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Carbon Neutrality

REVIEW

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Carbon capture and storage (CCS): development path based on carbon neutrality and economic policy

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Abstract

In order to limit global warming to 2 °C, countries have adopted carbon capture and storage (CCS) technologies to reduce greenhouse gas emission. However, it is currently facing challenges such as controversial investment costs, unclear policies, and reduction of new energy power generation costs. In particular, some CCS projects are at a standstill. To promote the development of CCS projects in different countries, this paper reviews and compares energy conservation and emission reduction policies and different national goals. From a policy perspective, CCS-driven policies are analyzed. Based on this, corresponding policy recommendations are put forward, in order to promote the healthy development of global CCS technology and deal with climate issues more effectively. With less than 10 years away from the short-term goal, promoting the development and application of CCS projects requires scientific research from universities, enterprises and governments in order to attain zero or negative CO_2 emission. On the basis of focusing on the development of CCS technology, according to the actual situation of each country, the appropriate application of CCS engineering should focus on the development of science and technology, rather than a unified requirement around the world.

Keywords: CCS, Carbon neutralility, Government policies, Emission target

1 Introduction

Climate change is the most important environmental problem and challenge facing mankind nowadays and emission of greenhouse gases has become a worldwide focus [1–3]. In order to mitigate the effects of global warming, many countries have instituted a myriad of measures. According to the International Energy Agency (IEA) [4], global carbon dioxide emission from fuel combustion in 2016 was 32.31 $GtCO_2$, which is twice that in early 1970s and corresponds to an increase of about 40% in 2000. The 5th assessment report issued by the Intergovernmental Panel on Climate Change (IPCC) points out [5] that the global average air carbon dioxide concentration has risen to 400 ppm compared with 280 ppm before the industrial revolution and the concentration has reached nearly 80 ppm. At the highest level in the last 10,000 years, the average global temperature has increased by 0.3–0.6 ℃. Hence, carbon capture technologies are important to meeting climate goals and attaining low carbon emission. CCS techniques can reduce CO_2 emission from the power industry up to 90%. Cuéllar-Franca and Azapagic have compared the CO_2 reduction effects of CCS technology and shown that the global warming effects of power plants can be reduced

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by 63–82% by taking the proper measures. The World Development Bank predicts that by 2050, the share of coal power plants using CCS technology will exceed 56% and CO_2 emission can decrease to 1428 Mt. Moreover, carbon capture has been identified to be an economical strategy and many countries are actively promoting the pertinent technology (see Fig. 1) [6–9].

However, CCS projects are facing a number of challenges. For example, the technology is not yet cost-effective on the industrial scale and deemed to be unreliable by doubters [10]. In fact, one of the important CCS projects was behind schedule by 2021 and Chevron admitted it broke restrictions imposed by regulators to get its $54 billion Gorgon Liquid Natural Gas (LNG) processing center approved by Australia. Others argue the trouble stems from the large power consumption of CCS facilities making themselves significant carbon emitters. A coal power plant with carbon capture facilities would need 25% more electricity and after separation, an unknown amount of carbon dioxide is emitted to the atmosphere. When considering the additional energy demand and potential leakage downstream, there is no strong evidence that all the CO_2 can be captured. Furthermore, there is disagreement about the utility of CCS and associated concepts like carbon capture, utilization, and storage (CCUS) [11, 12]. Two members of the Global Carbon Absorb and Storage Institute assessed 26 CCS facilities around the world in 2021 and concluded that the technology had been implement on a scale to safely capture and store carbon dioxide. However, in a review comprising 39 CCS programs in the United States, researchers have arrived at a different conclusion. The CCS project development has a poor track record [13] and the fact that the oil and gas industry frequently recommends as a critical carbon reduction option does not bode well for the technology. One of the few applications where CCS seems to have unquestioned success is enhanced oil recovery in which carbon dioxide is injected into a well to help extract more fossil fuel, but this is not a good way to reduce climate change [14]. Meanwhile, in the power sector, the capture rate is almost zero and even the International Energy Agency which is long seen as a booster to the oil and gas industry casts doubts on the large-scale viability of CCS [15]. Globally, owing to the economical constraints and lack of profitable sources, CCS development is in a bad state and far below the scale proposed by the IEA [16]. To improve this situation, the economic value of CO_2 has been widely discussed, and the Carbon Sequestration Leadership Forum (CSLF) changed the term "CCS" to "CCUS" (Carbon Capture, Utilization, and Storage,

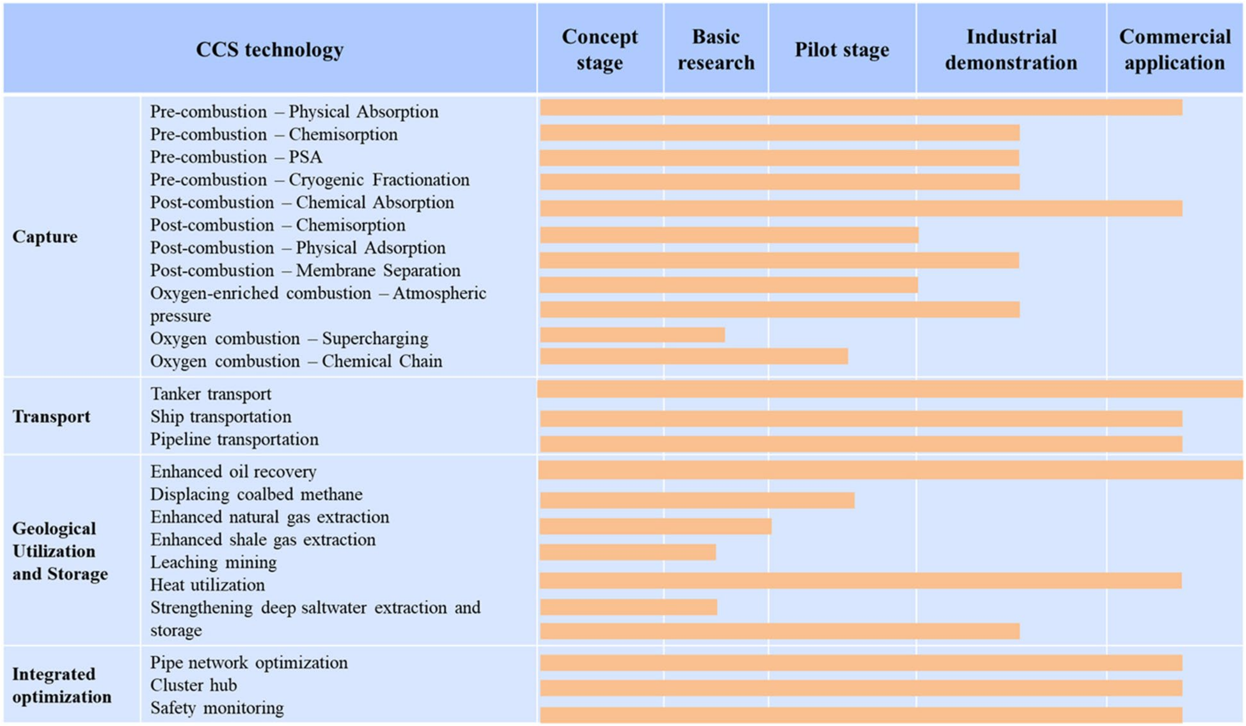


Fig. 1 CCS technology development level in 2022

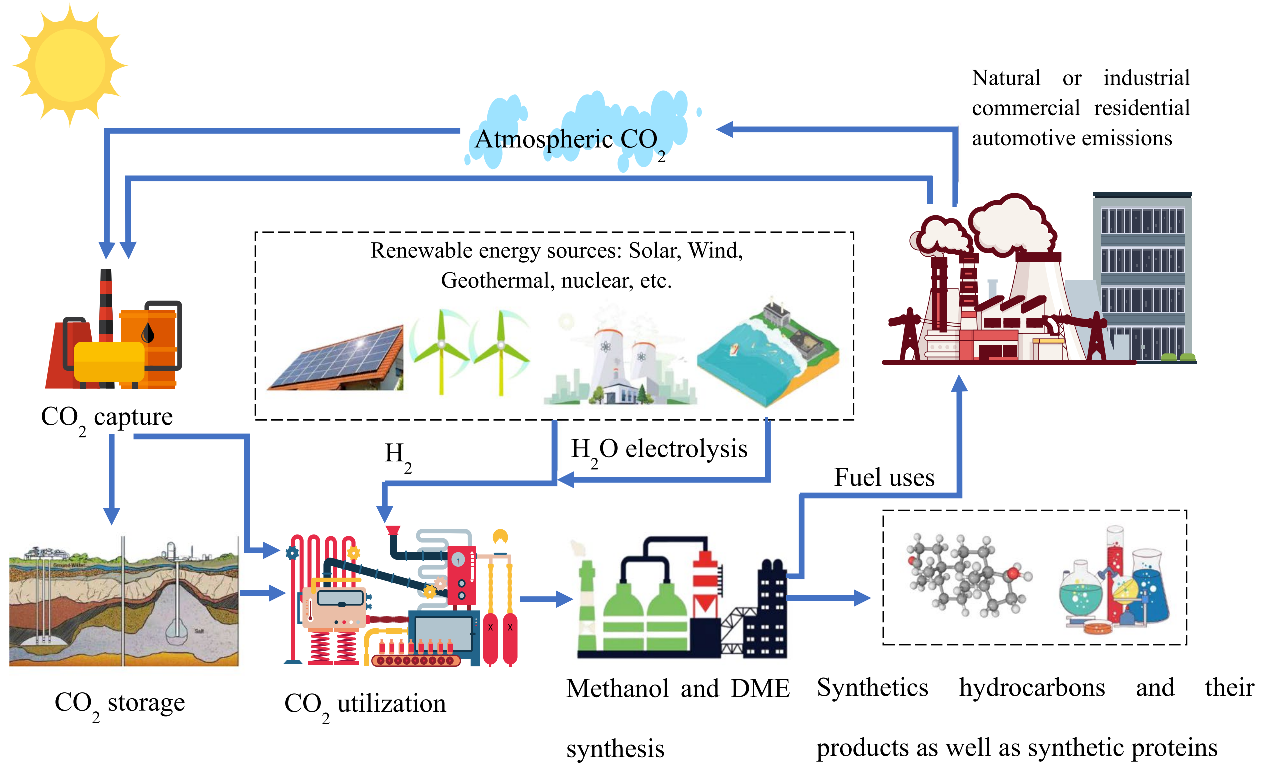


Fig. 2 Main CCUS strategy

CCUS) [17]. CCUS technology is a technology that directly separates CO_2 from the emission source that produces CO_2, compresses, transports, and carries out geological storage or resource utilization. Among them, the carbon capture process is the part with the highest energy consumption and cost in the whole process, so the research on carbon capture technology is also the focus of CCUS technology development [18, 19]. The CO_2 emission sources include stationary source emissions (including energy consumption emissions from power plants and other large industrial processes) and mobile CO_2 emissions (including transportation, etc.), of which stationary source emissions account for about 60%. Figure 2 shows the main route of the current CCUS technology. But the net-zero emissions pathway proposed by the IEA envisages a smaller role for CCUS and CO_2 removal than the ambitious scenarios developed by the United Nations' Intergovernmental Panel on Climate Change.

