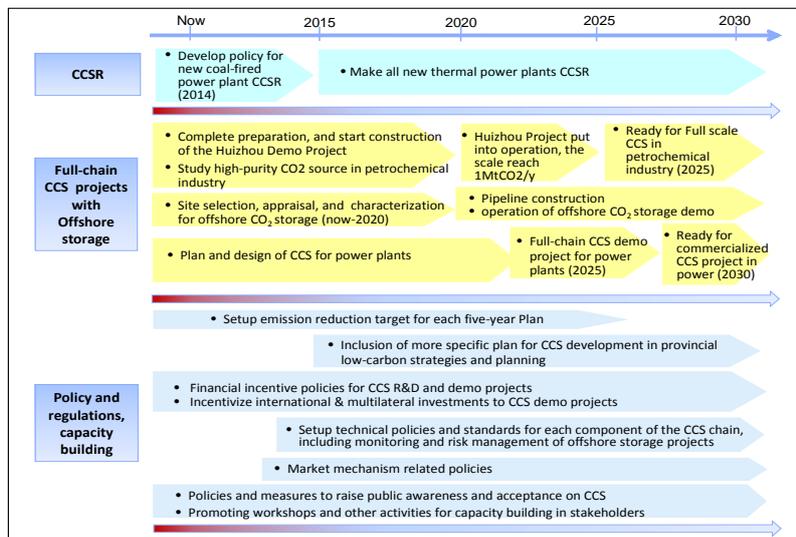


Feasibility Study of CCS-Readiness in Guangdong Province (GDCCSR)

Final Report: Part 6

CCUS Development Roadmap Study for Guangdong Province, China



GDCCSR Project
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Announcement

This is the sixth part of the final report of the project “Feasibility Study of CCS-Readiness in Guangdong Province, China (GDCCSR)”, which is funded by the Strategic Programme Fund of the UK Foreign & Commonwealth Office joint with the Global CCS Institute.

The report is written mainly based on published data. The views in this report are the opinions of the authors and do not necessarily reflect those of their affiliations, nor of the funding organizations.

The full list of the GDCCSR project reports are as follows:

- Part 1 Analysis of CO₂ emission in Guangdong Province, China.
- Part 2 Assessment of CO₂ Storage Potential for Guangdong Province, China.
- Part 3 CO₂ Mitigation Potential and Cost Analysis of CCS in Power Sector in Guangdong Province, China.
- Part 4 Techno-economic and Commercial Opportunities for CCS-Ready Plants in Guangdong Province, China.
- Part 5 CCS Capacity Building and Public Awareness in Guangdong Province, China
- Part 6 CCUS Development Roadmap Study for Guangdong Province, China.

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Executive Summary

Carbon Capture and Storage (CCS) is a technology to separate the CO₂ generated from energy production and industry and transport it to a storage site, store it in deep geological formations to isolate it from the atmosphere for a long term (IPCC, 2005). It is considered as one of the most important technologies to make a deeper cut in the greenhouse gas emissions in the use of fossil fuels and to achieve the global target of emission reduction of least 50% below 1990 levels by 2050 (IPCC, 2007).

The Chinese Government emphasizes the need to utilize captured CO₂ as a resource and promotes CCUS. Because the utilization of CO₂ can partly offset the cost of CCUS, it is considered a priority for developing CCUS, and it is particularly important for developing countries.

In order to study the prospect and roadmap of developing CCUS in Guangdong Province, the project “Feasibility Study of Developing CCS-Readiness in Guangdong Province” (GDCCSR) was conducted from April 2010 to March 2013. The project was implemented by seven institutions in China and UK (the South China Sea Institute of Oceanology of Chinese Academy of Sciences (CAS), the Energy Research Institute of the National Development and Reform Commission, the Guangzhou Institute of Energy Conversion of CAS, the Wuhan Institute of Rock and Soil Mechanics of CAS, Shenzhen Linkschina Ltd., the University of Edinburgh, and the University of Cambridge) and funded by the UK Government Foreign & Commonwealth Office and Global Carbon Capture and Storage Institute (GCCSI). This report is the key deliverable of the GDCCSR project.

1. Key findings on CCUS development in Guangdong Province

(1) CCUS is essential for the low-carbon development in Guangdong Province

With the largest provincial economy in China, Guangdong Province is facing the twin challenges of rapidly growing energy consumption at the same time as coming under pressure to achieve CO₂ reductions.

Guangdong Province has relatively limited resources for renewable energies, while the development of nuclear power has a significant lead time. Modelling suggested that the dominance of fossil-fueled energy in the province will not change radically in the foreseeable future, and that CO₂ from coal-fired power stations will remain the largest source of greenhouse gas emissions in the province. In terms of energy security, even with significant growth in renewables and nuclear, fossil-fueled power will be needed to ensure a more reliable and more robust energy structure.

Thus the application of CCUS would be necessary in order to achieve large-scale emission reduction while using fossil-fueled energy for power generation. CCUS is also likely to be needed for deep cuts in CO₂ emissions from the large point sources in cement, petrochemical, and steel industries.

(2) The importance of CCUS is growing

After 2020, as demands for China to address climate change increase and emissions trading schemes begin to move beyond trials, the need for new carbon reduction techniques including CCS will increase. The early opportunities for CCUS, such as CO₂ capture from hydrogen production and CO₂ storage using existing infrastructure from depleted oil and gas fields, might start to be cost competitive once sufficient carbon pricing is in place.

By 2030, carbon reduction targets are likely to be more rigorous and binding, and the carbon price may be reflected by carbon taxes, a carbon market or other targeted incentive schemes. Modelling of the power sector suggests that when the carbon prices increase to the level of 200 to 350 RMB per tonne CO₂, CCUS in power generation, especially ultra-supercritical coal-fired power plants (USCPC) plus CCUS, will be cost competitive relative to conventional coal-fired power without CCUS. Under these conditions USCPC plus CCUS could even begin to be developed on a commercial basis.

(3) Large CO₂ storage capacity exists offshore of Guangdong Province

CO₂ capture cannot reduce the atmospheric CO₂ concentration unless the captured CO₂ is stored safely underground. Thus high quality and sufficient storage capacity is the prerequisite of CCS development. Assessment shows that the onshore storage capacity is limited in Guangdong Province. In addition the population density and heavy land use make onshore CO₂ storage less attractive.

However the Pearl River Mouth Basin offshore of Guangdong Province has a very large effective CO₂ storage capacity. The capacity in its shallow water (<300 m) areas, is sufficient to store over one hundred years of the CO₂ emitted from the large point sources in Guangdong Province. The geological conditions are favorable as reservoirs and seals in the basin are generally of very good quality. Therefore, offshore underground CO₂ storage is effectively the only choice in Guangdong Province.

The source-sink matching between stationary emissions sources suitable for CO₂ capture and prospective storage areas is reasonably good. The large point sources of CO₂ emissions (coal-fired power, petrochemical, and steel plants) are distributed mostly along the coast and within 120 to 300 km of potential offshore storage sites.

Between the onshore source and offshore storage site, the captured CO₂ would to be transported by pipeline or ship, both of which are proven technologies. Regional planning for pipeline networks would increase the viability of many capture projects and substantially reduce the unit cost of transportation.

(4) CCUS will bring business opportunities to Guangdong

CCUS is one of the “emerging industries of strategic importance” as defined by the State Council of China in 2013. CCUS research, demonstration and commercialization in Guangdong Province will either bring or accelerate the development of a number of industries, such as equipment manufacturing, chemical absorbents, onshore and offshore pipelines, marine engineering, as well as associated financial and other services. It will also allow industry to build up a sustainable low

carbon manufacturing base.

CCUS techniques have been viewed by many countries as an important step in the future competition for low-carbon technologies. Guangdong Province should make an effort to develop the most advanced CCUS technologies in order to share the potentially large market in China and worldwide.

In relation to CO₂ utilization, the CO₂-EOR potential is limited in the Pearl River Mouth Basin, as the oil fields in the basin have strong water drive and high primary recovery rates.

However there may be opportunities for CO₂ utilization in a number of fields, although the scale is like to be limited relative to the size of overall emissions. The province has a long coast line which is favorable for algae cultivation and algae-fuel production; the province has an extensive chemical industry and related skills, and these will be helpful in developing CO₂ utilized chemical techniques and industries. Guangdong Province is rich in geothermal resources, which might enable the application of CO₂ enhanced geothermal recovery.

(5) Technical research and policy building for CCS should start now

Because CCUS projects have a long supply chain and value chain, significant lead time will be needed for developing large scale projects. Such projects require extensive preparation including equipment, construction design and planning, evaluation of the security of long-term storage, impacts evaluation, risk mitigation, mechanism of injection management and monitoring, and financing.

In order to realize the commercialized operation of CCS by 2030, the preparatory work, technical research and policy building for CCUS should start now. CCUS should be included as soon as possible into the low-carbon development plan of Guangdong Province, accompanied by necessary support measures, action plans, and incentive policies.

(6) CCUS-ready for new coal-fired power plants should be introduced as soon as possible

CCUS-ready (or CCUSR) is the concept of designing a large-scale power or industrial facility so that it can be retrofitted with CCUS technology when the necessary regulatory and economic drivers are in place. A CCUS-ready facility should have reserved space and modified design for retrofitting CO₂ capture equipment, as well as a feasible plan to transport and store/use captured CO₂.

As the commercialized CCUS development is expected to start around 2030, before then all new coal-fired power plants should be designed to be CCUS-ready. Modelling of an ultra-supercritical pulverized coal power plant (USCPC) in Guangdong Province has indicated that a small incremental (i.e. 0.5 to 3%) capital investment in CCUSR can not only prevent the “carbon lock in” effect, but also bring a large saving in any future retrofitting of capture equipment.

The future saving will be increased if the CCSR system is designed on a regional level (i.e. the CCSR hub concept). Thus CCUS-ready is a “no-regrets” policy choice to ensure a smooth and less-expensive transition toward CCUS-equipped fossil-fueled plants.

(7) Early opportunities of CCUS in Guangdong USCPC are provided by CO₂ capture in the

petrochemical industry and storage in depleted offshore oil fields

The cost of CO₂ capture decreases with increasing CO₂ concentration in the gas stream, thus the high-purity CO₂ flow produced from hydrogen production in the petrochemical industry will enable cost-effective CO₂ capture.

The petrochemical industry in Guangdong is developing rapidly. It is the second largest industrial CO₂ emitter (8% of the total industrial emissions) in 2010 and is projected to be the largest source of CO₂ emissions in the industry sector in 2020 (16% of the total industrial emissions). Thus there are good potentially cost-effective opportunities for large-scale and low-cost CO₂ capture in the petrochemical industry in Guangdong Province.

In the offshore Pearl River Mouth Basin there are a number of producing oil fields, some of which are close to the depletion stage. If after depletion the infrastructure (such as platforms, wells, and pipeline, etc.) can be used for CO₂ injection, the cost of offshore CO₂ storage can be significantly reduced. Prolonging the utilization of the field infrastructure will provide economic benefit once there is a financial incentive for CO₂ storage.

(8) The proposed CCUS Development Roadmap for Guangdong Province

The CCUS Development Roadmap for Guangdong Province was proposed as a guide to a technically feasible and economically affordable CCUS development in the province in different stages from now to 2030. The roadmap includes a general roadmap and a number of individual component roadmaps for CO₂ capture, transport, storage and utilization, respectively.

The major milestones for the proposed roadmap are as follows:

- CCUS-ready policy for all new coal-fired power plants by 2014;
- CCUS included in the low-carbon action plan of the 13th Five-Year Plan of Guangdong Province in 2015;
- Operation of a full chain CCUS Huizhou Demonstration Project by 2020;
- Operation of full chain CCUS demonstration on a coal-fired power plant by 2025;
- Start of commercialized CCUS development in Guangdong Province around 2030;
- Building policies, regulations, and capacities for the CCUS development in Guangdong Province.

The “Huizhou Demonstration Project” is proposed as the first full-chain demonstration project in Guangdong Province. This project envisages capturing CO₂ from hydrogen production in a refinery plant in Huizhou City and storing CO₂ in a depleted offshore oil field using existing infrastructure. The target capacity of the project is one million tonnes CO₂ per year. Its construction and operation will provide a platform for research and development of key techniques in CO₂ capture and offshore storage and for related policy and regulatory development activities.

