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ORIGINAL PAPER

Water-CCUS nexus: challenges and opportunities of China's coal chemical industry

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Abstract Carbon Capture and Storage (CCS) technology has begun to transform into the boom of CO_2 utilization technology, which is of great significance to China considering its coal-based primary energy mix. CO_2 utilization technology can be divided into three categories, i.e., CO_2 geological utilization (CGU), CO_2 chemical utilization, and CO_2 biological utilization. In this paper, first, the development status of the different utilization technologies in China is introduced, and then, the situation, distribution, and water characteristics of China's Coal Chemical Industry (CCI, i.e., an industry to convert coal to synthetic fuel and/or chemical products) are analyzed in detail. Subsequently, utilization technologies suitable for China's CCI are proposed combining water consumption of CCS technology. The results of this research led to the following conclusions: (1) CO_2 utilization technology is undoubtedly the best choice for the CCI; (2) CGU technologies are viewed as the best choices for the coal chemical industry, with supplementary, small-scale chemical utilization of three wastes, i.e., waste gas, wastewater, and industrial residue; (3) The CO_2-Enhanced Oil Recovery (EOR), CO_2-Enhanced Uranium Leaching (EUL), CO_2-Enhanced Coal Bed Methane recovery (ECBM), and CO_2-Enhanced (Saline) Water Recovery (EWR) technologies show great promise, and CCI preferentially uses the option with low water consumption, such as CO_2-EWR. However, as the carbon market matures, CO_2-EOR will become the first priority.

Keywords CO_2 geological utilization · Emission reduction · CO_2-EWR · Coal · Water shortage · CO_2 capture, utilization, and storage (CCUS)

Introduction

With the increasing pressure for the global reduction of CO_2 emissions, CO_2 Capture and Storage (CCS) technology is generally discussed in term of carbon sequestration to reduce CO_2 content in atmosphere and it is widely cited as a mitigation technology of greenhouse gases. With the development of CCS technology, many issues including cost and risk have been emerging constantly; however, CCS technology has begun to transform into the boom of CO_2 Capture, Utilization, and Storage (CCUS) technologies, which also have the potential to achieve large-scale reductions in CO_2 emissions in future decades. The international community is beginning to pay more attention to CCUS, and governments are actively planning and conducting research on CCUS technologies as well as designing and constructing demonstration projects (Xie et al. 2013; Zhang et al. 2015). However, CCUS technologies are still in the early stages of development and demonstration, and many issues remain to be addressed, including high energy consumption, high costs, and the security and reliability of long-term storage (Ingwersen et al. 2014; Wang and Peng 2014). Therefore, it is important that CO_2 utilization technologies be developed that would foster CO_2 emission reduction in the real sense (ACCA21 2014; Ng et al. 2012). In past few decades, the international community has begun to pay increasing attention to research related to various CO_2 utilization technologies and their potential applications associated with the CO_2 emission reduction efforts (ACCA21 2011; Ranjith and Perera 2012). These CO_2 utilization technologies include CO_2-enhanced oil recovery

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technology (CO_2-EOR) (Yang et al. 2012; Pang et al. 2012) and CO_2 and methane reforming to produce synthesis gas and biomass (Vishal et al. 2013; Yang et al. 2009). To this end, international organizations, academics, and industry practitioners have planned, demonstrated, developed, and deployed processes for the utilization of CO_2 (GCCSI and Parsons Brinckerhoff 2011; Xie et al. 2013).

China is a major consumer of coal, and its consumption in 2013 was more than 1900 Mt (OECD/IEA 2013). The worldwide increase in CO_2 emissions is considered to have a significant role in global climate change. The Chinese government has paid close attention to the development of CCS (ACCA21 2011, 2014), but it is also aware of the associated risks (Lei et al. 2015; He et al. 2011) and economic issues (Kravanja et al. 2015). These risks and issues include the massive investments required, the uncertain and indirect economic benefits, and various obstacles that CCS projects continue to encounter. Therefore, the utilization issues after capture are proposed, which gain the international peer recognition (CSLF 2011). CO_2 utilization technology has great significance to energy security, improvement of the environment, alleviating resistance to the reduction of CO_2 emissions, providing a new economic growth point, and the enhancement of international competitiveness (ACCA21 2014). In addition, it is fully in line with the actual situation in China. China has attached great importance to strategic planning and implementation related to the development and implementation of CO_2 utilization technology (ACCA21 2011, 2014). Current research activities related to the development and demonstration of this technology currently depend on the government's guidance, business-oriented implementation, and the research conducted by various institutes and universities. To date, CCS technologies and the concept have been around for decades, and the research activities related to CO_2 utilization technology have emphasized on basic research to a significant extent except for CO_2-EOR technology, which has been practiced in China for a long time since the 80–90s (Xie et al. 1997; Zhang et al. 1988).

China's resource endowment, with the characteristics of "more coal, less oil, and poor gas," underlines the necessity for extensive development activities in the coal chemical industry (CCI, i.e., an industry to convert coal to synthetic fuel and/or chemical products). However, as an important component of China's coal industry, the production issues in the coal chemical industry, with its high carbon emissions and water consumption, have caused a series of environmental and social problems. Thus, developing and using CO_2 utilization technology must be an inevitable choice for sustainable development. Definitely, in the whole range of CCUS technologies, the consumption of additional resources, such as large amounts of water resources, is inevitable, which will further hinder the development of coal-fired power plants and the coal chemical industry in the arid regions. Therefore, the selection of CCUS technologies which are fit for coal (chemical) industry is so essential. In this paper, first, we present the current situation of China's coal chemical industry. Then, the issues concerning CO_2 utilization technology are analyzed and discussed in detail. Finally, several CCUS technologies are proposed for application in China's coal chemical industry.

