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A long-term Strategic Plan of Offshore CO_2 Transport and Storage in Northern South China Sea for a low-carbon development in Guangdong province, China

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Abstract

Strategic regional planning is an important step towards a successful CCUS development. This paper is the first effort of proposing a development plan of offshore CO_2 storage and transport for Guangdong in 2030 and 2050. We attempt to make an ambitious and achievable plan. The cluster-hub model of sources and sinks is adopted, and reuse of existing infrastructures is preferred. The targets of CCUS in Guangdong by 2050 are approximately 8% of the CCS targets that proposed for entire China (ADB, 2015), except a smaller target of 2050. The dual-phase and dual-track approach of ADB's roadmap is followed. The CCUS Phase I before 2030 is characterized by the capture of high-purity CO_2 from petrochemical industry and the storage of CO_2 mainly related to CO_2-EOR. The target of ~3 Mtpa CCUS in 2030 will be achieved by source-sink match A1. The Phase II from 2030 to 2050 is characterized by a wider deployment of CCUS. The target of CCUS in Guangdong is ~35 Mtpa in 2040 and ~110 Mtpa in 2050, leading to the cumulative CO_2 avoidance of ~187 $MtCO_2$ for 2031-2040 and ~730 $MtCO_2$ for 2041-2050. Four source-sink matches are proposed for this phase, including the storage clusters in the Pearl River Mouth Basin and in the Beibuwan Basin in the northern South China Sea. Research with sufficient lead time to support the phased CCUS development is proposed, including databases, feasibility studies, technique R&D, cost estimation, and optimized system design. We are fully aware of the large uncertainty in the years ahead, and regard this planning as a highly general and hypothetic proposal.

Keywords

CCUS; strategic planning; CO_2 transport and storage; offshore; South China Sea; Guangdong

1. Introduction

The 2015 Paris Agreement emphasized the urgent need in "holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels" (UNFCCC, 2015). China has submitted to UNFCCC the document on China's Intended Nationally Determined Contributions (INDC), promising to peak the CO_2 emission around 2030 or earlier.

The carbon capture and storage (CCS) is the only technology that can enable the continued use of world's proven fossil fuel reserves in a manner compliant with the 2.0°C limit, allowing countries to maintain their energy security (GCCSI, 2016). Without CCS, the cost of mitigation would more than double – rising by an average of 138% (IPCC, 2014). To meet the 2°C scenario, the world needs to capture and store almost 4 Gtpa (10^9 tons per year) CO_2 in 2040 and 6 Gtpa CO_2 in 2050 (IEA, 2016b). As current carbon capture capacity for projects in operation or under construction sits at ~40 Mtpa (10^6 tons per year), there is a lot of ground to make up (GCCSI, 2016).

CO_2 geological storage is an essential component in the CCS chain (IPCC, 2005). In many parts of the world, such as Western Europe, Australia, US Gulf Coast, Japan, and southeastern Asia, offshore CO_2 storage is a principal or the only choice for CO_2 storage, because onshore storage capacity is small and/or the land is heavily occupied, and because there is large storage capacity under the seabed near the large CO_2 emission sources along the coast. Offshore CO_2 storage has been successful in the Sleipner and Snøhvit projects offshore Norway, and a number of other projects are in construction or planning in the world. The large potential of offshore CO_2 storage has been confirmed for the northern Atlantic continental shelves (Halland and Riis, 2014; Pale Blue Dot Energy and Axis Well Technology, 2016), US offshore (Eccles and Pratson, 2013; Meckel et al., 2014); Australia offshore (Borissova et al., 2013; Pale Blue Dot Energy and Axis Well Technology, 2016).

In China, CCUS is used to replace CCS in the sense of emphasizing the importance of CO_2 utilization. CCUS has been included in the 13th Five-year Plan for Energy in China. CO_2-EOR as a major form of CCUS has been implemented in several major oil producing sedimentary basins. In 2016 there are 8 large-scale CCUS projects in planning, construction or operation in China. In particular, the Yanchang project in Shanxi province is to be the first 1 Mtpa integrated CCUS project over Asia by 2020 (GCCSI, 2016). The CO_2 storage suitability and capacity in Chinese offshore sedimentary basins were evaluated as a part of the national evaluation program (Guo et al., 2015). The estimated effective storage capacity in 9 main offshore sedimentary basins is 573 $GtCO_2$, which is about half of the estimated capacity in 23 main onshore basins (1300 $GtCO_2$) (ADB, 2015). The majority of the storage capacity is in saline formations. The oil and gas fields have the storage capacity of 4 $GtCO_2$ offshore and 32 $GtCO_2$ onshore respectively, 2.5% or less of the total. By adopting CO_2 enhanced recovery, the storage capacity in oil and gas fields will be enlarged meanwhile producing incremental oil and gas, which will be important to China given the need to maintain domestic oil supply.

Guangdong is the largest provincial economy and one of the five low-carbon pilot provinces in China. The necessity and feasibility of CCUS in Guangdong have been confirmed by a study from 2010-2013 (Zhou et al., 2013). The 2010 CO_2 emission of the province was 510 Mtpa, in which about half was from large point sources (LPSs) of power and industry (power 207 Mtpa, petrochemical 34 Mtpa, steel 12 Mtpa) (GDCCSR-GIEC, 2013). The study also shown that the storage capacity is limited onshore Guangdong, while the Pearl River Mouth Basin offshore Guangdong has very large effective CO_2 storage capacity (GDCCSR-SCSIO, 2013). As most LPSs in Guangdong are distributed along the coast, the source-sink matches can be made within 300 km distance (GDCCSR-GIEC, 2013). Thus offshore storage is recognized as the primary form of CO_2 storage for Guangdong (Li et al., 2013; Zhou et al., 2013). In 2013, the UK-China (Guangdong) CCUS Center was established for promoting CCUS development in Guangdong. In 2015, the Guangdong Offshore CCUS Project is included as one of six US-China Climate Change Working Group (CCWG) projects.

In 2016, the Asian Development Band (ADB) set up a special fund to support the capacity building of the UK-Chine (Guangdong) CCUS Center and to complement the Guangdong Offshore CCUS Project (GOCCUS) (ADB, 2016). The general timetable for the GOCCUS project is specified as those in Table 1.

Table 1.The general timetable for the GOCCUS project.

Stage	**Feasibility study (2015-2017)**	**FEED[1] (2017-2018)**	**Demo projects (2023-2025)**	**Commercial-scale CCUS projects (2026 and later)**
Capture	Develop a capture testing Platform	FEED of demo capture	Construction & operation of demo capture	FEED, construction & operation
Transport	Transport type selection & design	FEED of demo transport	Construction & operation of demo transport	FEED, construction & operation
Storage	Site selection, characterization, design for test injection	Test CO_2 injection, FEED of demo CO_2 injection	Construction & operation of demo injection	Monitoring of demo injection site; FEED, construction &operation

[1] FEED: Front End Engineering Design.

While working on the feasibility study of GOCCUS, the Guangdong CCUS team is also preparing for the long-term and large-scale greenhouse gas reduction stages beyond the GOCCUS project. This paper presents a development plan of offshore CO_2 storage and transport for Guangdong in 2030 and 2050 as part of the effort.

2. General geography and geology of Guangdong and offshore

Guangdong Province of South China is located in subtropical zone, with a land area of 180,000 km^2. Morphologically the province consists of the Pearl River Delta and coastal zones in the south, the E-W-running mountain range in the north, and low mountains and terraces in the west and east. The middle and lower reaches of the Pearl River form a network through the province and enter the South China Sea at the river mouth near the city of Hong Kong (Fig. 1).

Geologically the Guangdong province belongs to the Caledonian Fold Belt of the South China Block. The tightly folded basement consists of Proterozoic and Lower Paleozoic metamorphic rocks. The overlying platform cover consists of Devonian to Middle Triassic clastic and carbonate strata, which was folded and uplifted during the Indosinian Orogeny. Large-scaled granitic intrusions and volcanic eruptions occurred during the Mesozoic Yanshannian Orogeny.

Inland Guangdong, sedimentary basins developed in Cretaceous and Tertiary periods. Studies shown (GDCCSR-SCSIO, 2013) that these are small fault-blocked basins filled with fluvial-lacustrine and volcanic sediments containing poor reservoirs. Only two basins have individual area over 2000 km². Among these the Sanshui Basin is the only oil-bearing basin, located in the densely-populated Pearl River Delta, and has only 20 Mt_{CO2} effective storage capacity. The Maoming Basin to the west produced oil shale (Fig. 1). Thus there is little storage potential onshore Guangdong.