2. Suggested actions for CCUS development in Guangdong Province

CO₂ Capture

(1) CO₂ capture in the petrochemical industry: Early opportunities for CO₂ capture in

Guangdong exist in the capture of high-purity CO₂ sources from hydrogen production in the petrochemical industry. A study should be started soon to locate and quantify the resources of high-purity CO₂ sources in the province.

A feasibility study of the Huizhou Demonstration Project should start as soon as possible to ensure that the project will be started in time to be in operation in 2020. The program should enable full-chain CCUS projects (i.e. including capture, transport, and utilization/storage) in the petrochemical sector to operate by 2025.

(2) CO₂ capture in the power sector: The power sector is the most important sector for a deep cut in CO₂ emissions through CCUS. Research indicates that capturing CO₂ from an USCPC plant has the highest cost advantage, and that post-combustion capture would be the technique with the largest application potential in the province.

Intensive research and development in the fields of new absorbents, improved system configurations and testing through large scale pilot and demonstration operations have taken place worldwide. Stakeholders should focus on the application of capture techniques most suitable for CCUS projects in the province, and also prioritise techniques which might bring business opportunities to the province. A full-chain CCUS demonstration project in the power sector should be in operation by 2025, allowing the deployment of commercial scale CCUS power plant(s) by 2030.

(3) CCUS-ready policy for new coal-fired power plants: The policy or regulation for new CCUS-ready coal-fired power plants should be setup by 2014 to prevent carbon lock in and to ensure a smooth and lower-cost transfer to retrofitting CCS after 2030. New plants which are CCUS-ready should be given priorities by government in the authorization process. By 2015 the design of the first CCUS-ready demonstration project should be implemented, and all the new coal-fired power plants must have CCUS-ready design after 2015.

(4) Other capture techniques: Techniques for pre-combustion capture, including IGCC, and for oxyfuel capture in the power sector and also suitable capture techniques in the cement and steel industries are currently in the research and development stage. Guangdong Province should encourage and support related research and development through low-carbon development funds to strive for innovation and breakthrough.

CO₂ transportation

(1) Pipeline transportation: Pipeline transportation of CO₂ has been demonstrated as being most effective method for large-scale, long-distance, and long-term CO₂ transportation. To design a regional pipeline network in the pattern of “source cluster – source hub – trunk pipeline – sink hub – sink cluster” should help increase the efficiency and reduce the costs of transportation.

Local stakeholders should make an integrated design of an onshore and offshore pipeline network according to the distribution of sources and potential storage sites, and start pipeline infrastructure construction according to the pace of CCUS development.

(2) Ship transportation: Shipping might be a viable option for CO₂ transportation in the early demonstration stage for Guangdong. The comparison between shipping and pipeline transportation should be made case by case. LNG, LPG and existing smaller CO₂ ships may be referenced to

compare the relative advantages of ship charter and ship modification.

CO₂ utilization and storage

(1) CO₂ utilization: From an economic perspective the utilization of captured CO₂ should be the considered as a priority. However, past data shows that the amount of CO₂ which can be utilized is only a small fraction of the total anthropogenic CO₂ emissions (IPCC, 2005). Investigation is needed to clarify the potential of CO₂ utilization in Guangdong Province by major industries and other users, and to understand the total amount which might be usable.

This will be useful not only for planning the CO₂ utilization industry but also the CO₂ storage. Given its natural conditions and industrial advantages, Guangdong should focus on research and development of high-efficiency CO₂ utilization techniques in the chemical industry, and CO₂ algae cultivation and algae-fuel production, try to achieve a technical breakthrough by 2020, and to form a CO₂ utilization industry by 2030.

(2) CO₂ storage in offshore depleted oil fields: For offshore CO₂ storage the main obstacle is the high engineering cost. As the potential of CO₂-EOR in the oil fields offshore Guangdong is limited, the best way to offset the cost is to use the existing infrastructures of depleted oil fields. Usually an offshore oil field will be abandoned soon after its depletion to avoid the high maintenance cost. After the abandonment the infrastructures will rapidly become un-usable.

Thus it is urgent to conduct a study on near depleted oil fields in the Pearl River Mouth Basin to identify those fields where the infrastructure may be used for CO₂ injection after depletion. This must be completed several years before the field depletion in order to leave sufficient time for preparing the storage project.

(3) CO₂ storage in offshore saline formations: The storage capacity in oil fields in the Pearl River Mouth Basin is limited in scale and unlikely to be adequate for large scale CCUS deployment. Therefore CO₂ storage in saline formations is the inevitable choice when the CCUS development reaches a large scale.

Guangdong Government should coordinate relevant national departments to survey the Pearl River Mouth basin to locate potential storage sites in saline formations that meet the requirements of large-scale CO₂ storage.

According to the pace of CCUS development in Guangdong Province, the characterization of selected sites should start in 2015, the design and setup of an offshore storage demonstration project should start in 2020, and commercial storage operations should start between 2025 and 2030 to meet the requirements of CCUS in the petrochemicals and power sectors (as described above).

(4) Demonstration of offshore storage. Offshore CO₂ storage requires specific technologies and equipment, which are different from those used in onshore storage. Gaining actual experience in site characterization, risk assessment, injection, and monitoring is important. A demonstration on an existing oil field will be a low-cost and low-risk approach to gain experience and to establish the best practice activities for the offshore storage. It also can also be used to test and validate saline formations in a suitable location and to determine the feasibility of combining demonstration of saline and depleted oil storage at the same site.

Full-chain CCS demonstration project

The “Demonstration project of Huizhou refinery coal-to-hydrogen CO₂ capture and offshore depleted oil field storage” (the Huizhou Demonstration Project) is expected to be a low-cost full-chain CCUS demonstration project. The pre-feasibility study of the Huizhou Demonstration Project should start now, so that the project may be setup and start construction in 2015, and begin operation in 2020 at the scale of one million tonnes of CO₂ per year. The Huizhou Demonstration Project will be the first CCUS demonstration project in China with offshore storage. It will be a flagship project in the low-carbon development of Guangdong Province. It will help raise the competitiveness of Guangdong in CCUS technical research and development and equipment manufacturing. It will also serve as an example for other areas in the world, including southeast China, where the offshore CO₂ storage is crucial for CCUS development.

3. Policy Suggestions for CCUS development in Guangdong Province

The development of CCUS may be divided into two stages: (1) research and demonstration, and (2) commercial implementation. In the first stage progressing CCUS relies mainly on the incentive policies and financial support from government and on international cooperation; while in the second stage market mechanisms may play a major role (for example associated with the established carbon pricing system). At the present, Guangdong Province is at the beginning of the first stage, thus the government should play a crucial role through financial support and targeted policy incentive.

(1) Policies on emission reduction target: Guangdong Province should set up targets for carbon reduction in line with the requirements of the subsequent Five-Year Plans and establish emission quotas for major industries. These will be key requirements for the development planning of the emerging low-carbon technologies including CCUS. The later should be included as soon as possible in the low-carbon development plan of the province.

(2) Policies on financial incentives: In the CCUS research and demonstration stage, the government of Guangdong Province should enhance the financial support for CCUS technical research and development, and especially for the Huizhou Demonstration Project.

The incentive policies, such as tax reduction or exemption and low-interest loans, should be established to encourage stakeholder investment. Because CCUS can transform coal into a source of clean energy with near zero emission of CO₂ and other pollutants, it should be entitled to the incentive policies that have already been applied to other clean energies such as renewables and nuclear.

(3) Policies on market mechanism: Regulations on carbon markets, carbon tax, and low-carbon electricity contract pricing mechanisms have been introduced in some western countries. CCUS has been included in the Clean Development Mechanism (CDM).

The Guangdong Government might take foreign experiences and multilateral mechanisms as references and set up targeted innovative incentive mechanisms in the Guangdong context. The market mechanism should be designed to accelerate the CCUS development through its research and demonstration stage, and to assist the CCUS development in its commercialization stage.

(4) CCUS-ready policy and standards: The policy for new coal-fired power plant to be designed with CCUS-ready should be implemented by 2014 to prevent the “carbon lock-in” effect.

(5) Technical standards and regulation: Technical standards and regulatory frameworks for each segment of the CCUS chain should be developed based on the learning process from CCUS demonstrations and other developments in China and abroad. These should include site permitting, risk management and monitoring of offshore storage projects in order to ensure safe storage.

(6) Programs on public awareness and capacity building: Programs and activities to encourage CCUS-awareness and capacity building should be set up, such as networking, websites, media communications, as well as regular and special workshops.

These activities are important to enhance capacity building for CCUS, to facilitate message dissemination and knowledge sharing, and to raise the awareness and acceptance of CCUS amongst stakeholders including government, enterprises, and the public. Specific attention should be placed in attracting the engagement of power, petrochemical, cement, and steel industries in these activities.

(7) Enhance international and domestic exchange and collaboration: Policies and measures should be introduced to enhance the exchange and collaboration on CCUS among experts and domestic and international stakeholders. These should promote the collaboration with developed countries in CCUS research and development, knowledge sharing, and technology transfer, and to incentivize multi-lateral supports for CCUS demonstration in Guangdong.

Introduction

Carbon Capture and Storage (CCS) is a technology to separate the CO₂ generated from fossil energy conversion and fossil use in industry, transport it into a storage site, and store it in deep geological formations to isolate it from the atmosphere for the long term (IPCC, 2005).

It is an emerging technology developed to reduce the atmospheric greenhouse gas concentration and to tackle global climate change. Its distinctive significance is to support the continued use of fossil fuel at the same time as achieving large-scale CO₂ reductions.

The China Government has emphasized the need to utilize the captured CO₂ as a resource, and has brought forward a CCUS technology roadmap (MOST and ACCA21, 2011), in which U refers to the utilization of CO₂. Because the utilization of CO₂ can partly offset the cost of CCS, it is considered a priority for developing CCS, and it is particularly important for developing countries.

Guangdong Province is one of the most developed provinces in the south of China. In late 2010 the province was designated as one of the five pilot low-carbon provinces in China. In order to study the feasibility and prospect of developing CCS in Guangdong Province and to draft a CCUS development roadmap for the province, the South China Sea Institute of Oceanology of the Chinese Academy of Sciences (CAS) allied with the Energy Research Institute of the National Development and Reform Commission, the Guangzhou Institute of Energy Conversion of CAS, the Wuhan Institute of Rock and Soil Mechanics of CAS, the University of Edinburgh, the University of Cambridge, and the Linkschina Investment Advisory Ltd. conducted a project called the “Feasibility Study of Developing CCS in Guangdong Province (GDCCSR)” from April 2010 to March 2013. This project has been funded by the Strategic Programme Fund of the UK Foreign & Commonwealth Office and Global CCS Institute (GCCSI) in Australia.

In the GDCCSR project, the status and trend of CO₂ emissions in Guangdong Province and the necessity for the province to develop CCUS were analyzed; the potential and capacity of CO₂ storage onshore and offshore Guangdong were assessed; a carbon reduction optimization modeling was conducted for the power sector in Guangdong. Based on these studies, the demand, timing, influence, challenge, and benefit for Guangdong province to develop CCUS were analyzed, an early opportunity for Guangdong CCUS demonstration project was suggested, and the Guangdong CCUS development roadmap was proposed.

1. The Significance of CCUS technology

1.1 The prospect of global CCS development

In recent years, global warming issues have aroused extensive concerns worldwide. Research has indicated the CO₂ generated from burning fossil fuels is the main cause of global warming. In order to control global warming, we must limit the global average temperature increase to within 2°C by 2050, which requires the stabilization of the CO₂ concentration in the atmosphere below the 450 ppm level. This means the world needs to cut CO₂ emissions by up to 50%-85% from 2000 emission levels (IPCC, 2007).

Carbon Capture and Storage (CCS) is an emerging technology developed for achieving large scale CO₂ reductions when using fossil fuels. According to the projection by the International Energy Agency (IEA, 2009), the fossil-fueled energy will remain the major energy source worldwide in the medium term.

