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REVIEW ARTICLE

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# Reduction potential of the energy penalty for $CO_2$ capture in CCS



**Abstract** $CO_2$ capture and storage (CCS) has been acknowledged as an essential part of a portfolio of technologies that are required to achieve cost-effective long-term $CO_2$ mitigation. However, the development progress of CCS technologies is far behind the targets set by roadmaps, and engineering practices do not lead to commercial deployment. One of the crucial reasons for this delay lies in the unaffordable penalty caused by $CO_2$ capture, even though the technology has been commonly recognized as achievable. From the aspects of separation and capture technology innovation, the potential and promising direction for solving this problem were analyzed, and correspondingly, the possible path for deployment of CCS in China was discussed. Under the carbon neutral target recently proposed by the Chinese government, the role of CCS and the key milestones for deployment were indicated.

**Keywords** $CO_2$ capture and storage (CCS), $CO_2$ separation, energy penalty

## 1 Introduction

Being "net-zero" or carbon neutral, has made the spotlight in the past several years as the most commonly accepted target for climate change mitigation. The number of countries, which had already reached 127 by the end of 2020, that made net-zero pledges, has been increasing. Indeed, a carbon neutral target leaves fossil fuel dependent countries with no other choices than decarbonize the fossil fuel. Among all mitigation options, only $CO_2$ capture and storage (CCS) provides a solution for using fossil fuels in a low carbon way. Accordingly, the role of CCS is specifically clarified as the only technology that contributes to both reducing emissions in key sectors directly and removing $CO_2$ from the atmosphere (so-called "negative emissions", including bioenergy with carbon capture and storage (BECCS) and direct air capture (DAC) to counterbalance emissions that cannot be avoided [1].

CCS has attracted extraordinary attention in the last two decades. Positive research and development programs of CCS had been supported and dozens of roadmaps envisioning the development and deployment of CCS had been issued by different organizations and countries, including the International Energy Agency (IEA) (2009 and 2013) [2,3], the Department of Energy (DOE) and the National Energy Technology Laboratory (NETL) of the US (2002 and 2010) [4,5], the Department of Energy and Climate Change (DECC) of the UK (2012) [6], Norway (2015) [7], Canada (2006) [8] and the National Development and Reform Commission (NDRC) and the Ministry of Science and Technology (MoST) of China (2015, 2013, and 2019) [9–11], etc. Supporting policies, such as the well-known 45Q sponsored by the US government from 2018, provide tax incentives for CCS and are expected to promote the capture and storage of 49 million tons of $CO_2$ by 2030. Generally, ever since being officially recognized in 1995, CCS has taken on great expectations to make a significant contribution to $CO_2$ emission reduction [12,13].

However, for a long time, CCS had been considered an achievable technology because most of its component technologies have many years of industrial experience. For example, since the 1960s, the $CO_2$ separation technology has been widely used in $NH_3$ and methanol

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production. $CO_2$ geological storage, such as the enhancement of oil recovery, has been successfully commercialized in many onshore and offshore oil fields since the 1970s [14–17]. Consequently, CCS has been commonly recognized as a mature technology, and its large-scale demonstration has been set as the priority task in many roadmaps issued in the last two decades [2,3].

Contrary to the high expectations and maturity recognition, the progress of CCS worldwide is far behind. The comparisons of 2009 and 2013 targets in the CCS roadmaps of IEA and the latest situations in 2020 are summarized in Table 1. As indicated, the progress of demonstration deployment of CCS as of 2020 is still lagging behind the 2013 target (only 20 large-scale demonstration projects were constructed), even though the 2013 target had already significantly shrank compared to the ambitious target in 2009. Additionally, the storage capacity and financial investment did not meet the expectations. The reasons for this delay are of multi-aspects and rather complicated, which may include the high investment and operation cost of $CO_2$ capture, concerns about the safety of $CO_2$ storage, gaps in legality and regulations, unsmooth coordination between project partners, limited public understanding, and negative attitudes toward fossil fuels [18–20]. Among all these causes, a rather high $CO_2$ capture cost of approximately 45–140 \$/t $CO_2$ is the primary and direct one, while behind the cost, high extra energy consumption caused by $CO_2$ capture is the critical technical gap.

Figure 1 illustrates the efficiency involvement of power generation in the last century to help understand the energy penalty imposed by $CO_2$ capture. Through cycle upgrades such as increasing the initial temperature and pressure of the cycle and introducing reheating and regeneration, two dominant power generation technologies (coal fired power plants and natural gas fuelled combined cycle) went through an efficiency evolution, where the former increased from 17% to 45% and the latter as high as 60% [21–23]. At the current efficiency level, approximately 1.0 kg $CO_2$ will be emitted for 1 kW·h power generated, which means that nearly 2 million tons of $CO_2$ should be captured per year for a typical 300 MW coal fired power plant with a 90% recovery ratio. Correspondingly, at the current technical level, 8–14 points will be paid in a power plant adopting post-combustion capture [24–26], 6–10 points in

**Table 1** Worldwide progress of CCS referring to IEA CCS roadmaps

| | Targets in 2009 edition [2] | Targets in 2013 edition [3] | Progresses by 2020 [1] |
|---|---|---|---|
| Contribution by 2050 | "Delivers 1/5 of the lowest cost GHG reduction solution" | "Contributes 1/6 of $CO_2$ emissions reductions required in 2050" | |
| Demonstration plan | 100 CCS projects<br>300 million $CO_2$ t/a | 30 CCS projects<br>63 million t/a | ~20 CCS projects in operation<br>~29 million $CO_2$ t/a |
| Financial demand | \$5.0–6.0 billion per year between 2010 and 2020 | no targets updated | 2010–2020:<br>total of \$15 billion investment |

