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REVIEW PAPER

Current status and future scenarios of carbon capture from power plants emission: a review

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Abstract The emission from power plants highly contributes to the increase of CO_2 concentration in the atmosphere. Enhancing the utilization of renewable energy and improving energy efficiency are widely considered to be a key to reduce emissions, however, certain solutions need time to be implemented. Carbon Capture and Storage is considered as a crucial solution for the situation that contributes to reduce the ultimate emission. Most studies have dealt with the current available technologies such as pre-combustion capture, post-combustion capture, and oxyfuel combustion. Several challenges of Carbon Capture technologies are being addressed without being given more attention to the optimum solution. Although post-combustion capture is considered one of the best options to be retrofitted to a power plant, the challenges of the processes and the possible solutions have not been dealt with in depth. This review article investigates the three techniques (pre-combustion, post-combustion, and oxyfuel combustion) to identify the best option to be used for CO_2 capture from the power plant. The gap in the field of decarbonization for researchers and policy makers has been identified and a future roadmap has therefore been proposed. Post-combustion capture is the best option for carbon capture from power plants. Solvent selection, process configuration, and process emissions to environment need to be resolved for better capture results. Three future scenarios are hereby proposed, the recirculation of the clean flue gas, synergistic effect of different solvents or replacement of stripper unit with ultrasound technique.

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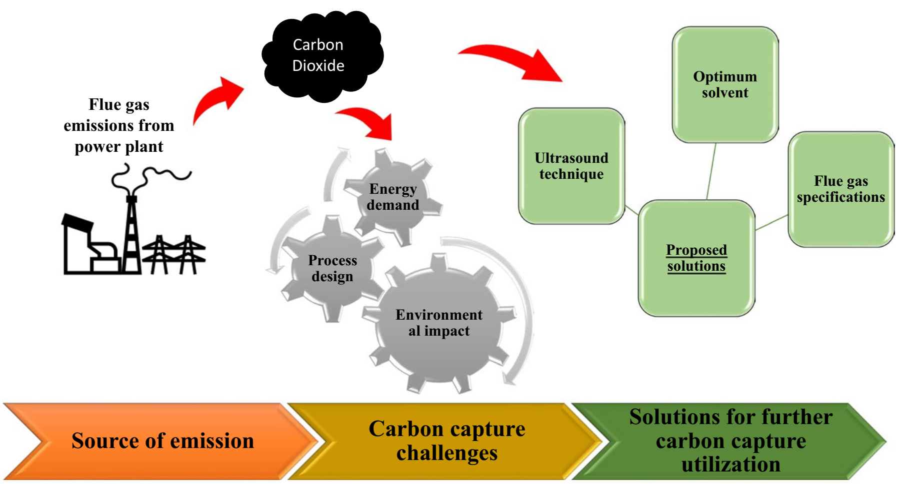
Graphical abstract



Keywords Pre-combustion capture · Post-combustion capture · Oxyfuel-combustion capture · Regeneration energy · Synergistic effect · Ultrasound

1 Introduction

Power plants are the main source of energy that operates mainly using fossil fuels, either coal or natural gas, which are considered to be the largest producer of Greenhouse Gases (GHGs) (Bahman et al. 2022; Xu et al. 2022). The global energy demand is an accelerating trend thereby contributing to increase Carbon Dioxide (CO_2) emission from power plants, although the utilization of renewable energy increases but yet unable to replace power plant processes using fossil fuels or reduce the CO_2 emissions (Sultan et al. 2021). Among the GHGs, CO_2 is the most significant contributor to impact the environment through climate change and global warming. The Intergovernmental Panel on Climate Change (IPCC) issued a special report (SR15), addressing the critical consequences of global warming if it increases by 2 °C compared to the preindustrial level. The IPCC report shows that the risk from precipitation, drought, rise of sea level and damage to many ecosystems will be higher at 2 °C compared to 1.5 °C. Therefore, IPCC recommended solutions to reduce CO_2 emissions by improving electrification, increasing the contribution of alternative energy sources such as hydrogen and bio-fuels and investing more in Carbon Capture Utilization and Storage (CCUS) (IPCC 2018). According to the International Energy Agency (IEA) report, 1 Gt_{CO2} per year must be captured from power plants, iron, cement, and chemical industries by 2030 to achieve the target of net zero emission (IEA 2020). Research and development related to CCS technology and CCUS have increased over the past decade as one of the promising methods to reduce CO_2 emissions, specifically from power plants (Oh et al. 2018; Tiwari et al. 2023). Although CCS is not cost-effective if compared with renewable energy, the carbon tax and incentive policy for CCS encourages further implementation to provide the required support to the renewable energy to achieve net zero emissions (Arnette 2017; Ma et al. 2023). According to Osman et al. (Osman et al. 2021) there are ~22 demo projects globally for CCS in power plants. Power plants generating electricity using natural gas are divided into two types: “Open Cycle Gas turbine” (OCGT) and “Combined Cycle Gas Turbine” (CCGT). The working principles of OCGT are based on Brayton cycle whereas the power is generated using gas turbine through a shaft, the efficiency of the power production is within 35–42%. The CCGT produces extra power using a heat recovery steam generator to recover heat from exhaust gases thereby improving thermal efficiency by up to 60%. Over the last few decades, the CCGT technology is utilized more compared with OCGT due to higher power production and better efficiency (Rao and Francuz 2013). The power plant generating electricity using coal is the coal-fired power plant also use turbine (Romero-García et al. 2022). However, the CO_2 emission from other sources such as iron, steel, cement, refineries etc. have been investigated to find the possibility of integrating CCS as part of the solutions to reduce the emission (Leeson et al. 2017).

Around 77% of the GHGs is CO_2 (Deiana et al. 2017), wherein 40% of the total CO_2 emission comes from power plants using fossil fuels that needs more investment to reduce the emission (IEA 2018). The CCS is considered the most efficient method for reducing CO_2 emissions in power plants. The CCS process starts with capturing CO_2 and prevent it from being released into the atmosphere, followed by transportation of the captured CO_2 gas that ends with either utilization or storage (IPCC 2005). The CO_2 can be captured using one of the three techniques namely, pre-combustion (Liu et al. 2020), post-combustion (Wang et al. 2011) and oxy-fuel combustion (Toftegaard et al. 2010). Indeed, various researchers have studied the three CO_2 capture approaches and are attempted to conclude the best option among the three (Goto et al. 2013; Kunze & Spliethoff 2012).

This paper presents a recent review of the practices related to CO_2 capture using three techniques (pre-combustion, post-combustion, and oxy-combustion) by following bibliometric analysis. The review assesses the most applicable option for CC among the three techniques. The paper also aims to propose guidelines for the best option to enhance the utilization of CC processes specifically in power plants. Moreover, the gap for future investigation in the decarbonization field for researchers and policy makers has also been identified.

2 Pathway of CC technologies

Primarily, CC stage is the most expensive stage of CCS process, 50–90% of the overall cost of the process is taken by captured stage (Pera-Titus 2014). There are various variables need to be considered prior to building a CC system for instance, the amount and type of solvent or sorbent utilized, the pre-treatment requirements of impurities, environmental impact of the chemicals, the concentration