To meet the goal to at least halve the greenhouse gas emission by 2050 in the most cost-efficient way, a portfolio of technologies is needed, in which CCS will contribute 17% contribution of emission reduction in 2050, with 14% contribution in total (Fig. 1.1). According to the IEA's projection, without CCS the overall costs of reaching the emission reduction target by 2050 would increase by 70% (IEA, 2009). Currently, some countries have already incorporated CCS as the crucial carbon reduction technology. Globally 72 large-scale integrated CCS projects have been identified by Jan. 2013 (GCCSI, 2013)

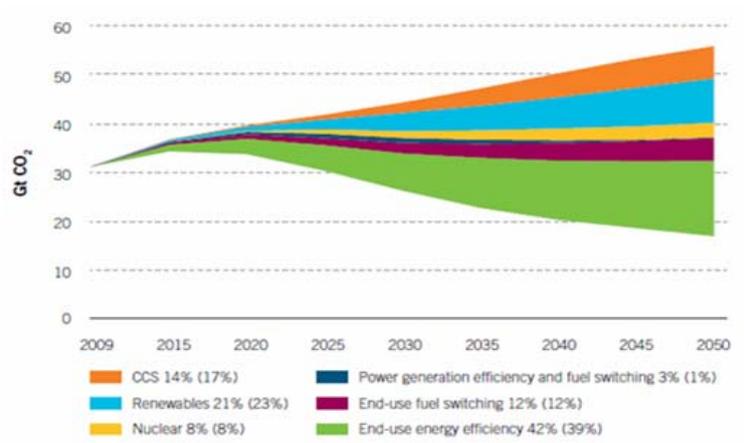


Figure 1.1 the contribution of key technologies for global CO₂ emission reduction (IEA, 2012)

1.2 The prospect of CCUS development in China

In China, energy demand is growing. The dependence on imported crude oil and natural gas is already over 50% of national demand and still increasing rapidly. Coal offers a means for ensuring energy security but is a high carbon energy source. Therefore, CCUS is a strategic technology to maintain energy security while limiting CO₂ emission.

According to the projection of IEA (2011), coal will still account for over 50% in China's primary energy mixture by 2050. To achieve deep emission reductions, a portfolio of emission reduction technologies and measures are needed; among these the clean utilization of fossil energy represented by CCS technology will play an important role. IEA (2011) projected that by 2050 the CO₂ emission reductions achieved by CCS will reach 2.86 billion tonnes, which accounts for 18% of total emission reductions in China, just below the estimated contribution from improving energy efficiency.

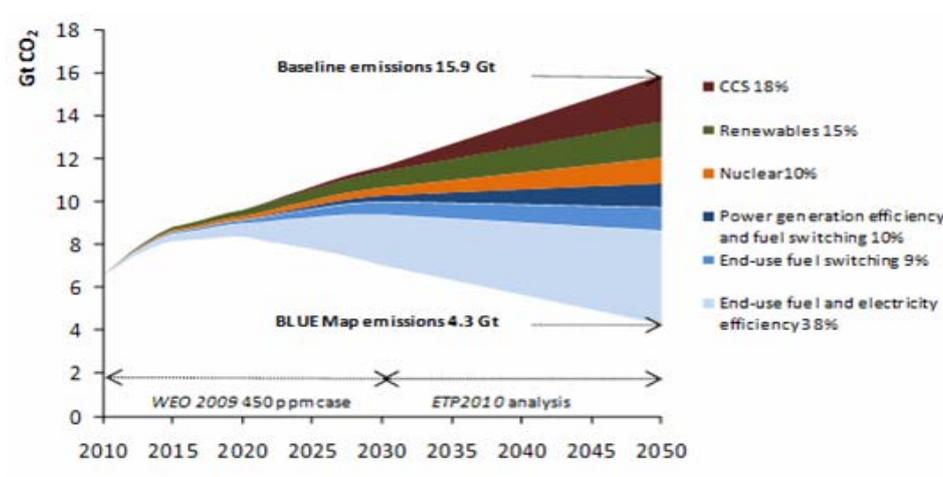


Figure 1.2 the contribution of various technologies to Chinese CO₂ reduction (IEA, 2011)

1.3 China CCUS technology development roadmap

The Technology Roadmap Study of Carbon Capture, Utilization, and Storage (CCUS) of China was released in 2011 (MOST and ACCA21, 2011). Goals for CCUS technology development in China by 2015, 2020 and 2030 were proposed, prior technologies were identified, and pertaining actions were proposed. The step by step goals for the CCUS technology development in China proposed by the roadmap are set out briefly as follows:

(1) By 2015, achieve breakthrough in key technologies in low energy consumption capture; establish storage security research and development systems; develop full-chain pilot and demonstration projects at scale of over 200,000 tonne per year with an energy penalty <25% and a cost of about 350 RMB per tonne of CO₂ avoided; develop integrated technology of CO₂ efficient utilization and storage; promote technology demonstration; and achieve the total scale of EOR utilization and storage of 1 MtCO₂ per year.

(2) By 2020, establish storage security systems; build a megaton-level full-chain CCUS technology demonstration; realize an energy consumption increment of less than 20% and a cost

of about 300 RMB per tonne of CO₂ avoided; develop integrated and comprehensive CO₂ efficient utilization and storage technologies; create preliminary CCUS commercial projects in the petroleum, chemical, electricity, coal and bioengineering industries; and reach the total scale of CO₂ utilization and storage of 2 MtCO₂ per year.

(3) By 2030, develop the technical capacity to design, construct, and operate a full-chain commercial CCUS project; achieve a system at the scale of >1 MtCO₂ per year with energy penalty <17% and a cost of about 240 RMB per tonne of CO₂ avoided; create CCUS commercial projects in the petroleum, chemical, electricity, coal and bioengineering industries; and exceed 2 MtCO₂ per year total CO₂ utilization and storage.

2. Demand for CCUS development in Guangdong Province

2.1 Goal and action plan for low-carbon development in Guangdong Province

Guangdong Province has the largest provincial economy in China, with GDP ranked first in the country for the last 24 consecutive years. In 2010, Guangdong Province was selected as one of the five low-carbon pilot provinces in China. In the provincial low-carbon pilot implementation plan (PGGP, 2012) the target of 19.5% carbon intensity reduction by 2015 with respect to the 2010 level was announced, which is 2.5% higher than the national carbon intensity reduction target.

The Guangdong Government also set targets that the share of non-fossil fuels in primary energy consumption should increase from 14% in 2010 to 20% by 2015 and to 23% by 2020, all higher than the national average levels.

An action plan was published for promoting industrial low-carbonization, energy structure optimization, energy saving and efficiency increase, low-carbon transportation and construction, and increasing green carbon sink, etc. However, CCUS is not incorporated in the action plan at that time.

2.2 Status and trend of energy structure and CO₂ emissions in Guangdong Province

2.2.1 Status and trend of energy structure

In 2010, the total primary energy consumption of Guangdong Province was 220 million tonnes of standard coal, an increase of 67% from 2005. The amount of energy end-use was more than 260 million tonnes of standard coal, an increase of 52% from 2005, accounting for 8.4% of the total national energy consumption (Statistics Bureau of Guangdong Province, 2011).

In relation to the breakdown of energy end-use consumption in 2010, coal, oil and power accounted for 11.4%, 18.9% and 41% of the total energy consumption respectively. In the power supply, more than 79% was from thermal power, most of which was from coal power, while renewable power's share was only less than 15%. The dominance of thermal power is the main reason for the high CO₂ emissions in the power sector of Guangdong.

According to the 12th Five Year Plan for energy development in the province (Guangdong DRC, 2011), by 2015 the coal-fired and gas-fired power generation capacities will increase by 20 GWe and 4.3 GWe over 2010 levels respectively. Although low carbon measures (such as closing small thermal power plants, and strongly promoting nuclear, natural gas, and renewable power etc.) have been adapted, the increase in non fossil power is subject to limitations on project progress and resource availability. According to the low-carbon pilot programme of the province (PGGP, 2012), the proportion of non fossil-fueled energy consumption will increase but only to 20% by 2015.

In the GDCCSR project a cost minimization simulation was undertaken for the development of the electricity system in Guangdong Province (GDCCSR-ERI Team, 2013). In the baseline

scenario (i.e. a continuation of the mitigation policies and measures specified by the current low-carbon pilot program), in 2030 installed power capacity will reach 145 GWe, in which coal power still has a 42% share, and coal plus gas power a 64% share (Fig. 2.1a). Even in the energy-saving scenario (i.e. the adoption of more intensive energy saving and efficiency enhancing policies but without CCUS), by 2030 the provincial power installation capacity will still be 115 GWe, in which coal power's share will be 32%, and coal and gas power together 56% (Fig. 2.1b). The power structure will continue to be dominated by fossil-fueled power plants.

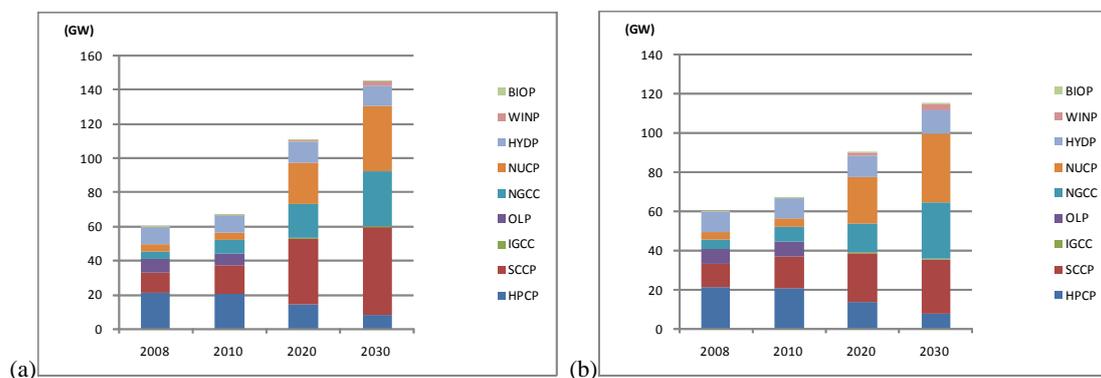


Figure 2.1 Installed power capacity mixtures in Guangdong

(a) Baseline scenario (current policy); (b) Energy-saving scenario (improved policy)

2.2.2 Status and trend of CO₂ emission

Considering overall end-user energy consumption, the total greenhouse gas emission in Guangdong Province was 590 Mt CO₂ equivalent in 2010, an increase of 35.3% compared to 2005. The CO₂ emissions were 510 Mt and accounted for 87% of the total greenhouse gas emissions (Guangdong R&D Center for Technological Economy, 2012).

The power sector is the biggest CO₂ emission source in Guangdong, accounting for 42% of total provincial CO₂ emissions. If the emissions from imported electricity are included, the ratio will go up to 54%. The industrial sector is the second largest CO₂ emitter and accounts for 30% of total provincial CO₂ emissions. In the industrial sector the primary CO₂ emitters are the cement, petrochemical, and steel industries (Fig. 2.2).

The high total CO₂ emissions from the power sector in Guangdong Province are predominantly from coal use. According to the China Electric Power Yearbook (CEPYEC, 2011), the 2010 power sector CO₂ emissions in Guangdong account for 54% of the total provincial emissions, amongst which the in-province power generation and imported electricity account for 78% and 22% respectively. CO₂ emissions from large scale coal-fired power plants is about 190 MtCO₂ in 2010, accounted for 88% of total emissions of the in-province power generation (GDCCSR-GIEC Team, 2013).