CO_2 utilization technologies in China

The term "CO_2 utilization technology" refers to the industrial and agricultural technologies that use the physical, chemical, or biological functions of CO_2 to produce products that have commercial value, thereby reducing the overall total of CO_2 emissions to the atmosphere. According to different disciplines (principles), CO_2 utilization technology can be divided into three categories, i.e., geological utilization, chemical utilization, and biological utilization. These three categories cover energy mining (Xu et al. 2015) and synthesis, the enhancement of resource mining, chemical synthesis, the production of consumer goods, and many others (Table 1) (ACCA21 2014). Only a few of the CO_2 utilization technologies, in particular CO_2 geological utilization, in China have been commercialized, and the current emphasis is on basic research.

In geological utilization terms, only the technologies of CO_2-EOR and CO_2-EUL have approached or reached the level of commercial applications. CO_2-ECBM technology is in the pilot stage, and a demonstration project is under construction. Other technologies are still in their early stages of development (ACCA21 2014). In chemical utilization terms, several technologies have achieved commercialization, including the use of ammonia to convert CO_2 to urea, the use of sodium chloride to convert CO_2 to soda ash, and the use of alkylene oxide to convert CO_2 to polycarbonate and salicylic acid. In biological utilization terms, the technology in which microalgae fix CO_2 into bio-fertilizer (CO_2-AF) has entered the pilot-scale stage, and the construction of a demonstration project is underway; most of the other related technologies are still in the early research stage (ACCA21 2014).

There are many carbon sources distributed throughout China, with diverse geological conditions and completed industrial infrastructure; various utilization technologies exist in regions or industries for implementation in good condition (Liu and Li 2014; Zeng et al. 2013). At present, the thermal power industry, steel industry, cement industry, and coal chemical industry are the primary industries, and they are known to have "three highs," i.e., high energy consumption, high pollution, and high CO_2 emissions. Their total CO_2 emissions account for more than 90 % of the total

Table 1 Classification of CO_2 utilization technologies

Classification	Application fields	Technologies/target products
CO_2 geological utilization (CGU)	Energy	CO_2-enhanced oil recovery (CO_2-EOR)
		CO_2-enhanced coal bed methane recovery (CO_2-ECBM)
		CO_2-enhanced gas recovery (CO_2-EGR)
		CO_2-enhanced shale gas recovery (CO_2-ESGR)
		CO_2 enhanced geothermal systems (CO_2-EGS)
	Resource	CO_2-enhanced uranium leaching (CO_2-EUL)
		CO_2-enhanced (saline) water recovery (CO_2-EWR)
CO_2 chemical utilization (CCU)	Material	CO_2 to polymers directly (CO_2-CTP)
		CO_2 to isocyanate/polyurethane indirectly (CO_2-CTU)
		CO_2 to polycarbonate indirectly (CO_2-CTPC)
		CO_2 to vinyl polyester indirectly (CO_2-CTPET)
		CO_2 to poly ethylene succinate (CO_2-CTPES)
	Energy	CO_2 reforming of methane to syngas (CO_2-CDR)
		CO_2 to liquid fuel by carbon monoxide (CO_2-CTL)
	Organic chemicals	CO_2 to methanol with hydrogen directly (CO_2-CTM)
		CO_2 to dimethyl carbonate (CO_2-CTD)
		CO_2 to formic acid (CO_2-CTF)
	Inorganic chemicals	Direct steel slag mineral carbonation and utilization (CO_2-SCU)
		Indirect steel slag mineral carbonation and utilization (CO_2-ISCU)
		Phosphogypsum mineral carbonation and utilization (CO_2-PCU)
		Potash feldspar mineralization (CO_2-PCM)
CO_2 biological utilization (CBU)	Energy	Algae to biofuel or chemicals (CO_2-AB)
	Consumption goods	Algae to fertilizer (CO_2-AF)
		Algae to food/feed additives (CO_2-AS)
		CO_2 gas fertilizer (CO_2-GF)

CO_2 emissions. Thus, CO_2 utilization technologies, depending on the outcomes of their demonstration projects, have the potential for a huge role in these industries. In recent years, Chinese enterprises have undertaken positive activities and developed several approaches with respect to CO_2 utilization, including CO_2-EOR, CO_2 chemical utilization (CCU), carbon sequestration with microalgae, and others (ACCA21 2014). Particularly in the field of CO_2-EOR, a series of demonstration projects have been undertaken, such as the Sinopec Shengli Oilfield EOR Project and the PetroChina Jilin Oilfield EOR Project (Li et al. 2013b; Liu et al. 2014; Lv et al. 2015; Yang et al. 2014).

Analysis of the characteristics of the coal chemical industry

Distribution characteristic

Coal is the primary source of energy in China, and the quantity of its coal resources has been estimated to be about 5.56 trillion tons, with currently proven reserves of approximately one trillion tons, accounting for 11 % of the total world reserve (TCG 2010). The overall geographical distribution pattern of China's coal is rich in the north and west and poor in the south and east. The six northern provinces of Shanxi, Shaanxi, Inner Mongolia, Ningxia, Xinjiang, and Heilongjiang contain approximately 79 % of the total reserves. The Climate Group (TCG) (2010) reported that China's dependence on coal made it imperative to achieve both clean coal power generation and the comprehensive clean utilization of coal in China. These cleaner approaches to the extensive utilization of coal are more suitable for China's national condition than traditional coal combustion. Based on China's national energy development strategy, the coal chemical industry will be a crucial option to ensure national energy security. Currently, there are more than 700 coal chemical plants operating in China, and the number will continue to increase in the future. These plants include plants that convert coal to ammonia, coal to methanol, coal to oil, coal to gas, and some others, and the annual cumulative emissions of CO_2 from such plants are approximately nine billion tons.

