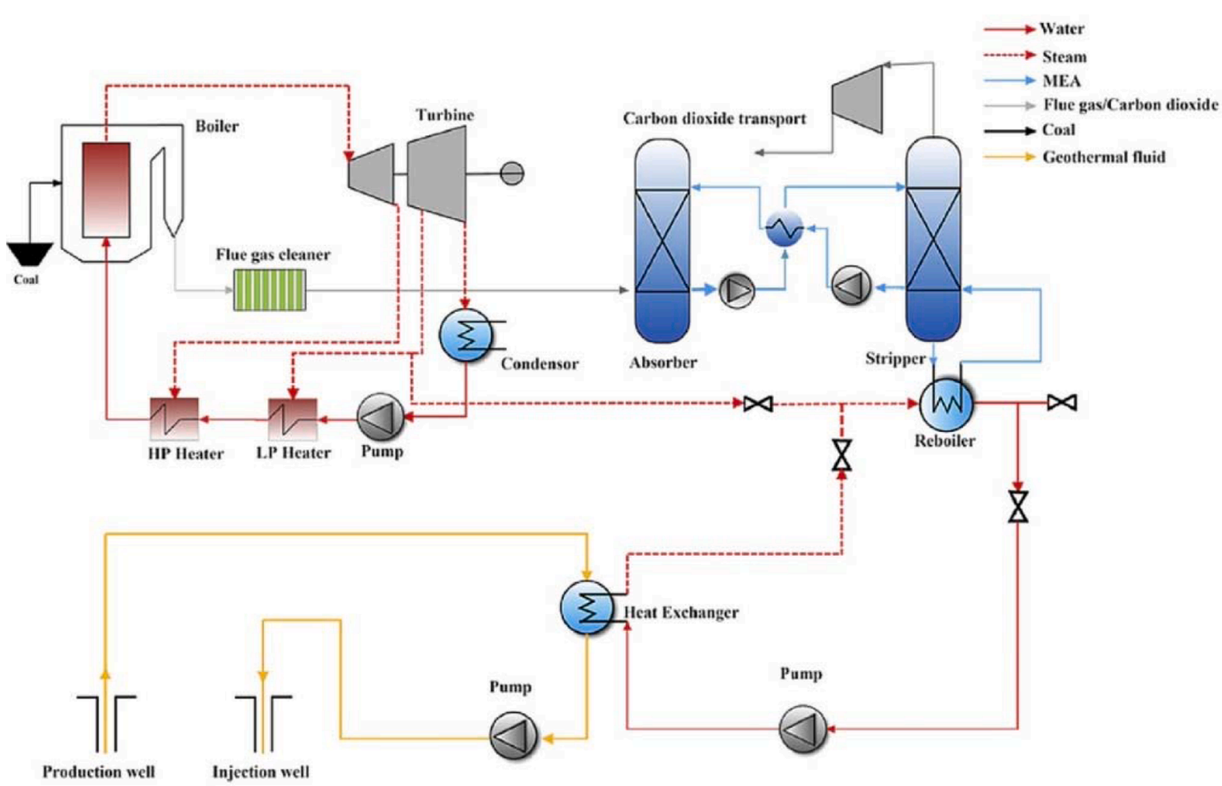


Fig. 12. A schematic of the proposed integration system of GA-PCC in a coal-fired power plant (Wang et al., 2017a).

SA-PCC without TES (29.6%) but very compatible to that for SA-PCC with TES (30.36%) (Wang et al., 2017b). In a specific location, the LCOE and the cost of CO_2 avoidance for SA-PCC are greatly affected by the price of solar collector and the TES cost; meanwhile those for GA-PCC are varied significantly with the drilling depth, drilling price and the reservoir temperature.