Offshore Guangdong there exist five large sedimentary basins in the northern South China Sea (Fig. 1). These are petroliferous basins filled with thick Cenozoic sediments, which contain high-quality reservoirs and cap rocks favorable for CO_2 storage. Among these basins, the Pearl River Mouth Basin (PRMB) is the largest, with 200,000 km^2 area and thick sediments (up to>6 km in shelf areas and >14 km in slopes). Oil production started in 1990 and maintained about 10 million tons per year since 1996. The oil fields are distributed in clusters, thus the production was organized in clusters to improve efficiency. The 2008 estimation of geological resources in the PRMB is 2.2 Gt crude oil. Since then several new gas fields have been discovered in the deepwater areas.

The geological conditions and the CO_2 storage capacities in the sedimentary basins offshore Guangdong have been evaluated (GDCCSR-SCSIO, 2013). The Tertiary strata, especially the Upper Oligocene and Lower to Middle Miocene strata, contain thick and high quality aquifers and are capped by regional or local seals. These strata are of mainly neritic and deltaic facies and thus have good lateral continuity. The region is tectonically relatively stable with sparse earthquakes mainly at the edges of the basins. The PRMB has the effective CO_2 storage capacity of more than 300 $GtCO_2$, in which 77 $GtCO_2$ (P85 probability level) resides in the shallow water areas (mostly <200 m water depth). As PRMB is the basin most proximal to the coastal Guangdong where most LPSs of CO_2 emission are located, it was concluded that offshore CO_2 storage will be the major form of CO_2 storage for Guangdong, and the most favorite areas are the shallow areas of the PRMB (GDCCSR-SCSIO, 2013).

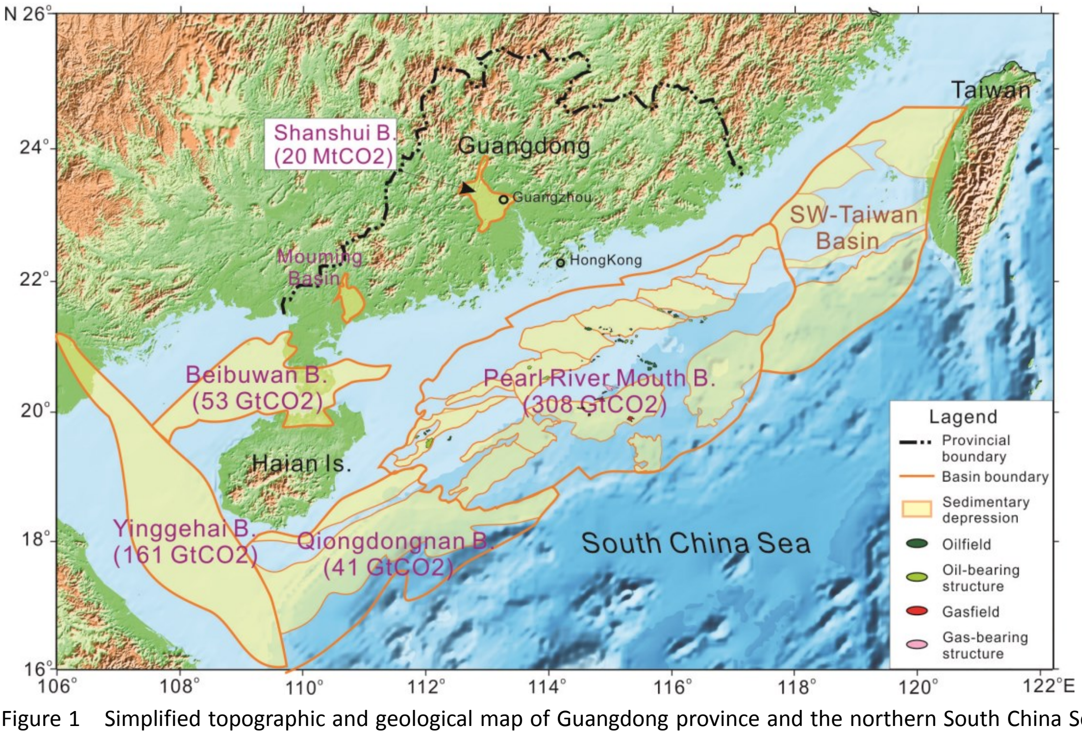

Figure 1 Simplified topographic and geological map of Guangdong province and the northern South China Sea, showing major sedimentary basins in the area as well as the oil/gas fields in the Pearl River Mouth Basin. Numbers in parenthesis are estimated mean effective CO_2 storage capacity in the basins. (Zhou et al., 2013)

3. Status of CCUS development in Guangdong

The first CCUS project in Guangdong (the GDCCUSR project) was conducted in 2010-2013 with the financial support from the UK Strategic Prosperity Fund and GCCSI funding, and with the recognition of National and Guangdong provincial Development and Reform Commissions. In this project the total emission and major point sources in Guangdong was investigated (GDCCSR-GIEC, 2013), the storage capacity inland & offshore was estimated (GDCCSR-SCSIO, 2013), the mitigation potential and cost of CCS in power industry was simulated (GDCCSR-ERI, 2013), the commercial opportunity of capture-ready power plant was evaluate (GDCCSR-ED, 2013), and the CCUS roadmap was drafted (GDCCSR, 2013). This project also successfully contributed to raising public awareness and recognition on CCUS in the province (Zhou et al., 2013). In 2011, CCUS has been listed for the first time as a potential technique in the low-carbon development agenda of the Guangdong province. In 2012, CCUS was listed in the Greenhouse Gas Control Action Plan in the 12th Five-Year Plan of the province. In 2013, the UK-China (Guangdong) CCUS Center was established which provides a platform for communications and joint actions of enterprises and academic communities for the CCUS development.

Meanwhile, the preparation for the first CCUS demonstration project with offshore CO_2 storage (the Guangdong Offshore CCUS Project, GOCCUS) has been conducted actively. On the capture side, the #3 and #4 units of the Haifeng Power Plant (Fig. 4) of the China Resource Power Holdings Co., Ltd. have been designed in 2015 as CO_2 capture-ready, which is the world's first capture-ready design of coal-fired power plant. In March 2017 the China Resource Power made the investment decision to build in the Haifeng Power Plant a platform for testing post-combustion CO_2 capture technologies. This open testing platform (each train 20 to 50 tons per day) will benefit innovative and potentially disruptive capture technologies moving from laboratory to engineering, and contribute to lowering the cost of deployment for both Chinese and international technologies.

On the storage side, efforts were concentrated on identifying early opportunities of CO_2 storage in the Pearl River Mouth Basin (PRMB) (Li et al., 2015). We believe that early opportunities exist in producing oil fields, because their existing infrastructure and exploration data may be reused and therefore capital costs may be lowered, and in addition the implementation time may be shortened. 16 producing oil fields in the PRMB were screened for their suitability to CCUS, and three sites were selected as candidates for the first demonstration project (Table 2). The HZ21-1 site is considered the most favorite one at the present, but more detailed work is needed to reach a final decision.

Table 2 Main features of the selected candidate sites (Li et al., 2015).
Data source: Zhu and Mi (2010) and Luo and Editorial Board (2011); data deadline by end 2007 or 2005 unless specified.