During the "twelfth five-year plan" period (2011–2015), 14 large "coal bases (i.e., massive industrial complexes)" are given priority for construction (Song 2013). In the upstream and downstream industry chains of these bases, the coal chemical industry has become a significant branch. Fifteen coal chemical demonstration projects also have been planned and constructed during the twelfth five-year period. From the perspectives of the projects' scales and their water demand, Xinjiang, Inner Mongolia, Shaanxi, Shanxi, and Ningxia have been identified as China's primary coal chemical industry bases (Song et al. 2012). In 2010, a significant strategic concept was proposed that consisted of developing and constructing the "Energy Golden Triangle" (EGT) of Ningdong–Erdos–Yulin (Fig. 1), the industrial belt of the Great Western Development, connecting the East and the West. The EGT has had significant impacts on the economies, societies, and environments of the associated provinces (Liu and Liu 2011). The data show that there are 351.4 billion tons of proven coal reserves in the EGT, accounting for approximately 26.2 % of the total proven reserves in China (Zhang et al. 2013). Due to this significant resource advantage, many projects are in operation or under construction, and they are predominantly related to the coal power and coal chemical industries.

Coal, which is an abundant resource in Xinjiang, also is a significant pillar industry. In order to accelerate the pace of the energy strategy relocated to west, Xinjiang was identified as the fourteenth largest coal base in the "twelfth five-year plan". In the future, Xinjiang will become one of the regions with the most-concentrated and largest-scale coal power and coal chemical industries. According to current plans, five additional bases for developing and processing coal reserves will be built by 2020, including bases in Eastern Junggar, Turpan–Hami, lli, Kuqa-Bay, and Hefeng–Karamay (Hu 2012). Among the 15 coal chemical demonstration projects planned during the "twelfth five-year plan" period, four projects are planned in Xinjiang, including, in Eastern Junggar, a coal electric integration project of 34.9 billion m^3/year and a comprehensive coal

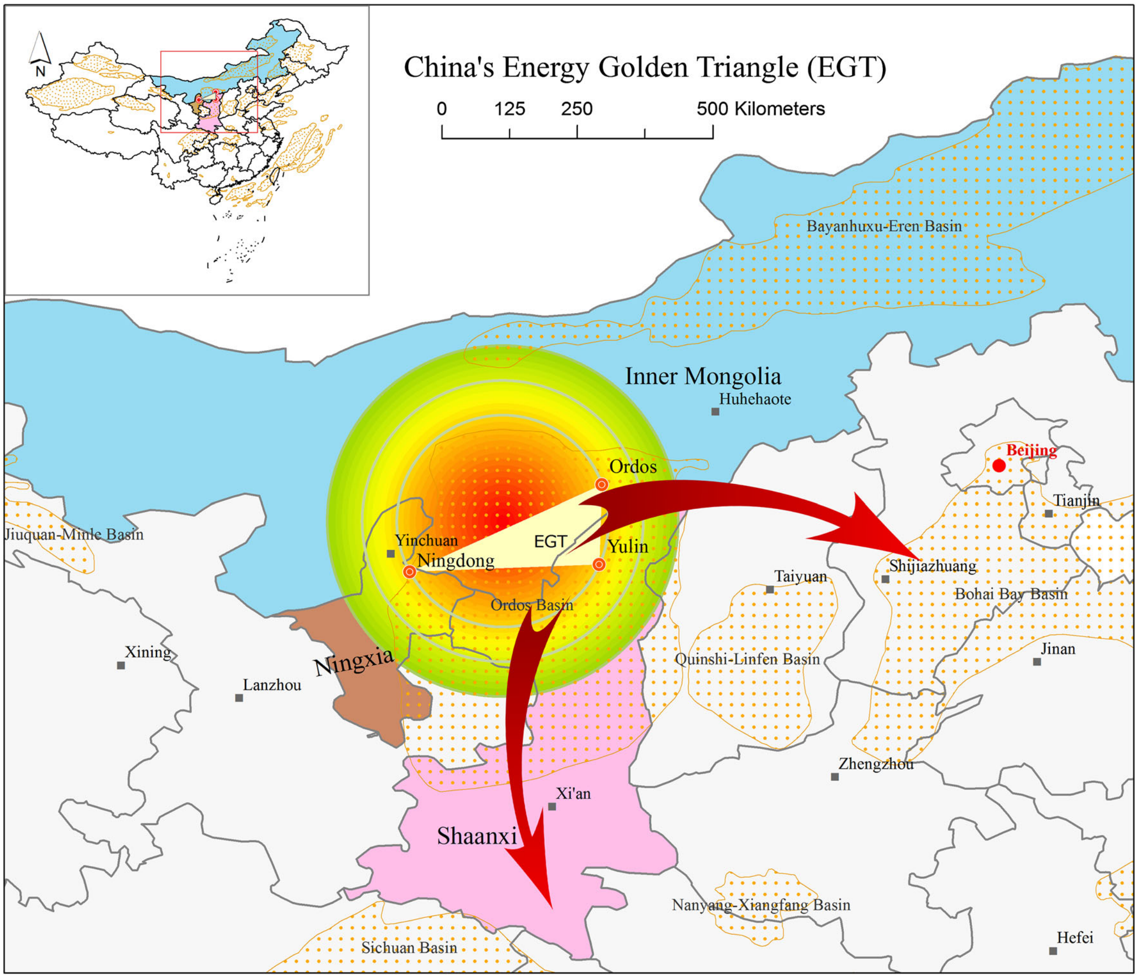

Fig. 1 Location map of China's Energy Golden Triangle

utilization of 500,000 tons/year and, in lli, a coal to gas conversion project to produce 5.5 billion m^3/year and a coal electric integration project to produce 6 billion m^3/year.