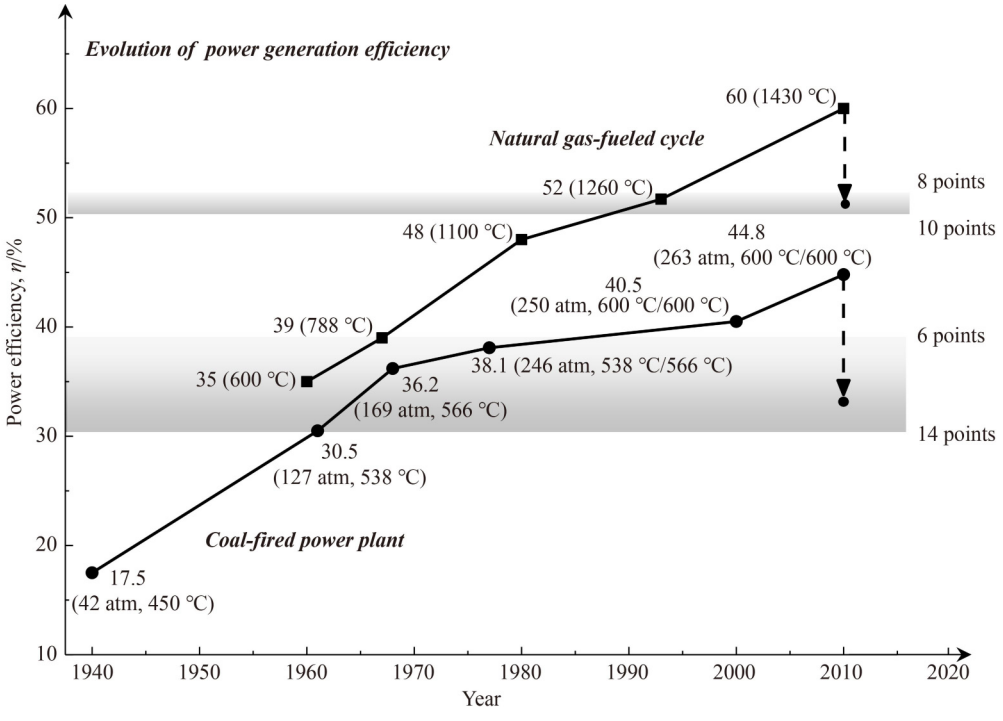


**Fig. 1** Impact of energy penalty of $CO_2$ capture on power generation.

pre-combustion capture [27–29] and approximately 8–12 points in oxy-fuel combustion [30,31]. It is apparent that the power efficiency will suffer a dramatic drop due to the extra energy consumption if $CO_2$ capture is adopted, which nearly sacrifices the efforts of a half century by the power industry.

The rather high energy consumption and cost had already been verified by most $CO_2$ capture demo projects, as shown in Table 2, and damage had occurred [32,33]. A rather high cost was the leading cause for suspending Kemper County facilities in 2017, which was well known as the first and largest pre-combustion capture demonstration project in the world [34]. The only existing large-scale CCS demonstration projects in the power sector (Petronova project and Boundary dam project) are trapped by the high capture cost, which can only be operated relying on the subsidies from public funding and the benefit from EOR. This is also why the operation of $CO_2$ capture in Petronova ceased and the facilities mothballed due to low prices of oil in early 2020 [35]. More seriously, considering the need for the construction of hundreds of CCS operations worldwide in the 2020s, rising to thousands in the 2030s and beyond, to capture, transport and store over 8 Gt of $CO_2$ per year by 2050, these scenarios imply extra energy consumption of more than 1.0 Gt standard coal per year, which is apparently hard to accept under the current conditions. Unaffordable energy consumption and cost due to $CO_2$ capture undermined the confidences of key stakeholders of CCS and blocked the path from engineering practices to the commercial deployment of CCS. Cutting down the energy consumption and cost of the $CO_2$ capture process may be the only way to rescue CCS from the current dilemma.

This paper aims to point out the dilemma, lessons and opportunities for CCS development and deployment, and provide a promising direction for energy saving of $CO_2$ capture. By pointing out the time window of CCS technology, the possible future development path of CCS technology will be given.

## 2 Methods

### 2.1 Equivalent work

The boundary of $CO_2$ separation process in this study is considered from the emission sources to pure $CO_2$ without compression. Considering the diversity of energy consumption forms according to various technical routes, the value and unit for each type of energy, such as heat for reboiler or cold energy for refrigeration (GJ/t $CO_2$ ($Q$)) and work for pump and compressors (MJ/t $CO_2$ ($W$)), have to be unified before evaluation and comparison. The reboiler duty in chemical absorption process was converted to equivalent work ($W_{eq}$) according to Eq. (1) given by a Carnot cycle efficiency with a turbine cycle efficiency of 75% [30,36,37]:

$$W_{eq} = 0.75 Q_{re}\left(1 - \frac{T_L}{T_H}\right). \quad (1)$$

Equation (1) indicates the work that the steam extracted from the turbine could have done in the turbine, and 0.75 is the average turbine efficiency. Thus, Eq. (1) is applicable to the scenario for meeting the duty of the reboiler by extracting steam from the turbine.

### 2.2 Exergy efficiency

From the thermodynamic viewpoint, exergy efficiency is used as the criterion assessing the separation process, which is defined as the ratio between ideal work and exergy corresponding to the actual energy consumption, as illustrated by Eq. (2).

$$\eta_s = \frac{W_{min}}{\sum W + \sum Q\eta}. \quad (2)$$

The ideal work, represented by $W_{min}$, is the thermodynamic minimum exergy required to separate $CO_2$ from the emission source. The denominator is the exergy corresponding to the actual energy consumption, which is generally composed of work and heat that depend on the separation technical routes. Equation (2) is applicable in almost all $CO_2$ separation technologies currently.

## 3 Opportunities and potential of $CO_2$ capture

The concepts and relationships of separation and capture are illustrated in Fig. 2. $CO_2$ separation is a process index as the kernel course of the $CO_2$ capture technology, which specifically refers to the separation of $CO_2$ from mixed streams. As illustrated by the red boundary in Fig. 2, chemical absorption for post-combustion capture is a representative separation process. Comparatively, $CO_2$ capture is a systematic technology that not only

**Table 2** Energy consumption and cost of CCS demonstration projects

| Project | Capture rate/% | Efficiency penalty/% | Capture cost/($/t $CO_2$) |
|---|---|---|---|
| Boundary dam | 91 | 10.1–13.9 | 100–130 |
| Petro Nova | 90 | 12.4–13.2 | ~114 |
| Rotterdam | 90 | 10.7 | 52–61 |

includes the separation process but also includes the integration between the separation and the emission source.