To address these issues, this paper reviews recent advances and reassesses the feasibility of CCS. Development of CCS technology, changes in policies and regulations in various countries, and carbon capture strategies are summarized. Challenges facing the development of CCS are discussed and future strategy and development are proposed.

2 Status of CCS policies in various countries

The Paris Agreement has paved the way for global greenhouse gas reduction after 2020 by breaking the legal stalemate created by the climate agreement in 2009. The Paris Agreement aims at limiting the rise of the global average temperature to 2 °C or lower in this century [8, 20]. The agreement also sets the goal of achieving carbon neutrality by the middle of this century, while the European Union, United Kingdom, Japan, and other countries have pledged to attain zero carbon emission. Since then, global attention to temperature control has spurred the development of national policies. Table 1 shows the current energy conservation and emission reduction targets and corresponding national policies. The current policy is implemented only until 2050 but global CCS projects are being developed rapidly. As of September 2021, the number of commercial CCS facilities planned, under construction, and in operation has reached 135, that is more than double from that in 2020, and will capture approximately 1.5×10^8 t of CO_2 per year when completed. There are 31 large-scale CCS projects in the construction or

Table 1 Energy conservation and emission reduction goals and policies of various countries [21–25]

Country	Short term goals	Long-term goals	Policies	whether to legislate
Australia	26–28% emissions reduction in 2030 relative to 2005	-	Support renewable energy	Yes
England	Reduce greenhouse gas emissions by at least 68% by the end of 2030 compared to 1990	Emission reduction target raised to 78% by 2035, zero carbon emissions by 2050	Expand electric vehicle coverage, expand offshore wind power, reduce meat and dairy consumption, and plant new forest land. It plans to quadruple offshore wind power capacity over the next decade and plans to ban the sale of petrol and diesel vehicles from 2030	Yes
America	Reduce greenhouse gas emissions by 26–28% in 2025 compared to 2005	-	Support renewable energy, improve energy efficiency	Yes
China	CO_2 emissions will be 60–65% and peak by 2030, with non-fossil energy accounting for 20% of primary energy consumption	Achieving the goal of "2 °C" by 2060	Support policies to use energy and clean fuels, improve energy efficiency and economic restructuring	Not yet
EU-28	Reduce greenhouse gas emissions by 40% in 2030 compared to 1990	95% reduction in greenhouse gas emissions by 2050, in line with the "Clean Planet Strategy for All" and climate neutrality goals	Enhanced EU Emissions Trading System (ETS) carbon pricing, CO_2 standards, energy efficiency measures, supportive policies for energy and clean fuels	Yes
Brazil	37% reduction in greenhouse gas emissions by 2025 compared to 2005	Reduce greenhouse gas emissions by 43% by 2030	Support the use of renewable energy and renewable fuels	Not yet
Russia	Reduce greenhouse gas emissions by 25–30% in 2030 compared to 1990	88% reduction in CO_2 emissions between 1990–2050	Support renewable energy, improve energy efficiency	Not yet
Canada	Reduce greenhouse gas emissions by 30% in 2030 compared to 2005	80% reduction in greenhouse gas emissions from 2005 to 2050	Support policies to use energy and clean fuels, improve energy efficiency and phase out coal-fired power generation	Yes
Japan	26% reduction in greenhouse gas emissions in 2030 compared to 2013	80% of greenhouse gas emissions in 2050	Support renewable and nuclear energy, improve energy efficiency	Yes
India	33–35% CO_2 emissions by 2030, with non-fossil energy accounting for 40% of primary energy consumption	-	Adopt energy efficiency measures, increase the use of clean fuels/technologies, support policies for renewable energy	Not yet

operation stage in the US (13), China (5), Canada (4), Europe (4), Middle East (3), Australia (1), and Brazil (1).

Several 10 million-ton CCS industrial clusters will be built, the largest of which is the "Houston Channel CCS Innovation Zone" that utilizes multiple CCS industrial carbon sources and store 1×10^8 t of CO_2 per year offshore in the Gulf of Mexico. The number of CCS industrial clusters in the late stage of development or in operation has reached 24: US (6), UK (6), Holland (4), Greece (1), Norway (1), Denmark (1), Canada (1), China (1), Middle East (1), Australia (1), and Brazil (1). Among them, 5 commercial full-process integrated facilities for more than one million tons are under construction and in operation in the US and 3 are in Canada [26]. According to the type and scale of the CO_2 emission sources, they are mainly concentrated in power plants, natural gas processing, syngas, and oil refining facilities, as well as the chemical industry. In particular, power plants capture the largest amount accounting for 52%. From the perspective of CO_2 capture for a single project, natural gas processing, syngas, coal liquefaction, and power industry are dominant. The average capture volume is 2 million to 3.7 million tons per year and the average capture volume of fertilizer, hydrogen production, steel, oil refining and chemical production is 900,000 to 1.2 million tons per year.

2.1 National low-carbon status and targets

2.1.1 United States of America (US)

US has a big energy industry which is number 1 in nuclear energy and solar and wind energy is developing rapidly. The agricultural base is solid, so that production of ethanol and biodiesel is substantial. In addition, oil and natural gas production ranks first in the world. Historically, coal as the largest source of energy. For example, in 1949, coal accounted for about 37% of the energy consumption mainly for electricity generation and heating. By 1958, natural gas consumption exceeded coal for the first time and became the second largest source until today. After 2005, the use of coal has decreased significantly and peaked in 2007 [27, 28].

In 2019, renewable energy such as hydroelectric power, wind energy, solar energy, geothermal energy, etc. surpassed coal for the first time and has become the third largest source in the US. Together with nuclear energy, non-fossil energy in the US has accounted for 20% of the total primary energy consumption. Coal accounted for only 13% in 2020 thus contributing to carbon emission control [29]. The US added 12 CCS commercial projects in 2020 and plans large-scale deployment of CCS technology within 25 years. As shown in Fig. 3(a-c), CCS projects have proliferated rapidly in the past 5 years. In the start-up stage in the next 5 to 7 years, investments amount to \$50 billion and the scale of CCS will reach 60 million t/a. In the expansion stage, the investment is anticipated to be \$175 billion in the next 15 years and the scale of CCS will reach 150 million t/a). Subsequently in the application stage (following 25 years), the investment is expected to be \$680 billion and the CCS scale will reach 500 million t/a).

Up to now, the number of projects in operation in the United States has increased to 38 and accounts for about half of the total number of projects in the world and the carbon dioxide capture capacity exceeds 30 million tons [32]. In addition to government funding and policies, there are many incentives. Coal power plants emit more carbon dioxide per megawatt than gas power plants, but retrofitting coal power plants requires up-front capital investment. A coal power plant costs about \$18 million per megawatt to achieve a 90 percent carbon capture rate, while a gas combined-cycle power plant costs \$800,000. Moreover, capital incentives such as depreciation, partnership, and investment tax credits positively impact CCS investments in coal power plants compared to those of gas plants. Therefore, development and construction of CCS in the US are at a faster pace than those in other countries.

2.1.2 European Union (EU)

In the EU, 13 commercial CCS projects are in operation in 2020, including 1 in Ireland, 1 in the Netherlands, 4 in Norway, and 7 in the United Kingdom, and another 11 projects are planned by 2030 [33], as shown in Fig. 3(b). Major commercial CCS facilities in Europe are concentrated around the North Sea, whereas projects in continental Europe have progressed relatively slowly due to various factors such as politics, cost, and public acceptance [34]. Norway is the first country in the world to set CO_2 emission reduction objectives as well as a leader in CCS implementation and policy development [35]. This is primarily due to the country's "civil war" in which economic growth depends on the production and sale of oil and gas, which is accompanied by carbon dioxide emission, while the government and citizens have lofty emission reduction goals. CCS has been a topic of political debate in Norway since the 1990s. Two planned gas power stations drew a lot of attention in 1994 since they were expected to raise domestic emissions by 6%.