In short, the integration of geothermal energy with fossil-fuel fired energy systems has shown some advantages to CO_2 capture technologies. Even though, the capital cost for GA-PCC is usually higher than that for a conventional PCC, it is able to generate more electricity and higher power production efficiency, and as a result, it produces electricity at a lower cost. Moreover, the cost of CO_2 avoidance is found to be lower than that of a conventional PCC process. Compared to solar energy, geothermal is almost a constant energy source, which does not endure a significant day/night or seasonal variation. The geothermal and fossil fuel hybrid has proved to have tangible benefits to the CO_2 capture process that could be clearly realized when the geothermal resources are in vicinity of the power plant location. Note that the data obtained from the literature are for the conventional process that utilizes MEA as CO_2 absorption solvent. The geothermal energy integration does not alter CO_2 capture process; it only replaces or combines the energy sources required for the reboiler where the absorbent/adsorbent is regenerated. Considering more advanced solvents or adsorbents, the power generation efficiency and the cost of electricity may be further improved. Current studies only consider the integration of geothermal energy into coal-fired power plant coupled with CO_2 capture. In the future, more advanced CO_2 capture processes and novel sorbents should be investigated with the integration/hybridization concept and capturing CO_2 from various sources such as that directly from the atmosphere or flue gases from other industries and transport sectors.

6. Renewable energy integration in hard-to-abate emissions

6.1. In heavy industries

Industry sector is the second largest contributor with total direct and indirect emission reaching approximately 20.1 $Gt_{CO2\text{-}eq}$ in 2018 (Lamb et al., 2021). It is expected to be higher since the demand for major industrial products including steel, cement, plastic, paper, and alumina is anticipated to be doubled by 2050 (Allwood et al., 2010). Industrial CO_2 is usually emitted from both fuel combustion and material processing. The CO_2 concentration in industrial flue gases varies from few ppm to pure CO_2, depending on type of the process (Bains et al., 2017; Romeo et al., 2011). Flue gas emitted from iron and steel production, for example, contains 20–27% CO_2 for the blast furnace and 16–42% basic oxygen furnace, respectively (Bains et al., 2017). In general, the existing CO_2 capture technologies are applicable to other industrial plants with some modifications (Plaza et al., 2020; Onarheim et al., 2017). Like power plants, capturing CO_2 from industrial vents would encounter a great deal of energy consumption. Since there is no typical steam production process in many of these large-scale industries, more process innovation combined with low-grade energy would be necessary to reduce the capture cost. According to Philibert (Philibert, 2017), both renewable energy and CCS are key pillars to CO_2 reduction initiatives in industries, thus, the integration of renewable energy with CO_2 capture process to remove CO_2 could be a good way for CO_2 emissions reduction. Otto et al. demonstrated that steel produced by a blast furnace with gas recirculation and CO_2 capture can reduce 68% of CO_2 emission against the 1990 emission level benchmark and the reduction can reach up to 82% if the renewable energy integration is considered (Otto et al., 2017). In this process, renewable energy can be integrated in either as an electric power or via contributing in synthetic fuel production such as methane or hydrogen. Rao et al. proposed the combination of a solid oxide fuel cell (SOFC) technology that supplies power for steel production with CO_2 capture as shown in Fig. 13 (Rao et al., 2019). Coke oven gas including CO, CH_4 and H_2 is cleaned and sent to SOFC system for power production. The CO_2 generated from SOFC system is capture by a PSA process then the flow from the adsorption process is sent to gas turbine for power generation. This system can reduce the CO_2 emissions by 50% while enhancing the electricity production efficiency by 34% compared with the system that solely retrofitted with CO_2 capture process.

Shirmohammadi et al. conducted a techno-economic assessment of a SA-PCC process that captures CO_2 from the flue gas of ammonia plant to utilize in a urea production process (Fig. 14) (Shirmohammadi et al., 2021). Solar thermal energy collected from SCF is used to generate steam in the regenerator. The proposed system includes a thermal storage to store the excess energy when solar irradiation is high and use it later when solar irradiation is low. In case when solar energy is insufficient, steam can be extracted from the ammonium reformer and use in the regenerator. The advantage of this system is in simultaneous exploitation of solar energy, capture the CO_2 and utilization of the captured CO_2 for urea production. Their model indicated that by increasing the solar fraction, while the cost of heat supply decreases as the solar thermal energy storage expands from 6 to 18 h. The CO_2 capture system designed with TES for 18 h gives the lowest cost of thermal energy (3.85 ¢/kWh) and can operate independently and solely based on solar thermal energy during summer season. The study