As the kernel process of $CO_2$ capture, the separation technology is undoubtedly the focus in the field of reducing energy consumption, whose aim is to selectively separate $CO_2$ from mixed gases. Separation technologies can be grouped into two categories according to the principle: equilibrium separation process (ESP), and rate separation process (RSP). ESP is related to phase equilibrium, in which insoluble phases are created in or added to emission sources and reach phase equilibrium with different components, such as absorption and adsorption with liquid or solid mass separator additives (MSA) and energy separator additives (ESA), while cryogenics realizes phase separation only by ESA (heat or work). RSP relies on the differences in mass transfer rates between various components in the same phase, such as membrane separation [38].

For most separation technologies, there are two ways to reduce the energy consumption: exploring new separation media [39–44], such as absorbents with lower reaction heat, and adsorbents with higher adsorption capacity, or membranes with higher selectivity, and upgrading the separation process [45–47], such as absorber intercooling, multi-pressure stripping, and combination of various separation techniques.

Chemical absorption is known to be relatively mature, as it has reached TRL 9 compared to the lower TRLs of other technologies, which has been widely adopted by early CCS demonstration projects, especially for emission sources with low $CO_2$ concentrations, such as flue gas from power plants.

The data of chemical absorption in the literature were collected to show the performance and energy saving potential of the $CO_2$ separation process. In this study, the heat duty of reboiler is focused and its internal causes has been investigated because it accounts for more than 99% of the energy consumption in the chemical absorption process. Moreover, the heat required to regenerate solution in the reboiler can be divided into three parts [45,48–50]: desorption reaction heat $Q_{des}$, sensible heat for heating rich solution $Q_{sen}$, and evaporation heat for producing stripping steam $Q_{vap}$. In Fig. 3, the purple pentacle icons represent a variety of novel absorbents, which shows a dramatically decline in $\eta_s$ within a small range of $CO_2$ concentration. In addition, the highest point in Fig. 3 refers to a non-aqueous solvent in Ref. [39], whose separation efficiency is much higher than 30% MEA at the same entrance $CO_2$ concentration. The reason comes from the better characteristics of such novel absorbents with a lower reaction heat, a lower $C_p$, a larger $CO_2$ loading capacity, and less water contained, which is what chemical researchers struggle to achieve. According to the data referenced in Fig. 3, exploring novel absorbents shows a greater potential in energy saving than upgrading the separation process, even though these two aspects of improvement are not simply additive, but closely interactive.

With the innovation of absorptions, such as amine blends, multi-phase absorbents, non-aqueous solution, and ionic liquid, the duty of the reboiler of chemical absorption was significantly reduced from higher than 3.5 GJ/t $CO_2$ to lower than 2.5 GJ/t $CO_2$, approaching a 50% separation efficiency. According to the latest information from demonstration projects such as Guohua Jingjie projects (150 thousand t/a in Shaanxi Province, construction completed in Jan. 2021), 2.4 GJ/t $CO_2$ had already been achieved in industrial conditions. In addition, in the well-known TCM center, 2.6 GJ/t $CO_2$ had already been announced on amino acid salt absorbents by the end of 2020. In the decade that follows, improving the efficiency will continue to be the priority task of the separation technology, and 2.0 GJ/t $CO_2$ may be the next target.

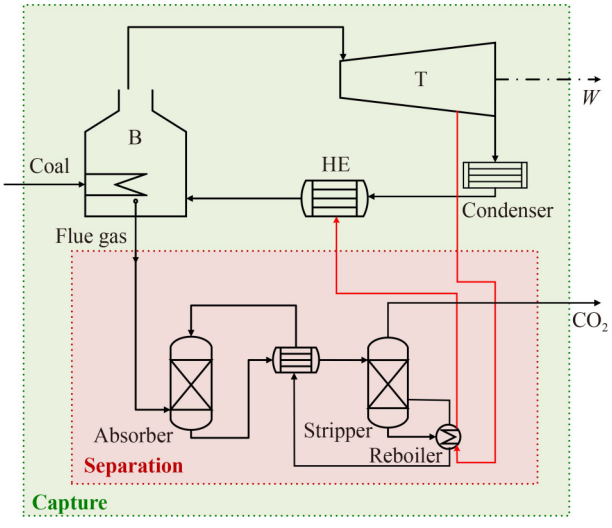


**Fig. 2** Physical denotation of $CO_2$ separation process and $CO_2$ capture system.

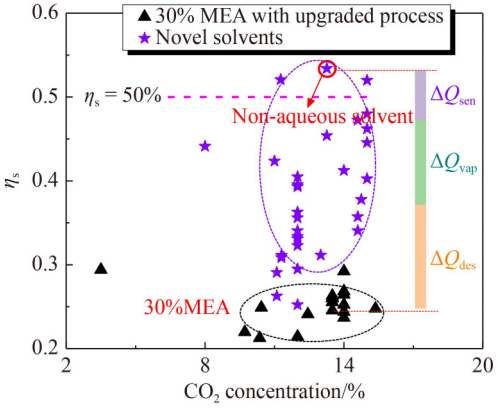


**Fig. 3** Distribution of energy consumption of chemical absorption technology.

Removing $CO_2$ in concentrated form from emission sources is termed $CO_2$ capture. Although the concepts of $CO_2$ separation and $CO_2$ capture are usually not to be distinguished in many conditions, the latter is much more comprehensive than the former: in contrast to the concept of separation as a process, $CO_2$ capture can be considered a systematic technology that can generate power (or other products for industrial emission sources) from fossil fuel and simultaneously produce concentrated $CO_2$. Correspondingly, the energy penalty for $CO_2$ capture is generally defined as the decline of system efficiency due to $CO_2$ production, which ranges from 6 points to 14 points in different technical routes, as indicated in Fig. 1. It is understandable that the energy penalty of $CO_2$ capture may not only be caused by energy directly consumed by $CO_2$ separation but also related to the deterioration of energy utilization associated with adding $CO_2$ production.