Water resource characteristics

The distribution of coal bases and water resources is highly incompatible. The coal resources exist mostly in the north and west, whereas the most abundant water resources are elsewhere (Huazhong University of Science and Technology et al. 2014). Apart from the Yunnan–Guizhou coal base, which has relatively abundant water resources, the other bases are certain to encounter varying degrees of water shortages (Li et al. 2013c, 2015). Table 2 (Song et al. 2012) shows that, by 2020, the water demands of the coal bases at Shendong and Ningdong will exceed the available supplies by about 623,000 and 998,000 m^3/d, respectively. Therefore, availability and utilization of water remain key issues because they pose constraints on the development of coal bases, particularly on coal chemical industry with high water consumption in the arid northwest region of China.

As an example, Xinjiang, which belongs to the fourteenth large-scale coal base, will become the target area of the westward shift of the coal industry in the future, but its water resources will not be adequate for the expected the economic development and distribution of mineral resources. In Xinjiang, the distribution pattern of water is that there is an abundant supply in the north, a poor supply in the south, and a scarce supply in the east (Water Resources Department of The Xinjiang Uygur Autonomous Region 2015). Among the five coal chemical bases, the Eastern Junggar, Turpan–Hami, and Hefeng–Karamay bases have considerable anomalies between the supply and demand for water resources (ACCA21 2014).

In Eastern Junggar, the surface water resource is 1.265 billion m^3, and groundwater resource is 393 million m^3. Currently, the surface water utilization rate has exceeded the warning level. In addition, a very large depression cone has emerged in this region due to the over-exploitation of groundwater. The Kuitun-Ussuri region, located at the southern edge of the Junggar Basin, has experienced a declining groundwater level, with a drop out value of 2.20–6.98 m and a descent rate 0.314–0.811 m/a. In the east, a depression cone of approximately 95 km^2 has emerged in Kuitun City, and the average annual decline is 0.698 m (Guo and Liu 2012). If this condition continues uncontrolled, the groundwater inevitably will be depleted. In addition, a series of ecological and social issues also will be triggered, including the death of vegetation, desertification of the soil, and reductions in the fertility of the soil and the production of crops. Therefore, the existing water resource cannot support sustainable economic and social development (Hu 2012). According to the document entitled "Function Layout and Overall Planning of Coal Power and Coal Chemical Industrial Belt in Eastern Junggar," the demand for water will reach 921 million m^3 in 2020, when the available water supply will be only 200 million m^3, as shown in Fig. 2.

Product category and water consumption

The coal chemical industry uses coal as a raw material and converts it to gaseous, liquid, and solid fuels and other chemicals by chemical processing. This industry can be divided into two segments based on their end products, i.e., the traditional coal chemical industry and the modern (new energy) coal chemical industry (Fig. 3) (Pei 2011). As early as the 1940s, China began to develop its traditional coal chemical industry, but the scale was rather small, and the products generally included only coke, synthetic ammonia, calcium carbide, and methanol. In recent years, however, the traditional coal chemical industry has undergone significant changes at a relatively rapid pace due to the upgrading of the technical equipment, the increasingly mature markets, relatively low capital investment, and other factors, including overproduction. Driven by high oil prices and economic demands, the modern coal chemical industry has developed rapidly, and, while it is based on the traditional coal chemical industry, it has fostered the clean utilization and the high-efficiency conversion of coal (Li 2013). In recent years, this industry has produced some significant breakthroughs, including coal liquefaction, the production of synthetic oil, the conversion of coal to gas, the conversion of coal-based methanol to olefins, and the conversion of coal to glycol (Wang 2012).

Table 2 Water supply and demand of national planning mines in coal bases in 2020

Coal base	Planning scale (10^4 t/a)	Planning water demand (10^4 m^3/d)	Water supply capacity (10^4 m^3/d)	Water demand gap (10^4 m^3/d)
Shendong	18,500	136.46	74.2	62.26
Huanglong	6590	12.4	5.95	6.45
Ningdong	6300	102.75	3.0	99.75
Shanbei	5800	40.58	–	40.58

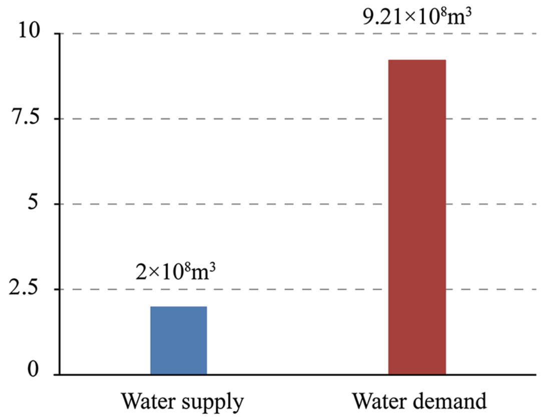

Fig. 2 Water supply and demand in Eastern Junggar by 2020

However, even though the rapid development of the coal chemical industry has been good for China's economy, some practical issues also must be recognized, such as protecting the environment and water resource constraints. It is undeniable that the coal chemistry industry consumes tremendous amounts of water and produces high carbon emissions (Hu 2012; Ren 2014). For example, in the coal to olefins project, the ratio of tons of CO_2 emissions to tons of olefins produced is 9.6/1, indicating that the mass of the CO_2 emissions produced was almost a factor of 10 more than the production of olefins. For the project in which synthetic ammonia and coal were concerted to dimethyl ether, the water consumption was up to 14 tons per ton of product (Table 3) (Pei 2011). The blind exploitation of the available resources will inevitably result in adverse effects on the green, low-carbon economy and produce irreversible adverse effects on the local water supply. Therefore, CO_2 utilization and water resource planning should be considered carefully in order to promote the healthy and steady development of the coal chemical industry (Song et al. 2012).