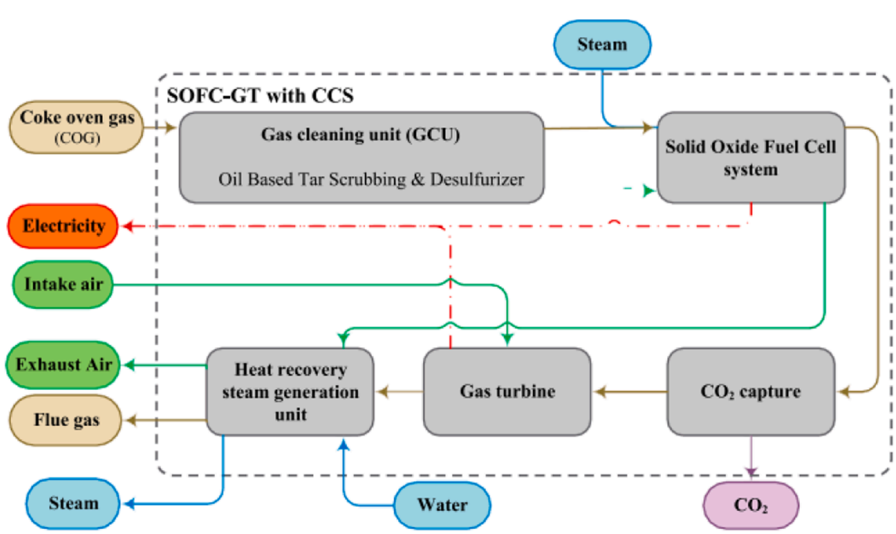


Fig. 13. Layout of SOFC-GT system with CO2 capture in steel production (Rao et al., 2019).

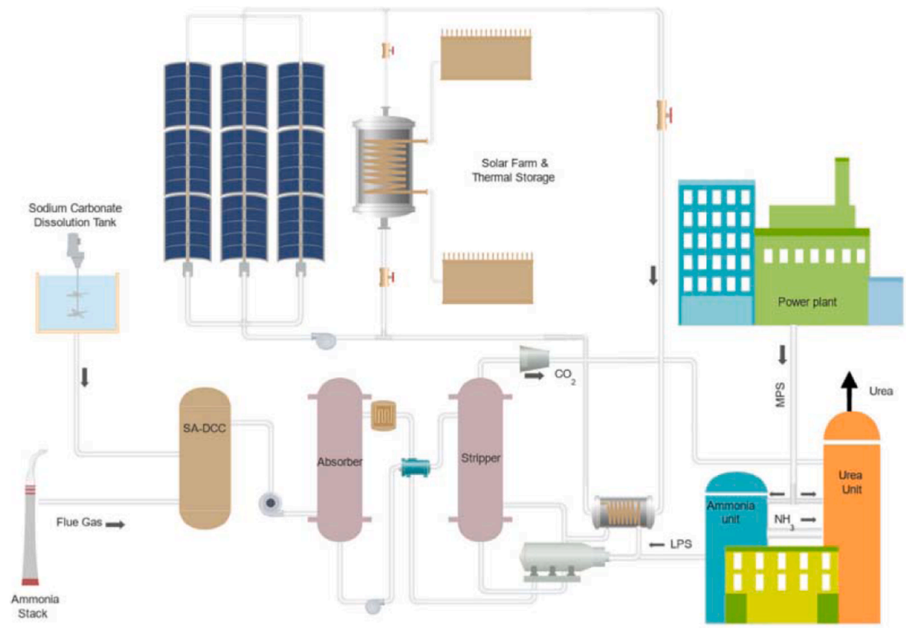


Fig. 14. The SA-PCC system in urea production plant (Shirmohammadi et al., 2021).

revealed that CO_2 emission can be reduced by 7100 t_{CO2}/year if solar energy fraction reaches 70%.

Apparently, the integration of renewable energy with CO_2 capture in industrial processes is a viable approach to reach a meaningful CO_2 reduction. The integration can be considered in multiple options: providing renewable energy for CO_2 capture process, converting renewable energy to fuel for anticipated industrial process, and/or utilizing captured CO_2 in as a raw material in another process. In general, there would be no standardized concept for all industries, each industrial sector and production process would have its own optimal way to the net CO_2 reduction.