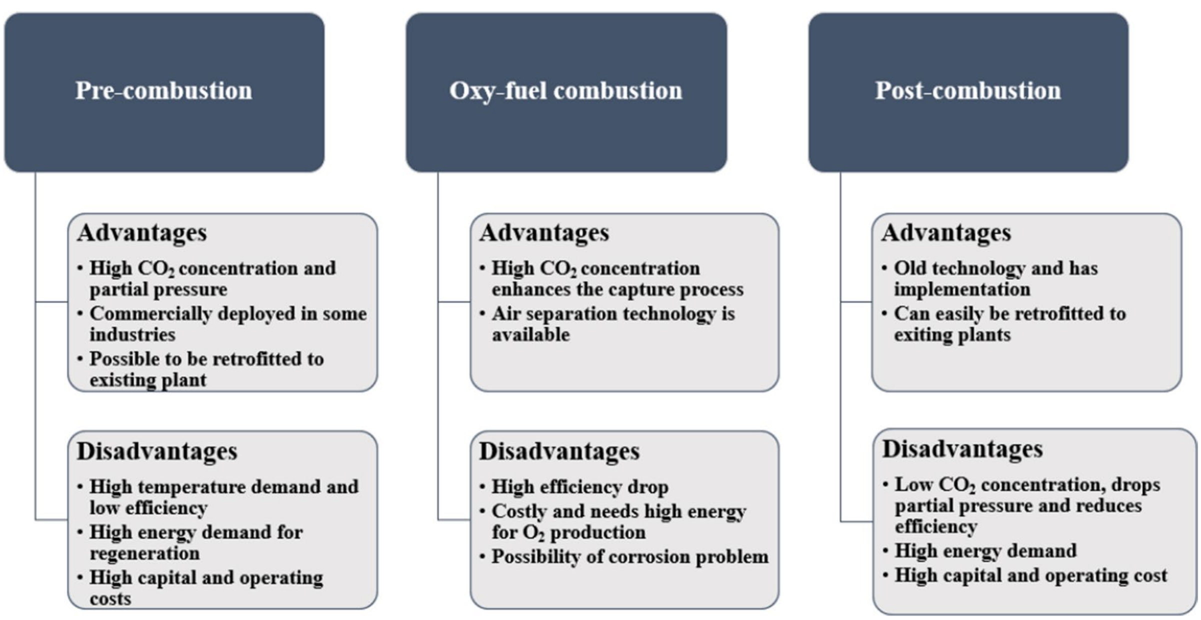


Fig. 1 Advantages and disadvantages of the carbon capture technologies including (1) Pre-combustion capture, CO_2 is captured from fuel before burning using air, (2) Oxy-fuel combustion capture, CO_2 is captured from flue gases after burning fossil fuel using pure oxygen, and (3) Post-combustion capture, CO_2 is captured from flue gases after burning with air

of CO_2 in the flue gas, and the selected carbon capture techniques (Gür, 2022). Three techniques are currently available for carbon capture from stationary system and to be reviewed in this section, the pre-combustion carbon capture, oxy-combustion capture, and post-combustion capture to identify the best option for CC from power plant. The advantages and disadvantages of the three technologies are summarized in Fig. 1, among these the post-combustion capture is extensively used and attracted the researchers attention (Bui et al. 2018; Kearns et al. 2021; Pan et al. 2016).

2.1 Pre-combustion carbon capture

In this method, the CO_2 is captured before burning the fuel in the combustion chamber (Eide & Bailey 2005). The fossil fuel such as coal is reacted with steam and oxygen at elevated temperature and pressure that results in synthesis gas, contains Carbon Monoxide (CO) and hydrogen (Cormos 2012; Jansen et al. 2015). After that, the CO is converted to CO_2 using steam therefrom CO_2 is captured outside the stream using solvent such as Selexol, the pure hydrogen gas is burned to generate electricity (Rubin et al. 2012) as shown in Fig. 2. CO_2 can be captured from natural gas by a reforming process which is similar to the Pre-Combustion (PC) using coal that is used for hydrogen production (Rubin et al. 2012). Although the PC process can be operated in power plant for generating electricity using natural gas at low energy than post-combustion capture, but the process is commercially less viable than post-combustion capture (Rubin et al. 2015). However, research in PC technique is focused on cost reduction, for example integration of renewable energy as a source of energy for CC or using alternative fuel such as biomass or solid waste for coal gasification (Cormos et al. 2015). The pre-combustion CC is also used for hydrogen production including CO_2 capture unit known as blue hydrogen production (Rubin et al. 2012). The technique has gained more attraction in research and development, owing to the reason that it works toward climate change mitigation. The process could use coal or natural gas as a source of fuel where gasifier is used for burning the fossil fuel, followed by sending the burning products for a shift reactor to ensure burning and formation of hydrogen (Rubin et al. 2012).

The driving force for the PC process is the solubility of CO_2 in the solvent used that is increased

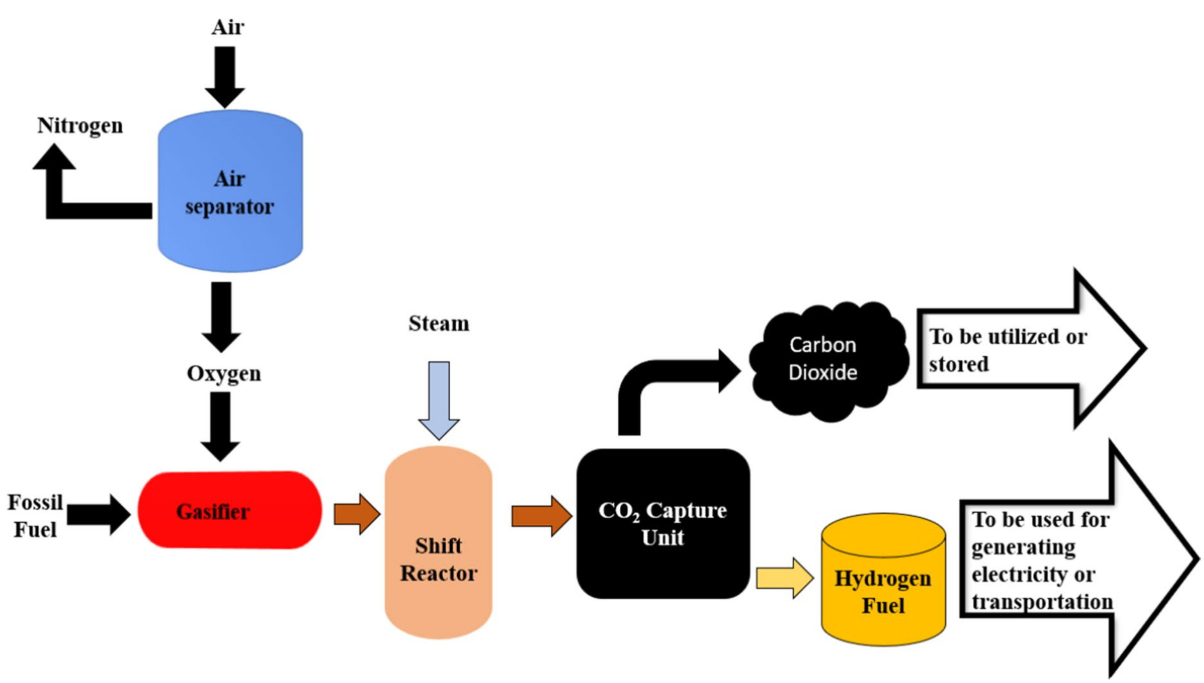


Fig. 2 Pre-combustion carbon capture process using coal as a sources of fuel

at high pressure and low temperature according to Henry's law (Smith et al. 2022). The CC using PC process by solvent absorption techniques does not require chemical reaction due to the high CO_2 partial pressure. The studied solvents for this application are amines, amino acid salts, carbonate compounds, aqueous ammonia, immiscible liquids, ionic liquids, hydrophobic polymers and some other solvents that are able to reduce overall cost of the capture process, improve the absorption rate, reduce the solvent degradation, minimize the equipment size, and reduce the solvent regeneration energy (Mumford et al. 2015). The selected solvent has a high potential on the cost of the CCS process where the solvent properties have a direct effect on the economic cost of the process (Siefert et al. 2016). According to Li et al. and Miller et al. (Li et al. 2020; Miller et al. 2011) the features of the hydrophobic solvents that increases the CO_2 solubility and have low evaporation rate are promising to be used for PC carbon capture process.

2.2 Oxy-fuel combustion carbon capture

Oxy combustion is an alternative proposed technique against the post-combustion capture process. The process is specifically used for coal-fired power plants where pure oxygen (95–99%) is used for burning coal instead of air at high temperature in the combustion chamber (Metz et al. 2005). The burning processes produce CO_2 that is separated without further processing due to the high CO_2 concentration being formed (Tan et al. 2006). The CO_2 from the oxy-fuel combustion has 90% purity, is passed to be compressed and stored (Shaw and Mukherjee 2022). The description of the oxy-fuel combustion carbon capture is shown in Fig. 3. It includes three stages, O_2 is separated from air using air separation unit, pure O_2 is used to burn the fossil fuel and energy is generated, and finally the CO_2 formed during the burning processes is compressed and transported for storage.