Industrial process of typical coal chemical industry

Coal liquefaction technology, a primary representative of the clean conversion of coal, refers to using solid coal as a raw material and, using a series of chemical processes, converting it to liquid oil products, such as diesel fuel, naphtha, liquefied petroleum gas, and other chemical products. This approach helps solve some of the environmental issues associated with coal consumption, such as the emissions of CO_2, SO_2, and particulate matter, thereby accomplishing the dual goals of low carbon emissions and the clean use of the available coal resources (Trautmann et al. 2015; Zhuang et al. 2015). Depending on different processing approaches, the coal liquefaction process can be divided into two categories, i.e., direct and indirect coal liquefaction. This section describes an example of the direct coal liquefaction process in which pretreated coal (coal that has been washed, milled, and dried) is mixed with recycled solvent to make an oil-coal slurry that can be pumped at certain temperatures (420–470 °C) and pressures (6–30 MPa). Then, the slurry is reacted with hydrogen in the presence of a catalyst, producing both liquid and gaseous products, the latter in small amounts (Wu 2013).

In the 1930s, direct coal liquefaction was commercialized in Germany, but the oil crisis in the 1970s promoted the development of modern direct coal liquefaction technology at a pilot plant scale that consumed coal at the rate

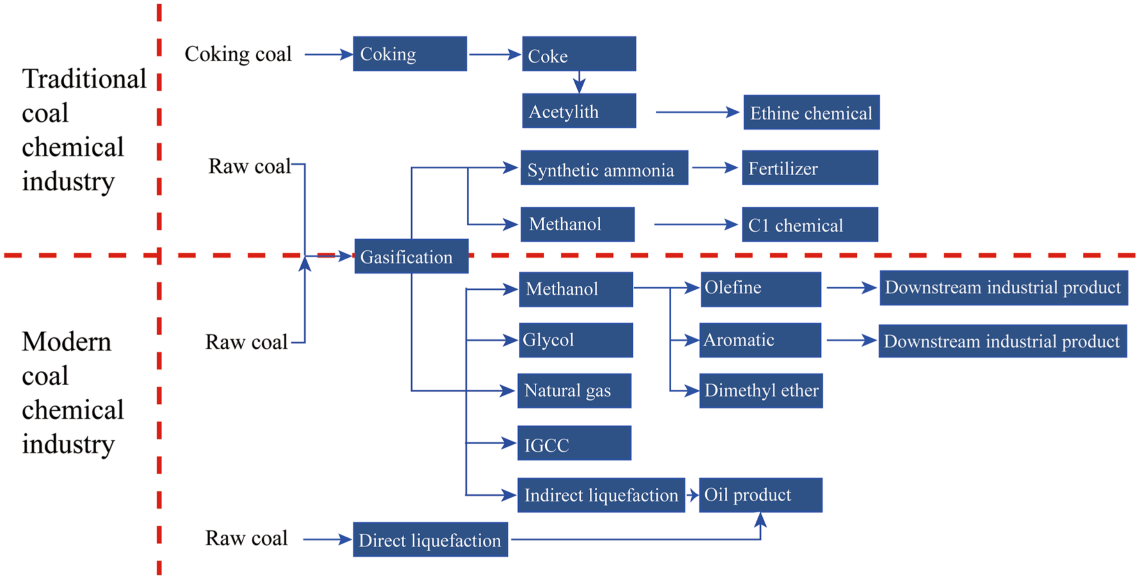

Fig. 3 Coal chemical industry: traditional versus modern

Table 3 Water and coal consumption and CO_2 emission in China's coal chemical industry

Type of coal chemical industry	Coal consumption (t/t)	Water consumption (t/t)	CO_2 emissions (t/t)
Indirect coal to oil	4.03	12	5.28
Direct coal to oil	3.8	7	3.36
Coal to olefin	5.1	10	9.6
Coal to gas	3.05	10	2.7
Coal to methanol	1.55	4.5	3.2
Coal to glycol	3.25	6.5	2.56
Synthetic ammonia	1.7	14	3.68
Coal to dimethyl ether	3	14	6.4

of 600 t/d. The first large-scale, commercialized coal liquefaction plant in the world was built by the Shenhua Group in Erdos, Inner Mongolia (Fig. 4) (Li et al. 2013a). The plant used the Shenhua direct coal liquefaction process, and the designed processing capacity of dry coal was 6000 tons/day. The plant was capable of producing one million tons/year of liquefied oil, 102,100 tons/year of liquefied gas, 249,900 tons/year of naphtha, and 714,600 tons/year of diesel fuel (Wu 2013).

Water consumption of CCUS

Water consumption in capture process

Rather than being a single technology, CCUS is an integration of multiple technical processes and a family of technologies, including capture and compression technology, transportation technology, and storage technology. Among these, the highest costs and the largest water consumptions are associated with the capture technology. TCG (2010) reported that the costs associated with the capture technology account for approximately 80 % of the entire cost of CCUS. Also water consumption differs depending on the type of business, the capture technology used, the operation of the plant (process and cooling water), and energy efficiency. Figure 5 shows that, after plants were equipped with capture technology, the consumption of water increased by 50–90 % compared to traditional plants without CCUS (Newmark et al. 2010; Zhai and Rubin 2011).