6.2. In heavy transport

Aviation, cargo shipping, road passengers and heavy-duty vehicle transport have been considered as the most intensive sources for emission activities (Davis et al., 2018). For example, a heavy-duty vehicle with a gross mass of 30 tonnes and rated engine power 300 kW can emit up to 800 g_{CO2}/km travel (Ligterink et al., 2016). Global transportation emission reached 8.5 $Gt_{CO2\text{-}eq}$ in 2018, which accounts for 14% of the total global emissions (Lamb et al., 2021). The net-zero emission target will be difficult to achieve if the mitigation measures are not considered in the transport sector, and therefore, the idea for capturing CO_2 from mobile sources have broadly been discussed in recent years. Venkatesh et al. retrofitted a zeolite-based post combustion chamber to a diesel car exhaust to evaluate CO_2 emissions reduction (Venkatesh et al., 2016). Their experiments showed that 43% of the CO_2 could be captured from the exhaust gases. A similar experiment was tested by Rajdurai and co-workers using activated alumina to capture CO_2 from the exhaust gases of a gasoline engine (Rajdurai et al., 2016). Those adsorption processes can reduce CO_2 in the exhaust gas, however, they relatively have a low capture efficiency. Pye et al. indicated that a novel technological solution or a change in approach is required for this hard-to-decarbonize sector (Pye et al., 2021). Sharma and Maréchal

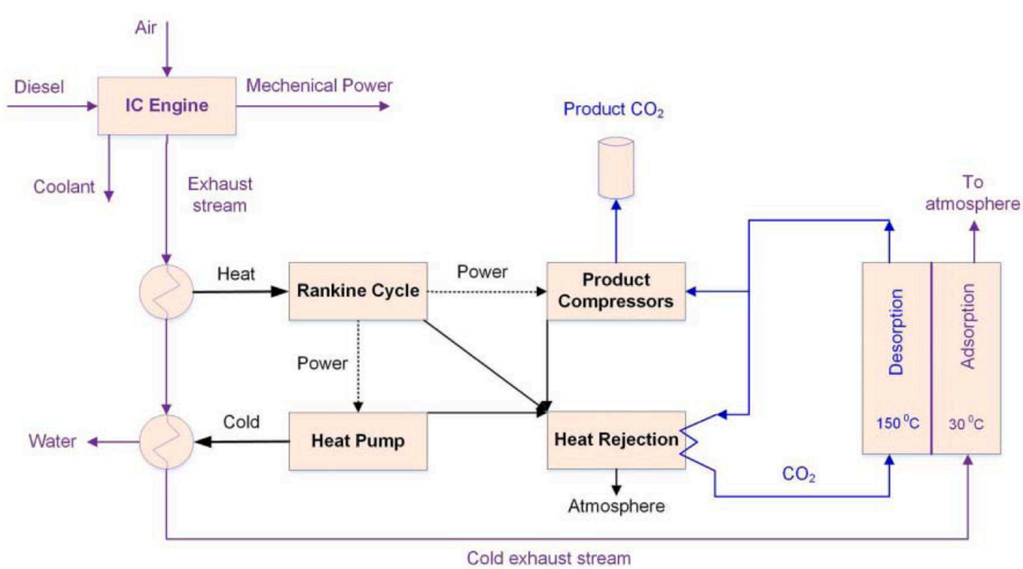


Fig. 15. CO_2 capture from engine exhaust with a temperature swing adsorption, CO_2 compression, and liquefaction (Sharma and Maréchal, 2019).

proposed a process that combine an organic Rankine cycle with TSA process to capture 90% of emitted CO_2 (Fig. 15) (Sharma and Maréchal, 2019). The organic Rankine cycle recovers waste heat (14.21 MJ per one litter of diesel) to generate power for adsorber cooling, adsorbent regeneration, and CO_2 compression or liquefication. CO_2 capture and storage can be performed on the truck, or alternatively capturing the CO_2 on the truck but regenerating the adsorption media in a parking lot. The system is thus expected to have energy self-sufficiency. Furthermore, the compressed CO_2 could be integrated with a hydrogen production unit using the solar power to produce green fuels. This proposed process is deemed to be suitable for mobile emission sources such as airplanes, ships, buses, cars, etc.