There was no voice in favor of CCS technology until the mid 2000s, when the new government promised to be "CCS-based" and only gas power plants are permitted in order to achieve the "CO_2-free" goal [36]. Norway has been promoting CCS on a worldwide basis since then. As part of the Climate Solutions 2007, the

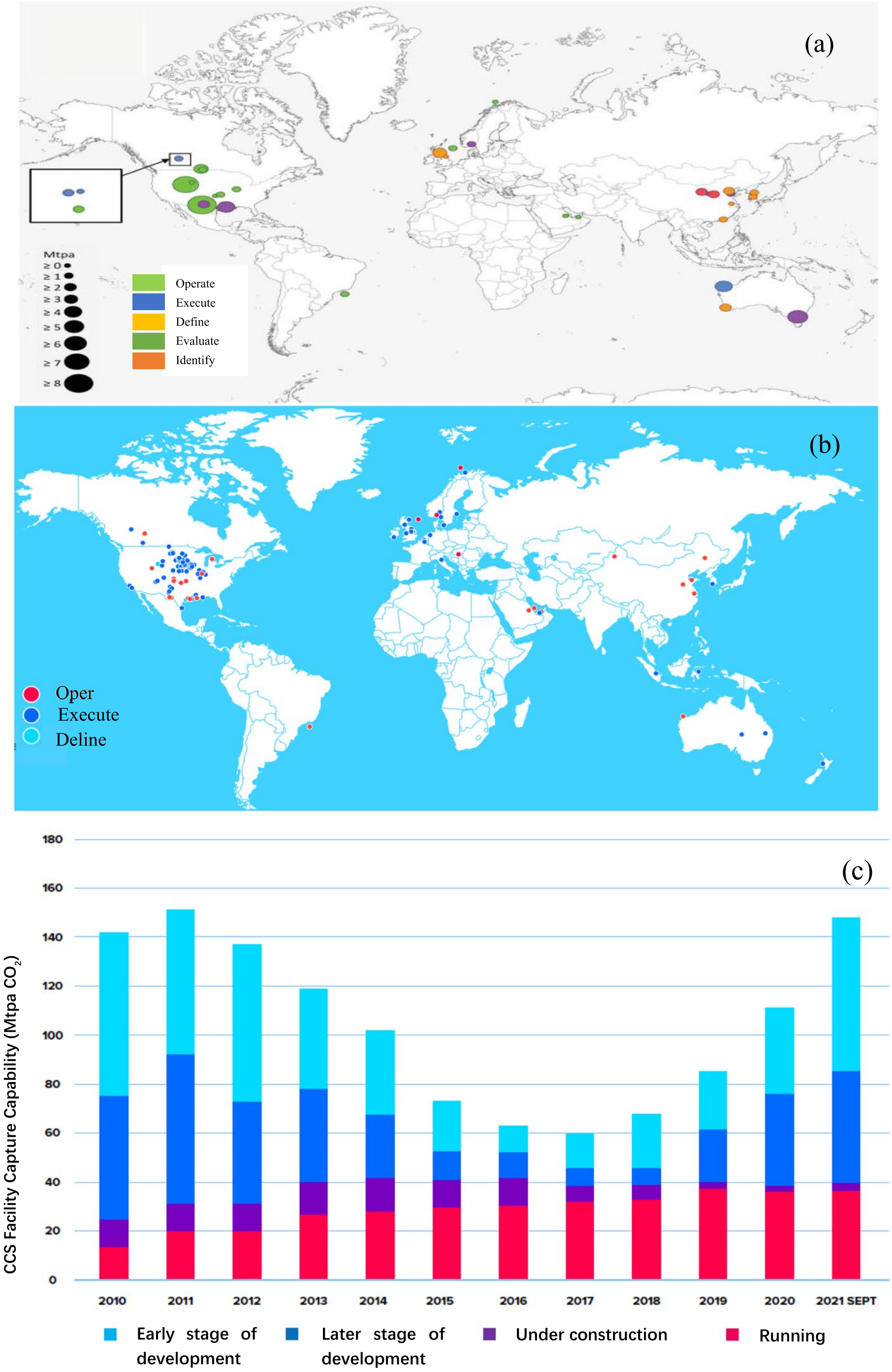
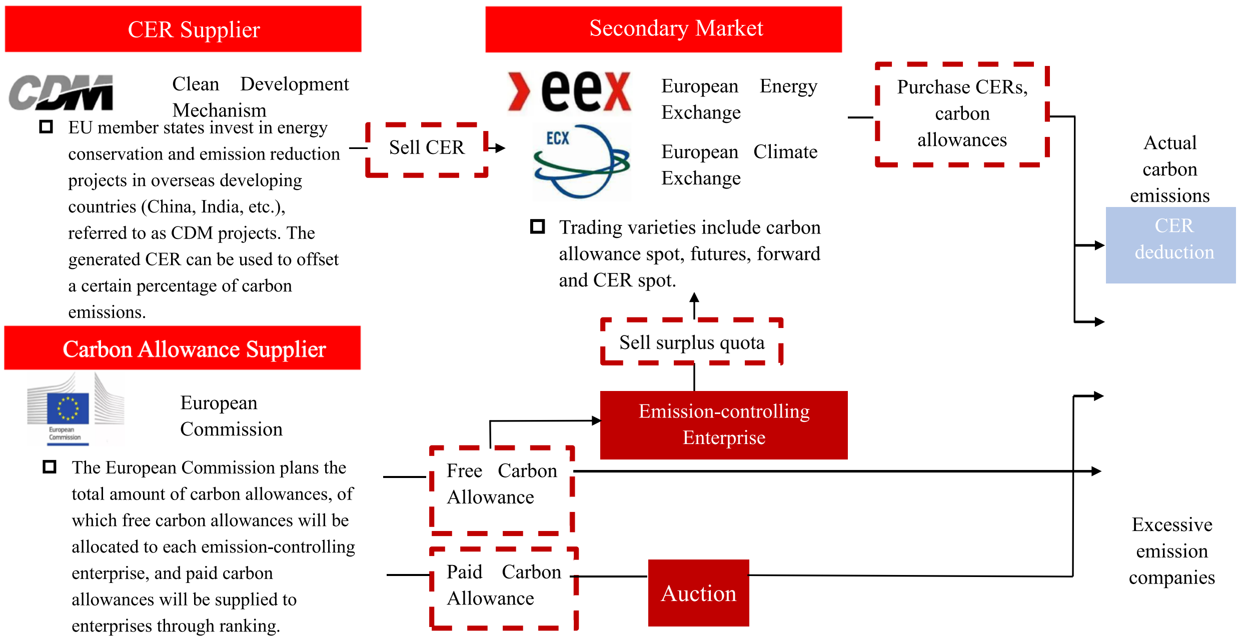


Fig. 3 Scale of global commercial CCS development: (**a**) 2016 [30]; (**b**) 2021 [31]; (**c**) 2010–2021 Commercial CCS Facilities Plan [31]. Data from the Global CCS Institute

International CCS Action Plan was formed with the goal of making Norway a net carbon neutral country in order to persuade other governments to embrace climate change mitigation. Because of international collaboration and self-initiatives, Norway has conducted several feasibility studies and launched some large-scale CCS projects [37] and is shooting for carbon neutrality by 2030 through international offsets and domestically by 2050.



- ☐ EU member states invest in energy conservation and emission reduction projects in overseas developing countries (China, India, etc.), referred to as CDM projects. The generated CER can be used to offset a certain percentage of carbon emissions.
- ☐ Trading varieties include carbon allowance spot, futures, forward and CER spot.
- ☐ The European Commission plans the total amount of carbon allowances, of which free carbon allowances will be allocated to each emission-controlling enterprise, and paid carbon allowances will be supplied to enterprises through ranking.

Fig. 4 EU Emissions Trading Scheme (EU-ETS)

Copenhagen is temporarily abandoning its 2025 goal of becoming carbon neutral because the environmental company Amager Island Resource Center does not meet funding criteria for carbon capture, the mayor of Copenhagen said. Copenhagen had hoped to be the first capital city in the world to become carbon neutral. After more than a decade of efforts, Copenhagen's carbon dioxide emissions have been reduced by 80% compared to 2009. But plans to be carbon neutral by 2025 have to be put on hold for a while now. Denmark is not the only EU country with variables. Germany previously planned to achieve 80% renewable energy power generation in 2030, achieve "close to greenhouse gas neutrality" in the power generation field in 2035, and achieve greenhouse gas neutrality in 2045.

The so-called greenhouse gas neutralization covers not only carbon dioxide, but also methane, etc., which is more difficult than achieving carbon neutrality. But in the most recent draft submitted to federal lawmakers, they only retained the 2030 plan and deleted the 2035 target. Of course, Germany has not "abandoned its carbon neutrality goal". At present, the climate neutrality timeline in Germany has not changed, but the emission reduction targets for the power industry have changed. Regardless, the EU remains a pioneer in the global move towards carbon neutrality. The energy crisis will disrupt planning in the short term and make the EU pay for its over-reliance on imported natural gas. After the labor pain, the EU will embrace new energy more quickly.

Unlike the United States, which supports the development of CCUS technology through fiscal and taxation policies, the EU mainly contributes to the EU's emission reduction goals through market-oriented means such as the European Emissions Trading System (EU-ETS), the world's largest carbon emissions trading market. The annual trading volume is nearly 170 billion euros, accounting for more than 80% of the global carbon market share. The trading mechanism is shown in Fig. 4.

Its main trading principle is: the government sets the greenhouse gas emission limit of a certain industry, and reduces the total carbon emission limit year by year according to the EU emission reduction target. Greenhouse gas emissions permits are then issued to businesses. During the validity period, if the greenhouse gas emissions caused by the actual production of the enterprise exceed the quota allocated by the government, then the enterprise needs to purchase carbon allowances on its own in the carbon trading market. Conversely, excess carbon allowances from companies can also be sold in the carbon trading market. The carbon emission price is determined by the mutual matching of market transaction entities. It aims to use cost constraints to promote the internal motivation of responsible entities to increase carbon emission reduction, and at the same time, to promote investors to lean towards clean and low-carbon industries, and ultimately achieve the purpose of controlling the total amount of carbon emissions.

In addition, the European Innovation Fund, which was established in June 2020 with a total of 10 billion euros, is considered to be the main source of public funding for CCUS projects in the future.

2.1.3 United Kingdom (UK)

The United Kingdom once suffered from pollution due to the rapid economic development and lack of attention to environmental protection. In December 1952, the "London Smog", a serious air pollution incident, directly or indirectly caused more than 12,000 deaths. Afterwards, the British government became the first country in the world to start environmental governance resulting in a carbon peak in 1991. On May 31, 2002, the UK and other EU member states signed the "Kyoto Protocol" and actively participated in greenhouse gas reduction. For example, in 2002, the world's first zero-carbon community, Beddington, was built. The UK was the first major economy to legislate to reduce greenhouse gas emission to net zero [38]. As early as 2007, the British government also launched a competition to promote the development of CCS technology. However, research and development of CCS technology at that time was mainly based on reduction of carbon emission from coal power plants, but the UK has stopped building them 2009 and instead started to build gas power plants. This has led to a hasty conclusion of the then CCS demonstration project design competition in 2011 [39].