The air separator unit is required for separating oxygen from air to be used for burning, is considered to be expensive (Rubin et al. 2012; Wu et al. 2018). According to Fu and Gunderson (Fu & Gundersen 2012) the minimum energy required to separate oxygen from air is 176 MJ/t_{O_2} using air separation unit that is considered the main process challenge. However, a new technique for separating O_2 is introduced using membrane or oxygen capturing solids, that targets the reduction of energy demand (Zhang 2015). Challenges such as high temperature and the risk of air leaks into the system (Yadav and Mondal 2022) need further study, hence, oxy-fuel process is not expected to be of economic attraction unless more legislation for carbon price is issued (Wall et al. 2011).

2.3 Post-combustion carbon capture

Post-Combustion Capture (PCC) has gained most of the attention and has been demonstrated in industries at different level, for example, TMC Mongstad in Norway that captures 300,000 tones/year CO_2 and BD3 SaskPower in Canada captures 1 million tones/year, are the biggest PCC projects (Liang et al. 2015). In PCC process, the CO_2 is removed from the flue gas once fossil fuel is burnt (Hong 2022) followed by storage of the captured CO_2, Fig. 4. Most of the power plants produce electricity using fossil fuels such as coal or natural gas, PCC is applicable to capture CO_2 from this sector to support the achievement of net zero emission (Gür 2022). Once the flue gas is burnt to release energy in the form of heat, byproducts such as CO_2, water vapor, Sulfur Dioxide (SO_2) and Nitrogen Oxides (NO_x) are formed which

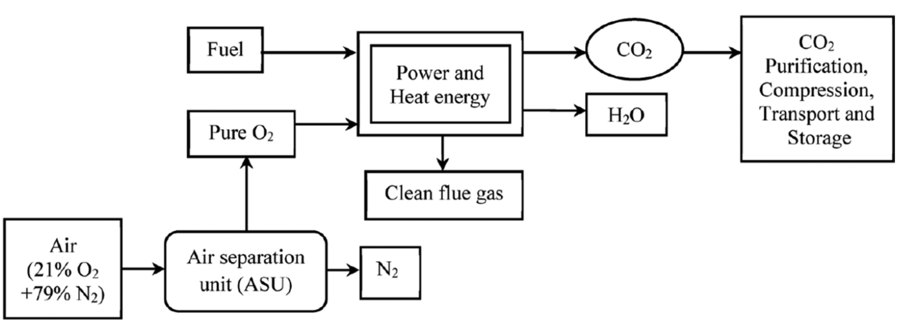


Fig. 3 Description of oxy-fuel combustion carbon capture process, adopted with permission (Maniarasu et al. 2021)

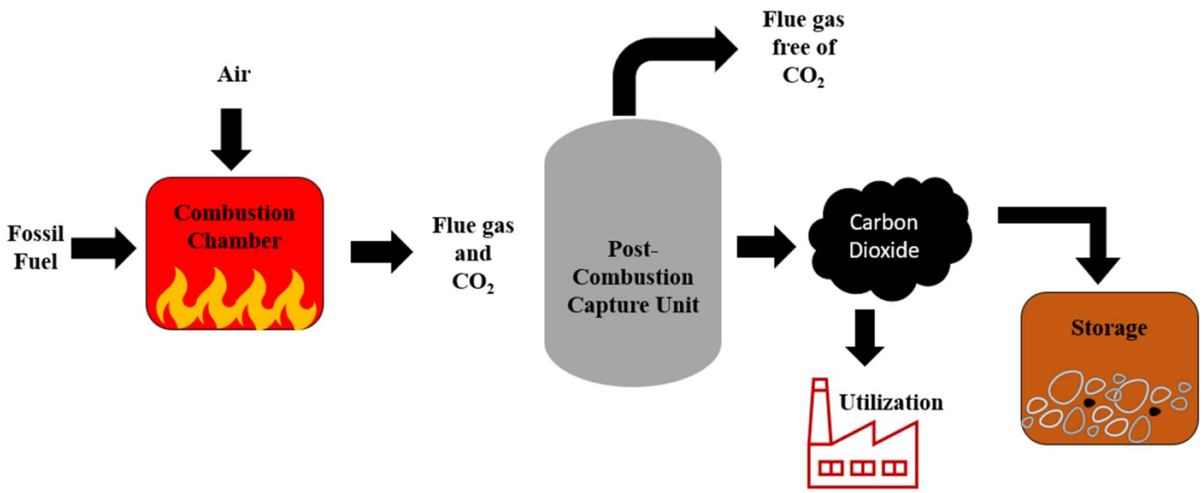


Fig. 4 Process block diagram of PCC. The flue gas contains CO_2 leave the combustion chamber passed through the capture system. The clean flue gases and CO_2 are separated. The pure CO_2 is either stored in the reservoir or sent to specific industries for utilization

required to be removed prior to CO_2 capture (Merkel et al. 2010).

Currently, the PCC is grouped in to three categories; biological, physical and chemical methods (Maniarasu et al. 2021).

The absorption column in the PCC process captured CO_2 from flue gas using solvent such as Monoethanolamine (MEA), then the gas/solvent mixture (MEA + captured CO_2) is sent to the stripper for solvent regeneration. Thus, solvent regeneration requires energy that is provided by the steam resulted for electricity generation (Rubin et al. 2012; Wang et al. 2011). The energy demand for solvent regeneration is the process constrain, according to a report, the minimum energy demand for carbon capture using PCC is 2.4 MJ/KgCO$_2$ (House et al. 2009). However, if the heat of the flue gases from combustion chamber is recovered to be used in the stripper section, it will save the power plant efficiency (Hanak et al. 2014).

The PCC process challenges are, the low CO_2 concentration in the flue gas, the low CO_2 partial pressure that reduces the capture efficiency and increases the energy demand (Wang and Song 2020; Younas et al. 2016). Furthermore, the removal of the flue gas

Table 1 Cost estimated for the carbon capture technologies and viability to be retrofitted to a power plant

Carbon capture technology	CO_2 Capture efficiency (%)	CO_2 capture Cost (USD/t CO_2)	Visibility to be retrofitted into power plant	Reference
Pre-combustion carbon capture	90	34 – 63	Difficult fitting without process modification if the power plant is working Visible only for new power plant	Kheirinik et al. (2021), Rubin et al. (2015)
Oxy-fuel combustion carbon capture	90	52–257	More studies to find the possibility of retrofitting	Dinca et al. (2018), Kheirinik et al. (2021), Rubin et al. (2015)
Post-combustion carbon capture	90	46 – 74	It can be easily fitted into power plant if the required place is available Visible for both new and working/old power plant	Jiang et al. (2021), Kheirinik et al. (2021), Vega et al. (2019)

pollutants such as SO_2 and NO_x increases the energy demand and reduces the power plant efficiency (De Visser et al. 2008).

The estimated cost of carbon capture by the three technologies is shown in Table 1, carbon capture by oxy-fuel combustion technique has the highest operating cost due to the high purity of oxygen needed for the process and others process specifications. Although the pre-combustion requires the lowest cost to capture carbon, the invisibility of pre-combustion to retrofit into an existing power plant increases the potential of post-combustion capture to be the optimum technique for carbon capture from power plant.

3 Post-combustion carbon capture process

Such a capture of CO_2 is the most effective method for reducing CO_2 emission from power plants using fossil fuels (Sun et al. 2020). The PCC process captures CO_2 emitted as a result of burning of fossil fuel and it considers as the best option to be retrofitted to the existing power plants (Paraschiv & Paraschiv 2020). The flue gas leaves the stuck near the atmospheric pressure and at temperature range between 50 and 150 °C, while the CO_2 concentration in the flue gas is in the range 10–15% by volume (Chen et al. 2013). In addition, research is in progress to resolve PCC challenges and to ensure the PCC process is the best option among the other CCS techniques. The three most efficient PCC techniques for separating CO_2 from the flue gas are using adsorption, chemical absorption, and membrane techniques (Zhang et al. 2018) as shown in Fig. 5. The PCC options are reviewed in this section to screen the process challenges and the obstacles against the process implementation, and to investigate the process best options.