Post-combustion, pre-combustion, and oxy-fuel combustion are currently three main capture technical routes, which seemingly indicate the orders of combustion and separation but essentially adopt different fuel conversion and $CO_2$ generation paths. With a $CO_2$ separation process attached downstream of power generation, the post-combustion system keeps the combustion and $CO_2$ generation processes unchanged. Comparatively, the pre-combustion and oxy-fuel combustion technology integrates $CO_2$ production upstream of power generation and changes direct burning with air into indirect combustion (gasification, decarbonization, and then combustion) or burning with pure oxygen. The superficial motivation for changing the fuel conversion path is to increase the concentration of $CO_2$ at its generating point, which is approximately 30% for pre-combustion and as high as 90% for oxy-fuel combustion. From a thermodynamic viewpoint, the minimum work for $CO_2$ separation ($W_{min}$ in Eq. (3)) can be expressed as a function of $CO_2$ concentration $X$ of the emission source and recovery ratio $K$ [51]. As illustrated by Fig. 4, $W_{min}$ declines along with the increment of $X$ with a fixed $K$, and in Fig. 4, this reduction will be enhanced (whose enlargement factor equals the reciprocal separation efficiency, as indicated by Eq. (3)) and imposed on the energy consumption of separation. As can be seen from Fig. 4, with post-combustion as the reference, the theoretical energy consumption will be reduced by 47% for pre-combustion capture and nearly 86% for oxy-fuel combustion.

$$W_{\min} = RT_0 \cdot \frac{X(1-K)\ln[X(1-K)] - (1-XK)\ln(1-XK) - X\ln(X)}{XK} = f(X,K). \quad (3)$$

In addition to the intention to reduce $W_{min}$, the deeper principle supporting the exploration of new fuel conversion paths lies in the potential of chemical energy utilization. In addition to the process generating $CO_2$, fuel conversion is also the breakpoint for improving chemical energy utilization because it has the largest exergy destruction (nearly 1/3 of the availability of fuel in traditional combustion) in power systems. This close tie inspires the possibility of finding a new fuel conversion path with less exergy destruction and at the same time generating concentrated $CO_2$. On the one hand, a higher $CO_2$ concentration can promise a lower or even a near zero energy consumption in separation. On the other hand, a better chemical energy utilization can compensate for the efficiency reduction due to $CO_2$ separation. Exploration of fuel conversion paths with coupling effects, the so-called "source control technology", provides a new dimension for reducing the penalty of the $CO_2$ capture technology in addition to improving the efficiency of the $CO_2$ separation technology.

In the direction of the source control technology, chemical-looping combustion (CLC) and some new emerging technologies have demonstrated attractive performances [52,53]. In the 1990s, Chinese scholars took the lead in discovering the new phenomenon of high-concentration $CO_2$ enrichment in CLC [54]. As a representative source control technology, flameless CLC (Fig. 5(a)) divides direct combustion into an oxidation reaction and a reduction reaction to form a looping. CLC is a typical process realizing $CO_2$ capture during the energy conversion process without any $CO_2$ separation energy penalty. The flow sheet of the chemical-looping process is shown in Fig. 4(a). During the CLC process, a metal oxide acts as the oxygen carrier and transports oxygen from the air to the combustion process of the hydrocarbon fuel. After that, the metal oxide is reduced to metal in the fuel reactor and re-oxidized into metal oxide in the air reactor. As the fuel contacts with air indirectly, $CO_2$ is not diluted by air, and high purity $CO_2$ is obtained via the condensation of the exhaust gas of the fuel reactor with a low energy penalty in $CO_2$ separation. In this fuel conversion path, by avoiding the direct contact between

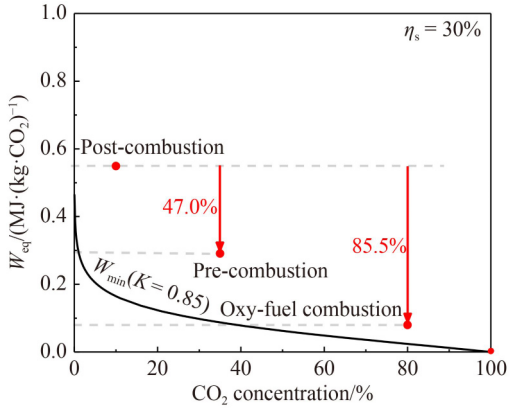


**Fig. 4** Another dimension for saving energy consumption of $CO_2$ separation through reducing minimum work required.

fuel and air, $CO_2$ is generated in conditions that contain only $H_2O$ and solid reactants, which promises that $CO_2$ can be separated without energy consumption. Meanwhile, the exergy destruction of chemical combustion can be reduced by more than 10% compared to traditional direct combustion [55]. Correspondingly, CLC can capture $CO_2$ with a near zero energy penalty, whose performance has already been commonly recognized [55–58].

Another interesting case of the source control technology is a polygeneration system adopting postsynthesis $CO_2$ capture (Fig. 5(b)). After gasification and purification, the syngas is sent to the methanol synthesis unit, and a part of the unreacted gas at the outlet of the synthesis unit is recycled back to re-enter the synthesis reaction. The remaining unreacted gas is shifted, decarbonized and delivered to the combined cycle as the fuel for power generation. The black point represents $CO_x$, the blue one represents $H_2$, and the red one represents methanol. The relative number of different particles simply expresses their concentration in the stream. This coal-based system produces methanol upstream and generates power downstream. Different from the traditional process producing methanol from coal, methanol synthesis in a polygeneration system does not need a shift reaction to adjust the $CO/H_2$ of syngas before synthesis, and only a part of the unreacted gas is recycled back to re-enter the synthesis reaction. The remaining unreacted gas is shifted, decarbonized and delivered to the combined cycle as the fuel for power generation. Instead of pursuing a conversion as high as possible between syngas and the product, the polygeneration system adopts a partial conversion scheme and postsynthesis $CO_2$ capture (also pre-combustion capture) and achieves dual positive effects on $CO_2$ capture and energy utilization. On the one hand, the carbon components (CO and $CO_2$) will be concentrated in the unreacted gas because methanol synthesis takes 3 times more H than C, while the syngas from coal generally contains much more C than H. Correspondingly, the $CO_2$ separation process can obtain shifted syngas with more than 50% $CO_2$, whose energy consumption can be saved by 30%–40% compared to post-combustion capture. On the other hand, by avoiding the pursue of the total chemical conversion and a better energy integration between chemical production and power generation, the energy utilization of the system will be significantly improved. As a result, the efficiency of the polygeneration system with a $CO_2$ recovery of 72% is even superior to that of the IGCC system without $CO_2$ capture [59–62].