Another model for onboard CO_2 capture called CO_2 capture fuel cell vehicle (CCFCV) proposed by Schmauss and Barnett is expected to be a viable CO_2 neutral approach for transport sector (Schmauss and Barnett, 2021). The vehicle is equipped with SOFC for power generation under the consideration for CO_2 mitigation. The turning point of this model is the design of the fuel tank with the addition of a movable partition that allows to store generated CO_2 in the volume of consumed fuel in the same tank. The captured CO_2 is transferred for storage and/or utilization at fuel stations where the vehicle fills up again with a renewable-energy generated fuel. The difficulty of this idea is the deployment of assisted infrastructure, however, it has high potential to achieve CO_2 neutral target or even negative emission for biofuel usage (Jaspers et al., 2021; de Moraes et al., 2022). According to Jaspers et al., using the captured CO_2 and renewable H_2 to produce biofuel such as ethanol to refuel vehicles can generate negative emissions by 1.509 kg CO_2 for every litter of bioethanol consumed (Jaspers et al., 2021). This revealed that neutral and negative emissions can be achieved by the deployment of onboard CO_2 capture and storage in combination with biofuel utilization and SOFC technology. The idea, however, requires more time and efforts for technological demonstration and infrastructural development.

7. Renewable energy integration in direct air capture (DAC) processes

Capturing the CO_2 from point-source emitters such as power plants can mitigate CO_2 emission to a great extent. However, this option alone may not be able to bring the global atmospheric CO_2 concentration below the safe level (350 ppm) (Keith, 2009). Therefore, it is necessary to deploy negative emissions technologies such as renewable energy and direct air capture (DAC) to reduce the atmospheric CO_2 concentration, which has recently surpassed 410 ppm (NOAA, 2023; Seo and Hatton, 2023). One of the benefits of DAC systems is that the CO_2 can be produced anytime, anywhere, and at any scale in vicinity of the endpoint (either a utilisation plant or geological storage) that eliminates long-distance CO_2 pipeline transportation costs and environmental impact. Co-location of CO_2 capture and the utilisation and/or storage terminals simplifies the supply chain, avoiding the need for potentially complex commercial and legal arrangements between owners of CO_2-sources and the CO_2-sinks stakeholders (Feron, 2019).

Basically, the technologies that were long established for the PCC can be modified for DAC systems. Different technologies based on calcium looping (Nikulshina et al., 2009), alkaline (Keith et al., 2018; Fasihi et al., 2019), aqueous amine (Sanz-Pérez et al., 2016), and adsorption (Santori et al., 2018; Brilman and Veneman, 2013; Azarabadi and Lackner, 2019; Drechsler and Agar, 2019; Elfving et al., 2017; E. Bajamundi et al., 2019) have also been examined for DAC technology. However, because of the very low CO_2 concentration in the atmosphere, these technologies have to confront the high cost of capturing the diluted CO_2 stream in DAC systems. Compared to the CO_2 capture from flue gases, DAC could be much costlier due to the diluted CO_2 concentration in the atmosphere. The estimated cost for capturing CO_2 from flue gas is 30–100 USD/t_{CO2}, while it could be much higher and uncertain for DAC in the range of 100–1000 USD/t_{CO2} (Goldberg et al., 2013; Kiani et al., 2020; Meckling and Biber, 2021). Kiani et al. reported that the cost of CO_2 capture via a DAC system can be lowered from the equivalent MEA-based benchmark of 1452 USD/t_{CO2} down to 114 USD/t_{CO2} only, via a chain of technology improvement and optimization steps (Kiani et al., 2021). However, there is still a great costs uncertainty comes from the CO_2 capture technological selection and assumptions that used to estimate the capture cost, since there is not much on-ground large/commercial scale DAC units to support these claims. For example, Fasihi et al. (Fasihi et al., 2019) reported that the cost of CO_2 capture of a high temperature aqueous solution DAC process that was initially estimated by Keith et al. (Keith et al., 2006) at 376 €/t_{CO2}, can be reduced to 258 €/t_{CO2} only by changing the gas/liquid contact design (Holmes and Keith, 2012). Similar to the CO_2 capture from point-source emitters, the CO_2 capture cost could be reduced with the right application of renewable energy (Goldberg et al., 2013; Sanz-Pérez et al., 2016).