Site	HZ21-1	HZ32-3	XJ24-3
Time of production start	1990	1995	1994
Proved oil reserve (Mt)	15.8	29.7	30.1
Recoverable oil reserve (Mt)	7.9	20.3	28.9
Recovery by 2010* (%)	88.7	91.8	44.4

Potential of reserves growth by 2014	Limited	Good	Good
Water content (%)	98.5	65.6	88
Number of reservoir layers	8	8 (one main layer with 75% reserve)	21
Reservoir total thickness (m)	26	30.4	16.6
Oil column height (m)	9.0~23.0	10.5~42.0	18.9~65.5
Reservoir top depth (m)	2821~3001	1955~2280	1872~2317
Reservoir effective porosity (%)	12.8~16.6	18.0~22.8	17.1~24.6
Reservoir effective permeability (mD)	68~317	247~2729	54~1982
Reservoir original pressure (MPa)	28.6~29.8	19.8~24.1	18.8~23.7
Reservoir lithology & facies	Sandstone Littoral to delta front	Sandstone Littoral to delta front	Sandstone Littoral to deltaic
Reservoir faults	No	No	Yes
Trap type	Draping anticline	Draping anticline	Draping anticline
Trap height (m)	11.5~23.0	12.2~46.0	35~64
Trap area (km^2)	10.5	23.6	14.5
Caprock thickness (m)	>75		
Caprock fracture	One fault concealed		
Caprock continuity	Good		
Geothermal gradient (℃/km)	33.3	31	29.7
Existing infrastructure	4-leg jacket with 15 slots, gas processing platform, pipeline to land	4-leg jacket with 12 slots	8-leg jacket with 24 slots
Number of Wells	15	22	16
Water depth (m)	116	110	99
Distance to CO_2 source in Huizhou refinery (km)	170	190	150
CO_2 storage capacity**（Mt）	5.7	13.7	16.2
Advantages	1) Oil production is close to the limit 2) More reusable infrastructure including gas processing platform, a pipeline to coastal terminal, CO_2-resistant components	1) Large capacity and most concentrated in one major layer 2) Several adjacent oil fields favorable to capacity expansion 3) High reservoir relief that might be favorable to CO_2-EOR	Thick saline aquifer (280m net thickness) above oil reservoirs.
Disadvantages	Relatively small and deep aquifers	Possible interference to oil production	Seal quality for the upper saline aquifers is uncertain

* The percentage of recovery at the time over estimated total recoverable reserve of the field.

** CO_2 storage capacity is estimated simply by volume replacement of recoverable reserves of oil with supercritical CO_2.

4. Principles for the planning

Strategic regional planning is an important step towards a successful CCUS development. Studies of regional planning for CO_2 offshore transport and storage has been conducted for the Central North Sea (SCCS, 2012), Australia (GCCSI, 2015), and the Gulf of Mexico (Kuuskraa, 2017). In this paper, we propose a preliminary development plan of offshore CO_2 storage and transportation for Guangdong in 2030 and 2050, in order to provide a reference for policymakers and stakeholders. Our planning shall follow the principles of being both ambitious and achievable, and in accordance with both the demand and ability for offshore CO_2 storage and transportation for Guangdong. In addition, minimizing the cost is also an important principle.

The demand is determined mainly by the status of CO_2 emissions from large point sources in Guangdong, and the target of CO_2 emission reduction in Guangdong. These are further controlled by global, national, and provincial targets and schemes for CO_2 emission reduction, such as:

- The Paris COP21 agreement on limiting global warming to below 2°C. According to the analysis of IEA (2016a), CCS will be the third largest contributor (12%) to the cumulative emission reduction (following end-use fuel and electricity efficiency (38%) and renewables (32%)) in the 2°Cscenario over the period 2013-2050.
- China's intended enhanced actions of peaking the CO_2 emissions in ~2030 or earlier and of lowering the CO_2 emissions per unit of GDP in ~2030 by 60% - 65% from the 2005 level (Xinhuanet, 2015).
- Guangdong is a pilot province in China of low-carbon development, and thus its emission reduction target should be set higher than the national average.

The ability of CCUS is determined by many natural, social, technical, economical and political issues. For example, low oil prices have reduced the incentives for CO_2-EOR, the early demonstration projects need to have financial and policy support such as adequate carbon prices and targeted incentives, etc.

As cost estimation is not conducted in this 1-year study, we follow generally accepted ideas on reducing the cost of CCUS. For example, the cluster-hub model is adopted in the transport and storage planning. The clustered LPSs and clustered storage sites are preferentially considered. The LPSs in a source cluster are connected by a local pipeline network to a source hub, the potential storage sites are connected by pipelines to a sink hub, and the source hub(s) and sink hub(s) are connected by stem pipeline(s). Another cost-saving measure is to select storage sites at or near producing oil fields, because by reusing existing installations and data in these fields we may reduce the cost and the implemental time of storage. If CO_2-EOR is technically and economic feasible in the fields, the cost may be reduced further by incremental oil production.

As the years of 2030 and 2050 are far beyond the present time, there will be unpredictable variations ahead in economic and policy, in exploration status, and even in natural conditions. Thus the prediction for the future is very difficult and must rely on many assumptions with large uncertainty. In addition, this study was finished in one year and is based on published data only. We are fully aware of the shortages of the paper, and regard it as a rather general and hypothetic proposal, just like the Chinese saying, we are "pāo zhuān yǐn yù" (casting a brick to attract jadestones).

5. The demand in Guangdong for offshore CO_2 storage and transport

In order to plan offshore CO_2 storage and transport for Guangdong in 2030 and 2050, we need to predict the potential "demand", i.e. how much anthropogenic CO_2 from Guangdong needs to be stored by 2030 and 2050. The demand is determined mainly by the status of CO_2 emission from LPSs in Guangdong and the target of CO_2 emission reduction in Guangdong. The later is further controlled by the national and global targets and schemes for CO_2 emission reduction, such as to peak the CO_2 emission before 2030.

In the previous project we have estimated the 2010 CO_2 emission of Guangdong Province (GDCCSR-GIEC, 2013). The estimated total emission was 510 $MtCO_2$, in which about half from LPSs of power and industry (power 207 $MtCO_2$, petrochemical 34 $MtCO_2$, steel 12 $MtCO_2$). The LPSs are located mainly in the Pearl River Delta and along the coast areas of Guangdong (Fig. 3-4 in GDCCSR-GIEC, 2013).

Unfortunately, there has been no further project to assess the CO_2 emissions in Guangdong. There is no comparable ARP in the ADB RDTA8714 project on emission assessment either. In the limited project time we collected the 2016 data of thermal power, steel, and cement plants in Guangdong from public data sources. Then we estimated their CO_2 emissions in a simplest way (e.g., the emission of a thermal power plants is calculated by its unit capacity times 0.3648, the 2015 emission factor of the China Southern Power Grid). For the emissions in petrochemical industry we have only the 2010 data.

In addition, we deduced the general trend of CO_2 emission roughly from the annual statistics on economy and social development published by Guangdong government. In Table 3 we listed the growth rates (in percentage) of selected economy parameters of Guangdong Province from 2010 to 2016. This table shows a remarkable slow down since 2012 in GDP and power generation. Although the steel-iron and petroleum-chemical industries did not show the trend of slow down during these years, the total energy consumption of large industry has dropped from positive growth (>6.8 %) to near zero average growth since 2012. In addition, the energy consumption per unit growth of industrial production has been negative (in average -6% in 2010 and 2012, and -8% after 2012). These data reflected the significant achievements of Guangdong in reducing energy consumption and improving energy efficiency in the recent years especially since 2012. Based on these data, and according to the nations and provincial INDC of peaking the emission by 2030, we assume that the LPSs CO_2 emissions in Guangdong after 2010 might be approximated by the following pattern: 16% increase before 2012 and no change later for the power sector, and minor annual increase (3% annually for 2011-2020, and 1.5% for 2021-2030) for petrochemical and steel industry. Accordingly, the LPSs emissions are predicted and listed in the columns 2-4 of Table 4.

Table 3 Annual statistics on the growth rate (in percentage) of several economy parameters of Guangdong Province from 2010 to 2016. Data from the Annual Reports of Statistics on Economy and Social Development in Guangdong http://www.gd.gov.cn/govpub/tjsj/tjgb/ .

Year	GDP	Power generation	Energy consumption of large industry*	Energy consumption per unit growth of industrial production	Steel and iron industry	Petroleum & chemical industry
2010	12.2	16.4	8.8	-6.9	16	9.9
2011	10	16.6	6.8	-5.1	8.7	7.9
2012	8.2	1.3	-3.7	-11.2	10.1	5.8
2013	8.5	4.7	3.3	-5	14.6	6.3
2014	7.8	1	-1.6	-9.3	5.1	3.7
2015	8	0.8	-4	-10.5	6.4	9.9
2016	7.5	4.3	2.7	-3.75	13.8	2.3
Average (2010&11)	11.1	16.5	7.8	-6.0	12.3	8.9
Average (since 2012)	8.0	2.42	-0.7	-8.0	10.0	5.6

* Since 2011, "large industry" includes the industrial enterprises having annual prime revenue over 20M RMB.