There are already small and medium-sized demonstrations of CLC in the US, Europe, and Asia. The largest coal direct combustion CLC pilot is 250 $MW_{th}$ at Ohio State University in the US [63]. In addition, the polygeneration system has also been successfully demonstrated in the US and China. The coal-based CCS demonstration project from DOE co-products electricity and hydrogen, which has good economic benefits.

It is difficult to compare the significance of capture innovation and separation improvement, but it is undoubted that they are complementary to each other. Figure 6 projects the potential of energy savings for both efficiency improvement of separation technologies and systematic innovation of the capture technology. Typically, the penalty for the post-combustion capture technology will be decreased from 8–14 to 6–9 point loss, mainly benefiting from the separation technology (reboiler duty dropping to approximately 2 GJ/t $CO_2$). Pre-combustion, polygeneration, oxygen-fuel combustion, and CLC will benefit from improvements in separation upgrading and capture innovation, and the efficiency penalty may be reduced by 2–4 percentage points. The new generation of the $CO_2$ capture technologies such as source control may approach a zero penalty, which means solving the problem thoroughly.

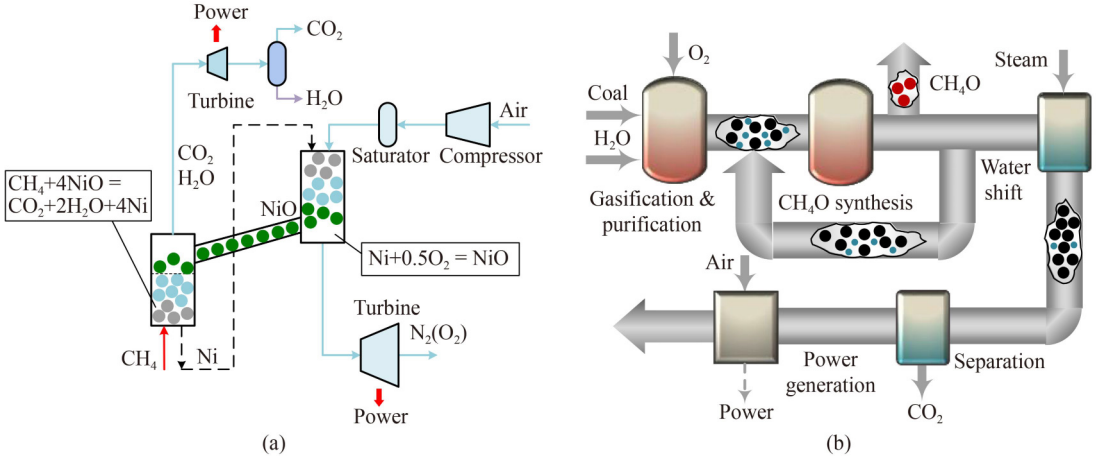


**Fig. 5** Conceptual scheme of CLC cycle and polygeneration system with postsynthesis $CO_2$ capture. (a) CLC; (b) polygeneration system.

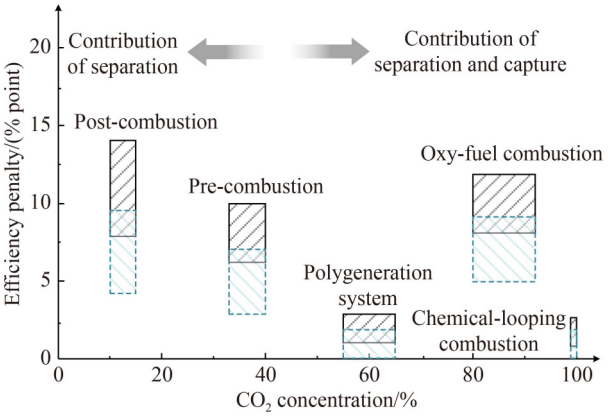


**Fig. 6** Reduction potential of the energy penalty for different technical routes.

## 4 A narrowing window: The last chance from carbon neutrality

It is difficult to identify the exact turning point for CCS, but it may be between Copenhagen (2009) and Paris (2015). In the past 5 years, CCS has obviously lost attention and expectations when compared to the progress of renewable energy. Even worse, CCS has to confront negative policies aimed at coal. Struggling to reach the goal set by the Paris Agreement, an increasing number of policies phasing out coal have been proposed. According to a report of E3G, 52% of Organization for Economic Co-operation and Development (OECD) and EU28 coal capacity has either closed already or is scheduled to close by 2030 [64]. Coupling with coal tightly, the space for CCS is sharply squeezed along with the steps of phasing out coal. It can be said that the window for CCS worldwide deployment is narrowing. The progress has to catch up, or else, CCS may be abandoned, even if much more energy, environment, and economic penalties will have to be paid in a mitigation scenario in the absence of CCS.

China has a little different situation from others. The Chinese government had announced their carbon neutrality before 2060 in the 75th session of the UN General Assembly (22 September, 2020, New York). It is commonly recognized that the share of coal will be significantly reduced, especially after the surprising growth of renewable energy in the last decade. However, given the huge amount of energy consumption, high reliance on coal, limited availability of oil and gas, defects of stability and continuity of renewable energies, and concerns about the security of energy supplies, it is hard to image that coal will be totally abandoned before 2060, which may still act as an important supplier to maintain the stability and security of China's enormous energy system. Consequently, a carbon neutral target and the necessity of coal will lead to a certain scenario in which the role of CCS has to be acknowledged in the technology package for reaching the multiple targets of energy security, efficiency, cleanliness and low carbon emissions. Carbon neutrality provides a new (maybe also the last) chance for CCS.