Water consumption in a CCUS project

The Gorgon CCUS project in Australia is the world's first industrialized CO_2-EWR project. The Gorgon is exemplified in this paper for the other stages besides the capture process to keep the integrity of the water consumption analysis of CCUS technology after "Water consumption in capture process" section. The plan is to inject CO_2 separated from a liquefied natural gas (LNG) plant into deep saline formations using eight to nine injection wells, and

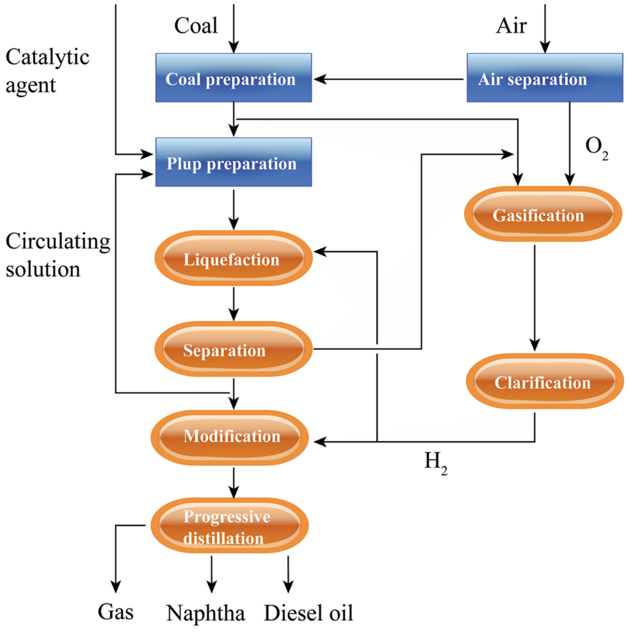

Fig. 4 Flow diagram of coal direct liquefaction in the Shenhua Group, China

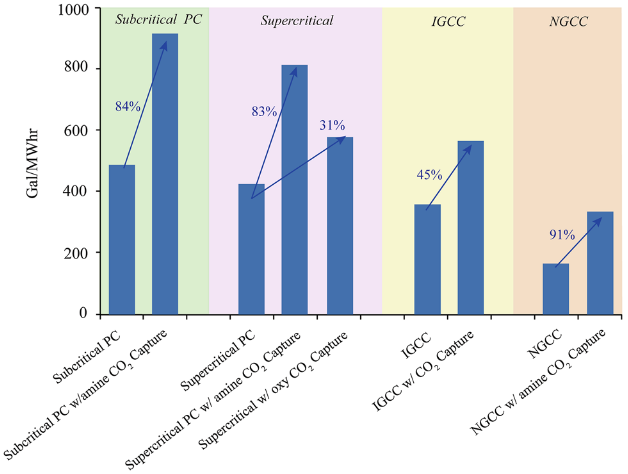

Fig. 5 Water requirements in fossil fuel power plants with or without a CO_2 capture process

the plan calls for four pumping wells to manage the pressure in the reservoir and to extract deep saline water to meet the water demand during the project's construction and operational periods (Flett et al. 2008).

Figure 6 shows the water demand and supply in the Gorgon project during the construction and operating periods (including the construction period from 2010 to 2015 and the operating period from 2015 to 2050) (Chevron 2010). In the operating period, the amount of CO_2 emissions will stabilize at approximately 4 million tons per annum (Mtpa). The largest storage capacity is 3.4 Mtpa, and the average amount is 3.1 Mtpa. Figure 6 shows that the demand for water at the beginning of the construction was so large that the combination of treated wastewater and the water available after the treatment of saline water with a reverse osmosis process cannot meet the demand. However, after that, the demand for water was reduced, and the demands for day-to-day living and the plant's production demands could be met. In terms of the operational period, the demand for water basically was stable at 960 m^3/d, while the capacity of the daily water supply was 1500 m^3/d; thus, the available supply was quite adequate for meeting the demands imposed by normal living and the plant's production.

A predicament analysis of the water–energy–climate change nexus in the coal chemical industry with CCUS in China

Possibility and feasibility analysis of CO_2 utilization

Global oil resources are always expensive, and neither China's resource endowment, i.e., more coal, less oil, and poor gas, nor the increasing demand for energy for the production of chemical products is likely to change in the foreseeable future. Therefore, the coal chemical industry has a promising prospect (Pei 2011), but it also must be noted that, in the process of converting coal into low-carbon terminal energy and other products, large amounts of CO_2 will be emitted. Taking as an example a project that converts a million tons of coal per year, the amount of CO_2 emissions will amount to millions of tons, perhaps exceeding 10 million tons for all of the conversion routes, with the coal to chemical and coal to olefins processes producing the most CO_2 emissions (Ren et al. 2009). Based on the detailed analysis in "Analysis of the characteristics of the coal chemical industry" section, coal chemical plants face severe water shortage challenges and also can expect great pressure to reduce the CO_2 emissions from the coal conversion process. How to accomplish the desired reductions has become a major impediment that restricts the further development of coal conversion technologies.

TCG (2010) noted that combining CCUS with the coal conversion field could stimulate the development of CCUS in China. Considering the technology benefits and the cost of the application, CO_2 utilization technology undoubtedly is the best choice for the coal chemical industry, because it can dispose of CO_2 effectively, thereby alleviating the tremendous pressure to reduce CO_2 emissions. In addition, the process may turn waste into treasure. Some valuable products are also produced, creating economic and social benefits. Some CO_2 utilization technologies may generate the primary resources needed by the coal chemical industry. For instance, among the geological utilization technologies, the CO_2-EWR technology stores CO_2 into deep saline aquifers and produces fresh water after desalination, which is a scarce resource in the coal chemical industry and/or in the arid regions, to meet industrial and agricultural demands (Li et al. 2013c, 2014). For the conventional