Table 4 Predicted CO_2 emissions from the large point sources (LPSs) of power and industrial (petrochemical and metal) sectors in Guangdong

Year	2010	2020	2030	2040	2050
Power /Mtpa	207	240	240	240	240
Industry /Mtpa	46	62	72	72	72
Total LPSs /Mtpa	253	302	312	312	312

Based on the analysis of technical, economical, and political issues related to CCS development in China, the Roadmap for CCS Demonstration and Development in China was released in 2015 (ADB, 2015). A phased and dual-track approach was suggested. The two phases includes the first phase untill 2030 of low-cost CCS applications (capture in coal-chemical plants and storage with CO_2-EOR), and the second phase of wider deployment of cost-competitive CCS from 2030 onward. The dual-track includes a track of CCS deployment and a track of research for cost reduction. The projected CCS contributions to CO_2 avoided in China are: 10 Mtpa in 2020, 40 Mtpa in 2030, 440 Mtpa in 2040, and 2400 Mtpa in 2050, which will lead to cumulative CO_2 avoidance of 10-20 $MtCO_2$ by 2020, 160 $MtCO_2$ by 2030, and 15 $GtCO_2$ by 2050 (Table 5, Fig. 2) (ADB, 2015).

Table 5 Projected CCS contributions to CO_2 avoided in China*

Year	2020	2030	2040	2050
Annual avoidance /Mtpa	10	40	440	2400
Period avoidance /$MtCO_2$	16	144	(3040)	(11800)
Cum. avoidance /$MtCO_2$	16	160	(3200)	15000

* Data after ADB(2015), except those in parenthesis which are added by the authors.

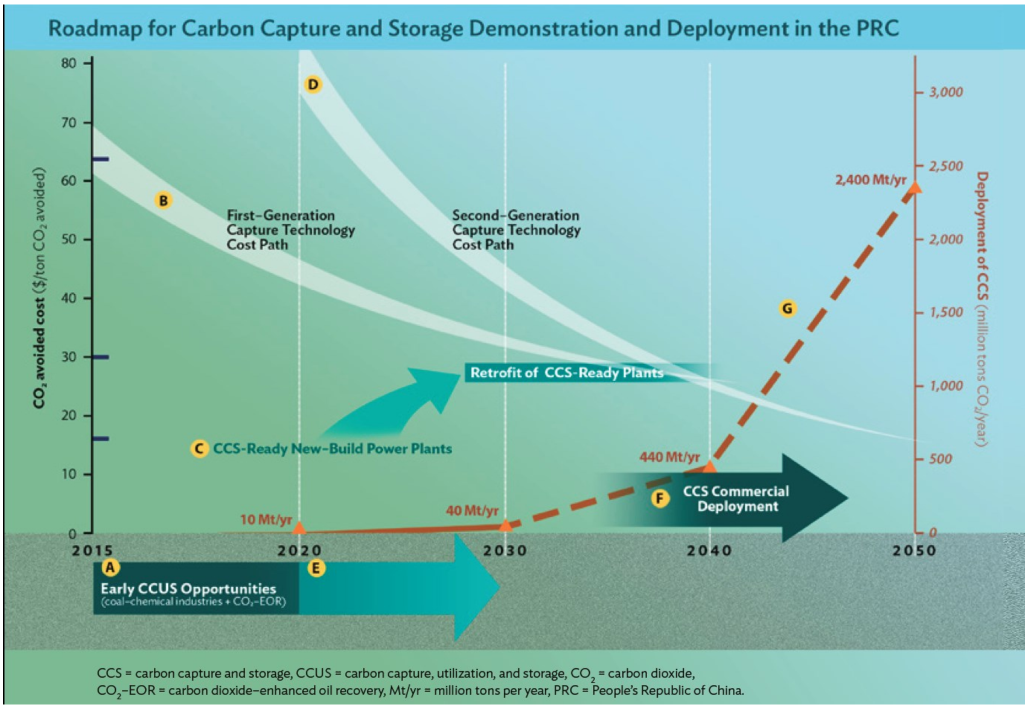

Figure 2 Proposed CCS Roadmap for China (ADB, 2015).

The phased and dual-track approach proposed in the Roadmap is also applicable to the CCS development in Guangdong, only the “coal-chemical plants” in the first phase of low-cost CCS need to be replaced by “petrochemical plants”. Compared with the national average, Guangdong has less high-emission industry and lower CO_2 emission intensity. For example, in 2010 the CO_2 emission in Guangdong (510 $MtCO_2$) is 6.6% of the total emission in China (7.75 $GtCO_2$), while GDP of Guangdong is 11.5% of national total. The CCUS development in Guangdong has to rely on offshore storage, which is more costly than onshore storage. However, as a low-carbon pilot province in China, Guangdong should have higher carbon-reduction contribution than the national average. Taken into account of these facts, we may suggest roughly that the CCUS contribution of Guangdong is ~8% of the Roadmap suggested for entire China, i.e., ~1 Mtpa in 2020, ~3 Mtpa in 2030, ~35 Mtpa in 2040, and ~192 Mtpa in 2050, with cumulative CO_2 avoidance of ~1 $MtCO_2$ by 2020, 13 $MtCO_2$ by 2030, 200 $MtCO_2$ by 2040,and 1200 $MtCO_2$ by 2050. This “8% of China” scenario, however, will resulted in the CCUS capacity in Guangdong in 2050 (~192 Mtpa) is as large as 62% of its LPSs CO_2 emission (312 Mtpa, see Table 4). Such a large contribution of CCUS might not be cost-effective. It is beyond the scope of this study to find what is the cost-effective contribution of CCUS in Guangdong. Worldwide studies showed that to minimize the overall cost of achieving the 2^{o} C target we need a portfolio of techniques, in which the contribution of CCS is 19% (IEA, 2009) or cumulatively 12% in 2050 (IEA, 2016a). Taken into account of the abovementioned issues, we would suggest 110 Mtpa as the annual CCUS capacity in Guangdong in 2050. This will lead to the CCUS contribution about 32% of the LPSs CO_2 emission in Guangdong in 2050, still an ambitious target. The suggested annual and accumulative CCUS capacities in Guangdong are listed in Table 6. These are also the demand for the CO_2 storage and transport offshore Guangdong , which form the basis for the general plans presented in the following sections.

Table 6 Predicted annual and cumulative CCUS capacity in Guangdong according to a “8% of China Scenario”. See text for explanation.

Year	2010	2020	2030	2040	2050
Annual avoidance /Mtpa	0	1	3	35	110
Period avoidance /$MtCO_2$	0	1	12	187	730
Cum. avoidance /$MtCO_2$	0	1	13	200	930

6. The plan for the CCUS Phase I before 2030

The CCUS Phase I before 2030 is characterized by low-cost early opportunities with capture of high-purity CO_2 from petrochemical industry and CO_2 storage mainly related to CO_2-EOR. The target of CCUS in this phase is ~1 Mtpa in 2020 and ~3 Mtpa in 2030. These will lead to the cumulative CO_2 avoidance of ~1 $MtCO_2$ by 2020 and ~13 $MtCO_2$ by 2030.

The low-cost capture of ~3 Mtpa CO_2 from the petrochemical industry in Guangdong is achievable. Guangdong is an important base in China for the petrochemical industry. Large refinery and ethylene plants (with individual CO_2 emissions over 1Mtpa) are concentrated in Huizhou, Guangzhou, Maoming, and Zhanjiang (Fig. 4). The CO_2 emissions from the petrochemical industry in Guangdong were 34 Mtpa in 2010 , among which 12.4 Mtpa were from Huizhou (Fig. 4). In addition there is the CNOOC Huizhou Refining & Petrochemicals Project Phase II in construction, which is expected to have CO_2 emission of 6.48 Mtpa, including high-purity CO2 of 1.68 Mtpa (internal presentation, 2010). Assuming one-fifth of the total CO_2 emission from a petrochemical plant is in high-purity, there will be more than 4 Mtpa high-purity CO_2 sources from the petrochemical industry in Huizhou, sufficient for supply the low-cost CCUS target.

The targets for the storage are also achievable via CO_2-EOR and/or saline-aquifer storage in the oil fields of the PRMB. The oil production in the PRMB started in 1990, and now there are more than 25 oil/gas fields in production. The original oil in place (OOIP) of the PRMB is 2.3 Gt (MLRC et al., 2008). Most oil fields in the PRMB contain light oil at 1600~3000 m depths and thus are suitable for high-efficiency miscible CO_2-EOR (Zhou et al., 2015). Although the CO_2-EOR potential in the PRMB has not yet been assessed in detail, we may give a rough estimation in the following way: Assuming30% of the OOIP is suitable for CO_2-EOR, the average incremental oil production by CO_2-EOR is 10% of the OOIP, and 3 tons of CO2 is needed for 1 tone of incremental oil production, then a total of 69 Mt of incremental oil may be obtained from the PRMB by CO_2-EOR, and ~207 $MtCO_2$ is need to be injected for CO_2-EOR in the PRMB. Although part of the injected CO_2 may be recycled, the demand on CO_2 supply will still be much larger than the targeted total storage of ~13 $MtCO_2$ during this phase.