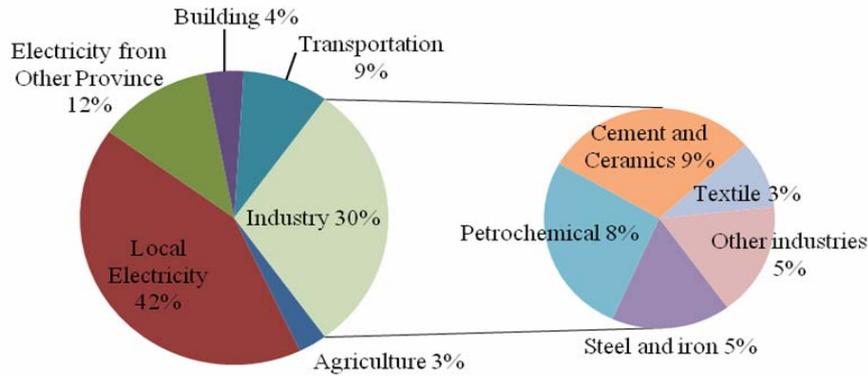


Figure 2.2 The CO₂ Emissions by sector in Guangdong Province in 2010

According to the projection of the Guangzhou Institute of Energy Conversion of Chinese Academy of Sciences (GIEC, 2010), the greenhouse gas emissions of Guangdong Province will increase further in the future. In the baseline scenario, the CO₂ emissions will reach 920 Mt by 2020, with emissions from the electricity, industry, transportation, construction, and agriculture sectors account for 43.0%, 42.5%, 11.4%, 2.6%, and 0.5% respectively. By 2030, the Guangdong CO₂ emissions are projected to reach 1150 Mt, and the emissions of these sectors will be 41.5%, 39.3%, 13.9%, 4.9%, 0.4% of the total respectively (Figs. 2.3 and 2.4). Obviously the power and industrial sectors are currently and will remain in the foreseeable future (at least to 2030) the largest emission sources in Guangdong.

The power sector in Guangdong Province is characterized by large, concentrated, and rapidly increasing CO₂ emissions, and by coal-dominated fuel structure. According to the Statistics Bureau of Guangdong Province (2011), in 2010, 54% of the total provincial CO₂ emission came from the power sector, 78% of the total emission of the power sector came from local power plants, and 88% (190 Mt CO₂) of the total local power sector emission came from large point sources. This indicates that CCUS would be a strategically important technology for Guangdong to achieve large-scale emission reductions in the power sector.

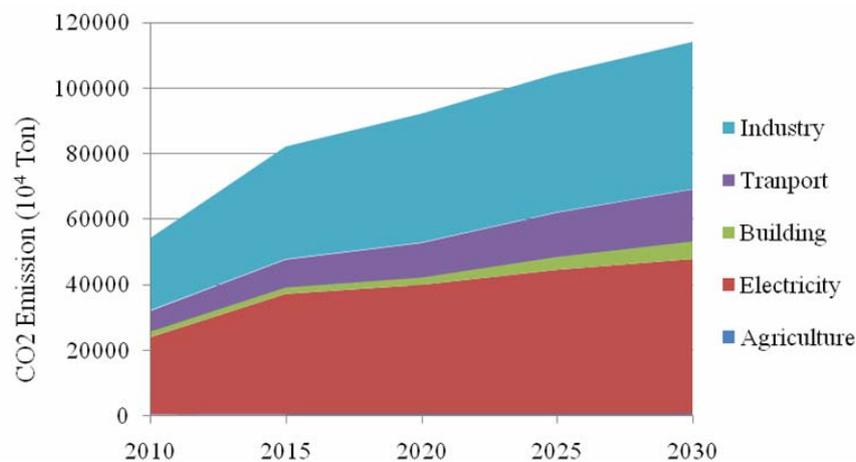


Figure 2.3 The CO₂ emissions structure in Guangdong in the baseline scenario (2010 to 2030)

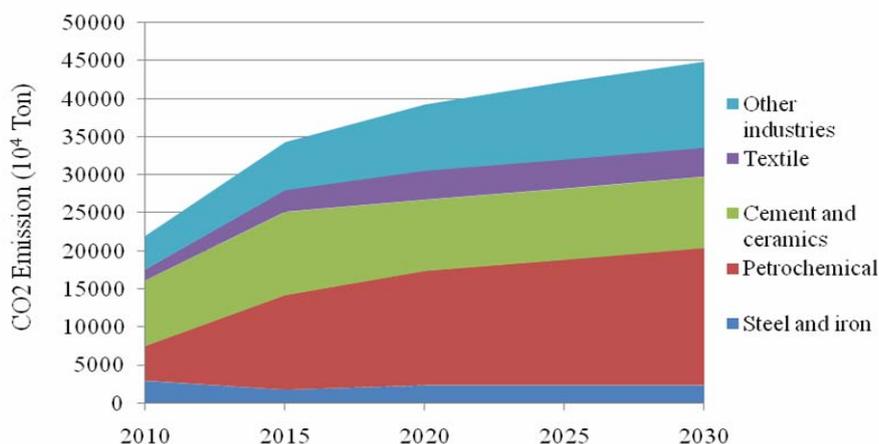


Figure 2.4 The structure of industrial CO₂ emissions in Guangdong in the baseline scenario (2010 to 2030)

CO₂ emissions from the industrial sectors mainly come from the petrochemicals, cement and ceramics, and steel industries (Fig. 2.4). According to the 12th Five-Year Plan (PGGP, 2011), large-scale oil refineries will be built in the western and eastern areas of Guangdong. A rapid increase in the share of emissions in the petrochemical industry is expected, i.e. from 8.5% in 2010 to 16.3% in 2020, meaning that by 2020 the petrochemical industry will overtake the cement and ceramics industry as the biggest industrial emissions source. Thereafter the increase in the petrochemical industry will slow down, but its CO₂ emissions will still account for 15.8% of total industrial emission in 2030 (PGGP, 2011). This indicates that the petrochemical industry should be a major industrial implementer of CCUS in Guangdong.

2.3 Prospect of CCUS development in Guangdong Province

CCUS is needed to contribute to the low carbon development in Guangdong Province. Firstly, with the fast growing provincial economy, the energy consumption will increase further in the foreseeable future, whilst as a low-carbon pilot province the pressure to reduce emissions will also increase. Therefore it is necessary to consider new low-carbon technologies including CCUS.

Secondly, the potential to develop renewable energies in Guangdong is limited by the natural resources available. Although nuclear power has better prospects, its development is also limited by engineering progress and site conditions. Therefore at least until 2030, Guangdong's energy structure will still be dominated by fossil fuels, and thermal power will provide a substantial share of total power consumption (Fig. 2.3). To effectively control the carbon emissions under this perspective, CCUS becomes a necessary and important option.

Thirdly, CCUS development also can achieve significant CO₂ emissions reduction from industrial sectors (e.g. cement, petrochemical, steel industries).

Finally in relation to energy security, the clean use of fossil fuels can contribute to the diversification of energy sources and the stability of the energy supply system. Therefore, Guangdong Province should take into account all the significant benefits in developing CCUS technology and identify related technical demands for carbon capture, transport and storage.

The importance of CCUS will grow with time. As the further advance of renewable energy, energy structure optimization, energy saving, and energy efficiency will be more and more difficult and expensive to achieve, the need for other carbon reduction techniques including CCUS will increase. By 2020, the early opportunities of CCUS, such as the CO₂ capture from hydrogen production and the CO₂ storage using existing infrastructures from depleted oil fields, might start to be cost competitive once carbon markets are established.

Approaching 2030, the targets for carbon reduction will become more rigorous, and a carbon price as reflected in a carbon tax or carbon market will be established. According to the modelling undertaken for the power sector of Guangdong made by the Energy Research Institute of the National DRC (GDCCRS Final Report, Part 3), when the carbon price increases to the level of 200~350 RMB per ton CO₂, CCUS power production, especially ultra-supercritical coal-fired power equipped with CCUS, will be cost competitive with respect to conventional coal-fired power without CCUS and will begin to be developed on a commercial basis.

2.4 Technical demands for CO₂ capture

2.4.1 Technical demands for CO₂ capture in the power sector

The installed thermal power capacity in Guangdong consists of coal-, oil-, and gas-fired, plants and other units (combined heat and power generation, comprehensive production, etc.). Because of the high oil price, the oil-fired power sets have been shut down rapidly, and a coal-based and gas-supplemented thermal power structure has been formed. Ultra-supercritical, supercritical and sub-critical units account for 15%, 21% and 34% of the total thermal power installed capacity respectively.

According to the 12th Five-Year Energy Development Plan (Guangdong DRC, 2011), the total installed power capacity in Guangdong will increase from 71GW in 2010 to 103GW in 2015. The modelling in this project (GDCCSR-ERI Team, 2013) projected that under the existing policy support, in 2030 installed thermal power will exceed 92GW, accounting for 64% of total power installation in Guangdong Province, in which ultra-supercritical, natural gas and IGCC will account for 42%, 35%, and 1% respectively of total installed thermal power (Fig. 2.1). Consequently, CCUS development in the power sector of the province should focus on ultra-supercritical coal-fired and gas-fired power plants.

Although CO₂ capture technology is not entirely new, the efficiency decline and the cost increase are very high after implementing CO₂ capture. These need to be improved for large-scale CCUS applications.

- **Post-combustion technology**

Post-combustion is a technology that can capture CO₂ from flue gas emitted from large point sources. The post-combustion capture system is relatively mature and large, but with high energy and water consumption, low efficiency, and high power generation cost. It can be directly applied to China's advanced coal fired power plants and combined with residual-heat utilization. This technology is still in demonstration stage worldwide. In the power sector currently only the Boundary Dam project in Canada is under construction and expected to be in operation by 2014.

Eighteen other post-combustion projects are at planning stage (GCCSI, 2012).

Currently considered post-combustion capture techniques include chemical absorption (amine solvents, etc.), physical adsorption (pressure temperature swing adsorption, PTSA), and membrane separation. The chemical absorption has already been tested at large scale in coal-fired power plants and is recognized as having the potential to be commercialized in the near future. The adsorption and membrane separation technologies have the potential to reduce energy consumption and offer other benefits (e.g. low or zero fugitive emissions of capture chemicals), but they are in laboratory stage at present with only small-scale demonstrations.

In order to meet the requirements of economic growth in Guangdong Province, the total power generation capacity needs to increase further. As shown in Fig. 2.1, the total installed power capacity in Guangdong Province will increase at least until 2030. Most additional power will be coal-fired power using supercritical and ultra-supercritical technologies. Therefore, the potential is large for the power plants in Guangdong to implement post combustion capture technologies. Because the R&D on these technologies have been conducted intensively for a long time elsewhere in China and worldwide, in Guangdong the focus should be placed on technology selection and large-scale demonstration, aiming to join the best worldwide advanced levels in technology application and improvement.

- **Pre-combustion technology**

Pre-combustion technology for power generation is mainly applied to integrated gasification combined cycle (IGCC) systems. Coal is gasified into synthetic gas (syngas), sulphur and other pollutants are removed from the syngas, and then the syngas is used to produce CO₂ and H₂ through a water-gas shift reaction. The high concentration CO₂ can be captured easily, and H₂ can be used as nearly carbon-free fuel for power generation. Pre-combustion CO₂ capture technology is also applied to coal to chemicals plants as part of the process.

The advantages of the pre-combustion technology are the small capture system with low energy and water consumption, and the great potential in efficiency and pollutant control. However, the IGCC technology has the problems of high capital investment costs and relatively low reliability. The hydrogen-rich gas turbine technology required by the pre-combustion system is still immature. Currently there is only about 4,000MW installed IGCC capacity in the world, and no pre-combustion CO₂ capture system has been installed in China or elsewhere.

The Dongguan 120MW IGCC retrofitting project under construction and the Taiyangzhou 4×200MW IGCC plant in planning are the only current IGCC projects in Guangdong (Dongguang News, 2012). Although CCS has not been included in these projects, the syngas generated by the IGCC is potentially a candidate for shift and CO₂ capture for CCUS. In addition, IGCC has the potential to contribute to the reduction of PM_{2.5} in atmosphere. Stakeholders could start research in IGCC-related CO₂ capture technologies based on existing IGCC installations.

- **Oxy-fuel combustion technology**

Oxy-fuel combustion technology removes the large proportion of nitrogen in the air with oxygen-making technology, and directly uses high purity oxygen mixed with a recycled fraction of flue gas in combustion. The flue gas acquired by this process contains a high concentration CO₂ which can be captured directly for storage. Since oxy-fuel combustion is a possible candidate technology for CO₂ capture at oil refineries, technical readiness will contribute to CCUS projects

in the refining industry.