3.1 Adsorption as a separation technique

The adsorption method is used to separate CO_2 molecules from flue gas by passing it through a solid surface in a packed column filled with solid at moderate temperature in the range of 26–65 °C (Leung et al. 2014; Mukherjee et al. 2019). According to the adsorbent regeneration technique, the adsorption method is classified either as temperature swing, pressure swing, or vacuum swing adsorption that separate CO_2 from flue gas using solid/sorbent located inside a vessel either as fixed bed or fluidized bed (Chao et al. 2021). Comparison between the three techniques according to their ability to deal with the impurities in the flue gas, the required energy demand, and other conditions to improve the process technical and economic challenges are described in Table 2.

The adsorption by temperature swing method works at low temperature following van der Waals

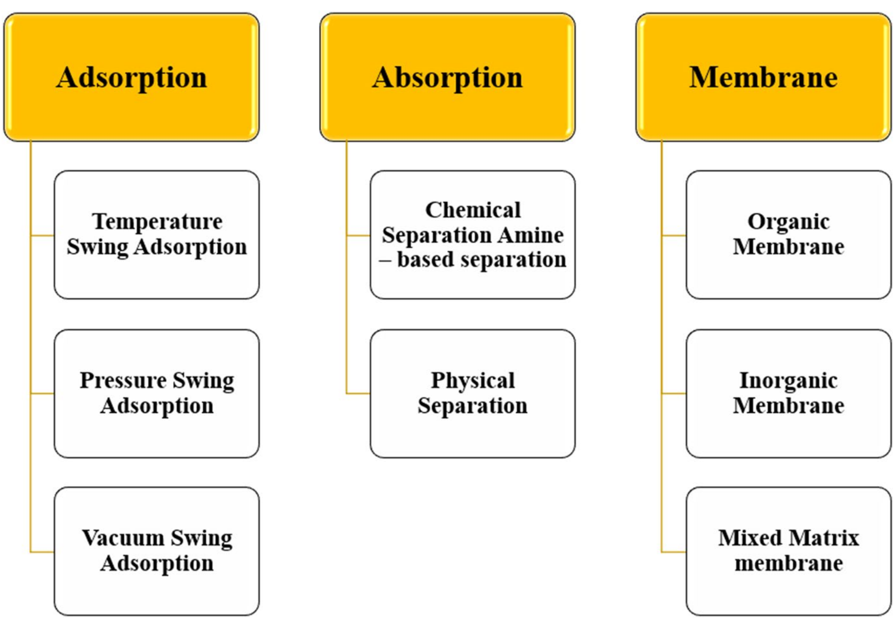


Fig. 5 Various options of PCC processes

Table 2 Description of the classification of adsorption separation techniques

No	Adsorption separation technique	Impurities in flue gas	Energy demand	Requirement
1	Temperature Swing Adsorption (TSA)	Removal of impurities from flue gas is not strict Impurities could be removed by the adsorbent and later separated from adsorbent at higher temperature	High energy demand around 140 °C is the regeneration temperature	Development of sorbent that has low regeneration temperature and high capacity for CO_2 capture
2	Pressure Swing Adsorption (PSA)	Impurities must be removed from flue gas before adsorption	Low temperature for adsorption step High energy demand for pressurization	Hot flue gas is required to reduce the process energy demand
3	Vacuum Swing Adsorption (VSA)	Impurities must be removed from flue gas before adsorption	Low temperature for adsorption step High energy demand to achieve vacuum stage	–

Data summarized from literature reports (Jiang et al. 2020; Su & Lu 2012; Wang et al. 2013)

force principle, once the sorbent reaches the saturation condition, regeneration of the sorbent is required at high temperature to enable CO_2 separation from the sorbent, followed by resending the generated sorbent for further CO_2 capture. The advantages of the adsorption process is the low process temperature, low operating cost, and easily integrated to existing power plants (Kuramochi et al. 2012). On the other hand, the adsorption by pressure swing method works by adsorbing CO_2 at high pressure and releasing it at low pressure during the regeneration stage (Ishibashi et al. 1996). The vacuum swing adsorption is the most applicable option at industries, the adsorption is carried out under atmospheric pressure and the regeneration is carried at vacuum where one column is used for adsorption and desorption (Kikkinides et al. 1993). To achieve the capture efficiency, dried and treated flue gas should be maintained for both pressure swing adsorption and vacuum swing adsorption that increases the cost of capture process (Zhang et al. 2008).

According to Tlili et al. (Tlili et al. 2009) the PCC by temperature swing adsorption is taken place between 40 and 60 °C while the regeneration of the sorbent is taken place at two temperature, 120 °C for separating CO_2 from sorbent and 160 °C for removing any other impurities. Furthermore, the process constraints are, the large amount of air is needed for heating the sorbent for regeneration stage, the low heat capacity of air, and the high amount of electricity required if the bed is heated electrically. The operating temperature, the energy consumption, and the amount of CO_2 captured, are important parameters to be considered during the design of adsorption process (Chao et al. 2021). For example, the higher the amount of CO_2 to be captured, the higher energy for regeneration is required (Clausse et al. 2011).

3.2 Absorption separation technique

Absorption separation involves physical and chemical techniques, however, the PCC process using chemical absorption considers the most feasible and easily installed to power plant (Feron 2010; Ferrara et al. 2017; Figueroa et al. 2008). Although, the technique of chemical absorption is similar to the adsorption separation, the principles are different where liquid is used as a separation media for chemical absorption compared to solid is used for adsorption separation (Spigarelli and Kawatra 2013). Furthermore, the solubility of the CO_2 in the solvent follows Henry's law that states "*the solubility of the gas is directly proportional to the partial pressure of the gas*" (Maniarasu et al. 2021).

The chemical absorption involves a counter current flow of the flue gas containing CO_2 and the lean solvent in the absorber column at a temperature range of 40 – 60 °C while the regeneration of the rich solvent that lift the absorber column carried the captured CO_2 takes place at range of 120–160 °C within the stripper column (IPCC 2005; Olajire 2010; Pires et al. 2011),

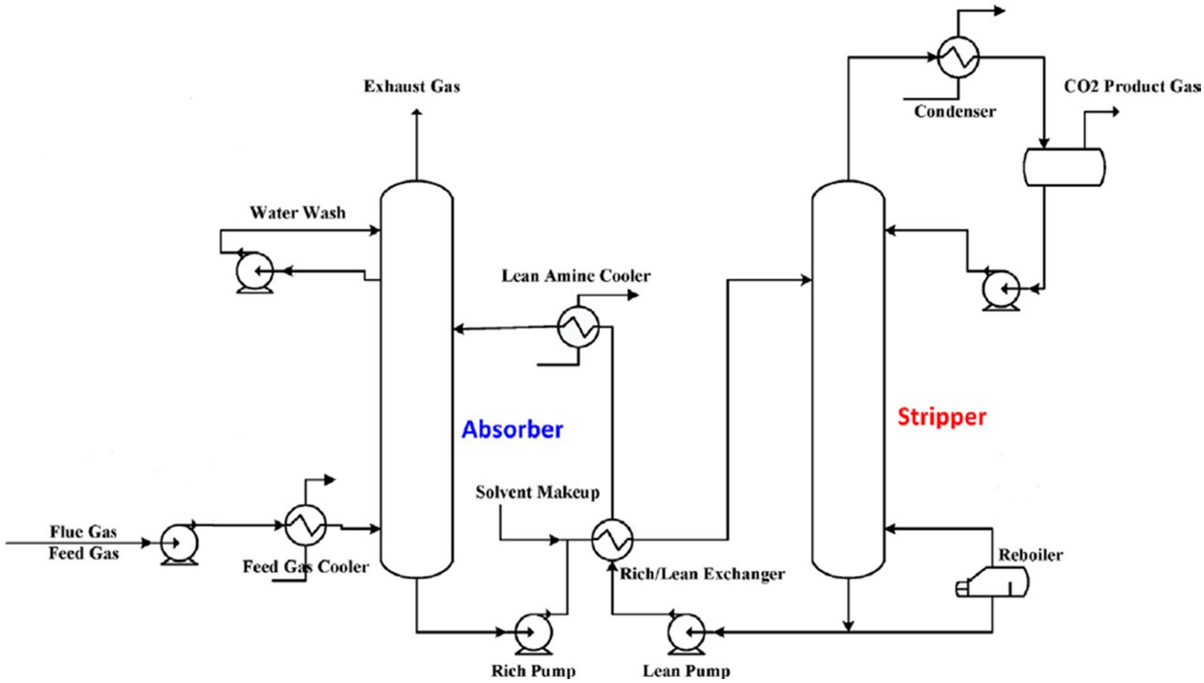


Fig. 6 Post-combustion CC diagram using chemical absorption, adopted with permission (Liang et al. 2015)**.** Includes two columns, the first column is the absorber that is used to capture the CO_2 from flue gas, the second column is the stripper that is used to regenerate the selected solvent used for further CO_2 capture. The reboiler is used to provide the required heat for separating CO_2 from the solvent, while rich/lean exchanger is used to adjust the temperature of the lean solvent before entering the absorber column to enhance the capture efficiency

Fig. 6 shows the process description of the PCC using chemical absorption.