A major obstacle for offshore CO_2-EOR is the high cost compared with onshore CO_2-EOR. The economic feasibility of CO_2-EOR in the oil fields of the PRMB is yet to be evaluated. Even without CO_2-EOR, the saline-aquifer storage of CO_2 in depleted oil fields of the PRMB might be still cheaper than the dry-trap storage, because in depleted oil fields the existing data and possibly existing facilities may be reused for CO_2 storage. The storage capacity will be much larger if not only the oil reservoirs but also the ambient saline formations are used for storage. Primary simulation studies (ignoring CO_2-EOR) suggest that the oil reservoirs and ambient saline aquifers in the HZ21-1 oil-gas field of the PRMB might be able to support 1 Mtpa or 2 Mtpa CO_2 injections for 20 years without causing sealing breakthrough and lateral spill out (Peng et al., 2013; Li et al., 2014).

Therefore, we suggest that two oil fields of HZ21-1 size or one oil field double the size (e.g., the HZ32-3 oil field) might have the storage capacity for achieving ~4 Mtpa and~13 $MtCO_2$ storage target in the CCUS phase I before 2030.

The HZ21-1 field is ~170 km SE off the Huizhou refineries (Fig. 3). It has two platforms: A for production and B for gas processing. There is a 233 km 20" gas pipeline connects the B platform to the Hengqin terminal of the Zhuhai City. As the gas produced from the HZ21-1 field contains CO_2, some components of this infrastructure were built as CO_2-resistant. Preliminary evaluation suggests that it is feasible to retrofit the facilities in HZ21-1 for CO_2 storage, and the HZ21-1 seems a favorable candidate to be a sink hub (Li et al., 2015).

The development plan for Phase I before 2030 is shown in Fig. 3. The CO_2 is to be captured from one or more high-purity sources of the Huizhou refineries and injected to HZ21-1 field and possibly also HZ32-2 oil fields for CO_2-EOR or for pure storage. The straight-line distance from HZ21-1 to HZ32-2 is ~30 km. In the early years of test injection, the CO_2 may be transported by ships, and the injection may be assisted by floating production storage offloading (FPSO) vessels. Then new pipelines are to be built for long-term CO_2 transport. We suggest that an offshore storage hub may be built at HZ21-1 using existing infrastructures, and the pipeline between HZ21-1 and the land terminal in coastal Huizhou city should be built with extra transport capacity for the next phase CCUS.

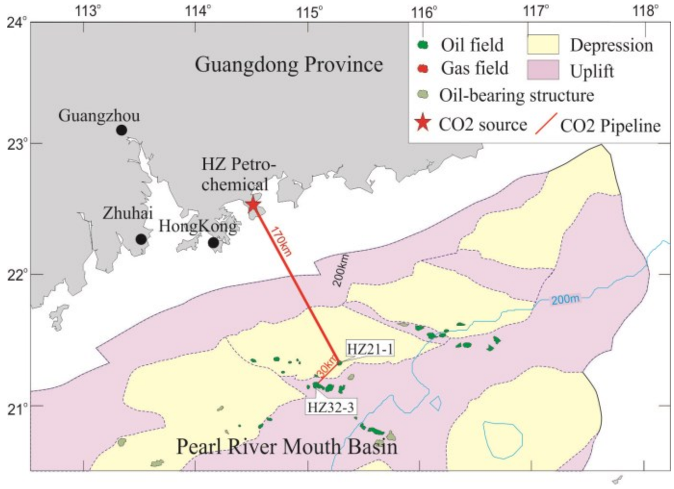

Figure 3 General plan of CO2 transport and storage in the phase I by 2030.

In this period the GOCCUS project is ongoing (Table 1). The abovementioned tasks will be incorporated into the GOCCUS project. In addition, if the capture testing Platform and demo capture in the Haifeng power plant will be operating, the CO_2 captured may be transport by ship to the storage sites.

As the second track of CCUS activities, extensive research and pilot projects will be carried out for preparing the next phase of development. Capture technologies for coal-fired power plants, petrochemical, steel and cement industries are to be improved, CO_2-EOR potential and economic feasibility for individual oil fields will be evaluated, sites for saline-formation CO_2 storage will be identified and characterized, and the source-sink match and transportation patterns will be designed. These will not be discussed in detail in this paper.

7. The plan for the CCUS phase II from 2030 to 2050

In the Phase II of wider deployment of CCUS from 2030 to 2050, the targets of CCUS in Guangdong are 35 Mtpa in 2040 and 110 Mtpa in 2050 (Table 6), corresponding to the total CO_2 avoidance of ~187 $MtCO_2$ for 2031-2040 and ~730 $MtCO_2$ for 2041- 2050 (Table 6).

The estimated CO_2 emissions from the petrochemical industry in Guangdong were 34 Mtpa in 2010 (GDCCSR-GIEC, 2013). Assuming the CO_2 emission increases with the same rate of the industry growth, and the industry growth will slow down towards zero by 2030, and then the estimated CO_2 emission from petrochemical industry might be ~50 Mtpa in 2020 and ~60 Mpta in 2030 and later. Assuming one fifths of the CO_2 is in high purity that allows a low-cost capture, then the high-purity CO_2 is up to 12 Mtpa since 2030, which is far from enough for the ~35 Mtpa target in 2040. This means the CO_2 capture from thermal power plants need to be started before 2040 or even before 2030. To meet the 110 Mtpa target of 2050, the power plants as well as the steel industry LPSs need to become the major CO_2 source.

The general scheme for this phase consists of 4 source clusters matching 6 storage clusters, as shown in Figs. 4-6 and Table 7.

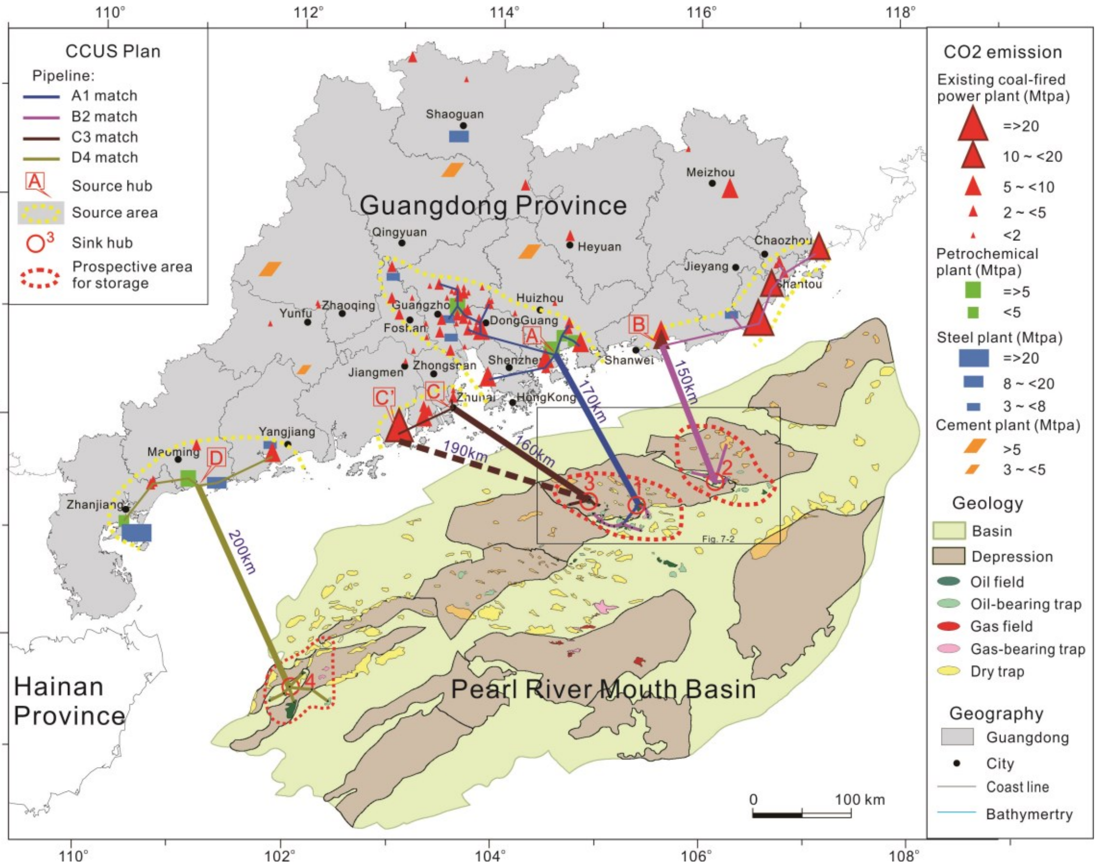

Figure 4 Planned source-sink matches for the CCUS in Guangdong in 2030 and 2050. Three source clusters with hubs A, B, C, and D onshore Guangdong match respectively three sink clusters with hubs 1, 2, 3, and 4 in the offshore Pearl River Mouth Basin. The dark red triangle indicates the location of the Haifeng Power Plant. The black-line box shows the area enlarged in Fig. 5.