The oxy-fuel system has high efficiency, low energy and water consumption, and can be applied to new built and existing power plants, but it is still at the small-scale demonstration stage, and its performance needs to be further tested and verified. The major problems faced by this technology are the high investment and energy needed for oxygen-separation facilities, the modification to the combustion facilities, and the need to avoid air in-leakage. From a strategic position Guangdong Province may deploy the research and development on low-cost air separation oxygen-making technologies and equipment.

2.4.2 Technical demands for CO₂ capture in chemical industry

The chemical industry is a major source of CO₂ emissions in the industrial sector of Guangdong Province. The fast-growing petrochemical industry is the second largest industrial CO₂ emitter in 2010 (8.5% of the total industrial emissions) and is projected to be the number one (16.3%) in 2020.

CO₂ capture is a mature technology in natural gas and synthesis gas chemistry and fertilizer production. The high-purity CO₂ produced in hydrogen production in the petrochemical industry enables low-cost CO₂ capture. Consequently, the petrochemical industry might provide early opportunities for CCS development. The research, development and demonstration of CO₂ capture technology in the petrochemical industry to further improve the efficiency and reduce the cost would be the first priority.

2.4.3 Technical demands for CO₂ capture in cement industry

At present, research of CO₂ capture in the cement industry is still in its infancy in the world, and the research to date has been focused on the application of post-combustion and oxy-fuel combustion capture techniques.

Post-combustion is an end-of-pipe treatment option for cement production, which can be applied to new kilns and the retrofitting of existing kilns because no change in the clinker burning process is needed. Moreover, the utilization of carbonate adsorption to generate the closed cycle of CO₂ is also a developing capture technology in the cement industry. For oxy-fuel combustion capture in the cement industry there are currently options for partial and full capture (UNIDO, 2010).

The cement industry is an important industrial emission source in Guangdong Province. Active researches on capture technology for the cement industry should be conducted in the province to achieve significant emission reductions in the future development of this industry.

2.4.4 Technical demands for CO₂ capture in steel industry

There is no ready and simple process available to achieve low CO₂ emissions in the steel industry. There are three CO₂ capture processes, namely the top gas recovery blast furnace (TGR-BF), the smelting reduction based on hot cyclone combined with bath furnace (HIsarna), and the process of direct reduction (ULCORED). At present, these technologies are still at the laboratory stage, thus there is still chance for Guangdong Province to make significant contribution in developing CO₂ capture technology for the steel industry.

2.4.5 Summary

CO₂ capture is the most costly component in the CCUS chain. The research and development of CO₂ capture technology has attracted great investment in finance and manpower and has made fast progress worldwide as well as in China. The demand for research and development of CO₂ capture technology in the various sectors in Guangdong Province is summarized in Fig. 2.5 based on the analyses in the above sections.

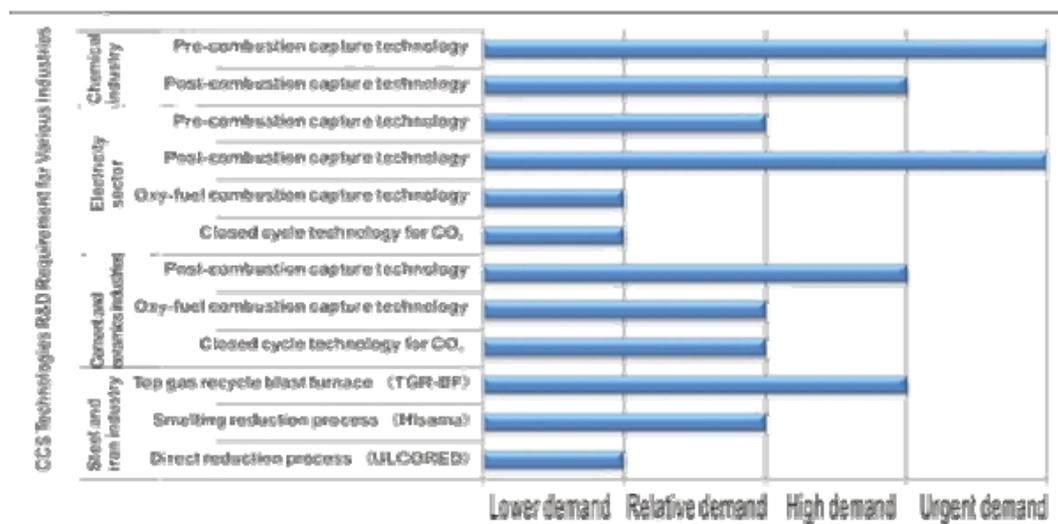


Figure 2.5 Demand for capture technology in various sectors in Guangdong Province

As Guangdong has significant installed capacity in thermal power, the demand for post-combustion technology is relatively high. It is necessary to conduct an investigation into the domestic and overseas R&D progress in post-combustion capture technology in order to identify the suitable technology and the R&D areas for Guangdong Province to pursue.

For pre-combustion capture, Guangdong may carry out research and demonstration based on existing and planned IGCC power plants. In addition, Guangdong should identify and utilize her talents and resource advantages to achieve breakthroughs in individual technologies, especially the technologies that are relatively immature and/or particularly suitable to Guangdong.

2.5 Potential and technical demands for CO₂ storage

Large-scale carbon reductions can be achieved by CCUS only if large quantity of captured CO₂ can be stored underground safely and permanently. Therefore, CO₂ storage is a key component of CCS. The GDCCSR project conducted an evaluation of the CO₂ storage potential of Guangdong's onshore and offshore areas.

2.5.1 Large CO₂ storage potential resides offshore

Onshore Guangdong Province sedimentary basins are small, scattered, and filled with continental sediments of poor reservoir quality. Taking into account of the dense population and heavy land use, there is essentially no CO₂ storage potential onshore the province.

Offshore from Guangdong Province there are several large sedimentary basins in the northern

South China Sea (Fig. 2.6). The geological conditions in these basins are usually favourable for CO₂ storage, with high-quality reservoirs at depths of 2000m-3000m below the seafloor and overlaid by good mudstone seals. Assessment indicated that the CO₂ storage capacity in the shelf area of the Pearl River Mouth Basin alone is 77 GtCO₂ at 85% probability level, which is more than 300 times of the 2010 CO₂ emissions from large coal-fired power plants in Guangdong Province (GDCCSR-SCSIO Team, 2013). Thus offshore CO₂ storage is the viable option for CCUS development in Guangdong Province.

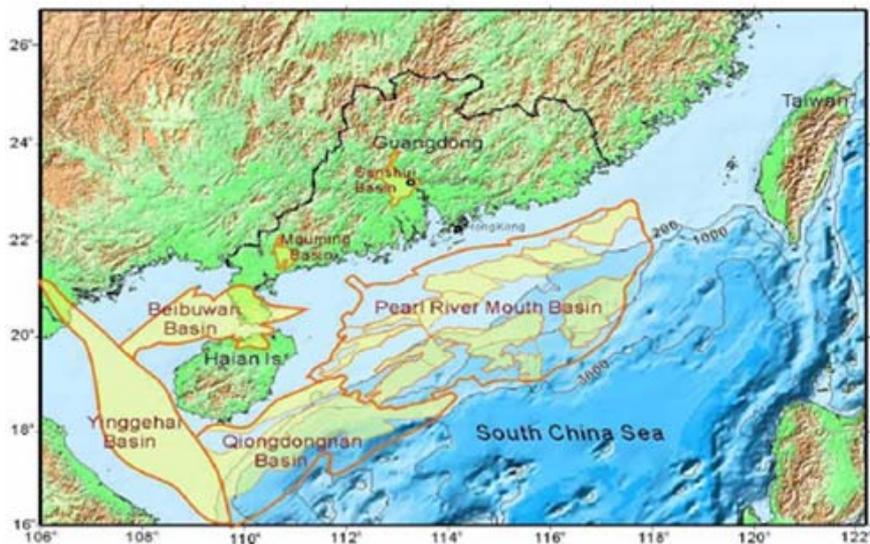


Figure 2.6 Major sedimentary basins onshore and offshore Guangdong

2.5.2 Cost reduction is the major challenge for offshore CO₂ storage

Offshore CO₂ storage has many advantages over onshore storage: less competition in land use, less risk to environment and groundwater, and thus higher public acceptance. Its major disadvantage is the high cost, several times higher than the cost of onshore storage. Cost reduction is the major challenge for offshore CO₂ storage.

The best way to offset the cost of CO₂ storage is to use the injected CO₂ for enhancing oil recovery (CO₂-EOR) or gas recovery (CO₂-EGR). However, the potential for CO₂-EOR is low in the fields in the Pearl River Mouth Basin, because the recovery rate is already high with strong water drive. In addition, as yet there are no offshore CO₂-EOR projects to date anywhere in the world perhaps due to the complexity and high cost of the operation. The potential of CO₂-EGR in this basin has not been studied, but the gas fields in the basin are mostly newly discovered and thus may not be suitable to CO₂-EGR at the present.

A practical way for Guangdong to offset the cost may be to use the existing infrastructure (platforms, wells, pipelines, etc.) of depleted offshore oil or gas fields for CO₂ transportation and injection. This may have multiple benefits, such as using the underground space left when oil and gas have been extracted out, reducing the cost of offshore CO₂ storage, and obtaining additional economic benefits when CO₂ sequestration has a significant market price. As the storage project is being carried out, it should be possible for the well to be connected with saline formations to resolve the problem of the relatively small storage capacity of the oil and gas fields.

An urgent task is to evaluate the feasibility of using the existing infrastructure for offshore CO₂ injection after the field depletion and to find sufficient storage capacity within and near the field. This task may be termed making the field “CO₂ storage ready”. This should be conducted several years ahead of the field depletion, otherwise the field will be closed and the infrastructure will be abandoned soon after the depletion in order to avoid the high maintenance cost.

2.5.3 Safety of CO₂ storage

Safe storage of CO₂ deep underground without significant leakage and environmental damage is the basic requirement for CCS. Storage sites should be selected carefully to have good sealing conditions and to avoid leaking faults and unstable areas (e.g. areas with frequent earthquakes, volcanoes, or active faults). The possibility of CO₂ leakage along existing or abandoned boreholes should be examined, especially when depleted oil/gas fields are used for CO₂ storage. Risk assessment and emergency management planning should be conducted on a site by site basis before the start of CO₂ injection.

CO₂ injection might cause a pressure increase in the reservoir. A key safety issue is to keep the formation pressure below the fracture pressure in order to avoid seal failure. Injection simulation and monitoring are major techniques to be applied before, during, and after the CO₂ injection to detect and predict the pressure variation and the movement of CO₂ in the reservoir.

For the safe operation of offshore CO₂ storage projects, much can be learned from international experiences in offshore CO₂ storage as well as from the experiences of offshore hydrocarbon exploration in the northern South China Sea. In addition, Guangdong should also learn through its own demonstration projects. Effort should be made to draft guides and regulations for the CO₂ storage operations offshore of Guangdong.

2.5.4 Summary

Because of the limited onshore CO₂ storage potential, offshore geological storage will be the main option for Guangdong. Large CO₂ storage capacity exists in the shelf area of the Pearl River Mouth Basin. Because the potential of CO₂EOR there is limited, the best option to offset the capital cost of offshore CO₂ injection is to use existing infrastructure in depleted oil or gas fields. The feasibility of using the existing infrastructure in offshore CO₂ injection must be evaluated several years before the depletion of the oil or gas field. The safety of offshore CO₂ storage may be achieved through careful selection of storage site and proper storage operations, monitoring, and post-closure management. Guangdong should draft relevant guidance and regulations based on international experiences as well as on the requirements of its own demonstration projects.

2.6 Technical demands for CO₂ transportation

Transporting CO₂ from capture sites to the storage sites is a necessary part of the CCS chain. Currently CO₂ transported in CCS projects is in the high-pressure (~100 atmospheres or higher) liquid state or in the supercritical state. The main transportation means are tanker, pipeline and ship, all of which already have mature technologies and quotable experiences.