The amine-based solvent used for absorption processes is widely used due to the low capital cost and high CC efficiency (Yang et al. 2008). Although the solvent regeneration energy, solvent loss and degradation are hurdles and challenge the process implementation highly, hence, research and development are in a continuous progress to resolve these challenges (Balraj et al. 2022). Several absorption techniques are commercially introduced (Kishimoto et al. 2009; Stéphenne 2014) aiming to reduce the energy demand and enhance the loading capacity using optimization technology. The advantages and disadvantages of PCC commercial absorption capture techniques are tabulated in Table 3. Thus, Process Intensification (PI) approach is implemented in the PCC absorption option, the approach directs to make the process more efficient, reduce the energy consumption, reduce the cost, improve safety and environmental performance (Haase et al. 2022). Accordingly, several developments and improvements are introduced to improve PCC absorption process that is reviewed in Sect. 4.

3.3 Membrane separation technique

Membrane separation of CO_2 captures is relatively new technology using semi-permeable membrane to separate two phases, based on the effect of diffusion, adsorption, molecular sieve action, or ionic transport (Mondal et al. 2012; Yuan et al. 2016), the process description of the membrane separation process is shown in Fig. 7. In fact, the selection of membrane is an important step to maintain the required capture efficiency, hence, the life-time, operational and material cost, CO_2 capture performance are important factors of membrane specification that needs to be studied before final selection of the membrane (Spigarelli and Kawatra 2013). The specifications of the most applicable membrane for carbon captured are listed in Table 4. The driving force for membrane separation

Table 3 Advantages and disadvantages of the highly commercial chemical absorption techniques

No	Chemical absorption technique[a]	Advantages	Disadvantages
1	The KMALC process[b]	Use low amount of MEA 15–20% Low regeneration energy	Use two absorption columns in parallel, high cost
2	The fluor EFG + process[c]	Designed to reduce the regeneration energy and capital cost Can be used under low pressure	High concentration of MEA is required Required of adding inhibitor to reduce MEA corrosive nature
3	KM-CDR technology[d]	Low CO_2 capture costs for oil industries Energy efficiency is improved	The utilized solvent is corrosive Low CO_2 loading capacity
4	Aqueous ammonia (NH_3) process	NH_3 is solvent that is cheap and has high CO_2 absorption capacity Less corrosive and low possibility to degradation	Possibility of formation the hazardous carbamate High NH_3 volatility Low operating temperature that affects CO_2 capture efficiency
5	Chilled ammonia process	Absorb CO_2 at low temperature that helps to reduce the losses of NH_3 Low energy for solvent regeneration	Needs multiple absorber vessels Low absorption rate
6	Dual alkali absorption	Sodium Chloride (NaCl) is added to enhance capture efficiency	Pre-treatment of the flue gas is required to remove impurities
7	Strong alkali absorption	Alkali metal-based oxides are used as solvent High regeneration temperature that reduces the possibility for solvent degradation	Low absorption rate of CO_2 Extensive equipment size is required

Data summarized from literature reports (Barchas and Davis 1992; Chao et al. 2021; Scherffius et al. 2013)

[a]The commercial absorption separation techniques, designed to capture CO_2 from flue gas either to be stored or to be utilized

[b]Technology developed by Kerr-McGee Chemical Corporation, CO_2 recover technology to be used for food production

[c]The PCC designed by Fluor using the Econamine FG Plus technology to capture 90% of CO_2 from power plant

[d]The technology developed by collaboration between Mitsubishi Heavy Industries and Kansai Electric Power to capture CO_2 in oil industries

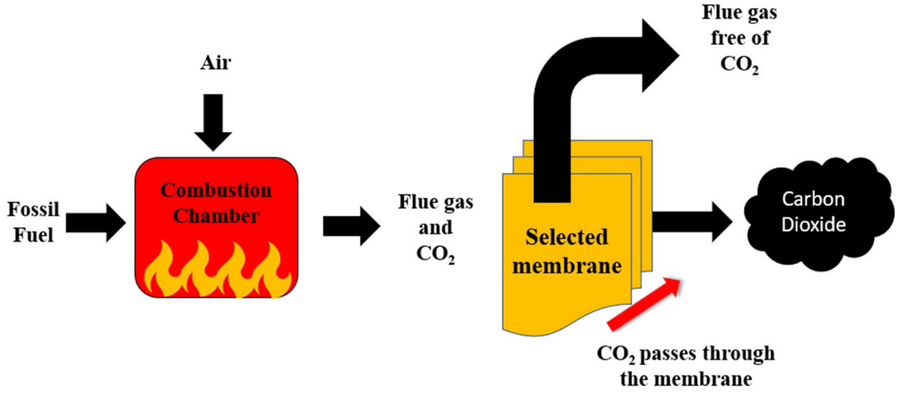


Fig. 7 Carbon capture processes using membrane separation technique

is the pressure and the concentration of CO_2, thus the membrane separation is preferable to be used for pre-combustion process, due to the high concentration and high partial pressure of CO_2, rather than PCC being operative at low concentration and low partial pressure of CO_2 (Wang and Song 2020; Zhao et al. 2010).

The study carried by Falk-Pedersen et al. (2005) shows that membrane capture efficiency reaches 85% for 2610 kg/h flue gas that is considered the best alternative to the chemical absorption technique with

Table 4 Challenges to the most applicable membrane for CO_2 capture

No	Type of membrane	Materials utilized	Challenges of membrane
1	Polymer membranes	Cellulose acetate Polysulfone Polyethersulfone Polyimide	Low solubility of CO_2 in the membrane material Needs modification of the membrane packing structure
2	Inorganic membranes	Porous inorganic Non-porous inorganic	Low CO_2 permeability Expensive
3	Mixed matrix membrane	Composite structure of polymers and inorganic fillers	Needs to ensure a good adhesion between the membrane layers Expensive

Data summarized from literature reports (Al-Mamoori et al. 2017; Chen et al. 2020; Norahim et al. 2018; Olajire 2010; Yuan et al. 2016)

Table 5 Cost estimated for the PCC technologies and the potential for cost reduction

Post-combustion carbon capture technology	CO_2 capture efficiency (%)	CO_2 capture cost (USD/t CO_2)	Potential to reduce the cost	References
Adsorption separation technique	88–95	89.66	Needs to Select a source of electricity with low cost	Cheng et al. (2021)
Absorption separation technique	85–90	44–64	Needs to reduce the sizes of absorber and stripper Needs to select solvent has low cost and high efficiency	Amrollahi et al. (2011), Li et al. (2016), Yun et al. (2020)
Membrane separation technique	70–90	80.46	Needs to enhance the research and development of the technology to be visible for application to power plant	Zanco et al. 2021)

a significant reduction to the size of equipment, and the cost of operation and capital. The Fig. 7 given below, includes a selected membrane that separates CO_2 from flue gases, the membrane is either porous or semi-porous that allows CO_2 to be separated from flue gases under high pressure and a specific CO_2 concentration in the mixture.

Although CO_2 capture by membrane is simple with no involvement of chemical or regeneration step, the technology is still under development due to certain challenges such as, the high initial pressure, increase mass transfer resistance once membrane is wet, and the high requirement of CO_2 concentration in the flue gas (Wang et al. 2017; Zhao et al. 2016). In addition, a multi-stage of membrane is required to achieve high separation of CO_2 that is attributed to the low practical transmembrane pressure ratio and membrane selectivity (Zhao et al. 2010).