Since then, the enthusiasm for CCS has diminished and many projects have been shelved. A recent report by the UK's National Audit Office shows that the overall development for CCS has been delayed by at least five years. One of the plans is to encourage more power plants to adopt CCS technology, so that they can learn and discuss with each other. In the future, 2Co Energy will be able to build a series of CCS projects in the Hubble waters of the North Sea, where CO_2 will be injected into some oil wells with declining production to aid oil extraction [40]. Existing zero-carbon scenarios appear to have disregard the current UK government policy on energy development and the work being done is to tackle sustainable energy project financing. In 2019, the United Kingdom revised the Climate Change Act and released a plan to achieve carbon neutrality by 2050. In the roadmap, the "Green Industrial Revolution" plan released by the British government in 2020 covers offshore wind energy, hydrogen energy, green shipping, and carbon capture and plans to invest £12 billion. The government will also invest £1 billion for offshore floating wind power generation and green energy storage systems.

At the same time, many cities are striving to be zero-carbon by deep decarbonization of heating, energy, transportation, and net-zero carbon emission from new buildings. There are only three new nuclear power plants under development in the UK, Hinkley Point C, Sizeville C and Bradwell B. Existing nuclear power projects cannot meet the goal of zero carbon emission and the cost for carbon capture and renewable energy is still high. Furthermore, most renewable energy can only be generated intermittently and requires substantial storage and power generation equipment thus increasing the cost. Nuclear energy is a critical but currently undervalued element in the UK energy system. Nuclear energy has lower technical risks but is challenged by financing models. With UK gas production in decline, nuclear power is the only reliable source of energy in the UK with a secure supply and it is an essential part of the most stable and cheapest energy system in the whole of Europe [41, 42].

2.1.4 Japan

Japan is another country that emphasizes CCS as a tool to coordinate economic growth with climate change mitigation [43]. Although only five CCS projects are operational or have been completed, Japan has demonstrated effective policy governance of CCS operation [44]. The 2007 Law on the Prevention of Marine Pollution and Marine Disasters, for example, allows carbon dioxide injection into subsurface saline aquifers and has established specified CCS guidelines. CO_2 capture (amine chemical absorption and CO_2 concentration > 99%), environmental impact assessment, permission; and long-term monitoring are the four primary factors. These requirements were emphasized in the 2009 CCS Demonstration Project Safety and Environmental Guidelines. In April 2014, the Japanese government released a strategic energy plan under the Basic Law of Energy Policy in response to the developments in the energy environment in Japan and abroad. The plan calls for the first practical implementation of CCS technology around 2020 as well as early building of CCS-ready plants to spur CCS commercialization.

Japan has no oil and gas resources that can be exploited for CO_2 enhanced oil recovery due to geological factors. As a result, the majority of the Japanese CCS initiatives such as the Petra Nova project in the US and EOR project in Southeast Asia are international ventures. Owing to the lack of domestic resources, fossil energy has been Japan's main energy source which heavily depends on imports. To avoid the energy dependence and minimize risks arising from oil crisis, Japan has gradually adjusted its primary energy structure in recent years aiming to reduce its dependence on oil. For example, in 1973, oil accounted for 75% of the primary energy source [45] but in 2017, it dropped to 41%, while the proportion of natural gas increased from 2 to 22%. However, due to carbon emission from the long-term and extensive use of fossil energy, Japan only achieved the carbon peak around 2020. In 2019, Japan announced its goal to achieve carbon neutrality "as early as the second half of this century", with CCS and hydrogen energy as two important research directions such as exploring the use of concrete that can absorb carbon dioxide and using algae to fix carbon dioxide and generate biomass fuels. Zero-carbon fuels such as hydrogen and ammonia are proposed to replace traditional fossil fuels in the transportation sector.

2.1.5 China

As a country with the largest population in the world, China actively implements a national strategy to address climate change [46], as shown in Fig. 5. In 2015, China put forward emission reduction targets in "Strengthening Action on Climate Change – China's Nationally Determined Contribution" outlining that carbon dioxide emission would peak around 2030 and carbon dioxide emissions per unit of Gross Domestic Product(GDP) would be reduced by about 20% compared to 2005 (60%-65%). Increasing the proportion of non-fossil energy consumption accounts for about 20% of primary energy consumption. By the end of 2018, China's national carbon emission has dropped by 45.8% compared to 2005, which is ahead of schedule [47]. In September 2022, according to the overall arrangement of China's carbon peak carbon neutral "1 + N" policy system, the Ministry of Science and Technology of China, together with nine departments, organized the compilation of the "Science and Technology Support Carbon Peak Carbon Neutralization Implementation Plan (2022–2030)". The plan proposes scientific and technological innovation actions and safeguards to support the carbon peaking goal by 2030, and make technical research and development reserves for the carbon neutrality goal by 2060. Strengthening scientific and technological support to achieve carbon neutralization involves basic research, technology research and development, application demonstration, achievement promotion, talent training, international cooperation and other aspects. The determination and perseverance of the Chinese government can be seen. In June 2022, CNOOC, Guangdong Development and Reform Commission, Shell Group and ExxonMobil signed the Memorandum of Understanding for the Daya Bay Industrial Park CO_2 Capture Utilization and Storage Cluster Research Project, which will be the first 10-million-ton offshore CCUS cluster project in China.

CCS projects in China started relatively late and most of them were implemented gradually after 2000. The initial technical route is similar to that proposed by European and American countries starting with geological storage and carbon dioxide flooding (EOR). Early projects include carbon dioxide flooding (EOR) in Daqing Oil Field. In the 2010s, various technical routes for carbon dioxide utilization began to appear in CCS projects, including pre-combustion capture in power plants, combining heat and power, etc. The use of catalytic hydrogenation to convert carbon dioxide into chemicals such as formic acid and chemical processes for plastics are also emerging [48]. China's CCUS research started relatively late, but around 2006, the Chinese academia and industry, according to the national conditions, made it clear that China's carbon capture and storage technology should take the road of CO_2 resource utilization. For the first time, the concept of "CCS + U" (ie CCUS) was proposed. At present, China's CCUS technology is still in the research and development and demonstration stage. There are about 40 CCUS demonstration projects in operation

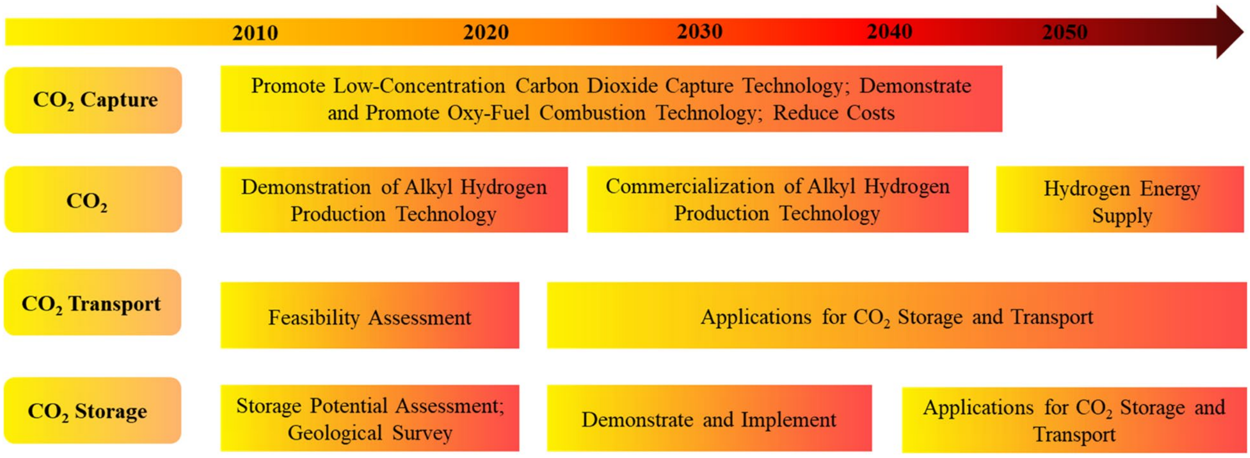


Fig. 5 2010–2050 development plan for CCS in China

and under construction, mostly small-scale oil capture and drive demonstration in the petroleum, coal chemical and power industries, lacking large-scale or full-process industrialization projects. Investment in pilot demonstration projects in China mainly comes from key state-owned enterprises, with low participation from private capital.

China's CCS projects are based on two main business models: independent operation of oil companies in the whole process and CCS operators. In the independent operation model, oil companies are independent operators for CCS and risks and profits can be shared more flexibly. In addition, coordination between various departments is easier to achieve, so that transaction costs are lower. In the CCS operator model, CCS has emerged as an independent market operator. Since this model involves cooperation of multiple enterprises and industry, it is necessary to promote the rational distribution of social responsibilities and economic and social benefits by legal means [49].

International cooperation is an important manifestation of the global development of CCS technology. For example, the Ministry of Science and Technology of China and the British government officially launched the "China-UK Near-Zero Emissions Coal (NZEC) Utilization Project " in Beijing. The Commonwealth Scientific and Industrial Research Organization (CSIRO) of Australia, China Huaneng Group Corporation and Xi'an Thermal Engineering Research Institute (TPRI) jointly built the Huaneng-CSIRO Post-Combustion Capture Demonstration Project. China Power Engineering Consulting Group Corporation (CPECC) signed an integrated coal gasification fleet combined cycle power generation and carbon capture and storage technology agreement with General Electric and the United States Trade and Development Agency respectively. Shanxi International Energy Group Co., Ltd. and APP Corporation of the United States signed a CCUS technology cooperation. EU-China Partnership on Carbon Capture and Storage. China–Europe Carbon Capture and Storage Regulatory Activities CO_2 Support Project, China–Europe Geological Sequestration Potential Assessment Project. A CO_2 capture fertilizer production project between Agrium and American College of Trial Lawyers (ACTL) in Canada. ACTL Canada and Northwest Redwater partnership Sturgeon bitumen refinery CO_2Stream for petroleum refining and more. In today's globalized world, countries cannot be separated from each other. In order to achieve global low carbon goals, countries need to cooperate with each other. Countries with advanced technology cooperate with countries with abundant capital, countries with high carbon production cooperate with countries suitable for storage, and mutually promote the development of technology and industry, so that the same goals can be completed on time.