2.6.1 Source-sink matching

The large point sources in Guangdong are mostly distributed along the coast and especially

concentrated in the Pearl River Delta. The most favourable storage area is the shelf area in the Pearl River Mouth Basin because the water is shallow, geological conditions are suitable, and there are producing oil fields whose infrastructures might be used to offset the cost of offshore CO₂ storage after the fields' depletion. These would make a good source-sink match with the distance ranging between 120 km to 300 km (Fig. 2.7).

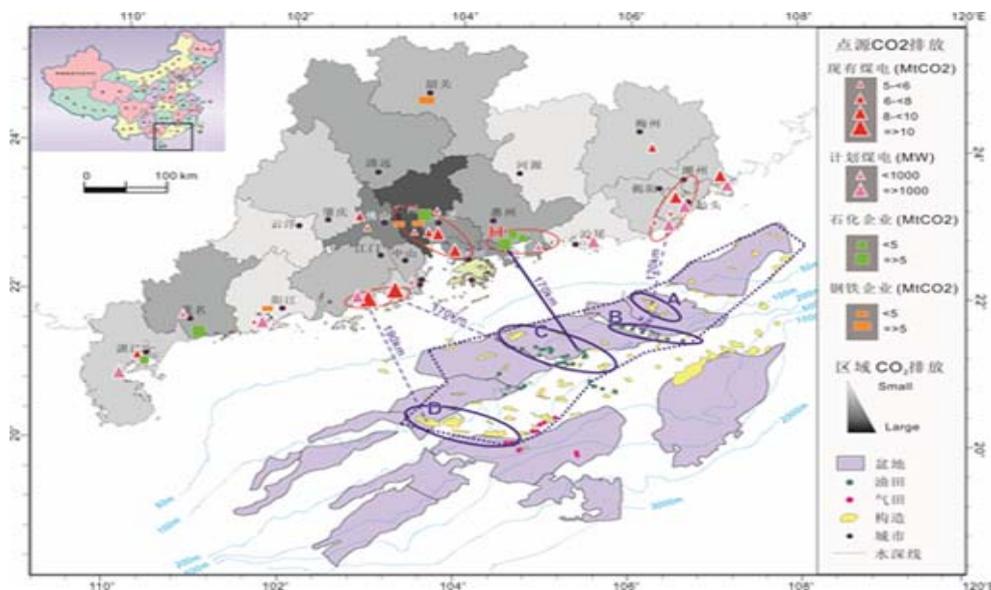


Figure 2.7 Location map for large point sources of CO₂ onshore Guangdong and potential storage sites offshore in the Pearl River Mouth Basin. The solid blue line connects the source and sinks for the Huizhou demonstration project.

2.6.2 Pipeline transportation

Pipeline transportation is an economic and effective way for large scale, long-distance, and long-term CO₂ transportation. CO₂ pipeline transportation is a mature technology. Over 2500 km of CO₂ pipelines have already been built in the US, transporting 50 million tonnes CO₂ per year, principally for EOR.

A CO₂ flow containing water vapour and other impurities (H₂S, SO₂, NO₂) is highly corrosive, which is the main concern for CO₂ pipeline transportation. However, by strict dehydration and purification of CO₂ the corrosion impact can be minimized, and normal carbon steel pipes can be used. The overpressure or leakage of CO₂ in transportation is also a risk in transportation, and thus monitoring and emergency planning is also very important.

Designing a CO₂ pipeline transportation network on a regional level may help to increase the efficiency and to reduce the overall cost of CO₂ transportation. For the source-sink match as shown in Fig. 2.7, the optimum network should be designed in the scheme of source cluster – source hub – trunk pipeline – sink hub – sink cluster to reduce the cost and increase the efficiency.

According to the IPCC (2005), under the same geographic condition, the unit cost of CO₂ pipeline transportation will increase rapidly when the annual transportation amount is less than 3 million tonnes. The cost of offshore pipeline is 40-70% higher than onshore pipeline (Fig.2.8).

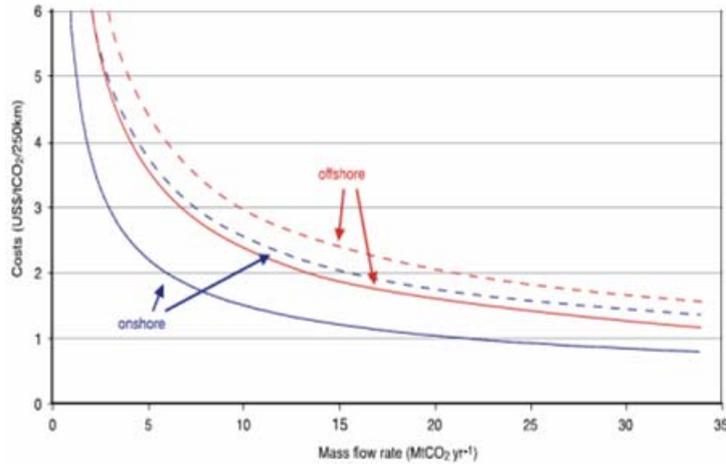


Figure 2.8 Relation Curve of CO₂ transportation cost and CO₂ volume by 250 km pipeline under Ordinary geological condition (IPCC, 2005). Note: the blue line represents onshore storage; the red line offshore storage; the solid and dashed lines the low and high end cost range respectively.

2.6.3 Ship Transportation

The requirements for low temperature and safety for transporting liquefied CO₂ are less onerous than those for transporting liquefied natural gas (LNG). Currently large quantities of LNG are shipped to Guangdong by LNG carriers, which have shown good performance in ultralow temperature (-163°C), fire resistance, and reliability. These LNG carriers may be referenced by Guangdong to compare the cost of various shipping schemes such as charting or recasting.

Costs of ship transportation include the vessel, loading, temporary storage device, terminal lease fee, and fuel. According to the IPCC (2005), under the scenario of 6 million tonnes annual transportation over 500 km, the total cost of chartering a ship is approximately 10 US\$/tCO₂/500km, much higher than the cost of pipeline transportation. However, because the cost of shipping is less sensitive to distance than pipeline transportation, when the distance is over 1250 km, the cost of shipping may be equal to or lower than that of pipeline transportation.

2.6.4 Selection of CO₂ transportation scheme

The selection of a transportation scheme depends on the situation of source-sink match and the scale and duration of CCS projects. As the large point sources in Guangdong are mostly distributed along the coast and especially concentrated in the Pearl River Delta, and potential storage sites are offshore at a distance ranging from 120 km to 300 km (Figure 2.7), pipeline transportation would be the most economic, viable, and reliable choice for long-term and large quantity CO₂ transportation.

However, pipeline transportation requires a substantial one-off investment and infrastructure construction. Guangdong Province is currently in the early demonstration stage of CCUS development with moderate storage capacity, for example one million tonnes CO₂ per year, and therefore the cost of pipeline transportation might be very high (Fig. 2.8). Specific studies should be made to compare the cost of different transportation schemes: either to build a pipeline route as the first phase of a unified pipeline network system, or to adopt more flexible ship transportation to avoid investment risk in pipeline construction.

2.7 The potential for CO₂ utilization and CCUS-related industry

The utilization of captured CO₂ would be the first option from the viewpoint of gaining an economic benefit. Available data indicate that only a small portion (0.5%) of anthropogenic CO₂ emissions can be utilized (IPCC, 2005), and some cases of utilization can only delay CO₂ emission and do not have a permanent mitigation effect. However, actively developing CO₂ utilization technologies and expanding CO₂ utilization fields may be beneficial in partly offsetting the cost of CO₂ capture, stimulating the development of related industries, as well as facilitating the development of CCUS technologies and projects.

CO₂ utilization involves several engineering fields, including oil and natural gas production, the chemical industry, and building material production, biological utilization, etc.

2.7.1 CO₂-EOR/EGR/ETR

Injecting CO₂ into oil or gas fields in order to enhance oil or gas recovery (CO₂-EOR/EGR) is to date the most effective use of CO₂. Because the injected CO₂ cannot be fully recycled, the remaining CO₂ is stored underground. The CO₂-EOR technology has been developed and applied for almost 40 years worldwide with ~100 projects in operation, although there is much less experience with CO₂-EGR. On average each tonne of CO₂ injected can produce 2.5-5 barrels of crude oil and increase the recovery rate by 4-18% for CO₂-EOR (IPCC, 2005). Among the existing large-scale CCUS projects there are about 46% involve CO₂-EOR. In China CO₂-EOR research and technical development have been started with the support from a number of 973 and 863 projects since 2006. CO₂-EOR demonstration projects in the Jilin and Shengli oil fields have made good progress.

To date all the worldwide CO₂-EOR/EGR projects are onshore. The implementation of CO₂-EOR/EGR in offshore fields would be more challenging and costly. However CO₂-EOR in the North Sea has been actively considered in recent years. It is expected that by 2030 CO₂-EOR in the UK's North Sea shelf would provide 15% of the total crude oil production at the same time achieving large scale CO₂ storage (Pershad et al., 2012) .

The suitability for CO₂-EOR/EGR depends on local geological conditions. The oil fields in the Pearl River Mouth basin are not suitable for CO₂-EOR because they have very strong bottom or lateral water drives, which has resulted in high recovery rates. Once the oil is extracted, the pore space is invaded quickly by water. Thus water flooding for the secondary recovery is not likely needed, and there is even less necessity for CO₂-EOR as the tertiary recovery. In addition, the small size of oil fields in the basin would limit the economic benefit from CO₂-EOR. Consequently the potential of CO₂-EOR in the Pearl River Mouth Basin is limited.

The use of CO₂ injection to enhance geothermal recovery (CO₂-ETR) is an emerging technology. It is currently at an early R&D stage. Onshore Guangdong geothermal resources are rich and might be an important source of clean energy. Guangdong should investigate the potential of CO₂-ETR and encourage related research and development.

2.7.2 Resource utilization of CO₂

Resource utilization of CO₂ refers to transforming the captured CO₂ into useful products by chemical or biological processes. The CO₂ will be stored permanently if the products are in solid state and are non-degradable.

Currently, resource utilization of CO₂ in Guangdong Province mainly focuses on the food processing industry (carbonated drinks, vegetables and fruits preservation, tobacco expanding agent, etc.) and on the chemical industry (metal protection welding, synthesize organic compounds, fire extinguishing agent, refrigeration agent, etc.). The aggregated amount of CO₂ used this way is approximately 20 thousand tonnes per year. Most of these uses can only delay CO₂ emissions instead of actually reducing the emission permanently.

To achieve the maximum mitigation benefit, the current most popular way to use CO₂ worldwide is in biofuel production, building material production, and chemical engineering applications. In these areas Guangdong has some advantages: Guangdong is located in the subtropics and has a long coastline, which is favorable for CO₂-assisted algae cultivation and algae-fuel production. Guangdong has strong cement and chemical industries and technical talents, which are favourable for developing industrial utilization techniques such as CO₂ synthetic building materials, plastics, and chemical fertilizers.

The large scale resource utilization of CO₂ is currently still in the actively R&D stage worldwide. Major challenges are the cost and energy efficiency. Guangdong should take part in the innovation and competition, strive for breakthrough in some areas, potentially share the massive technical and product markets, and create novel industries.

2.7.3 Industrial possibilities brought by CCUS

CCUS is one of the “emerging industries of strategic importance” as defined by the National Development and Reform Commission of China in 2012. CCUS research, demonstration and commercialization in Guangdong Province will either bring or accelerate the development of a number of industries, such as the manufacturing or processing of equipment, chemical absorbents, and onshore and offshore pipelines, marine engineering, as well as the associated financial, consulting, engineering, and legal services. These will also help Guangdong industry to be sustainable in a low carbon future.

CCUS techniques have been taken by many countries in the world as an important step in the future competition for low-carbon technologies. Guangdong Province should make an effort to develop the most advanced CCUS technology and CCUS related industries in order to share in the potential global market.

2.7.4 Summary

CO₂ utilization and CCUS-related industrial development may create additional economic benefits to offset partly the cost of CCUS, and thus help promote the development of CCUS. The natural, social, and industrial conditions of Guangdong favor the CO₂ utilization in the areas of onshore CO₂ injection for enhanced geothermal resource recovery (CO₂-ETR), CO₂ algae cultivation and algae-fuel production, CO₂ synthesized building materials, plastic, chemical fertilizers, etc. Guangdong Province should aggressively advance CO₂ utilization techniques and related industries to a strategic level and aim not only at domestic but also at international markets.