The utilization of solar thermal energy in DAC system based on a calcium looping process illustrated in Fig. 16 that has been proposed by Nikulshina team (Nikulshina et al., 2007; Nikulshina et al., 2009; Nikulshina et al., 2006; Nikulshina and Steinfeld, 2009). An air stream with the CO_2 concentration of 500 ppm was carbonated at 365–400 °C and the resulted $CaCO_3$ is calcined at above 800 °C to recover pure CO_2 and regenerate CaO. Nikulshina and co-authors (Nikulshina et al., 2007; Nikulshina et al., 2009; Nikulshina et al., 2006; Nikulshina and Steinfeld, 2009) analyzed the chemical thermodynamics, reaction kinetics, and material recyclability of the process, where the energy for $CaCO_3$ thermal decomposition and carbonation is supplied by CSP. The required solar thermal energy input for the complete CaO—$CaCO_3$ cycle was calculated to be 10.6 MJ/mole of the captured CO_2 (Nikulshina and Steinfeld, 2009). The calcium looping DAC process integrated with concentrated solar energy can be combined with H_2 production and the thermodynamic efficiency of such process can reach 22.7% (Nikulshina et al., 2006). Testing in a fluidized bed reactor showed that the removal efficiency can reach 100% with less than 1 ppm CO_2 remained in the exit gas.

Glodberg et al. suggested the integration of wind power in a DAC system located close to the CO_2 storage and/or utilization site (Goldberg et al., 2013). Kerguelen Island in the Indian Ocean (1000 km^2) has been chosen in order to exploit an almost steady wind resource and vast subseafloor storage capacities in nearby locality, while minimizing the risk of economic damage and potential public inconvenience. Resin-based solid sorbent composed of a polystyrene backbone with quaternary ammonium ligands attached to the polymer was utilized for the research in moisture swing process (Wang et al., 2011). The CO_2 capture is based on the variation in CO_2 adsorption versus the change in humidity. The total energy consumption for this process can be maintained at <100 kJ/mole of CO_2 (630 kWh/t_{CO2}) and the net cost of DAC is 50 USD/t_{CO2} (Goldberg et al., 2013).

Literature studies showed a great potential to improve the cost of DAC technologies by the integration with the appropriate renewable energy options. One of the most advantages of DAC deployment is its flexibility in the location selection. CO_2 capture plant can be co-located with CO_2 storage/utilization sites and renewable energy production facilities to maximize CO_2 capture and storage/utilization efficiency and to adopt various energy sources. In the long-term, it is expected that the cost could be reduced to 30 USD/t_{CO2} via the development of more advanced capture processes in combination with renewable energy and waste utilization (Breyer et al., 2020). Yet, the integration of renewable energy into DAC still has not yet attracted much attention as a highly applicable potential.

8. Net-zero emission by the integration of renewable energies with CO_2 capture

The goal of applying CCS technologies is to significantly cut the CO_2 emissions; however, CO_2 capture rates for power plants are usually recommended between 85 and 95% for an optimal economic trade-off. Higher capture rates lead to more investment, higher energy penalty

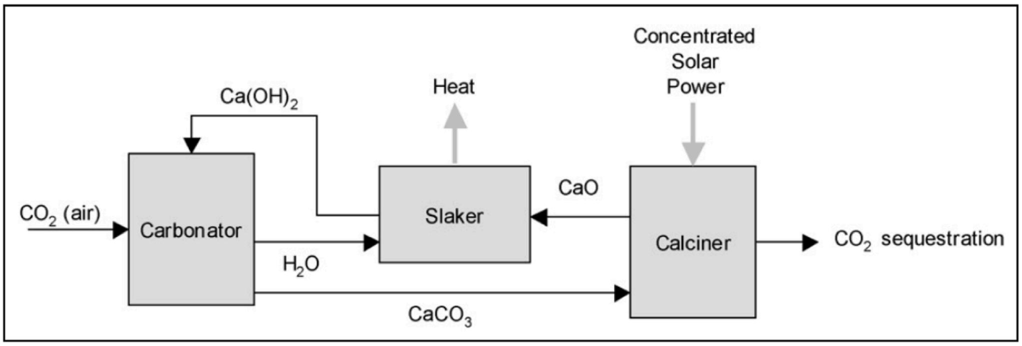


Fig. 16. A scheme of calcium looping process for DAC using concentrated solar power (Nikulshina et al., 2007).