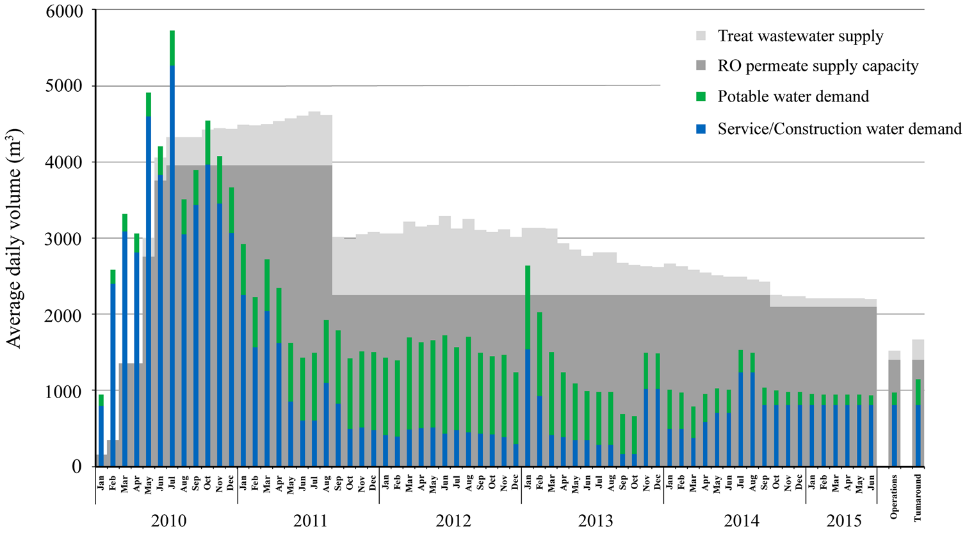

Fig. 6 Estimated water requirements and possible water supply in a typical CCUS project: Chevron's Gorgon LNG project in Australia

coal fuel combustion process, the cost of capturing the CO_2 will be unrealistically high due to the low volume fraction of only 3–15 % of CO_2 in the flue gas (Ren et al. 2009), whereas coal chemical plants generally emit high purity CO_2, which greatly reduces the cost of capturing the CO_2 and facilitates the following CO_2 utilization technology so that it runs smoothly at less cost.

There is a wide spatial distribution of CO_2 emissions from large point sources in China. This fact, along with the diverse geological conditions and extensive industrial base, creates a good condition for the implementation of various CO_2 utilization technologies (Li et al. 2013c; Liu and Li 2014). For example, considering geological utilization, there are many sedimentary basins distributed throughout the land and on the continental shelf, and they have extensive areas, thick sediment layers, and huge volumes of saline aquifers for CO_2 storage. In addition, these basins are located near coal chemical industry, particularly in the north and northwest. Other geological reservoirs, such as depleted oil and gas fields and non-mined coal beds, also are located near the large-scale carbon sources from the coal chemical industry.

Considering the advantages mentioned above for the reduction of carbon emissions and the lower cost, lower risk, additional benefit, and good geological conditions, CCUS may be a suitable and applicable option for the coal chemical industry (ACCA21 2014).

Superiority of geological utilization for the coal chemical industry in contrast to chemical and biological utilization

Overall, there is a wide variety of CO_2 utilization technologies that have the following characteristics, i.e., cross-industry, cross-disciplinary, cross-cutting, internationalization, high level of socialization, high investment, and uncertainty of expected return. Thus, different technologies have different features, advantages, and disadvantages. Geological utilization is suitable mainly for central, west, and northwest China. Chemical utilization and biological utilization can be used primarily in eastern and southern China, with good geographical complementarity and sound source-sink matching.

According to technical principles and classification, geological utilization has the following characteristics, i.e., huge reduction potential; great production potential; high maturity of the technology; good match with large-scale carbon resources; long development period; restriction by geological and geographical conditions, matching of sources and sinks; poor technical economy; complex relationships with other underground resources; and long-term safety. Chemical utilization has the following characteristics, i.e., insensitive to the costs associated with CO_2 capture and ease of achieving the utilization of CO_2 emission sources in situ. This kind of technology is a primary means of achieving CO_2 waste utilization and providing a production roadmap for cleaner chemicals. Biological utilization has the following characteristics, i.e., benefits people's livelihoods; enhances photosynthesis; low efficiency and high energy consumption; requires a large area and high water consumption; and not limited by the concentration or purity of the CO_2.

As mentioned above, the coal chemical industry has high CO_2 emissions and high water consumption, whereas China's coal resources are not co-located with its water resources, which is a serious obstacle to the development and productivity of the coal chemical industry (Ren 2014). Therefore, using a technology that has high water consumption undoubtedly will have a detrimental effect on the coal chemical industry. According to the various characteristics of utilization technologies mentioned above, biological technologies consume more water than the other two types of technologies. Therefore, these technologies should be the first one we exclude. Chemical utilization can combine wastewater, waste gas, waste residue, and other wastes discharged by the coal chemical industry effectively to form the comprehensive utilization of industrial chain. For example, according to the results of the material balance for the coal chemical production process, both nitrogen from the air separation unit and hydrogen generated by the conversion can be taken as raw materials to produce ammonia; then, the ammonia reacts with the CO_2 emitted by the denitrification of the raw gas to produce urea. In this way, a complete industrial chain can be formed for the utilization of the various inputs and intermediates in the coal chemical process (Ma and Ma 2013). However, it should be noted that, for a mature chemical utilization technology, the amount of CO_2 utilized is too limited to be considered for large-scale reduction. Consequently, it has a less significant effect on the coal chemical industry that has high CO_2 emissions (Yang et al. 2009). Therefore, among the three types of utilization technologies, geological utilization can meet large-scale CO_2 emissions and produce an important resource, such as the water required by the coal chemical industry. Like CO_2-EWR technology, it has a dual benefit in that it stores CO_2 and the saline water that is produced, which can be used for industry production after desalination.

Based on the analysis of the technical features and the geographical applicability, CO_2 geological utilization (CGU) technologies can be viewed as the best choices for the coal chemical industry, with small-scale chemical utilization, such as CO_2-SCU and CO_2-PCU as a supplement, so as to rationally utilize "three wastes," i.e., waste gas, wastewater, and industrial residue.