The estimated operating costs for carbon capture using the three post-combustion capture technologies are shown in Table 5. Among the three, absorption separation technique has the lowest operating cost with acceptable efficiency and has the potential to be the ideal option compared to the others. In addition, the research and development taken place on the absorption technique is expected to enhance the utilization of this technology once the process drawback is solved.

4 Challenges to PCC by chemical absorption process

Although PCC by chemical absorption is the best option among the other separation techniques due to its ability to be integrated to the existing power plant easily (Ferrara et al. 2017), the process struggles with hurdles related to energy demand and solvent stability (Zhuang et al. 2017). Hence, process intensification was introduced to sort out the challenges of PCC through studies. Further, the physical and chemical properties of the selected solvent or proposed an alternative, development of more efficient process, to improve process quality, with no environmental impact (Haase et al. 2022).

4.1 Efficient solvent

The selection of optimum solvent could be one of the possible drivers to reduce the regeneration energy demand and cost of the process (Hong 2022; Ochedi et al. 2021). According to Liang et al. (Liang et al. 2015) selection of the optimum solvent considers three aspects namely, CO_2 solubility in the solvent, the reaction kinetics of the solvent with CO_2, and the physical and chemical properties of the selected solvent. Alkanolamine compounds are a highly preferable option, that is derived from NH_3 by replacing one or more of its hydrogen atoms during reaction with ethanol. Hence, alkanolamines are classified as primary, secondary, or tertiary amines according to the number of substituents (Chao et al. 2021). Monoethanolamine is one of the most utilized solvent among the other options, Reaction 1 shows the chemical reaction that takes place where the high temperature drives the reaction to absorb CO_2 by MEA and forms MEA carbamic acid and the low temperature drives the reaction to separate CO_2 from MEA (Herzog & Golomb 2004).

$$C_2H_4O\text{-}NH_2 + H_2O + CO_2 \rightleftarrows C_2H_4O\text{-}NH_3^+ + HCO_3^- \quad (1)$$

Indeed, MEA requires high capital cost, degrades at high temperature, and the possibility to have an environmental issues in the presence of some gases such as O_2 and SO_2, all of these challenges open the investigation room for an alternative solvent (Davison 2007), some of the drawbacks and thermal degradation of the utilized highly solvent are shown in Table 6. Therefore, the search for an alternative and efficient solvent rather than MEA that requires high temperature for the regeneration stage was one of the possible options (Wang et al. 2011). The ultimate solvent should have properties like high reactivity with CO_2, high capacity to capture CO_2, needs low energy for regeneration, low degradation's rate, stable at high temperature, low impact on the environment, and low cost (Yu et al. 2012). Hence, solvents either amine-based or alternatives are investigated to find the possibility to replace MEA for PCC process.

The Methyldiethanolamine (MDEA) is considered another alternative solvent to MEA because of the low energy consumption in PCC (Ma et al. 2021). However, MDEA shows poor ability to capture CO_2 due to the slow kinetic reaction, in which it required to be promoted by other compounds such as PZ (Bishnoi and Rochelle 2000). The optimum amount of PZ to promote MDEA to maintain high efficiency and lower energy demand is investigated to find the ideal composition of the two compounds (Hosseini-Ardali et al. 2020; Mostafavi et al. 2021; Zhao et al. 2017). Piperazine is a secondary amine, has high ability to absorb CO_2, has high stability, and needs lower energy in the stripping column compared with MEA. Hence, PZ appears to be another alternative for MEA and consequently gained high attention in scientific community (Freeman et al. 2010; Rochelle et al. 2011). The ability of aqueous PZ to capture CO_2 without being promoted with appropriate compound was tested by several researchers (Otitoju et al. 2021; Pérez-Calvo and Mazzotti 2022; Rabensteiner et al. 2015), PZ was selected as an alternative solvent that needs less energy for the regenerating stage in the stripper compared to MEA. Rabensteiner and coworkers (Rabensteiner et al. 2015) found that 37.6 wt% PZ reduced the regenerating energy by 14% with reference to 30 wt% MEA once the optimum liquid/gas ratio and optimum absorber height is achieved. The optimum amount of PZ (30–40 wt%) is more

Table 6 The drawbacks and the degradation temperature of MEA, MDEA, and PZ

No	Solvent	Degradation Temperature (°C)	Drawbacks	Reference
1	MEA	100–120 °C	Consume high energy Corrosive Degradation	Stöver et al. (2011) Davis and Rochelle (2009)
2	MDEA	110–130 °C	Corrosive Degradation	Davoudi et al. (2014) Pal et al. (2014)
3	PZ	150–160 °C	Corrosive Degradation	Zheng et al. (2014) Rochelle (2012)

Table 7 The regeneration energy for different solvents using PCC chemical absorption

No	Solvent	Regeneration Energy (MJ/ Kg_{CO2})	References
1	EEMPA[a]	2.3	Jiang et al. (2021)
2	K_2Sol[b]	2.8	Hwang et al. (2019)
3	MEA	4.3	Hwang et al. (2019)
4	PZ/K_2CO_3[c]	3.3	Oexmann and Kather (2009)
5	MDEA/PZ[d]	2.74	Zhao et al. (2017)
6	MDEA/PZ	2.76	Hosseini-Ardali et al. (2020)
7	MEA	3.57	Hosseini-Ardali et al. (2020)
8	PZ	2.80	Otitoju et al. (2021)
9	MEA	5.34	Otitoju et al. (2021)

[a]2-Ethoxyethyl-3-morpholinopropan-1-amaine, a water-lean solvent

[b]Aqueous alkanolamine, one of water-lean solvent

[c]The solvent system contains potassium carbonate that is used to promote PZ to enhance the capture efficiency

[d]The solvent system is methyldiethanolamine, promoted by PZ to enhance the capture efficiency

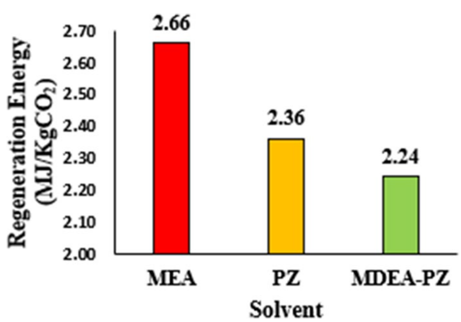


Fig. 8 Regeneration Energy for the three Selected Solvents

economically viable option to capture CO_2 compared to 30 wt% MEA being explored by Otitoju et al. (2021). The regeneration of energy for the highly efficient solvents are listed in Table 7.

The literature reports reveal that solvents have a significant effect on process efficiency and energy demand. The most applicable solvents are MEA, MDEA, and PZ owing to the fact they have the ability to maintain the required capture efficiency, Fig. 8 shows the minimum energy demand found in the literature for the three selected solvents. The MDEA/PZ requires the minimum amount of energy, while MEA demands the highest energy for regeneration.

4.2 Optimum process configuration

Primarily, MEA was considered the best option to capture CO_2 from flue gases due to its low cost and high capacity to capture low concentration of CO_2, but high energy demand for solvent regeneration is considered one of the serious limitations (Luis 2016). A comprehensive review has been conducted to improve PCC technology to reduce efficiency penalty, energy demand and total cost (Luis 2016). The term “Efficiency Penalty” is defined as the losses in the power generating due to installing the CCS system in a power plant that is estimated from subtracting the thermodynamic performance of a plant before and after installing CCS (Goto et al. 2013). A different process modification was introduced to enhance capturing efficiency and results in reducing the energy demand for regeneration stage (Sachde and Rochelle 2014), the most effective process configurations are listed in Table 8.

The integration of renewable energy sources such as solar energy and wind energy as part of a PCC process or power plant system received attention from several researchers (Mofidipour and Babaelahi 2020). The developed solar system is investigated to find out the optimal condition to achieve the maximum energy efficiency in the power plant includes PCC. The study found that the dimensions of the solar collector affect the power output. Hence, integration of solar energy as part of the power plant or PCC processes may possibly increase the utilization of PCC to capture CO_2 from power plants.