and finally higher cost that makes the technology economically unfeasible (Metz et al., 2005). Hence, it is almost impossible for a single CO_2 capture technology to reach net-zero emission as targeted by UN and IEA (UN, 2015; IEA, 2021). Yet, the case could be different when CO_2 capture technologies integrate renewable energies. In this section, the possibility of reaching net-zero or negative emission levels resulted from renewable energy integration with CO_2 capture process is discussed. For a better comparison, only amine-based CO_2 capture process integrated with renewable energies and applied to capture CO_2 from coal-fired power plants is considered. Furthermore, only cases with the CO_2 capture rate of 90% is taken into account. The LCOE, the cost of CO_2 capture, and CEI are the key performance indicators used for in this evaluation. Data collected from various literature are exhibited in Table 3. As discussed earlier, renewable energy integration is technically feasible, however, it is not always economically advantageous. As summarized in Table 3, renewable energy integrations could generate relatively low cost power and CO_2 capture, nevertheless, not all integration scenarios show an obvious advantage in comparison with the conventional technology that extracts steam from the power plant. The lowest LCOE that can be reached by wind energy integration (64 USD/MWh) is slightly higher than the reference case without renewable integration. Wind energy integration has a lower CO_2 capture cost (30 USD/t_{CO2}) but this is only compatible to the most advanced amine solvent capture technology (29 USD/t_{CO2}) (Metz et al., 2005). The most promising point of the renewable energy integration probably lies on the deeper CO_2 reduction. All integration scenarios generate lower CO_2 emission intensity in comparison with conventional processes, particularly for the combined bioenergy and wind energy integration. Wind energy integration can reduce carbon emission to 67 g/kWh, much lower than the reference case without integration (120 g/kWh), while maintaining a comparable electricity cost. Bioenergy integration is an extraordinary case that is possibly reaching to a negative emission of −95 g/kWh.

The actual CO_2 capture cost and LCOE associated with renewable energy integration may vary a lot with the price of materials and infrastructure such as collectors price for solar energy, drill depth and price for geothermal energy, or biomass price for bioenergy. Even though, the CO_2 capture cost and LCOE are sensitive and variable, it is undeniable that the application of renewable energies is the key to achieve net-zero emission target. The renewable energy integration should be considered with the most advanced CO_2 capture process as in the case of solid adsorbent or advanced solvent-based CO_2 capture technologies. Besides, the integration of renewable energy with an advanced DAC technology could have a greater way to realize net-zero emission initiatives. This strategy is in good agreement with the pathway to net-zero emission recommended by UN and IEA (UN, 2015; IEA, 2021).

Table 3
Variation in the cost of electricity and cost of CO_2 capture with different renewable energies.

No	Integration scenario	Capture Technology/ power plant	CEI (g/ kWh)	LCOE (USD/ MWh)	Cost of CO_2 capture (USD/t_{CO2})	Capture rate (%)	Ref.
1	Reference without integration	MEA solvent/coal fired power plants	120–286	54–126	37–110	90%	(Wang et al., 2016; Wang et al., 2017c; Li et al., 2012; Huang et al., 2017; Cau et al., 2014)
2	Solar thermal energy assisted post combustion capture	MEA solvent/coal fired power plants	94–145	69–145	39–150	90%	(Qadir et al., 2013; Li et al., 2012; Wang et al., 2017c; Wang et al., 2016; Cau et al., 2014; Zhao et al., 2015)
3	Bioenergy (Provide energy for CO2 capture system)	MEA solvent/coal fired power plants (Possible negative emission)	−95–100	76–108	–	90%	(Khorshidi et al., 2014)
4	Wind energy	MEA solvent /coal fired plant	67–261	64–151	30–70	90%	(Bandyopadhyay and Patiño-Echeverri, 2016; Bandyopadhyay and Patiño-Echeverri, 2014)
5	Geothermal energy -assisted post combustion capture (Enhanced geothermal system and Hot sedimentary, thermal load fraction >70%)	MEA solvent/coal fired power plants	107–111	~71–101	–	90%	(Wang et al., 2017a)
6	Geothermal energy -assisted post combustion capture, water dominated reservoir, thermal load fraction >41%	MEA solvent/coal fired power plants	–	~93	~36	90%	(Wang et al., 2017b)
7	Solar thermal energy assisted post combustion capture	Solid adsorbent: Zeolite 13X/coaled fired power plants	92–95	68–75	28–50	90%	(Zhao et al., 2019)