2.8 The demand for CCUS-ready new power plants

CCUS-ready (CCUSR) is the concept of designing a large-scale power or industrial facility so that it can be retrofitted with CCUS technology when the necessary regulatory and economic drivers are in place.

CCUSR consists of three parts: capture ready, transport ready, and storage ready. Capture ready requires reserved space and modified design for retrofitting CO₂ capture equipment, ensuring a smooth and less-expensive transition of the power plant to CO₂ capture retrofit in the future. Storage and transportation ready requires feasible plans to transport and store captured CO₂.

Implementing CCUS-ready can avoid carbon lock-in and reduce the future cost of CO₂ capture retrofit. The simulation of an ultra-supercritical pulverized coal power plant in Guangdong (GDCCUSR Final Report, Part 4) indicated that a small increment (0.5~3%) of capital investment will bring a large saving in the cost of future retrofitting with capture equipment.

A simulation for the Shenzhen city indicated that a regional integrated plan for CCUS-ready (i.e. the CCUSR hub design) might reduce the cost for future CO₂ capture retrofiting by 20%.

According to the energy economic model analysis, CCUS commercial operation is expected to emerge in Guangdong Province after 2030, but the energy demand and thus the installed capacity of power generation of Guangdong in the period from now to 2030 will still increase. In the current policy scenario, planned newly built coal-fired power will increase capacity by 20 GWe between 2010 and 2015, with an expected additional 6 GW capacity by 2030 (Fig. 2.1). The need for new built coal fired power plants to be CCUS-ready is significant for Guangdong.

The CCUS-ready concept should be popularized among the stakeholders. Early action should be taken to establish CCUSR policies and regulations. New plants which are CCUSR should be given preferential approval by government. At the same time policies are needed to ensure the incremental land and investment required by CCUSR.

2.9 The demand and opportunity for full-chain CCUS demonstrations

The development of CCUS as an emerging green technology needs to go through a demonstration stage to bridge the gap between research and commercialization. Demonstration projects are important not only for testing and improving various techniques, equipment, and processes, but also for demonstrating to the public the possible contribution of CCUS to reduce greenhouse gas emissions and the possibility of safe operation and low environmental impact in CCUS operations.

For the CCUS development in Guangdong Province, the urgent need is to demonstrate the feasibility of using the infrastructure of depleted offshore oil/gas fields in CO₂ injection, as offshore storage is the major feature of CCUS in Guangdong, and the technical specifications of CO₂ injection are dependent on local geological conditions.

The “Huizhou Demonstration Project” has been identified as an early opportunity of a full-chain

demonstration project in Guangdong Province. This project envisages capturing CO₂ from hydrogen production in a refinery plant in the Huizhou City and storing CO₂ in a depleted offshore oil field using existing infrastructure (see Fig. 2.7 for the locations of source and sink). The target capacity of the project is one million tonnes CO₂ per year.

As the cost of CO₂ capture decreases with the increase in CO₂ concentration in the gas flow, the high-purity CO₂ flow produced from the hydrogen production in the petrochemical industry will enable a cost-effective capture. By using the infrastructure (platforms, wells, pipeline, etc.) from depleted oil fields for CO₂ injection the cost of offshore CO₂ storage can be significantly reduced. Thus the “Huizhou Demonstration Project” can be a cost effective project.

2.10 The demand for policy and regulations on CCUS development

The CCUS development can be divided into two stages. The first stage is for R&D and demonstration, when the CCUS development mainly relies on government funding, incentive policies, and international cooperation. The second stage is for large scale commercial application, where CCUS development mainly relies on a mature carbon pricing system and/or other market mechanisms. Currently Guangdong is in the early days of the first stage, and policies and regulations need to be established in the following aspects:

(1) Policies on emission reduction targets

The carbon intensity reduction target for the province and the carbon reduction quotas for key energy consumption corporations in the future Five-Year Plans need to be established in order to guide the development of CCUS in the province and in related enterprises. CCUS should be incorporated into the provincial low carbon development program.

(2) Financial support and incentive policies

In the CCUS R&D and demonstration stage, government support in project approval and funding should be enhanced to encourage stakeholders’ involvement and investment to CCUS design, CCUS R&D, and CCUS demonstration projects. Incentive policies, such as tax reductions and low-interest loans, etc. are also needed. Because CCUS technology can transform coal into a clean energy with near-zero CO₂ emissions, the incentive policies being applied to other clean energies (e.g. renewables and nuclear) should also be applied to CCUS.

(3) Market related policies

Some countries have implemented market related policies or schemes to CCUS projects, such as carbon emission trading, carbon tax and contract electricity pricing, etc. Guangdong should set up market related policies for CCUS with regard to foreign experiences and local conditions, and continuously improve the existing policies and make policy innovations, so that the development of CCUS can be facilitated in the early R&D stage and can be fully supported in the later CCUS commercial operation stage.

(4) Technical standards and regulations

Incentive policies for new built coal fired power plant to implement CCUS and CO₂

emission standards for enterprises are urgently needed and should be established no later than 2015. Technical standards for all processes in the full-chain CCUS, including risk monitoring and emergency management for offshore CO₂ storage, are needed to ensure the high-quality construction and safe operation of CCUS projects.

(5) Public awareness and capacity building

Public acceptance and capacity building are key issues in CCUS development. Knowledge gaps often cause misunderstanding. Measures should be taken to promote CCUS knowledge sharing activities for stakeholders, including government, enterprises and the general public, through associations, networks, the media, and workshops. In the meantime CCUS training programs for stakeholders should be enhanced.

(6) International and domestic exchange and collaborations

Worldwide CCUS technology is still in the R&D and demonstration stage. The efficiency, safety and economics of CCUS technology should be raised through experience learning and knowledge sharing. Guangdong should take measures to encourage extensive CCUS academic and technical exchanges with domestic and international counterparts and stakeholders, to promote international collaboration, and to attract multilateral funding for the CCUS research and demonstration projects in Guangdong Province.

3. CCUS Development Roadmap for Guangdong Province

A CCUS development roadmap for Guangdong Province is proposed by the GDCCUSR project team as a major deliverable of the project. Our general vision is to make the roadmap a guide to a technically feasible and economically affordable CCUS development in the province. Thus the roadmap should be complimentary to the national CCUS roadmap (MOST and ACCA21, 2011) but also reflect the special features of the province. With this vision we analyzed the deliverables of the GDCCUSR project and summarized expert suggestions. The roadmap for Guangdong Province was then drawn up, which includes a general roadmap and a number of component roadmap for CO₂ capture, transport, storage and utilization respectively. The targets, actions, and required policies are suggested in the roadmap for CCUS development in Guangdong Province in different stages from now to 2030.

3.1 The general CCUS development roadmap for Guangdong Province

The general CCUS development roadmap for Guangdong Province is shown in Fig. 3.1. The major milestones for the proposed roadmap are as follows:

- CCUS-ready policy for new coal-fired power plants by 2014;
- CCUS included in the low-carbon action plan of the 13th Five-Year Plan of Guangdong Province in 2015;
- Operation of a full chain CCUS Huizhou Demonstration Project by 2020;
- Operation of a full chain CCUS demonstration on a coal-fired power plant by 2025;
- Start of commercialized CCUS development in Guangdong Province around 2030;
- Building policies, regulations, and capacities for CCUS development in Guangdong Province.

The “Huizhou Demonstration Project” is proposed as the first full-chain demonstration project in Guangdong Province. This project envisages capturing CO₂ from hydrogen production in a refinery plant in Huizhou City and storing CO₂ in a depleted offshore oil field using existing infrastructure. The target capacity of the project is one million tonnes CO₂ per year. The preparation and design of this project should start now, and the project is to be in operation by 2020.

The Huizhou Project will be the first CCUS demonstration project in southeastern China and the first CCUS project in China with offshore CO₂ storage. The engineering design, construction, and operation of the demonstration project will provide a platform for research and development of key techniques in CO₂ capture and offshore storage as well as for establishing related policy and regulations. This project will have flagship significance for the coastal provinces in southeastern China, where geological conditions are similar to those in Guangdong Province and where the potential for CO₂ storage would also be offshore.

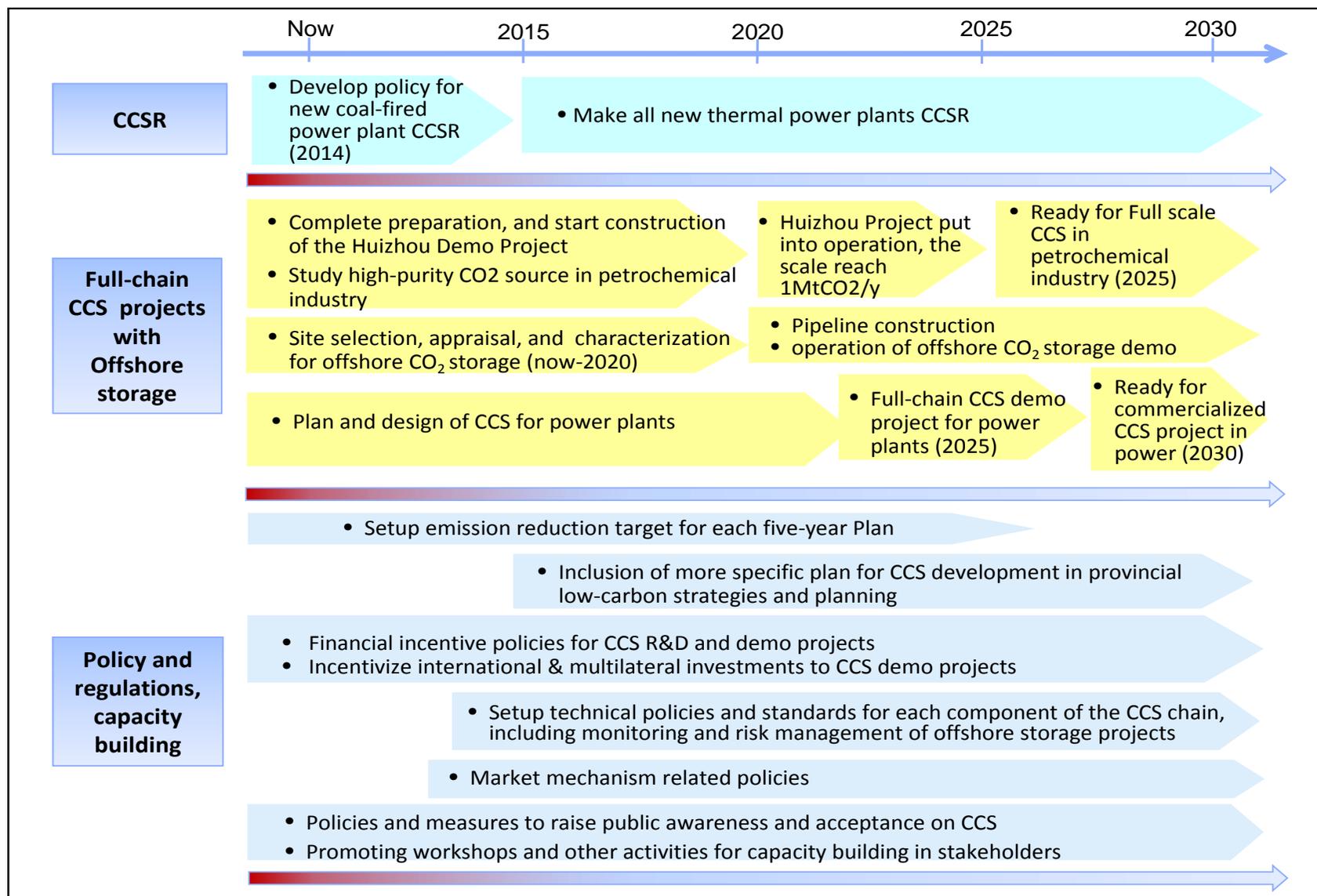


Figure 3.1 The General CCUS Development Roadmap for Guangdong Province

3.2 The development roadmap of CO₂ capture for Guangdong Province

The development roadmap of CO₂ capture for Guangdong Province is presented in Fig. 3.2 and includes the following four components:

(1) High concentration CO₂ capture in the petrochemical industry: An attractive opportunity for CO₂ capture in Guangdong is from high-purity CO₂ sources from hydrogen production in the petrochemical industry. A study should be started soon to locate and quantify high-purity CO₂ sources in the province. The design and construction of CO₂ capture installations for the Huizhou Project should be started soon so that they can be in operation by 2020. The construction of a large scale full-chain CCUS project is expected to start by 2025.