The effect of process modifications to reduce energy demand is represented in Fig. 9 that showing examples from the literature about the effect of process modifications on the energy demand for the three selected solvents. Although the system used MDEA promoted by PZ requires the highest energy for regeneration before modification, the energy demand reaches to 2.24 MJ/kg_{CO2} after process modification that is considered the lowest energy amount compared with other solvent types. Indeed, adding absorber intercooling is one of the major modifications in the process that facilitates to control the

Table 8 The most effective process configuration from the literature

No	Process configuration	Regeneration Energy (MJ/kg_{CO2})	References
1	Absorber intercooling	–	Walters et al. (2016)
2	Standard PCC[a]	3.58	Oh et al. (2018)
3	Absorber intercooling Semi-lean solvent stream of stripper Rich solvent splitting to the stripper	3.21	Oh et al. (2018)
4	Standard PCC	3.6	Li et al. (2016)
5	Absorber intercooling Stripper interheating Rich solvent splitting to the stripper	3.1	Li et al. (2016)
6	Standard PCC	5.45	Oh et al. (2020)
7	Lean vapor compression Cold solvent split Stripper overhead compression	4.95	Oh et al. (2020)
8	Two stripping columns	2.72	Frimpong et al. (2019)

[a]The standard PCC layout contains the main process units i.e., absorber, stripper, reboiler and heat exchanger

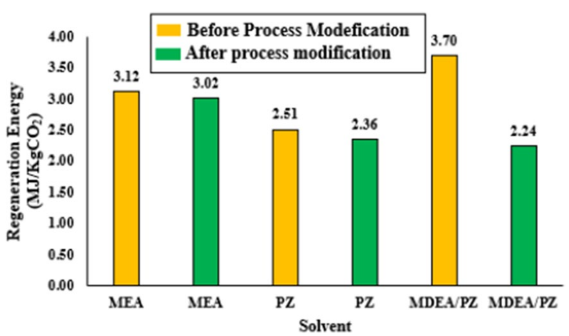


Fig. 9 Regeneration of energy for the three solvents before and after process modification

absorber temperature, which will enhance the process efficiency and reduce energy demand.

Integration of PCC within the power plant, in some instances, requires modification to the power plant system to provide the required steam for the regeneration stage without disturbing the efficiency penalty. In a study reported by Pan et al. (Pan et al. 2016) presented a new application to improve energy efficiency for a natural gas combined cycle power plant that includes the CO_2 capture system, using a heat transfer intensification technique and exhaust gas recirculation. The model helps to reduce the regeneration energy demand up to 3.8 MJ/Kg_{CO2}, examples are shown in Fig. 9. In another study some researchers estimated the efficiency increased in power plants due to thermal integration in the system (Bravo et al. 2021). The model designed by Bravo et al. to extract steam from the highest temperature point between the intermediate and low pressure of the turbine section. Furthermore, the temperature of the steam was adjusted to avoid the decomposition of MEA. The research found that the model improves the power plant energy efficiency and reduces the reboiler duty by 20.8%. Nevertheless, the thermal system proposed by another research group (Fu et al. 2021), introduces a carbon capture turbine that provides the required heat for solvent regeneration, thereby reducing energy losses. The designed system introduces a double-shaft power generation system that enhances the efficiency of power plant and improves capturing efficiency.

4.3 Notorious emissions to the environment

The emission from the degradation of amines (solvent) is one of the challenging aspect related to absorption PCC process, the triggers of the issues such as the amount and type of solvent, the flue gas composition and others are investigated (Supap et al. 2011). Although the solvent degradation reduces the amount of the available solvent, the degradation products are documented as highly toxic to human and environment with a possibility of death in specific cases (Rey et al. 2013). Nitrosamines and nitramines are the most dangerous degradation products due to their toxicity such as carcinogenicity and mutagenicity (Magee 1971). The lab test was carried out to find the potentials of selected solvents (MEA, MDEA, and PZ) to generate nitrosamines once mixed with a

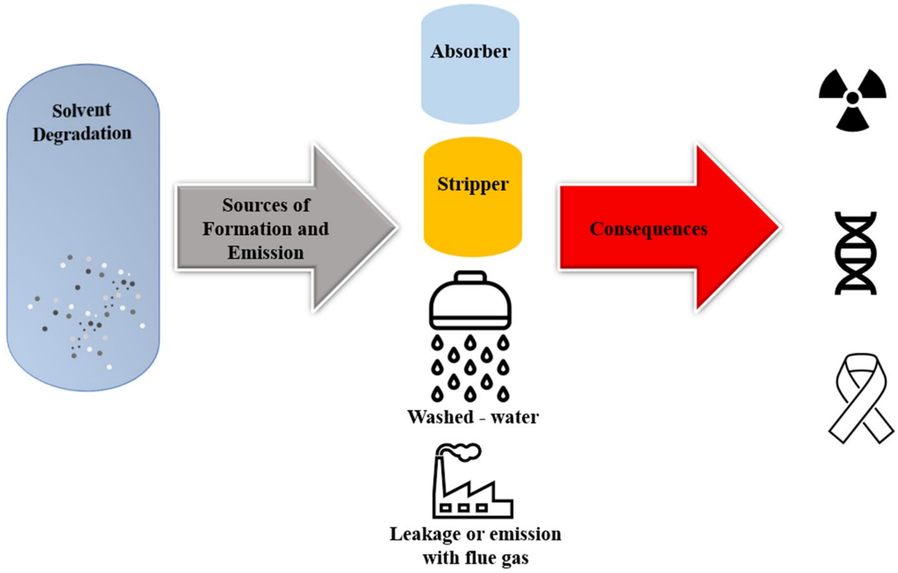


Fig. 10 Power plant, showing regions of solvent degradation and impact of hazardous compounds on life

mixture of Nitric oxide (NO) and Nitrogen dioxide (NO_2), showed that the highest nitrosamine is formed when PZ is used followed by MDEA and MEA (Dai et al. 2012). According to Liang et al. (Liang et al. 2015) degradation of amine and the formation of emissions need to be further investigated. Furthermore, to enhance the capture efficiency using minimum energy demand should not be studied solely without emphasis on the solvent degradation impact. Heat Stable Salts (HSS) is a side-product of PCC processes formed from the reaction of amine and its degradation compounds, once the HSS forms the solvent could not be generated in the stripper (Supap et al. 2011). The HSS include acetate, formate, thiosulfate, sulfate, thiocyanate, oxalate, butyrate, and propionates (Dai et al. 2012). The formation of HSS is to be avoided by preventing or reducing the solvent degradation as minimum as possible (Liang et al. 2015), solvent degradation in PCC are described in Fig. 10. Solvent degradation hazardous are mainly carcinogenicity, mutagenicity, and severe toxicity. It has been shown in the Fig. 10 that toxic compounds are formed in the (i) Absorber column in which it will affect the efficiency of CO_2 capture and increases the solvent demand, (ii) Stripper column: the formed compounds react with solvent to form HSS, which in turn disturbs and reduces the processes efficiency, (iii) Washed water: at the top of the absorber column, water is located to wash out the clean flue gas, the degradation compounds are carried by water to the sewage system and (iv) finally the degradation compounds escape to the atmosphere either through leakage or with the flue gas.

5 Process outlook to reduce the emissions and energy demand

The current review of CO_2 capture technologies shows that PCC using absorption separation is the most promising option, which needs to be expanded for utilization at a larger scale in power plants. To materialize the proposal, further investment in research and development sector is required (Rubin et al. 2012). However, the process is grappled with challenges to the cost specifically for solvent, the characteristics and performance of solvent during the capture process, and the high energy demand required for solvent regeneration (Haase et al. 2022). As a result of the literature review, three scenarios are recommended to resolve the drawbacks of the PCC-absorption technique listed in Table 9. Because of the lower capture cost and lower energy demand for solvent regeneration, the synergistic effect of different solvents is a promising solution to the post-combustion capture.

The recommended solutions to the PCC challenges are reviewed below, the solutions musttackle the environmental issues and technical aspects.