The "Roadmap for CCS Demonstration and Deployment in the People's Republic of China" was issued in COP21 of Paris by November 2015, which illustrates the strategy for CCS development in China [9]. Using the original graph of the roadmap as the background, Fig. 7 updates the progress of $CO_2$ capture technologies in the past 5 years. The latest information has been updated to illustrate the progress of CCS in the last five years as shown in Fig. 7: (A) for demo progress of the 1st generation of the $CO_2$ capture technology. By the end of 2020, more than 10 $CO_2$ capture demonstration projects had been constructed and operated (some projects are timely) in China, covering almost all representative technical options, including post-combustion (coal fueled and natural gas fueled), pre-combustion, and oxy-fuel, whose avoidance costs ranged from 44 to 66 \$/t $CO_2$. (B) Meanwhile, although the cost of the first large-scale CCS project (Boundary Dam Project) is around 140 \$/t $CO_2$, as high as a cost reduction of 67% will be anticipated (around 60 \$/t $CO_2$) in the second demonstration project (Shand Power Station) according to the pre-feasibility study of Saskpower [65]; (C) for innovation of new generation of the low energy penalty capture technology. A high priority on the innovation of the CCS technology was placed by MoST of China, who supported 11 projects on the development of a new generation of the CCS technology in the National Key Research Program. These projects include three on source control technologies and two on separation technologies, accounting for more than 20 million dollars of public funding. In the 14th Five-Year Plan issued in March 2021 by the Chinese government, CCUS is identified as one of the key tasks of Green Transition, which means that support will be enhanced, and at three large-scale full chain CCUS projects will be implemented in the subsequent years [66].

In the original roadmap, two core elements, industrialization of the first-generation $CO_2$ capture technology and innovation of the second-generation technologies with lower penalties, piece the possible path for CCS in China. The avoidance cost of the first-generation $CO_2$ capture technology, mainly post-combustion capture, is anticipated to be reduced to around 40 \$/t $CO_2$ by 2030, mainly driven by the improvement of separation technologies and accumulation of engineering experience, etc. Parallel to the industrialization of the first-generation technology, the second-generation technologies may reach the same cost level and take baton from the first-generation technology by 2040. However, given the narrowing window for CCS, this dual-track approach has to be accelerated. The cross point, which represents the relay between the first-generation and the second-gene-

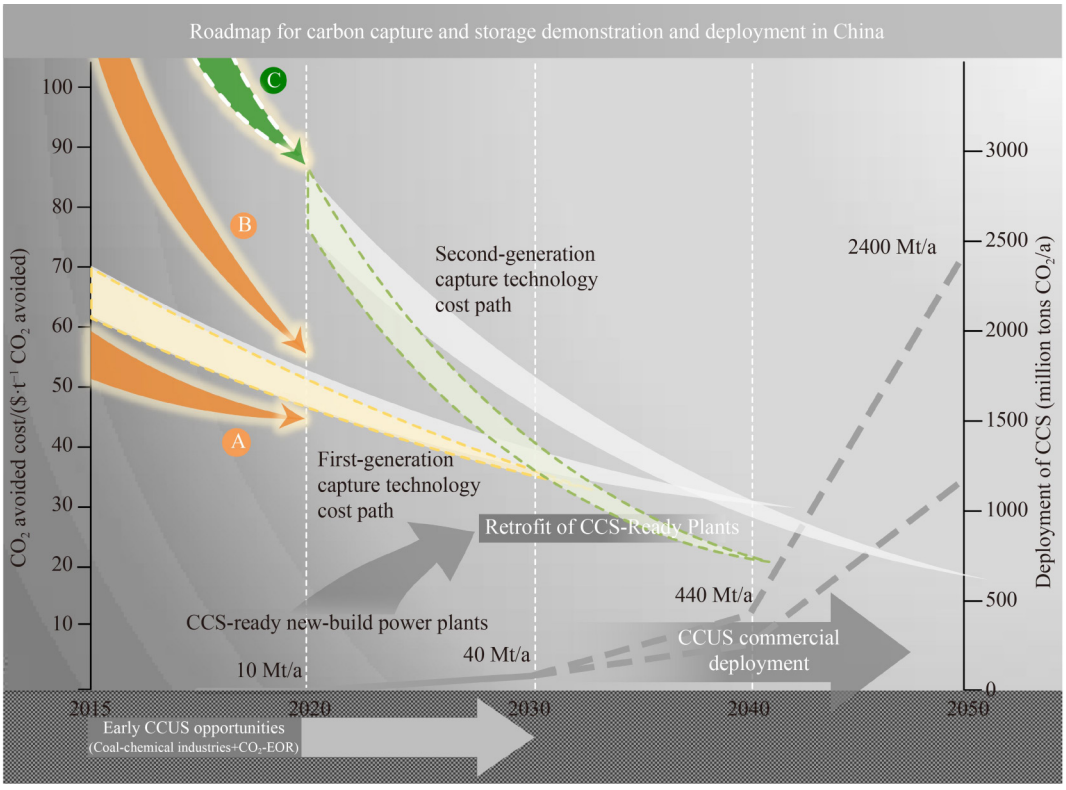


**Fig. 7** Roadmap for CCS demonstration and deployment in China.

ration technologies, should be advanced from 2040 to 2030, which can pave the way for a wider deployment of cost-competitive CCS. By 2035, the capture cost reductions achieved through the application of the second-generation $CO_2$ capture technologies and carbon pricing may reach a level that will trigger the wider commercial application of CCS.

The first- and second-generation capture technologies will play an individual important role in different periods in the future. Post-combustion capture is a key technology for the retrofit of existing power plants. Considering that the service life of most thermal power plants in China is relatively short, there will be a large retrofitting period for existing power plants to recover the sunk cost after the decline of the post-combustion capture cost. Then, a new generation of low-cost capture technology will take over and gradually replace the post-combustion capture power plant after the decommissioning of the retrofitted power plant, contributing a certain amount of emission reduction under the carbon-neutral scenario.