2.2 Countries' policies towards CCS

There are different CCS projects in the US including cement manufacturing, coal power generation, gas power generation, waste-to-energy generation, and chemical industry [50]. Half of the projects are no longer reliant on CO_2-enhanced oil recovery for revenue due to the subsidy by the US government. CCS projects can receive financial support through the federal government's 45Q tax credit and the California government's low-carbon fuel standard. These initiatives have improved the viability of CCS projects and enabled their long-term health. In 2020, the US Department of Energy invested $270 million to support CCS projects [51, 52].

After the revision of the tax credit policy in 2018, the subsidy amount per ton of carbon dioxide has increased significantly. The tax policy adopts a progressive carbon dioxide subsidy price-setting technology. Among them, the subsidy for geological storage of carbon dioxide will increase from $25.70/ton in 2018 to $50.00/ton in 2026 and that for non-geological storage (mainly referring to CO_2 enhanced oil recovery and carbon dioxide utilization) will increase from $15.29/ton in 2018 to $35.00/ton in 2026. On January 15, 2021, the US issued Article 45Q which made credit eligibility and allocation more flexible and clarified that private capital qualified for the credit, thus ensuring stable cash flow and reducing financial risks [53].

To achieve the 1.5 °C targets in 2030, 2040, and 2050, emission reduction in the US will be 91–800 million tons, 600–1.73 billion tons, and 0.9–2.45 billion tons, respectively. Compared with the 30 million tons of CCS capacity in operation in 2020, the US needs to implement a large number of CCS projects by 2050 to meet the climate goal. The US, like China, uses the phrase "CCS" to promote the growth of fossil fuels but its policy is more developed than the Chinese one. Since the Supreme Court declared greenhouse gases to be pollutants in 2007, CCS has been a critical technology in the transition from fossil fuel power generation to greenhouse gas reduction. Subsequently, a series of additional federal-level legislations such as the US Electricity Act of 2010 have enacted new emission limitations for power plants and there are laws addressing disposal of hazardous pollutants in separation processes. However, local governments have not been persuaded to support capture technology by these political measures because residents refuse to fund the construction costs of installing capture units and several state authorities refuse to develop new capture-based coal-fired power stations, although both the transit and storage components have legal backing at the federal and state levels.

Pipeline governance in the US is rather mature and various federal departments and state authorities have established legislation and rules to control, oversee, and enforce pipeline transportation and safety. In the realm of geological storage, several norms and standards have been created. For example, the Underground Injection Control (UIC) program for CO_2 geological storage wells and the Illinois Clean Coal Future Act of 2011 monitor, categorize, and reimburse individuals accountable for operational procedures. From the political standpoint, the US should broaden legal coverage to include the "post-EOR injection" and "post-closure storage" stages in the future. Moreover, integrating storage in aquifers in the CCS legal framework is important, not simply enhanced oil recovery (EOR) and enhanced coal bed methane (ECBM) [54].

Different from the US, carbon dioxide emission reduction by CCS projects in Europe is mainly reflected by the European Emission Trading Scheme (EU ETS) and enhanced oil recovery [55]. Until 2020, the carbon dioxide price is low in Europe and there is limited support for CCS projects. In addition, the uncertainty of carbon price in the market affects the motivation for CCS investment for companies. Funds such as European NER300, Horizon 2020, and Horizon Europe provide public funding for CCS projects, but NER300 has been criticized for not supporting any CCS projects. The EU has been actively promoting a low-carbon economy and has adopted policies and institutions to promote low-carbon transition [56].

The 2020 European Green Deal and European Climate Act has transformed the 2050 goal of net-zero emission into a political goal and legal obligation, making it possible to implement more emission reduction policies in Europe in the future. Since CCS is an important means to reduce emission, it is foreseeable that Europe will adopt more active policies. The €10 billion European Innovation Fund created in June 2020 is widely regarded as the main source of public funding for future CCS projects. Nevertheless, compared with other low-carbon energy projects, EU support for CCS is cautious and conservative. To achieve the 1.5 °C target, emission reduction in the EU will be between 20 and 604 million tons in 2030, between 140 million and 1.57 billion tons in 2040. In the 1.5LIFE (sustainable living) and 1.5TECH (technology) scenarios announced by the EU in 2018, emission reduction of CCS in 2050 will be between 370 and 600 million tons. Compared with the emission reduction of other models, CO_2 capture, utilization. and storage emission reduction from 2030 to 2050 are significantly biased in the official model POLES in the EU policy and the 1.5 °C scenarios officially announced by the EU is low [57].

To achieve low-carbon development, Japan released the "2050 Carbon Neutral Green Growth Strategy" in 2020 to encourage private capital investment for offshore wind power, hydrogen energy, and other industrial projects. It is estimated that import of hydrogen energy will reach 3 million tons by 2030. The capacity of offshore wind power will reach 30–45 GW in 2040 and 20% of the power plants will use mixed ammonia combustion laying the foundation for Japan to achieve carbon neutrality. Full projects in Japan include the Tomakomai Carbon Capture and Storage Project which started construction in 2012 and operation in 2016. The Hiroshima Integrated Gasification Combined Cycle (IGCC) project has started CO_2 capture and is preparing to conduct a demonstration pilot of CO_2 utilization in the future. In 2020, the Japanese government announced the goal of net-zero emission by 2050. In the same year, the parliament adopted a growth strategy and formulated an implementation plan. CCS is one of 14 areas in which a roadmap for cement, fuels, chemicals, and power has been developed [58]. It should be noted that the focus of the Japanese government in recent years has been utilization of carbon dioxide and the investment in geological storage has decreased compared with that in the past. In order to accomplish the goal of 1.5 degrees Celsius in 2030, 2040 and 2050, Japan's CCS emission reductions will be 200 million to 210 million tons, 23 million to 430 million tons, and 110 million to 890 million tons, respectively [59].

To spur the development of CCS, China has undertaken several regulatory adjustments. The Five-Year Plan (FYP), a core national guideline that has promoted this technology since the 12^{th} Five-Year Plan, is an excellent example (2011). In July 2021, Sinopec started the construction of China's first million-ton CCS project, the Qilu Petrochemical-Shengli Oilfield CCS Project. Qilu Petrochemical captures carbon dioxide and transports it to Shengli Oilfield for oil displacement and storage. The project can reduce carbon dioxide emission by 1 million tons per year, which is equivalent to shutting down nearly 600,000 economical cars for one year. After years of institutional practice, the Chinese government has established a dual-track carbon emission policy and legal system [54]. The first is project-based carbon emission trading based on the United Nations Clean Development Mechanism projects and domestic voluntary greenhouse gas emission reduction projects. The second is to pilot total-capacity quota-based carbon emission trading in provinces and cities. Although the relevant bill has not yet been announced and put into operation, the government has accelerated the progress due to the pressure of the dual carbon goal. To achieve carbon neutrality, China needs to invest ￥2.2 trillion per year before 2030, and ￥3.9 trillion per year from 2030 to 2060. Carbon emission and carbon sinks can be traded in the carbon market at a price called the carbon price. The EU believes that the carbon price should be \$40–80 per ton of carbon dioxide in 2020 and \$50–100 in 2030. The current average capture cost per ton of carbon dioxide in China is \$45–150. The transportation cost by trucks is about \$0.15–0.22 per ton-kilometer and the cost of storage varies greatly [60]. Obviously, completion of the entire CCS industry chain requires considerable capital investment.

The United Kingdom, Japan, Mexico, European Union, South Korea, the Philippines, US, and other countries have passed laws to deal with climate change and China is also following. However, owing to the pressure of production and COVID epidemic, many developing countries are still unable to advance the relevant bills. Countries have designed corresponding policies according to their national conditions, energy distributions, and economic development. CCS is included as a technology suitable for climate mitigation in the 2019 Joint Multilateral Development Bank Climate Finance Report. CCS is also a significant mitigation technology in both the World Bank's newly adopted Climate Action Plan and the Asian Development Bank's 2021 Energy Policy Paper, with ADB designating CCS as a critical mitigation technology in hard-to-mitigate industries.

Several major multinational development banks and donor countries including the US, Norway, Japan, and UK have implemented national policies encouraging the development and deployment of CCS. Greater efforts are needed to promote prospective CCS projects in the southern hemisphere and multinational banks should continue to play a role. Supporting the development of green new energy and renewable energy is a win–win for everyone, but it is impossible to completely replace environmentally friendly energy in the short term. To balance economic development, it is necessary to adjust the distribution according to the current energy conservation and emission reduction goals while it is necessary to boost carbon capture and reduce carbon emission for the long-term goals.

3 Challenge and prospective

Combustion of fossil fuels emits CO_2 to the atmosphere and the ensuing greenhouse effect has become a major environmental problem of mankind, as evidenced by extreme weather and natural disasters in recent years. With regard to CCS development, breakthroughs must be made in the four following areas in order to reach the 2 °C target.

3.1 Government policies

In 2050, just 700 Mt CO_2 yr^{-1} is expected to be captured, which is less than 6,000 Mt CO_2 yr^{-1} needed to achieve the 2 °C objective. As a result, new rules are required to encourage commercial CCS projects and all governments must perform commercial evaluation of the carbon dioxide storage capacity. The other option is to provide CO_2 storage certificates to fossil carbon producers requiring increasing proportion of CO_2 to be stored over time. Governments should and must support CCS projects that are poised to make a big difference to the environment, employment. and economy.