Table 7 Planned source-sink matches for the CCUS in Guangdong in 2030 and 2050.

Source			Matching	Sink		
Hub	**Cluster**	**CO_2 emission*** (Mtpa)		**Hub**	**Cluster**	**Specification**
A	East Pearl River Delta	Power plants 88 Petrochemical 20 Steel 13	- - →	1	Huizhou	Oil fields & saline aquifers
B	East Coast	Power plants 42 Steel 3	→	2	Lufeng	Oil fields & saline aquifers
C/C’	West Pearl River Delta	Power plants 48	→	3	Xijiang	Saline aquifers & oil fields
D	West Coast	Power plants 22 Petrochemical 14 Steel 52	→ - - →	4	Wenchang	Oil fields & saline aquifers
D’			- - →	5	WXNS	Oil fields & saline aquifers
				6	LDS	Saline aquifers

* The 2016 CO_2 emission from the large point sources.

7.1 The source-sink match A1

The first source-sink match is between the source cluster of East Pearl River Delta with Hub A and the Huizhou sink cluster with Hub 1 (Fig. 4 and Table 7). In this match, the source cluster consists of the LPSs in the cities of Huizhou, Shenzhen, Dongguan, Guangzhou, and Fushan. The 2016 CO_2 emission from this cluster is 121 Mtpa, including 20 Mtpa from petrochemicals, 88 Mtpa from power plants, and 13 Mtpa from steel plants (Table 4). Deduce the 13 $MtCO_2$ captured before 2030, the CO_2 emission of this cluster is still sufficient for the 35 Mtpa target in 2040 (Table 4) and may be used beyond 2040.

The source hub A is the onshore terminal for this LPSs cluster and will be placed at the coast near the site of the CNOOC Huizhou Refining & Petrochemicals Project Phase II. A network of onshore pipelines is to be built to transport CO_2 from the LPSs to Hub A. Then all the CO_2 will be transport to offshore sink through a stem pipeline between the source hub A and sink hub 1 (Fig. 4). This stem pipeline should have the transport capacity of at least 44 Mtpa CO_2.

The Huizhou sink cluster is located in the Huizhou Sag of the PRMB. The Huizhou Sag contains more than half of the producing oil fields in the PRMB. The effective storage capacity of the Huizhou Sag is ~10 $GtCO_2$, most of which is in saline formations (Li et al., 2013). The sink cluster 1 consists of 8 oil fields in the Huizhou Field Group (HZFG) and several oil-bearing traps nearby, which is the main part of the prospective area in the Huizhou Sag (Fig. 5). The CO_2 storage capacity and injectivity in these oil fields have not yet been estimated except the HZ21-1 field. However other fields in the HZFG are similar to the HZ21-1 in geology. To increase the CO_2 storage capacity and injectivity, several large oil-bearing traps are also included in the plan. Further work is needed to evaluate nearby traps for their storage capacity and containment. It is very likely that the in the HZFG area we may find enough storage capacity for the 44 Mtpa target of Phase II-1 before 2040.

As described in the previous section, The HZ21-1 field (Fig. 5) will be used for the CO_2 storage in Phase I and as the sink hub 1 in Phase II-1 before 2040. Thus when designing the platform retrofit and the stem pipeline for the Phase I injection, the processing capacity in Phase II-1 should be considered. Further work is needed for evaluating the potential of CO_2-EOR and the reusability of legacy wells, installations, and pipelines in the oil fields and oil-bearing traps in the HZFG. The existing exploration and production data are available to assist the evaluations and CO_2 storage design. These are factors that might be helpful to reduce the cost of CO_2 storage.

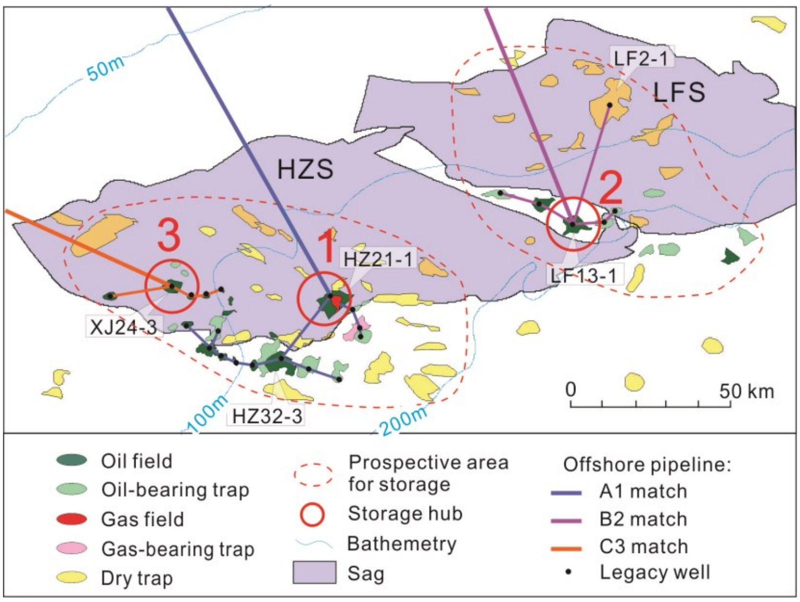

Figure 5 Enlarged map of sink clusters and hubs in the Huizhou Sag (HZS) and Lufeng Sag (LFS). The location of the map is shown as a box in Fig. 4.

7.2 The source-sink match B2

The source hub B will be placed near the coal-fired Haifeng plant of China Resource Power. In this plant the preparation for CO_2 capture has been actively carried out, including two 1000 MW units in CO_2 capture-ready design and one capture test platform in construction. We anticipate that this plant will start CO_2 capture before 2030 and achieve a full-scale capture before 2040. The application of capture techniques in this plant will stimulate the CCS implementation in other fossil-fuel power plants in Guangdong.

An onshore pipeline network will be built to connect Hub B to the LPSs in the East Coast cluster, including the Haifeng power plant and three big coal-fired power plants in Chaozhou, Shantou, and Jieyang (Fig. 4). The 2016 CO_2 emissions from this cluster are ~45 Mtpa.

The sink hub 2 is suggested to be built in the LF13-1 oil field (Figs. 4 and 5). The LF13-1 field is similar to the HZ21-1 field in reserve size, depth, geology and oil quality, but different from the HZ21-1 in that is without gas layers. The oil production in the LF13-1 field started in 1993, and exploration activities has been continuing with significant reserve growth. We suggest that the LF13-1 field will come to the production limit before 2040, and then its 8-leg platform and some other facilities might be used to build a CO_2 injection hub. The straight-line distance from the source hub B to the offshore sink hub 2 is ~150 km (Fig. 4).

The sink cluster will include the oil fields in the Lufeng Field Group and nearby saline formations, as well as a big trap LF2-1 in the center of the Lufeng Sag (Fig. 5). Studies indicated that the geological conditions of the sag are favorable for CO_2 storage. The effective storage capacity of the Lufeng Sag is ~5.2 $GtCO_2$, most of which is in saline formations (Li et al., 2013). The LF2-1 trap is a fault-bounded dome formed on-top of a basement high. It is one of the largest traps in the inner shelf of the PRMB, with an area up to 214 km^2 and amplitude up to 150 m. Its sandstone reservoirs are of ~220 m in thickness, with medium to high porosity and permeability. Thick neritic mudstones form excellent regional seals. A gas reserve of 153 Gm^3 was estimated for the LF2-1 trap, but one well was drilled and encountered no hydrocarbon. This failure was regarded as due to the lack of good source rocks (Su et al., 1988), which means that the available pore volume in the reservoir may be deduced by estimated gas reserve divided by gas volume factor. The CO_2 storage capacity of LF2-1 saline aquifers is estimated by the product of pore volume and reservoir CO_2 density, which resulted in 356 $MtCO_2$. Further investigations are needed to characterize the LF2-1 aquifers for CO_2 storage.