## 5 Conclusions: Lessons, opportunities, and challenges

Technically achievable should not be taken for granted as cost affordable, and unaffordable penalty is the critical gap deterring the deployment of CCS. Compared to copying more projects before the penalty is reduced (or the climate pressure increases), it is more important to learn experiences and lessons from existing demonstration projects.

Improvement of separation can provide a distinctive potential for energy savings, whereas $CO_2$ capture can provide systematic dimensions beyond the scope of the separation technology. By concentrating $CO_2$ in the source and improving chemical energy utilization, exploring new fuel conversion paths provides a promising direction for reducing the energy penalty for $CO_2$ capture. With joint force from innovation of capture technologies and improvement of separation efficiency, zero penalty for $CO_2$ capture may become reachable.

The carbon neutral scenario may be the last chance for CCS to obtain a foothold in the future emissions-reduction portfolio. Parallel to the innovation of a new generation of $CO_2$ capture technology, the improvement of the first-generation technology through learning from industrialization has equal importance. The smooth relay between two generations of technology should be foreseeable by 2030.

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## References


1. Organisation for Economic Co-operation and Development. Energy Technology Perspectives 2020—Special Report on Carbon Capture Utilisation and Storage. 2020, available at the website of OECD
2. International Energy Agency. Technology Roadmap—Carbon Capture and Storage. 2009, available at the website of IEA
3. International Energy Agency. Technology Roadmap—Carbon Capture and Storage. 2013, available at the website of IEA
4. Department of Energy. Carbon Storage Technology Program Plan. 2002, available at the website of DOE
5. Department of Energy. Carbon Storage Technology Program Plan. 2010, available at the website of DOE
6. Deployment of Energy & Climate Change. CCS Roadmap. 2012, available at the website of Deployment of Energy & Climate Change
7. Nordic CCS Competence Centre. Nordic CCS Roadmap Update 2015: A Vision for Carbon Capture and Storage towards 2050. 2015, available at the website of Nordic CCS Competence Centre
8. Government of Canada. Canada's Clean Coal Technology Roadmap. 2006, available at the website of Government of Canada
9. Asian Development Bank. Roadmap for Carbon Capture and Storage Demonstration and Deployment in the People's Republic of China. 2015, available at the website of Asian Development Bank
10. Ministry of Science and Technology (MoST) of China. Roadmap for Carbon Capture, Utilization and Storage Technology in China. 2013, available at the website of MoST
11. Ministry of Science and Technology (MoST) of China. Roadmap for Carbon Capture, Utilization and Storage Technology in China. 2019, available at the website of MoST
12. Intergovernmental Panel on Climate Change. IPCC Special Report on Carbon Dioxide Capture and Storage. 2005, available at the website of IPCC
13. Intergovernmental Panel on Climate Change. IPCC Special Report on Global Warming of 1.5 °C. 2018, available at the website of IPCC
14. International Energy Agency. 20 Years of Carbon Capture and Storage—Accelerating Future Deployment. 2016, available at the website of IEA
15. Global CCS Institute. The Global Status of CCS: 2015 Summary Report. 2015, available at the website of Global CCS Institute
16. Johansson T B, Patwardhan A, Nakicenovic N, et al. Global Energy Assessment Toward a Sustainable Future. New York: Cambridge University Press, 2012
17. Markewitz P, Kuckshinrichs W, Leitner W, et al. Worldwide innovations in the development of carbon capture technologies and the utilization of $CO_2$. Energy & Environmental Science, 2012, 5(6): 7281–7305
18. Scott V, Gilfillan S, Markusson N, et al. Last chance for carbon capture and storage. Nature Climate Change, 2013, 3(2): 105–111
19. Haszeldine R S. Carbon capture and storage: How green can black be? Science, 2009, 325(5948): 1647–1652
20. Cox E, Spence E, Pidgeon N. Public perceptions of carbon dioxide removal in the United States and the United Kingdom. Nature Climate Change, 2020, 10(8): 744–749
21. Henderson C. Upgrading and efficiency improvement in coal fired power plants. IEA Clean Coal Centre, 2013
22. Brooks F J. GE gas turbine performance characteristics. GE Power Systems, 2014
23. Campbell R J. Increasing the efficiency of existing coal-fired power plants. Congressional Research Service Reports, 2013
24. Global CCS Institute. $CO_2$ Capture Technologies—Post Combustion Capture (PCC). 2012, available at the website of Global CCS Institute
25. House K Z, Harvey C F, Aziz M J, et al. The energy penalty of post-combustion $CO_2$ capture & storage and its implications for retrofitting the US installed base. Energy & Environmental Science, 2009, 2(2): 193–205
26. Integrated Environmental Control Model. Amine-based Post-combustion $CO_2$ Capture. 2019, available at the website of IECM
27. Erlach B, Schmidt M, Tsatsaronis G. Comparison of carbon capture IGCC with pre-combustion decarbonisation and with chemical-looping combustion. Energy, 2011, 36(6): 3804–3815
28. Wheeler F. Potential for improvement in gasification combined cycle power generation with $CO_2$ capture. IEA Greenhouse Gas R&D Programme, 2003
29. Electric Power Research Institute. Evaluation of Innovative Fossil Fuel Power Plants with $CO_2$ Removal. 2000, available at the website of EPRI
30. Boot-Handford M E, Abanades J C, Anthony E J, et al. Carbon capture and storage update. Energy & Environmental Science, 2014, 7(1): 130–189
31. Buhre B J P, Elliott L K, Sheng C D, et al. Oxy-fuel combustion technology for coal-fired power generation. Progress in Energy and Combustion Science, 2005, 31(4): 283–307
32. Sgouridis S, Carbajales-Dale M, Csala D, et al. Comparative net energy analysis of renewable electricity and carbon capture and storage. Nature Energy, 2019, 4(6): 456–465
33. Reiner D M. Learning through a portfolio of carbon capture and storage demonstration projects. Nature Energy, 2016, 1(1): 15011
34. Lockwood T. The Kemper County CCS project—What went wrong and what next? IEA Clean Coal Centre, 2017
35. Dennis Wamsted D S. Petra Nova Mothballing Post-Mortem: Closure of Texas Carbon Capture Plant is a warning sign. IEEFA, 2020
36. Rochelle G, Chen E, Freeman S, et al. Aqueous piperazine as the new standard for $CO_2$ capture technology. Chemical Engineering Journal, 2011, 171(3): 725–733
37. Wagener D H V. Stripper modeling for $CO_2$ removal using monoethanolamine and piperazine solvents. Dissertations for the Doctoral Degree. Austin: The University of Texas at Austin, 2011
38. Xu D, Ye Q, Tao X. Separation Engineering. Beijing: Chemical Industry Press, 2012
39. Lail M, Tanthana J, Coleman L. Non-aqueous solvent (NAS) $CO_2$ capture process. Energy Procedia, 2014, 63: 580–594
40. Rochedo P R R, Szklo A. Designing learning curves for carbon capture based on chemical absorption according to the minimum work of separation. Applied Energy, 2013, 108: 383–391