Table 9 Technical and Economic comparison of the three scenarios to resolve the PCC drawbacks

Scenarios to resolve the PCC drawbacks	Solvent regeneration energy demand (MJ/kg_{CO2})	CO_2 capture cost ($USD/t\ CO_2$)	Potentials	Challenges	References
Recirculation of flue gas[a]	3.7	–	Assists in the absorption process Increase CO_2 partial pressure in the absorber	More amount of solvent is required It is not beneficial if the captured CO_2 is to be utilized	Frimpong et al. (2019)
Synergistic effect of different solvents	2.52–4.1	50.88	Enhances capture efficiency Reduce the regeneration energy once optimum variables are used for the process	Solvent degradation High energy demand for the reboiler	Derks et al. (2006), Zhang et al. (2001), Zhao et al. (2017)
Utilization of ultrasound technique	3.6	64.27	Assists regeneration process Less amount of solvent is required High mass-transfer efficiency Suitable for stripping high viscous solvent Enhance solvent regeneration at low temperature	Absorption stage is not affected by this method Solvent degradation due to the usage of ultrasound needs further study The time needed for the regenerating stage need further study The technology is not tested in continuous process	Balraj et al. (2022), Carreira-Casais et al. (2021), Ying et al. (2019)

[a]Limited research identified in the literature implemented this method in which part of the CO_2 capture was recycle to the absorber column

5.1 Recirculation of the flue gas

The flue gas that lifts the absorption column clean or contains the minimum amount of CO_2 are emitted to the atmosphere (IPCC 2005). However, the recirculation of flue gas to the absorber reduces the temperature within the absorber and increases the concentration of CO_2, which in turn enhances the capture efficiency (Croiset and Thambimuthu 2001). For example, Qian et al. (2011) found that the recirculation of flue gas suppressed the formation of NO_x. on the other side, it increases the processes efficiency (Frimpong et al. 2019). The CO_2 partial pressure in the absorber increases that enhances mass transfer thus increasing solvent capacity. However, the environmental impact of the process was not considered during testing this solution.

5.2 Synergetic effect of different solvents

The amine-based solvents are most applicable and attractive option to capture CO_2 from power plant using PCC absorption technique (Shaw 2009). Although the single solvent such as MEA, MDEA, and PZ is the most utilized options that remove CO_2 with a good efficiency (Apaiyakul et al. 2022; Budzianowski 2015), single solvent encourages to shift to high efficiency synergies raised from solvent blends in coming future (Liang et al. 2016). During the past decades, scientists were testing the synergetic efficiency of blending amine solvents to MEA (Rey et al. 2013) or synthesized amines. The latter option was not preferable due to the required high cost and uncertainty for large scale applications (Liang et al. 2016). The first synergy was the blend of MEA and MDEA, MEA has high regeneration energy while MDEA has low reaction rate, hence, the addition improved the behavior of each solvent independently (Budzianowski 2015).

The synergistic effect of blending PZ and 2-Amino-2-Methyl-1-Propanol (AMP) tested by Brúder et al. (2011) shows that the solvent performance is higher than MEA, the solvent precipitated at different blended ratio that adversely affected the absorption efficiency. The addition of MEA as a third solvent to PZ-AMP was also tested by Apaiyakul et al. (2022). It found that no precipitation is formed after the addition of MEA, furthermore, the CO_2 absorption capacity increases as the amount of AMP and PZ increases in presence of MEA at specific fixed amount. Furthermore, Nwaoha et al. (2017) obtained similar results for the blended solvent of MEA-PZ-AMP when they were used for capturing CO_2. Indeed, synergistic effect of different solvents could be one of the PCC promising solutions from both technical and environmental aspects.

5.3 Utilization of ultrasound technique

Ultrasound technique creates sound waves which travel through a medium and forcing molecules to vibrate, moreover, the sound waves create mechanical energy known as acoustic energy (Yao et al. 2020). That energy utilized in the industrial process cause an improvement, covered various aspects such as heating, extraction, removal of hazardous compounds, and environmental applications (Kadam et al. 2013). Moreover, the disturbance created by the energy enhances the agitation of particles, separation of substances, and removal of dissolved gases from liquid under high process efficiency and lower energy demand (Cao et al. 2018). To adsorb the flavonoids from baobab fruit pulp using ultrasound shows that utilization of ultrasound increased the adsorption capacity, efficiency, and reduced the time required to reach equilibrium (Ismail et al. 2020). Another application of ultrasound is for solvent regeneration in PCC process, the ultrasonic effect enhances CO_2 to be separated from the solvent and forms lean CO_2 solvent (Gantert and Möller 2012). The change in the PCC process to include the ultrasonic system is shown in Fig. 11, adopted from the work reported by Balraj et al. (2022). However, the ultrasonic solvent regeneration is limited to small scale and there are challenges to be developed into bench and on a larger scale, furthermore, there is uncertainty about the amount and source of the required power for deriving the ultrasound system (Balraj et al. 2022; Carreira-Casais et al. 2021).

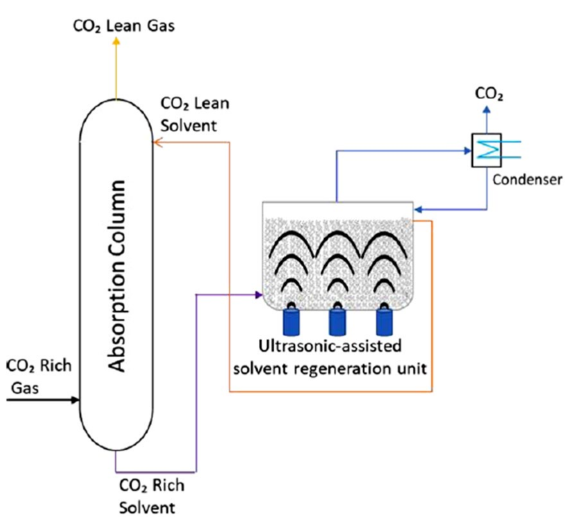


Fig. 11 The PCC absorption process with ultrasonic system, adopted from literature with permission (Balraj et al. 2022)

The stripper column is replaced with ultrasonic solvent regeneration unit, as shown in Fig. 11. The replacement enhances to solve the main drawback of the process that are the high energy demand for solvent regeneration, degradation of the solvent at high stripper temperature, and formation of hazardous compound or HSS, reduces the cost of the process due to the negligible requirement of the lean-rich heat exchanger and cooling of CO_2 lean solvent, reduces the size of the others equipment which are industrially not viable.

6 Conclusions and recommendations

This paper reviews the current techniques for capture CO_2, namely pre-combustion, post-combustion, and oxy-fuel combustion. This review targets to identify the best technique to be retrofitted to an existing power plant. The high cost and technical issues of pre-combustion and oxy-fuel combustion supported the post-combustion to be currently the best technique. However, pre-combustion capture is expected to be highly utilized in future as a technique for hydrogen production that is considered as an alternative energy source to fossil fuel.

The options of PCC processes are absorption, adsorption, and membrane technique. The absorption and adsorption separations are different techniques where liquid is used in absorption separation while solid is used in adsorption technique for CO_2 capture. However, cost is one of the obstacles in adsorption, hence, absorption separation using selected solvent is considered to be the best option. Post-combustion using membrane is not a feasible option for carbon capture from power plants, due to certain technical barriers.

The results of this study reveal that PCC capture using selected solvent is the best option to enhance the utilization of the carbon capture process in power plants. However, there are challenges concerning the selection of solvent, the process configuration, and the emissions from the process which need to be resolved to ensure that PCC using absorption is the optimum option. Three scenarios have been identified for future investigations. Recirculation of the flue gas, which helps to increase the CO_2 partial pressure in the absorber column wherein it enhances the capture efficiency. The synergistic effect of different solvents shows a potential to increase the process efficiency and has been considered a promising solution to reduce the environmental impact of the PCC process. The third scenario is utilization of ultrasound technology to replace the stripper column that is a promising solution to solve the environmental and technical issues of the PCC process as well, although the cost of the process and the source of power of the ultrasound need further study.

The PCC utilization to capture CO_2 is considered as one of the mitigation solutions to climate change. Furthermore, the gap for future investigations in the decarbonization field for researchers and policy makers is identified. Therefore, the utilization or storage of captured CO_2 needs further studies to judge the cost–benefit scenario of the solution.

It might help to resolve the problem of pollutants emitted from refineries, industries such as cement and steel, and transportation. Future studies on the synergistic effect of different solvents towards capture efficiency is exclamation of the day and the reduction of the hazards of the process emissions are recommended to enhance the utilization of PCC process to capture CO_2 as well as to ensure that this mitigation solution is not triggered a maladaptation issue.

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Author Contribution DA: Conceptualization, Writing—original draft, Methodology, Writing—review and editing. EK: Conceptualization, Supervision, Writing—review and editing.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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