Under the current electricity quota (4,000 h per year), even without CCS retrofits, coal-fired power plants (CFPPs) are in the red. And if additional power quotas are provided, it can profit from CCS retrofits. Figure 6 shows the critical conditions for the emission levels of CFPP retrofitted with CCS and the same power quota as gas-fired generators under different scenarios. As shown in Fig. 6(a), if CFPP emits at the same level as gas generators, it appears that CFPP should capture more than 40% of the total CO_2 emissions. Figure 6(b) shows the corresponding Levelized Cost of Electricity (LCOE) for coal-fired power plants with different capture levels under different power quota scenarios. It can be seen that with the increase of electricity consumption, the LCOE shows a downward trend [61]. Furthermore, it can be observed that as the electricity quota increases, the room for further decline is gradually narrowing [46], which can be attributed to the energy loss and efficiency loss caused by the large amount of captured CO_2.

To spur development of the CCS industry in the future, governments should launch more active industrial initiatives, formulate flexible regulatory policies, and provide reliable financial resources, as shown in Fig. 7. They also need to propose clear plans for the power sector to reduce carbon emission and provide reliable return for CCS project investors. One of the main reasons why CCS projects have been delayed in the past is the lack of reliable financing. Therefore, provisions to protect CCS earnings should be included to mitigate financial risks. By instituting policies to encourage and support innovations and with governments taking up some financial risks, it is possible to increase investment interest to promoting further development [62].

If there are no large-scale demonstration projects, there will be no corresponding data to share for further development. If combined laboratory and industrial demonstrations cannot be attained, the role of laboratory research in promoting the development will be relatively small. In addition, carbon emission trading can bring considerable benefits to CCS projects and financial resources for the implementation of CCS projects.

Considering the gaps in economic and technological development in different countries, to a certain extent, countries should learn from each other's policies and

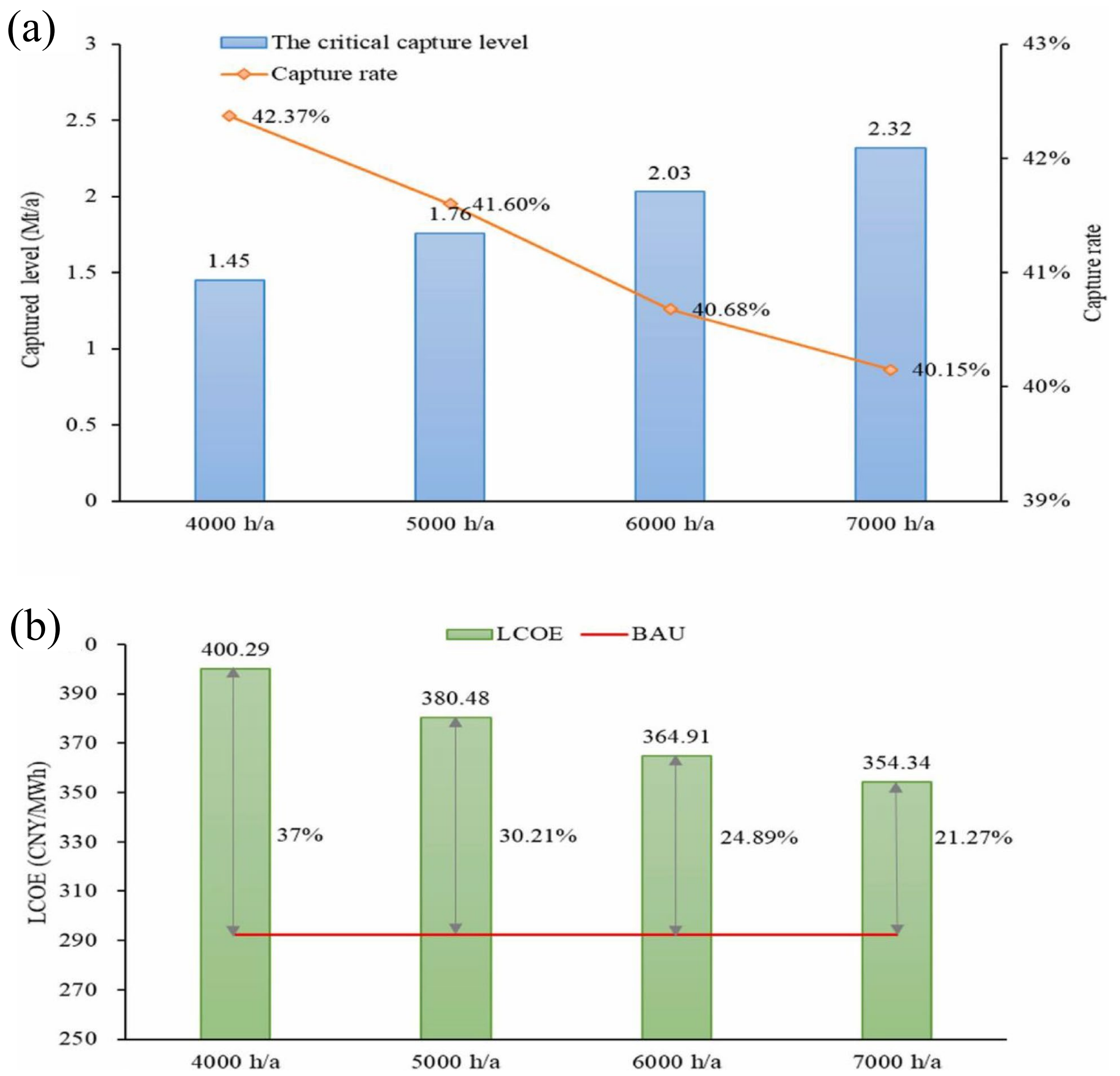


Fig. 6 Critical conditions for emission levels of CFPP retrofitted with CCS (**a**) and gas-fired generators (**b**) with the same power quota(COCE: levelized cost of electricity; BAU: business-as-usual) [61]

practices for CCS. However, they should make corresponding policy adjustments in line with their own development situation and the pressure they can bear. Details are as follows:

(a) Government organizations and countries should develop appropriate laws and regulations for CCS technology. Clarify the responsibilities of all parties, standardize all links, so that all links can be legally abided by, and promote the research and development and commercialization of this technology. CCS technology is a technology involving multi-field and multi-department collaboration [63]. However, in terms of policy legislation, some countries only mention this technology in the fields of energy conservation and emission reduction, clean energy, etc., and there is no special CCS legislation. The existing legal framework of developed energy countries can provide some reference [64].

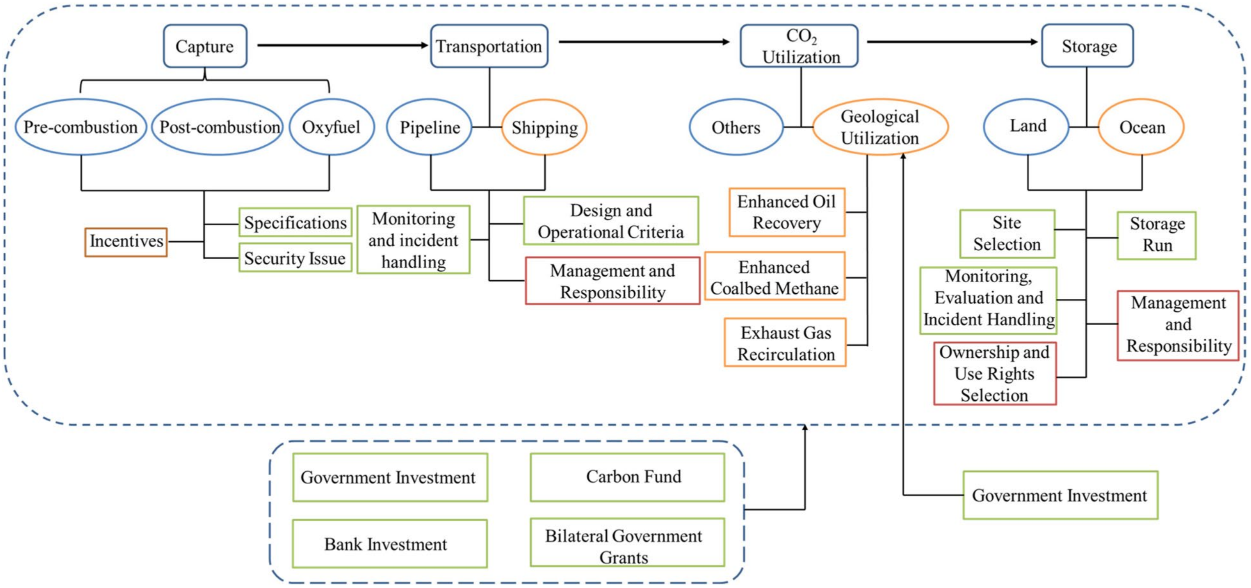


Fig. 7 Framework diagram of CCS policy and regulation requirements (green represents existing relevant standards or regulations, orange represents lack of relevant policies and regulations, and red represents the focus of debate among countries)

(b) In terms of CCS input, it is mainly reflected in the direct special funding support from the government and government support in the sales channels of CCS-related enterprises [46]. It is recommended that the government make stricter regulations on the amount of funds, the objects of funding, and funding links [65]. To give full play to its leading role, it is also possible to learn from the government procurement, power sales policies and other mechanisms adopted by developed countries (such as the United Kingdom and the United States) to expand funding sources and provide financial support for the large-scale commercialization of CCS technology.

(c) In terms of environmental policies, tax incentives can be provided to CCS-related enterprises [61], such as tax-free tax rebates for CCS-related equipment, tax reduction and exemption for important CCS links, etc. Second, take measures to broaden its financing channels [66], such as establishing CCS trust funds, "low carbon foundations", "carbon funds" and so on. Absorb socialized funds to form a financing situation led by the government and followed by socialized funds. Thirdly, a certain reward system (such as the United States) can be set up for CCS technological innovation, so as to increase the enthusiasm of the relevant personnel to develop and promote the project [67].

(d) Given that most of the public is currently not well aware of carbon capture and storage (CCS), there are questions about the potential risks of CCS projects (eg, impacts on the environment, human health) [68]. In terms of information disclosure,, the government should make the access procedures transparent, formulate a clear licensing system, and clarify the regulatory responsibilities of all parties [69]. Potential risks cannot be weakened, and corresponding risk information of CCS must be proactively disclosed to the public, so as to build a public awareness and public support system.