7.3 The source-sink match C3

The C3 match takes care of the CO_2 emission from the LPSs in the cluster of West Pearl River Delta (Fig. 4). This cluster consists of several large thermal power plants with total CO_2 emission of ~48 Mtpa in 2016. Especially the Taishan power plant alone has 9000 MW coal-fired generation capacity and estimated CO_2 emission of 32.8 Mtpa.

For the location of the source hub C we have two choices. One is to built Hub C in the Hengqin Island of the Zhuhai city, where the CNOOC has a terminal of the gas pipeline from the HZ21-1 field. This would be a cost-saving choice if this gas pipeline can be reused for CO_2 transportation. If not, then it is better to place Hub C′ on the coast near the Taishan power plant which is the principle CO_2 emitter in this cluster.

The XJ24-3 oil field is suggested as the location of the sink hub 3. The discovered oil reserve of the XJ24-3 oil field is about twice as large as that of the HZ21-1 oil field, and the reserve is still growing. Our candidate storage site is the saline formations above the XJ24-3 oil reservoirs. Well logs indicate that a section of sandstone formations lies at ~200 m above the topmost oil reservoir. This sandstone section has ~280 m net thickness and >40 km lateral extension, and is overlain by ~200 m regional seal (Li et al., 2015). If further work can confirm the effectiveness of the seal, then the CO_2 storage capacity in this section of saline formations will be rather large, comparable to that of the LF2-1 trap. The existing 8-leg platform and other facilities in the XJ24-3 field may be reused for CO_2 injection. In addition, if after 2030 the XJ24-3 and other nearby oil fields are feasible for CO2-EOR, or they become near depleted, they may also be used for CO_2 storage.

The straight-line distance between the sink hub 3 and the source hub C is ~160 km, or ~190 km if C′ is selected. A stem pipeline is to be built between C/C′ and 3, and then branched out to other sources or sinks (Figs. 4 and 5). The C3 match might be needed together with the A1 and B2 matches for the Phase II. However, studies need to be carried out as early as possible on the capacity of the saline aquifers above the XJ24-3 field and in its external areas and, especially, on the effectiveness of the seals of these aquifers.

7.4 The source-sink match D4

The D4 match is suggested to cope with the CO_2 emissions from the West Coast LPSs cluster along the West coast of Yangjiang, Maoming, and Zhanjiang cities (Fig. 4 and Table 7). The 2016 CO_2 emission from this cluster is 88 Mtpa, including 14 Mtpa from petrochemicals, 22 Mtpa from power plants, and 52 Mtpa from steel plants. The largest single CO_2 emitters are SinoPac Maoming Petrochemical plant (13.7 Mtpa), the Maoming Hengda Steel plant (12.7 Mtpa) and the Zhanjiang Baogang steel plant (36.3 Mtpa). The source hub D is to be placed on the coast of Maoming city near the Maoming Petrochemical plant (Fig. 4).

The sink cluster consists of the main oil fields and traps in the Zhu III depression of western PRMB. In this depression the Wenchang field group (WCFG) includes the oil fields in the Qionghai uplift and the Wenchang B sag, and gas-bearing traps in the Wenchang A sag. The oil production started in 2008 in the WCFG. It was estimated that the Zhu III depression has an effective storage capacity of 8.5 $GtCO_2$ (Li et al., 2013). We have circled the prospective area around the WCFG, and plan to set up the sink hub 4 at the WC13-1 oil field (Fig. 4). The straight-line distance between the sink hub 4 and the source hub D is ~200 km.

Another choice is to place the sink cluster and hub in the Beibuwan Basin (BBWB) in the northwestern South China Sea (the Beibu Gulf). The BBWB is closer to the West Coast LPSs cluster geographically. There may be two alternative choices:

One choice is to have the sink cluster in the Weixinan Sag (WXNS) of the BBWB, where the prospective sink area encloses numerous oil fields and dry traps (Fig. 6). The oil production from this sag started in 1986 in the WZ10-3 field, and successively extended to other fields. By end 2016 there are 9 fields in production. It is estimated that the WXNS has an effective storage capacity of 935$MtCO_2$ (Li et al., 2013). The sink hub may be placed at the WZ12-1 field (hub 5 in Fig. 6), which is connected by pipelines to the gas processing terminal in the Weizhou Island. In this case the source hub is better to be placed in the Zhanjiang City (D' in Fig. 6). For CO_2 transportation a stem pipeline will be built from the source sink D' to the Weizhou Island, and then to the sink hub 5. The straight-line distances is ~100 km (of which ~60 km onshore) from D' to the Weizhou Island, and 32.5 km from the island to hub 5 (Fig. 6).

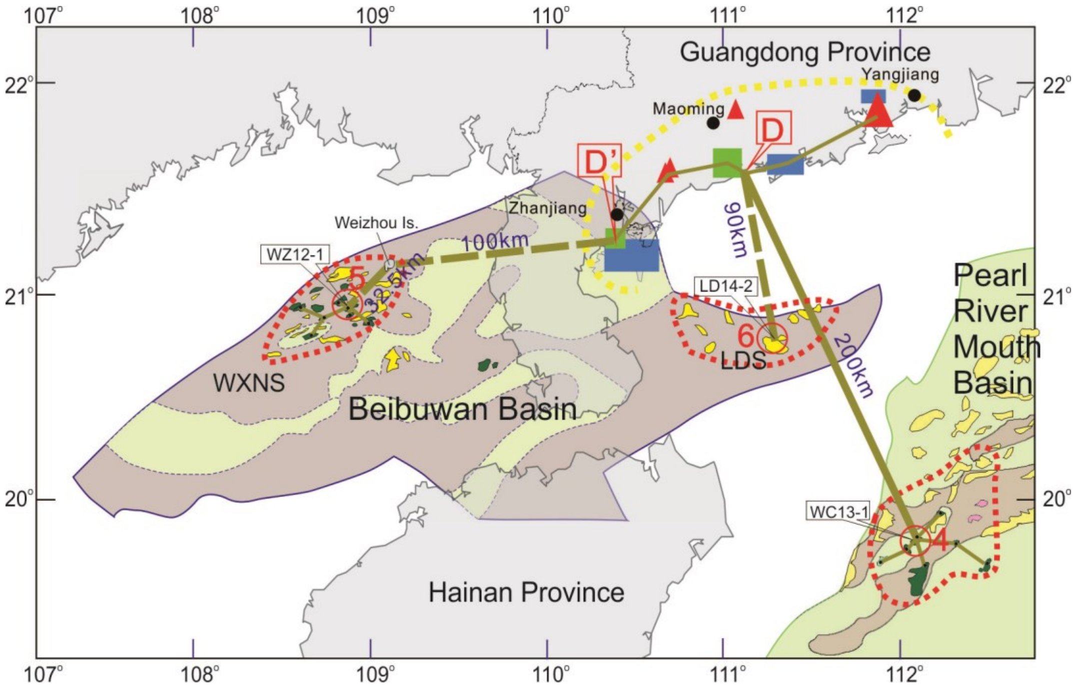

Figure 6 Alternative plans for the transport and storage of the CO_2 from the West Coast LPSs Cluster. WXNS – the Weixinan Sag. LDS – the Leidong Sag. For legend please see Fig. 4.

The other alternative is to have the sink cluster in the Leidong Sag (LDS) in the eastern BBWB (Fig. 6). This is a barren sag so far with no hydrocarbon found. The thickness of Cenozoic sediments is up to 3 km (Zhu et al., 2010), and several traps are delineated. A major advantage of the LDS is the proximity to the source hub D, and a major disadvantage is the lack of exploration data. More geophysical and geological investigations need to be done in order to know if the seal quality and the storage capacity can meet the requirements of CO_2 storage. For now we may place the sink hub 6 at the LD14-2 trap; the straight-line distance between D and 6 is ~90 km (Fig. 6, Table 7).

8 Concomitant research

The CO_2 transport and storage plan presented in the previous sections is based on many assumptions with very large uncertainty. Extensive research is needed to fill the knowledge gaps, not only for modifying the plan but also for implementing the plan. In the following we list some important knowledge gaps and research issues:

In this paper the LPSs clusters and hubs are proposed only based on 2016 data collected from public sources. No consideration is made on what proportion of the CO_2 can be captured, and no serious prediction for the future emissions. Further work is needed to build a LPSs database, in which all the data on CO_2 emission and capture are maintained and updated. This database will let us know how much CO_2 can be captured from every LPSs clusters, and how this will fit the general plan for CO_2 transport and storage.