41. Raynal L, Alix P, Bouillon P A, et al. The DMX$^{TM}$ process: An original solution for lowering the cost of post-combustion carbon capture. Energy Procedia, 2011, 4: 779–786
42. Niu Z, Guo Y, Zeng Q, et al. A novel process for capturing carbon dioxide using aqueous ammonia. Fuel Processing Technology, 2013, 108: 154–162
43. Puxty G, Conway W, Yang Q, et al. The evolution of a new class of $CO_2$ absorbents: Aromatic amines. International Journal of Greenhouse Gas Control, 2019, 83: 11–19
44. Wappel D, Gronald G, Kalb R, et al. Ionic liquids for post-combustion $CO_2$ absorption. International Journal of Greenhouse Gas Control, 2010, 4(3): 486–494
45. Stec M, Tatarczuk A, Więcław-Solny L, et al. Pilot plant results for advanced $CO_2$ capture process using amine scrubbing at the Jaworzno II Power Plant in Poland. Fuel, 2015, 151: 50–56
46. Kothandaraman A, Nord L, Bolland O, et al. Comparison of solvents for post-combustion capture of $CO_2$ by chemical absorption. Energy Procedia, 2009, 1(1): 1373–1380
47. Cousins A, Wardhaugh L T, Feron P H M. Preliminary analysis of process flow sheet modifications for energy efficient $CO_2$ capture from flue gases using chemical absorption. Chemical Engineering Research & Design, 2011, 89(8): 1237–1251
48. Wang J, Sun T, Zhao J, et al. Thermodynamic considerations on MEA absorption: Whether thermodynamic cycle could be used as a tool for energy efficiency analysis. Energy, 2019, 168: 380–392
49. Dinca C, Badea A. The parameters optimization for a CFBC pilot plant experimental study of post-combustion $CO_2$ capture by reactive absorption with MEA. International Journal of Greenhouse Gas Control, 2013, 12: 269–279
50. Kim H, Hwang S J, Lee K S. Novel shortcut estimation method for regeneration energy of amine solvents in an absorption-based carbon capture process. Environmental Science & Technology, 2015, 49(3): 1478–1485
51. Zheng Y, He S, Gao L, et al. Analysis and evaluation of the energy saving potential of the $CO_2$ chemical absorption process. International Journal of Greenhouse Gas Control, 2021, 112: 103486
52. Kierzkowska A M, Müller C R. Development of calcium-based, copper-functionalised $CO_2$ sorbents to integrate chemical looping combustion into calcium looping. Energy & Environmental Science, 2012, 5(3): 6061–6065
53. Blamey J, Anthony E J, Wang J, et al. The calcium looping cycle for large-scale $CO_2$ capture. Progress in Energy and Combustion Science, 2010, 36(2): 260–279
54. Jin H, Okamoto T, Ishida M. Development of a novel chemical-looping combustion: Synthesis of a looping material with a double metal oxide of CoO−NiO. Energy & Fuels, 1998, 12(6): 1272–1277
55. Ishida M, Jin H. A new advanced power-generation system using chemical-looping combustion. Energy, 1994, 19(4): 415–422
56. Li F, Fan L S. Clean coal conversion processes—Progress and challenges. Energy & Environmental Science, 2008, 1(2): 248–267
57. Bui M, Adjiman C S, Bardow A, et al. Carbon capture and storage (CCS): The way forward. Energy & Environmental Science, 2018, 11(5): 1062–1176
58. Fan L S, Zeng L, Wang W, et al. Chemical looping processes for $CO_2$ capture and carbonaceous fuel conversion—Prospect and opportunity. Energy & Environmental Science, 2012, 5(6): 7254–7280
59. Jackson R G. Polygeneration system for power and methanol based on coal gasification. Coal Conversion, 1989, 3: 60–64
60. Gao L, Jin H, Liu Z, et al. Exergy analysis of coal-based polygeneration system for power and chemical production. Energy, 2004, 29(12–15): 2359–2371
61. Wu H, Gao L, Jin H, et al. Low-energy-penalty principles of $CO_2$ capture in polygeneration systems. Applied Energy, 2017, 203: 571–581
62. Cai R, Jin H, Gao L, et al. Development of multifunctional energy systems (MESs). Energy, 2010, 35(11): 4375–4382
63. Zhang Y, Wang D, Pottimurthy Y, et al. Coal direct chemical looping process: 250 kW pilot-scale testing for power generation and carbon capture. Applied Energy, 2021, 282: 116065
64. Roberts L, Littlecott C. Burton J, et al. Global status of coal power—pre-Covid 19 baseline analysis. E3G, 2020
65. International CCS Knowledge Centre. The Shand CCS Feasibility Study Public Report. 2018, available at the website of International CCS Knowledge Centre
66. Ministry of Science and Technology (MoST) of China. The 14th Five-Year Plan for the National Economic and Social Development of China and the Outline of the Long-term Goals for 2035. 2021, available at the website of MoST