Table 4 Applicable area and dimensionless values of various factors for each CO_2 geological utilization technology

Technology option	Applicable area	Technology maturity			Economic potential		Emission reduction potential		Risk level	
		2012	2020	2030	2020	2030	2020	3030	2020	2030
EOR	Northeast, Northwest, and North China	3.5	5	5	2	4	3	4	3.5	3.5
ECBM	Coal bed methane basins	2.1	3.3	4.9	0	2	2	3	4	4
EGR	Midwest and Eastern China seas	1	2.5	3.6	0	0	0	3	4.5	4.5
ESGR	Southern marine shale formations and western basins	1	2	3.3	0	0	0	2	3	3
EGS	Southern Tibet and Western Yunnan	0.5	1.5	2.8	0	0	0	2	3	3
EUL	Sedimentary basins (North)	4.1	5	5	0	0	3	4	4	4
EWR	Sedimentary basins (North, Northwest, and Southwest)	1	2.3	4	0	1	2	4	4.2	4.2

The most appropriate CO_2 geological utilization technology for the coal chemical industry

Among the various geological utilization technologies, selecting suitable technologies for the coal chemical industry depends primarily on matching sources and sinks (Wei et al. 2015), the maturity of the technology, and its economic and emission reduction potential, as well as its risk level.

Table 4 lists the applicable areas and dimensionless values of technology maturity, economic potential, emission reduction potential, and risk level for each geological utilization technology in the predicted years, which refers to expert survey data (ACCA21 2014). From the point of the match, subsurface resources used for EOR, ECBM, EUL, and EWR technologies are distributed primarily in the sedimentary basins in the north and northwest of China, which is a good fit with the distribution of the coal chemical industry. However, for other utilization options, the energy resources required are concentrated primarily near the southeast coast of China and in parts of Tibet, which is a poor match with the distribution of the coal chemical industry. The comprehensive prospect of technologies can be predicted by weighted average calculations with the dimensionless values of technology maturity, economic potential, emission reduction potential, and risk level, all of which are assigned weights of 0.25. Based on the above assumption and calculations, the seven geological utilization technologies can be classified into four partitions: Zone I, technologies with maturity at present and good prospects for the future; Zone II, technologies with immaturity at present and good prospects for the future; Zone III, technologies with immaturity at present and ambiguous prospects for the future; and Zone IV, technologies with maturity at present and ambiguous prospects for the future. Figure 7 shows the results of the evaluation, and it can be concluded that the EOR and EUL technologies belong to Zone I, with relative maturity and good prospects compared with other technologies. The figure also shows that technologies EWR and ECBM, although in a low-maturity stage currently, have indefinite prospects in 2020, whereas they have great potential for development, and in 2030, the two technologies have greater prospects than even the EUL technology.

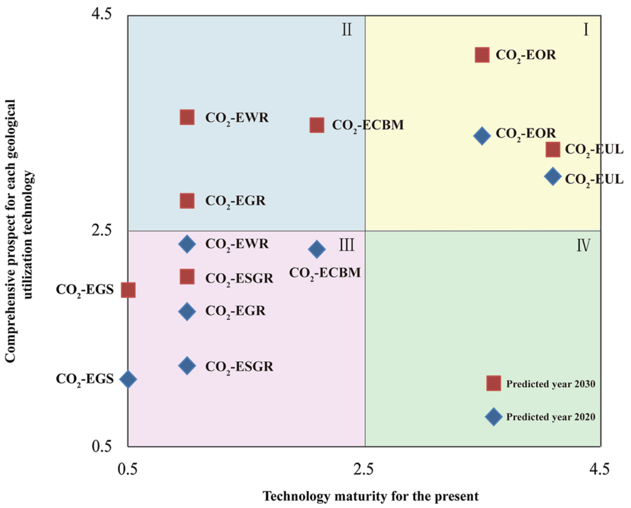

Fig. 7 Partitions of China's CO_2 geological utilization technologies according to their comprehensive prospect and maturity: Partition Zone I, technologies with maturity at present and good prospects for the future; Partition Zone II, technologies with immaturity at present and good prospects for the future; Partition Zone III, technologies with immaturity at present and ambiguous prospects for the future; Partition Zone IV, technologies with maturity at present and ambiguous prospects for the future

Based on our comprehensive analyses, technologies EOR, EUL, ECBM, and EWR all seem attractive to the coal chemical industry, which will choose the CO_2 utilization option with low water consumption, such as EWR, which can produce water, making it the top-priority option. In addition, under the condition of setting up a global and/or nationwide carbon market, the price of CO_2 will increase

(Peng et al. 2014). Thus, coal chemical companies could sign a CO_2 offtake agreement with hydrocarbon enterprises. Doing so would make EOR the priority option.

Conclusions

According to the aforementioned analyses, some concluding remarks can be addressed as follows:

1. The coal chemical industry, as an important branch of China's coal industry, is a crucial option to ensure national energy security. However, its high carbon emissions and water consumption have caused a series of environmental and social problems, and CO_2 utilization technology will be an inevitable choice for its sustainable development.
2. Different CO_2 utilization technologies have different features and advantages with respect to the situation in China. CO_2 geological utilization is suitable mainly for the central, west, and northwest regions of China. CO_2 chemical utilization and CO_2 biological utilization can be used primarily in eastern and southern China, where there are good geographical complementarity and sound source-sink matching.
3. Among the three types of utilization technologies, CO_2 geological utilization can handle large-scale CO_2 emissions and also may produce an important resource, such as the water required for the coal chemical industry. Just as the CO_2-EWR technology, it has a dual profit by sequestering CO_2 together with saline water produced for industrial use after desalination.
4. By the assessment of the comprehensive prospect for each geological utilization option, with dimensionless values of technology maturity, economic potential, emission reduction potential, and risk level, technologies EOR, EUL, ECBM, and EWR showed great potential for the development and use in China's coal chemical industry, which will use the CO_2 utilization option with low water consumption as the priority option, like the CO_2-EWR technology. In addition, with the maturity of the nationwide carbon market, coal chemical companies can easily sell the produced CO_2 to oil companies and/or build the joint venture. Thus, the CO_2-EOR technology will become the first priority.

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