3.2 Reduction of carbon dioxide disposal costs

There are only a handful of countries in the world that implement CCS projects and they are all small-scale exploratory ones because of the cost. In addition, some countries that originally support the development of CCS have lost interests, for example, the Norwegian government. At present, the cost of capture is in the range of 40 $/ton to 80 $/ton and the difference stems from the different investment factors and technologies in different countries. CCS ensures that fossil energy can continue to be used in a “zero-carbon” state while climate change can be mitigated. However, at this moment, carbon sequestration is not economical or even feasible. It is a project that requires government funding galore. A study sponsored by the Carbon Fund shows that the development of the carbon capture and storage can contribute £3 billion to £16 billion cumulatively to UK GDP by 2050 [39].

In practice, the substantial investment and operating costs hinder implementation of CCS projects. Rising oil prices can increase the cost of CO_2 bearing and for oil fields with a certain bearing capacity, for every $10/barrel increase in the oil price, the bearing cost will increase by $2–17/ton. However, less than a quarter of fields can afford a cost of more than $30/ton (capture + compression + transportation costs). From the perspective of the coal power industry, the situation seems to be even bleaker (see Fig. 8a). Under the current conditions, after installation of carbon capture devices in coal power demonstration projects, the operating cost of capturing each ton of CO_2 will increase by an additional US$ 20 to 100 per ton, which will directly increase the power generation costs thus undermining the emission reduction benefits. It also affects commercial interests for CCS demonstration projects.

Under the condition that the running time of each coal-fired unit is not saturated, increasing the cost of CCS technical transformation for coal-fired units will only increase the cost of each unit. A vicious circle is created, the power plant is poorly operated, and the CCS technical transformation equipment eventually becomes an idle asset. From the current situation, coal plants that have not undergone CCS technical transformation are facing the situation that it is more and more difficult to compete with wind energy and solar energy resources. As can be seen in Fig. 8(b), an additional carbon capture cost of $60 per ton, or an eventual increase of $30 per ton as advocates advocate, will further undermine the competitiveness of coal-fired power generation.

Although national CO_2 emission targets beyond 2050 have not been published, budget considerations project global emission to be 1,000 Gt CO_2 in this century, with cumulative emission needed to be close to zero in the second half of the century. If near-term emission follows the Nationally Determined Contributions (NDC) levels, net CO_2 reduction will be required in the second half of the century to be under 1000 Gt CO_2. The low-budget scenarios show that the national 2050 aim of reducing greenhouse gas emission by 80% may be a possible milestone in the context of the global 2 °C target, since the 2050 emission reduction level is nearly as high as the national 2050 goal in these scenarios (see Fig. 9). However, if additional mitigation measures are not adopted after the NDC, the low-budget scenario will be severely inadequate [71]. In most simulation studies, only decarbonization of the energy supply in 2050 is seen in the low-budget scenario.

The technical cost of CCS is divided into capture, transportation and storage. After comparison, the cost of capture and separation is the largest in the three links. Reducing its cost is the focus of future CCS technology research and development. The following costs are the focus of attention:

(1) Capture costs. There are two things to note about the cost of carbon capture: one is the direct cost of the carbon capture process. The second is the loss of enterprise output brought about by the implementation of CCS technology, minus the additional benefits brought by CCS technology [72]. There are three main technical routes for CO_2 capture: pre-combustion capture, oxy-fuel combustion capture, and post-combustion capture [73, 74]. Physical adsorption before combustion is the most promising carbon capture technology. The capture cost accounts for a large proportion of the entire CCS project cost, and is the main direction for reducing CCS costs in the future.

(2) Transportation costs. The modes of transport of CO_2 include pipelines, ships, roads and railways. Among them, pipeline transportation is currently the safest and most effective mode of transportation. Pipeline transportation is generally divided into road and sea, and the cost of onshore pipelines is 40% to 70% higher than that of offshore pipelines of the same scale. In terms of transportation costs, taking pipeline transportation as an example, the costs mainly include pipeline engineering investment and operation and maintenance costs [14]. Due to environmental concerns, pipeline transportation materials need to use materials with strong corrosion resistance. The current high price of anti-corrosion materials also means that material prices will have an important impact on the CCS value chain. The transportation cost of unit CO_2 generally increases with the increase of transportation distance and decreases with the increase of the total transportation volume. Therefore, reducing the transportation distance, increasing the total processing capacity and improving the load operation factor will be the focus of reducing the cost of CCS.

(3) Storage costs. The most studied carbon storage technology is geological storage, which is divided into three carbon storage and storage methods: salt water layer storage, oil and gas layer storage, and gas layer storage [75]. When it comes to carbon sequestration, the number one priority is safety. At present, a large amount of capital is still required to be invested in the cost of technical research [76]. The storage cost per unit of CO_2 varies greatly with the geological conditions of the storage site, and

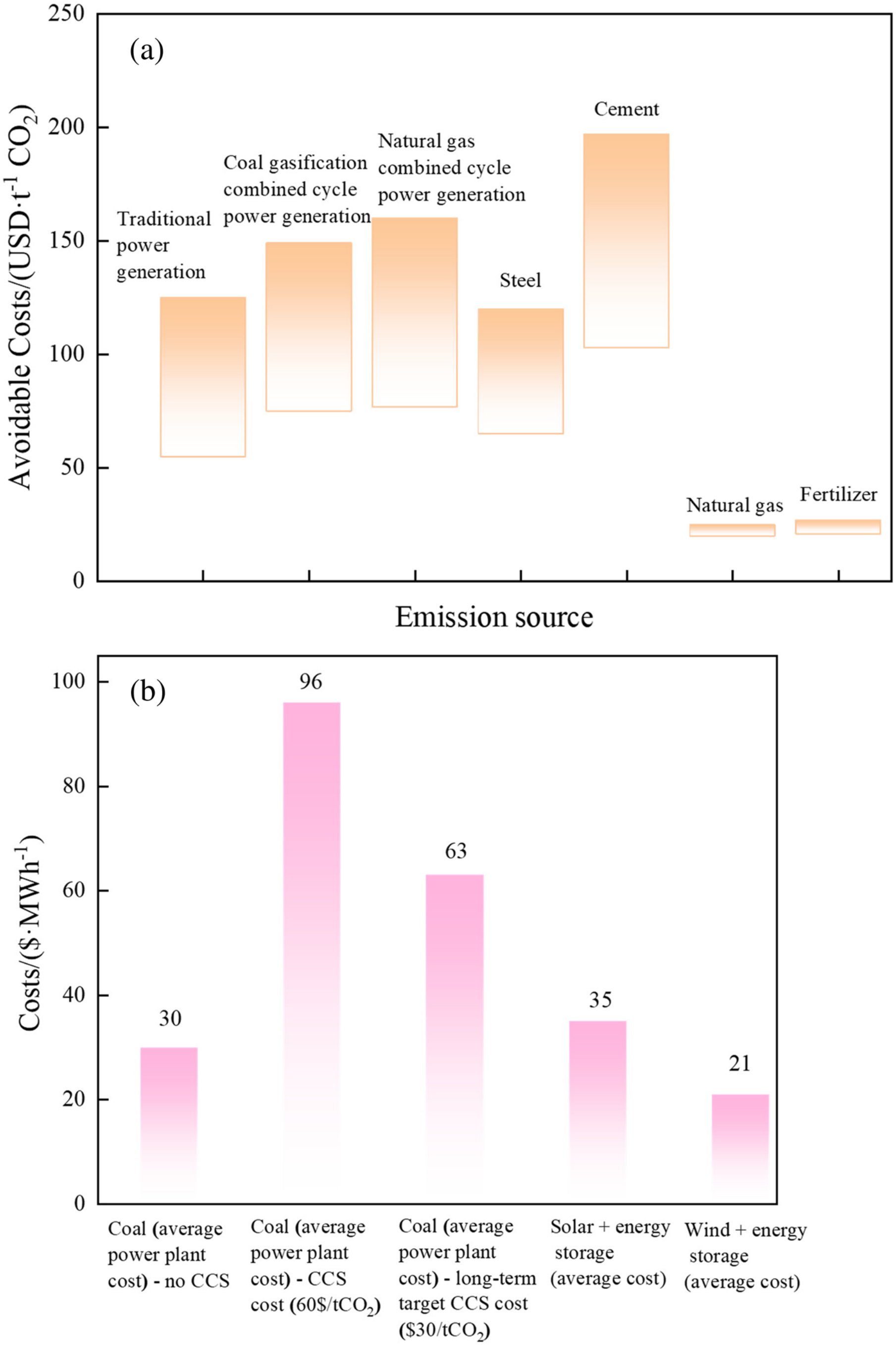


Fig. 8 **a** CO$_2$avoidance costs for different emission sources [70].; **b** Coal-fired power (with or without CCS cost) versus solar and wind power costs. Source: Institute for Energy Economics and Financial Analysis (IEEFA)

generally decreases with the increase of the total storage volume at the same storage site.

(4) Costs due to the evolutionary effect of CCS technologies. Through the analysis of changes in technology costs under various policy scenarios, it is concluded that high-tech development has the most significant impact on the evolution of CCS technology costs [77, 78]. This also means that the high upfront costs will not last forever. With the maturity of the technology and the influence of evolutionary effects, the cost of CCS technology will show a decreasing trend.