In this paper the sink clusters and hubs are proposed mainly based on published data. These data are rather incomplete and mostly cut off as early as in 2007 or even in 2005. We need a database on the potential storage sites consisting of updated and completed data from oil companies, at least for the prospective areas delineated in this paper. A comprehensive evaluation on storage suitability, capacity and injectivity, quality of confinement, cost, and ranking of candidate storage sites should be done based on this database.

The CO_2-EOR potential and economic feasibility of the producing oil fields need to be assessed first, because these are important factors in site evaluation and ranking. If an oil field has good potential and feasibility of CO_2-EOR, the CO_2 injection in this field could started much earlier without waiting for field's depletion, and higher incremental EOR oil could be obtained. This research should lead to the estimation on the storage capacity and injectivity of the candidate sites in the prospective areas, and thus assist a better planning of the CO_2 storage and transport.

The feasibility of reusing existing infrastructures is another important issue of research. In this paper we planned all the sink hubs at existing offshore platforms, and all pipelines being new built. The implicit assumptions are that all these platforms will be reusable for CO_2 injection and all the existing pipelines are not reusable. These assumptions may not be true. A database needs be built on individual platforms, pipelines, legacy wells, and other equipment. Assessment need to be made to see if these infrastructures may be reused in the time period relevant for CO_2 storage or transport, and if the reuse is more cost-effective than building new ones.

Extensive research must be conducted for preparing each development phase of CO_2 offshore transport and storage. This includes the selection and characterization of storage sites, the optimization of pipeline network, the estimation of total and component costs, the analysis of technical and economic feasibility, and the system optimization in FEED. Additional laboratory tests, offshore geophysical surveys, and even offshore drilling might be needed for site characterization, especially for the sites in saline formations. This research need to be arranged with enough lead time to support each development phase.

Research is also needed on techniques and designs for monitoring offshore CO_2 transport and injection. These are particularly important in the second phase of wide CCUS development.

With more complete and updated knowledge obtained from the research, the proposed development plan and alternatives should be evaluated and modified from time to time in terms of feasibility, cost effectiveness, and socio-environmental impacts. The final plan should be determined based on the outcome of the research. Carefully planned and seriously conducted research is essential for a successful development of CCUS in Guangdong.

9 Summary

A development plan of offshore CO_2 storage and transport for Guangdong in 2030 and 2050 is proposed in this paper. The principles of our planning are to be ambitious and achievable in accordance with the demand and ability of Guangdong, and to minimize the total CCUS cost.

The targets of CCUS development in Guangdong by 2050 proposed in this paper (Table 6) are about 8% of the CCS targets in China proposed in the roadmap published by ADB (2015). Only the projected CO_2 avoidance in 2050 was reduced to ~4.6% of China, which is ~32% of the total LPSs CO_2 emission in Guangdong in 2050.

The proposed plan on offshore CO_2 storage and transport for Guangdong in 2030 and 2050 is schematically generalized in Fig. 7. The Phase I before 2030 is characterized by the CO_2 capture mainly from the petrochemical industry and CO_2 storage mainly related to CO_2-EOR. The target of CCUS in this phase is ~1 Mtpa in 2020 and ~3 Mtpa in 2030, which will lead to the cumulative CO_2 avoidance of ~1 $MtCO_2$ by 2020 and ~12 $MtCO_2$ for 2020-2030 (Table 4). This will be accomplished by the source-sink match A1, which consists of the CO_2 captured from the Huizhou area of the Pearl River Delta with Hub A, the storage in one or two oil fields in the Pearl River Mouth Basin with Hub 1 at the HZ21-1 field, and a stem pipeline connecting hubs A and 1 (Fig. 3).

The Phase II from 2030 to 2050 is characterized by a wider CCUS deployment. The target of CCUS in Guangdong is ~35 Mtpa in 2040 and ~110 Mtpa in 2050, leading to the cumulative CO_2 avoidance of ~187 $MtCO_2$ for 2031-2040 and ~730 $MtCO_2$ for 2041- 2050 (Table 6). Four source-sink matches are proposed for this phase, including (in the order of expected entry time) the A1, B2, C3, and D4 matches (Fig. 4 and Table 7). For the D4 match, we proposed alternative matches of D'5 or D6 (Fig. 6 and Table 7).

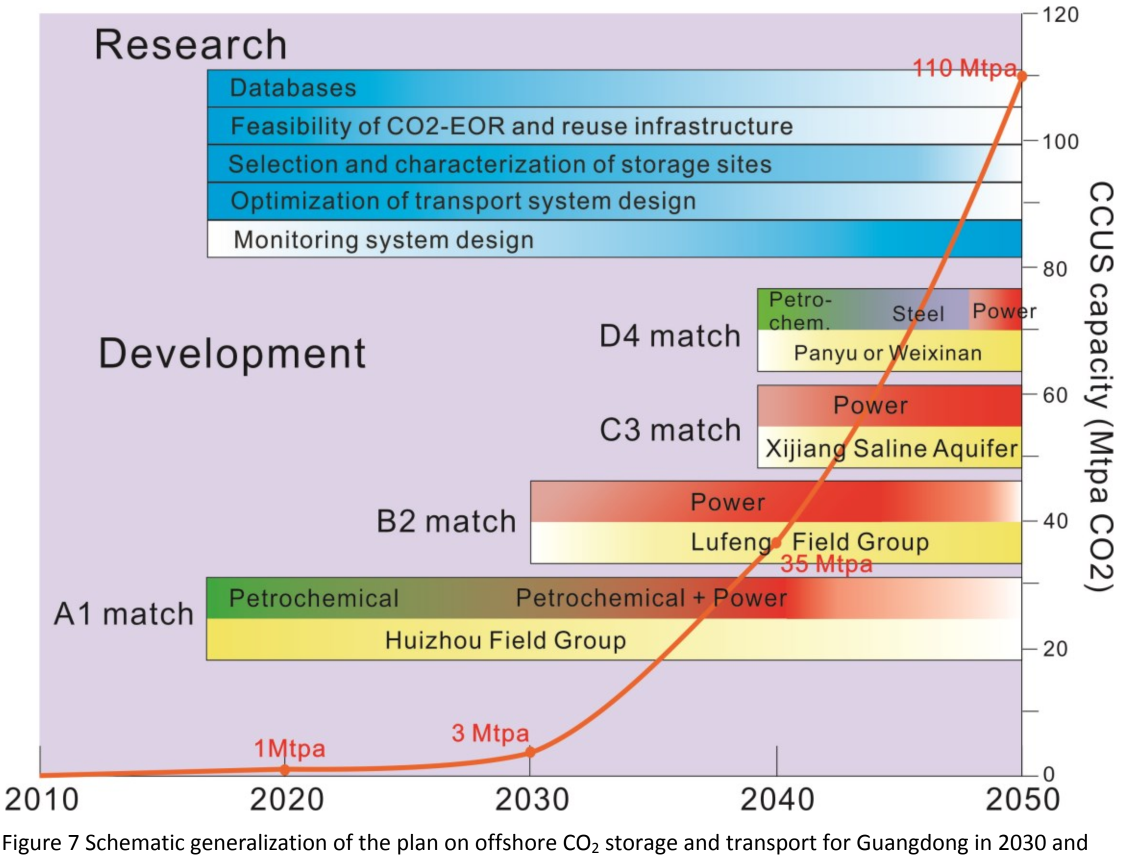

Figure 7 Schematic generalization of the plan on offshore CO_2 storage and transport for Guangdong in 2030 and 2050 as proposed in this paper. The curve indicates the variation of CCUS capacity with time. The horizontal bars show main topics of research and development, with color density signifying the variation of relative importance with time.

Research is essential to support the development phases. Databases need to be built on the large point sources of CO_2 emission, on the potential storage sites, and on existing infrastructure in the potential sites. Feasibility of CO_2-EOR and reuse existing infrastructure need to be evaluated. The storage sites need to be selected and characterized. The offshore transport and injection systems need to be optimized in the front end engineering design. The costs need to be estimated. This research must be conducted with enough lead time, so that the research results can guide and support the fulfillment of the CCUS development targets in each phase.

As the years of 2030 and 2050 are too far and too uncertain, and this study was based on published data only, we are fully aware that the planning presented in this paper is rather general and hypothetic. The plan need to be revised over the entire course of CCUS development in terms of feasibility, cost effectiveness, and socio-environmental impacts based on improved understandings and new findings from research and development.

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