9. Conclusions and outlook

CO_2 concentration in the atmosphere is ever increasing, and CO_2 abatement technologies may offer a platform to deep cut the carbon footprint of the industry, transport, and energy sectors. However, after three decades of research on CCS, this technology is still facing barriers in sustainability, feasibility, and commercial readiness. Renewable energy integration may significantly improve the sustainability and increase the value proposition of various carbon capture options. Each renewable energy source could offer certain advantages to substantially cut carbon footprint, energy penalty, or overall capture cost. This article reviewed key carbon capture technology options and categorized their performance in the integration with each renewable energy route. Among many research inputs, we highlighted the key trends of renewable energy integration and summarized the key findings in the following points:

- Solar energy integration provides a great option to reduce CO_2 emission intensity and the cost of CO_2 capture; however, its performance is still far below the expectation in-line with the current technological development. There would be an opportunity to advance this technology if it is integrated with more advanced solvents, adsorbents, and novel capture processes in addition to the potential of reducing the cost of solar field installation and solar collectors.
- Bioenergy is one of the most promising renewable energy resources that can be integrated with CO_2 capture to realize the negative emission ambitions via BECCS integration. The utilization of bioenergy in CO_2 capture process, however, causes a significant increase in both investment and operation cost. The viability of a bioenergy recourse is mainly based on biomass, which may face supply shortage, price sensitivity, and fierce competition with food industry in terms of land use. Therefore, this technology would require more advanced and flexible designs and diverse biomass resources to cope with the sensitivity of biomass price.
- Wind energy is one of the great candidates for the implementation of net-zero emission after bioenergy. In a flexible design with on/off function to exploit the low-price electricity periods and to mitigate the effect of its intermittence, it could offer an effective way to reduce the cost of the CO_2 capture compared to other alternatives. Wind integration should deserve more attention, particularly, when wind energy is combined with solar or any other renewable option.
- Geothermal energy integrated with aqueous amine-based CO_2 capture technology has been demonstrated as a promising option to reduce the cost of CO_2 capture and to improve the efficiency of thermal power plant via reducing the LCOE and the cost of CO_2 capture. Geothermal energy is a stable and continuous supply heat source; however, its economics is also greatly sensitive to the geographical location and the drilling cost that would probably need more technical improvement.

Most of research outputs so far have focused on contributing to the energy penalty via generating steam or electricity via renewable-assisted options. These integration configurations would normally increase process complexity because of more equipment requirement and energy/exergy degradation via heat conduction through the connecting pipes, heat exchangers, and TES tanks, which results in over-sizing and over-investment of these renewable options. Hence, it is evident that much more process improvement is required to effectively integrate renewable options with the CCS technologies, entailing continued research and development. This goal would require significant advancement in adsorbent and absorbent development, and novel capture processes in combination with flexible designs to compensate the intermittent nature of renewable energy sources and to optimize the low electricity price periods. To this end, the key objective in future research is to achieve:

1. stopping/minimizing steam extraction for CO_2 capture purpose.
2. minimizing the interaction between the power/industrial plant and CO_2 capture plant.
3. lowering the cost for carbon capture at almost zero carbon footprint.

Such ambitions could realize a fully independent carbon capture retrofits that would provide convenience to power/industrial plant operators and/or achieve more independent and scalable DAC systems installed on inexpensive land or in vicinity of the CO_2 storage/utilization sites.

CRediT authorship contribution statement

Dang Viet Quang: Conceptualization, collecting the data, Data analysis, Investigation, Writing- Original draft preparation. **Dia Milani:** Methodology, Data analysis, Validation, Writing the original draft, Editing. **Mohammad Abu Zahra:** Reviewing and Editing, Supervision.

Declaration of Competing Interest

The authors have no affiliation with any organization with a direct or indirect financial interest in the subject matter discussed in the manuscript

Data availability

No data was used for the research described in the article.

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