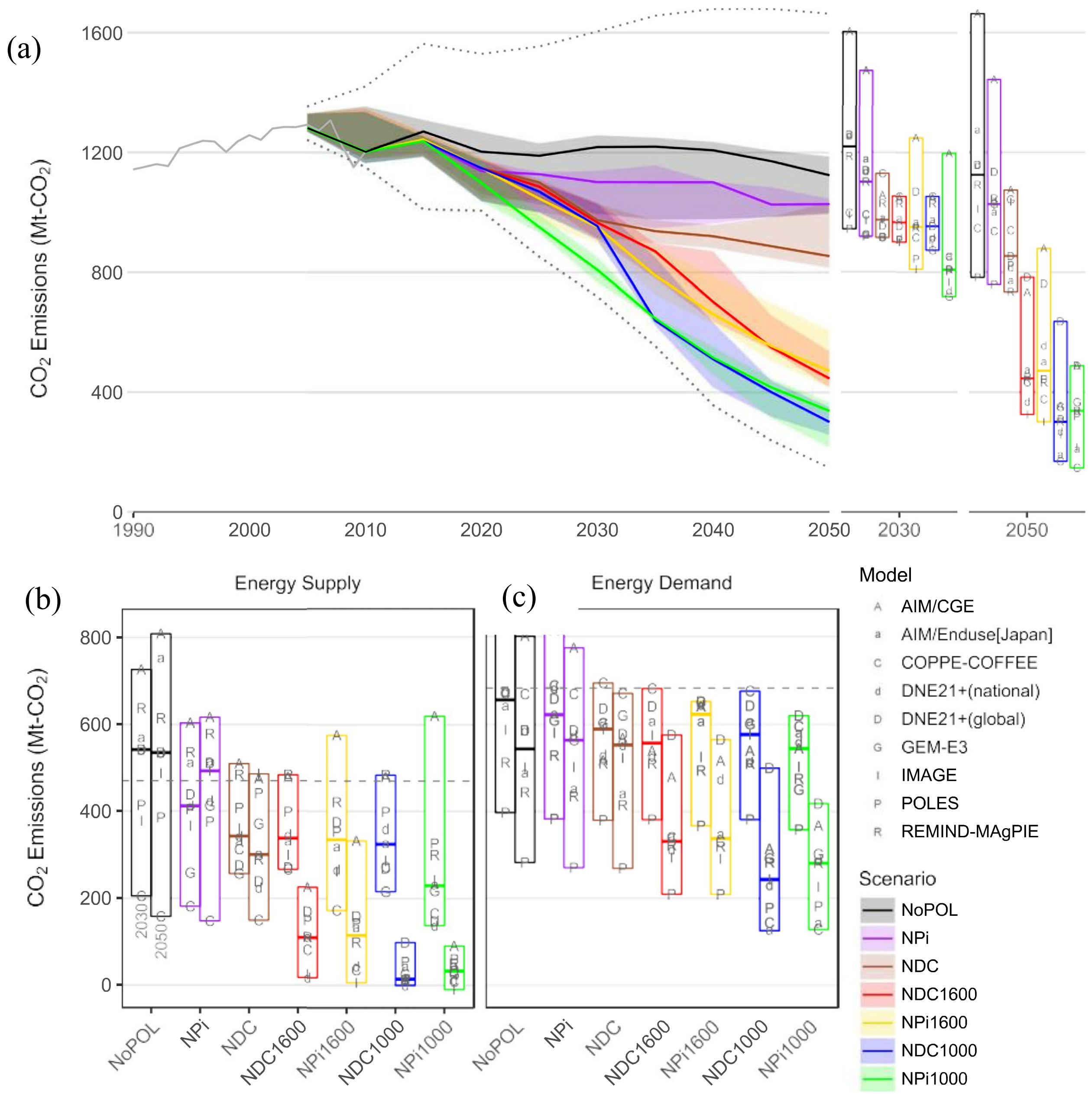


Fig. 9 Carbon neutrality simulation for Japan in 2010–2050: (**a**) Annual CO$_2$ emission from energy and industrial processes in various scenarios (Projected range of annual CO$_2$ emission for 2030 and 2050 shown on the right); Range of direct CO$_2$ emission in each scenario in (**b**) 2030 and (**c**) 2050 compared to 2010 (dashed line) [71]

4 Conclusion

The following issues should be evaluated carefully. The low-budget emission paths create obstacles against quick emission reduction and accompanying energy system transformation. It is also worth noting that expanding the mitigation efforts in 2030 will be difficult because it would necessitate integration of more variable renewable energies (VREs) and reopening of nuclear power facilities. Instead of depending entirely on CCS, the NPi1000 scenario would need to raise low-carbon power production to more than 60% by 2030.

In the latest technology outlook of British Petroleum (BP), CCUS is regarded as an important part of achieving a "2 °C world" at the lowest cost. But its economics are not ideal under the scenario of unrestricted carbon emissions. Combined with an analysis of the power sector, this result suggests that technological advancement alone cannot make CCUS sufficiently competitive to attract substantial investment. Therefore, targeted policy support and effective carbon pricing are also required.

First, the policy must have a clear purpose and be linked to the objectives of CCS investment. In this way, investors can be sure that CCS investments are the result of a policy-linked outcome, rather than an accidental outcome. Policies must be transparent and clear, allowing investors to fully understand and be able to quantify the opportunities and risks created by CCS investment policies under commercial conditions. Investors must be able to more accurately predict the degree to which the return on investment will be affected by policy under future development scenarios. Finally, considering the long-term nature of CCS projects, investors must fully trust that the policy will not change and will not significantly reduce the return on investment of the investment period project. Policy risk is also a key factor in assessing policy stability.

Although CCS is theoretically full of potential, its development has been controversial. One of the main disputes is reflected in the possible security risks of CCS technology. For example, in the capture stage, the environmental impact during the construction and operation of carbon capture equipment and the environmental health and safety risks caused by CO_2 compression. And will increase the consumption of carbon oxides, SO_2 and other chemicals. During the transport phase, CO_2 has global and local effects. The global impact manifests itself in causing global warming. Local effects are reflected in human health, groundwater, and terrestrial and marine environments. In the storage stage, carbon dioxide may lead to affect local climate, destroy regional ecology, pollute groundwater, and even induce earthquakes. These problems and potential risks have not yet found an exact solution so far, which can be said to be the “inherent deficiencies” of CCS technology. How to better overcome these problems is a necessary prerequisite for the widespread promotion of CCS technology.

Strengthen international cooperation and exchange, and enhance the capacity building of human resources. Include CCS as a priority area for support in the framework of multi-bilateral cooperation in science and technology. The CCS will be integrated into the framework of multi-bilateral cooperation in science and technology. Continue to promote the development of multi-bilateral cooperation among countries and organisations to a deeper level, and deepen knowledge sharing and technology transfer. To adopt more effective combinations to promote the deeper development of CCS technology in accordance with the state of national economic development, technological development and policy development. Strengthen the training of high-level scientific and managerial talents, and enhance the training of young and middle-aged talents. Actively build various collaboration and exchange platforms to enhance the innovation capacity of CCS technologies.

In terms of technology development, although a lot of research and development on CCS technology has been carried out in various countries, there are still many technical bottlenecks, such as the overall high energy consumption and cost of capture technology, the integration of oil drive and storage technology needs further research, and the monitoring and evaluation technology system of storage safety has not yet been established. Although a variety of carbon capture technologies have been developed, a variety of conversion routes have been explored, and a variety of storage methods have been demonstrated, most of these technologies are in the laboratory or industrial stage.

Therefore, it is necessary to further strengthen technology research and development to reduce the energy consumption of carbon capture. Continue to develop and promote the application of applicable technologies for CCS in the thermal power, steel and cement industries. Accelerate the research and development of new generation of high carbon capacity, low energy consumption phase change absorbers, catalytic absorbers and other capture absorbers and wear-resistant organic amine loaded adsorbents, calcium-based, sodium-based and other functionalized adsorbent materials. Improve process equipment, supporting multi-step thermal energy utilization technology, develop large flux, high mass transfer efficiency reactor, explore CCS and new energy coupled with negative emission technology, hydrogen energy technology combined with new technology systems and other cutting-edge new technologies. In terms of scale application, given the generally poor scale and economy of carbon utilization technologies at this stage, it is also difficult to break through in the short term. It is suggested that the construction of projects in the field of carbon utilization should be promoted cautiously and steadily, and some small-scale pilot projects can be laid out first, and the possibility of industrial demonstration will be considered after the successful test.

Overall, CCS can effectively reduce carbon emissions from fossil energy combustion and industrial processes, and is one of the key technologies essential for achieving carbon neutrality. As the technology continues to advance, it is expected to form a new industry with technological economy. CCS has become the frontier and competitive field of carbon neutral and green low carbon technology innovation in the international community.

How to improve the speed of CCS construction and operation is an important way for the sustainability of the carbon neutrality goal.

Abbreviations

ACTL: American College of Trial Lawyers; BAU: Business-as-usual; CCS: Carbon Capture and Storage; CCUS: Carbon Capture, Utilization and Storage; CFPPs: Coal-fired power plants; CNOOC: China National Offshore Oil Corporation; CPECC: China Power Engineering Consulting Group Corporation; CSIRO: Commonwealth Scientific and Industrial Research Organization; CSLF: Carbon Sequestration Leadership Forum; ECBM: Enhanced Coal Bed Methane; EOR: Enhanced Oil Recovery; EU ETS: European Emission Trading Scheme; FYP: Five-Year Plan; GDP: Gross Domestic Product; IEA: International Energy Agency; IEEFA: Institute for Energy Economics and Financial Analysis; IGCC: Integrated Gasification Combined Cycle; IPCC: Intergovernmental Panel on Climate Change; LCOE: Levelized Cost of Electricity; LIFE: Sustainable Living; LNG: Liquid Natural Gas; NDC: Nationally Determined Contributions; NZEC: Near-Zero Emissions Coal; TECH: Technology; TPRI: Thermal Engineering Research Institute; UIC: Underground Injection Control; VREs: Variable Renewable Energies.

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Authors' contributions

Shen M. and Kong F.: Conceptualization, Formal analysis, Writing-reviewing and editing; Tong L.: Data curation, Visualization, Writing-original draft preparation, Supervision; Luo Y.: Visualization, Formal analysis, Writing-original draft preparation; Yin S. & Liu C. & Zhang P. and Wang L.: Writing-reviewing and editing; Chu P. and Ding Y.: Formal analysis, writing reviewing and editing. The author(s) read and approved the final manuscripts.

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Availability of data and materials

All data generated or analysed during this study are included in this published article (and its supplementary information files).

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing financial interest.

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