(2) Power sector CO₂ capture: The power sector is the key for Guangdong to achieve deep carbon mitigation through implementing CCUS. Research indicates that ultra-supercritical power plus CCUS has the greatest cost advantage, while post combustion capture technology will be the most widely used CO₂ capture technique in view of Guangdong's power configuration. Because R&D in capture technology has been conducted extensively in past decades worldwide and in China, Guangdong could benefit by selecting the best-fit capture technology and the optimal application of the technology for the province.

(3) CCUS-ready design of new built power plant: In order to prevent “carbon lock in” and to achieve a low cost and smooth transition to large scale CCUS applications in 2030, Guangdong should implement a CCUS-ready (CCUSR) policy for new built coal-fired power plant no later than 2014, give CCUSR new plant preferential government approval, and require all new built coal-fired power plant to be CCUSR since 2015.

(4) R&D of other capture technologies: Guangdong should encourage and support her professional talents and related enterprises to conduct R&D in pre-combustion capture and oxy-fuel combustion capture technologies for innovation and breakthrough.

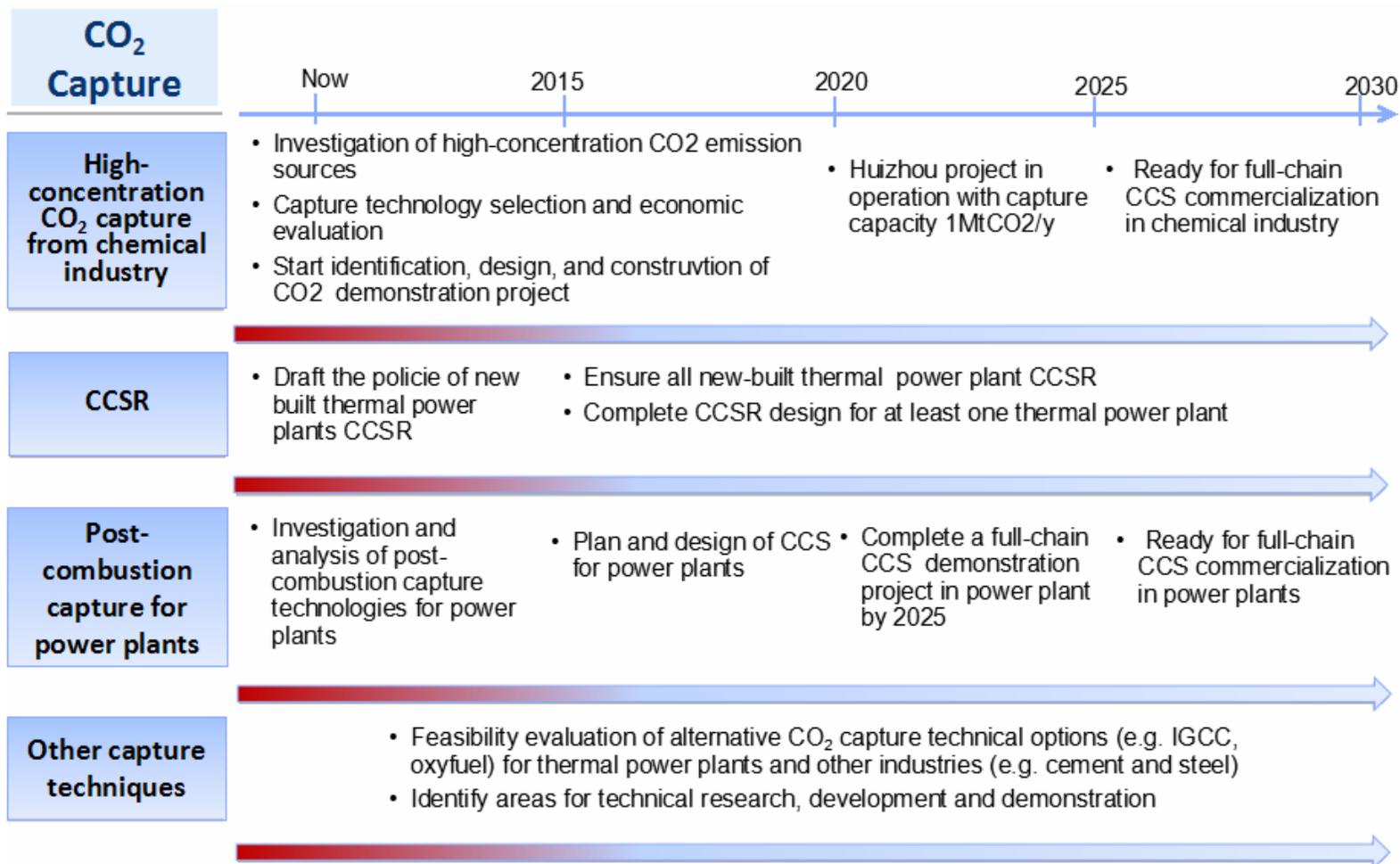


Figure 3.2 The development roadmap of CO₂ capture for Guangdong Province

3.3 The development roadmap of CO₂ transportation for Guangdong Province

The development roadmap of CO₂ transportation for Guangdong Province is presented in Fig. 3.3 and includes transport networking, pipeline transport, ocean ship transport, and related policy issues. Key points in the roadmap are as follows:

- (1) A feasible and efficient source-sink matching scheme should be established by 2020;
- (2) Transport methods and networks should be planned by 2020;
- (3) Related technical standards and regulations should be established.

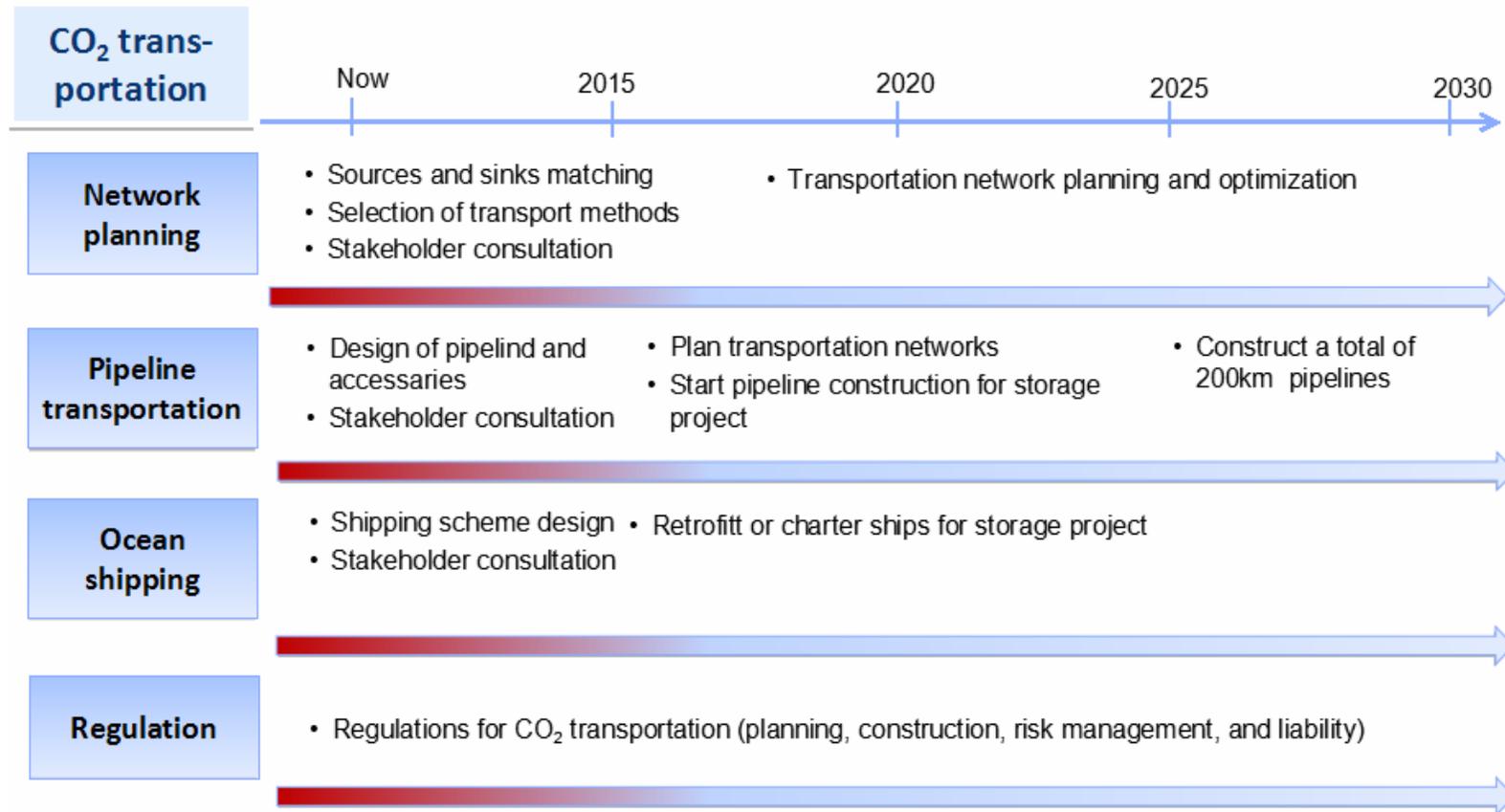


Figure 3.3 The development roadmap of CO₂ transportation for Guangdong Province

3.4 The development roadmap of CO₂ utilization and storage for Guangdong Province

The development roadmap of CO₂ utilization and storage for Guangdong Province is presented in Fig. 3.4 and includes

(1) CO₂ Utilization: Researches on the potential and key areas for CO₂ utilization should be started soon. According to the natural conditions and industrial advantages, Guangdong Province may focus on R&D of efficient utilization technology such as CO₂ enhanced geothermal resource recovery (CO₂-ETR), CO₂ enhanced algae cultivation and algae-fuel production, and CO₂ chemical industry utilization etc., aiming to achieve technology breakthroughs in increasing efficiency and reduce costs by 2020, and to build up CO₂ utilization industry by 2030.

(2) Offshore depleted oil/gas field CO₂ storage: Offshore geological storage is the major means of CO₂ storage for Guangdong Province; utilizing the facilities of depleted oil and gas fields for storage is an effective way to reduce the cost. Consequently the top priorities should be to conduct a feasibility analysis of the selected near-depleted oil field for the Huizhou Demonstration Project, complete the project design by 2015, and complete the construction and start operation with 1 MtCO₂/y storage capacity by 2020. Experiences on technology and regulations for a safe operation of offshore CO₂ geological storage should be accumulated through this project. The potential of enlarge the storage capacity to adjacent saline formations should be studied.

(3) Offshore saline formation CO₂ storage: Due to the limited CO₂ geological storage capacity of depleted oil/gas fields, offshore saline formation CO₂ storage will be necessary for future large scale CCUS operation. Guangdong Province should cooperate with relevant state departments to conduct a survey of the accessible offshore saline formation storage sites with commercial scale storage capacity. Characterization of preferred saline formation storage sites should start in 2015; the identification and design of a suitable offshore saline formation storage project should start in 2020; the project construction should start in 2025, and the first commercial scale offshore saline formation CO₂ storage project should start operation in 2030.

(4) Development of a CCUS industry: An investigation into the domestic and international demand for CCUS engineering and equipment and Guangdong's technical and industrial capabilities should be started soon. This should then be used to plan for developing CCUS related industries. In parallel, a CCUS industrial value chain should be identified, and special techniques and products associated with the CCUS industry should be developed, expanding into both Chinese and international markets.

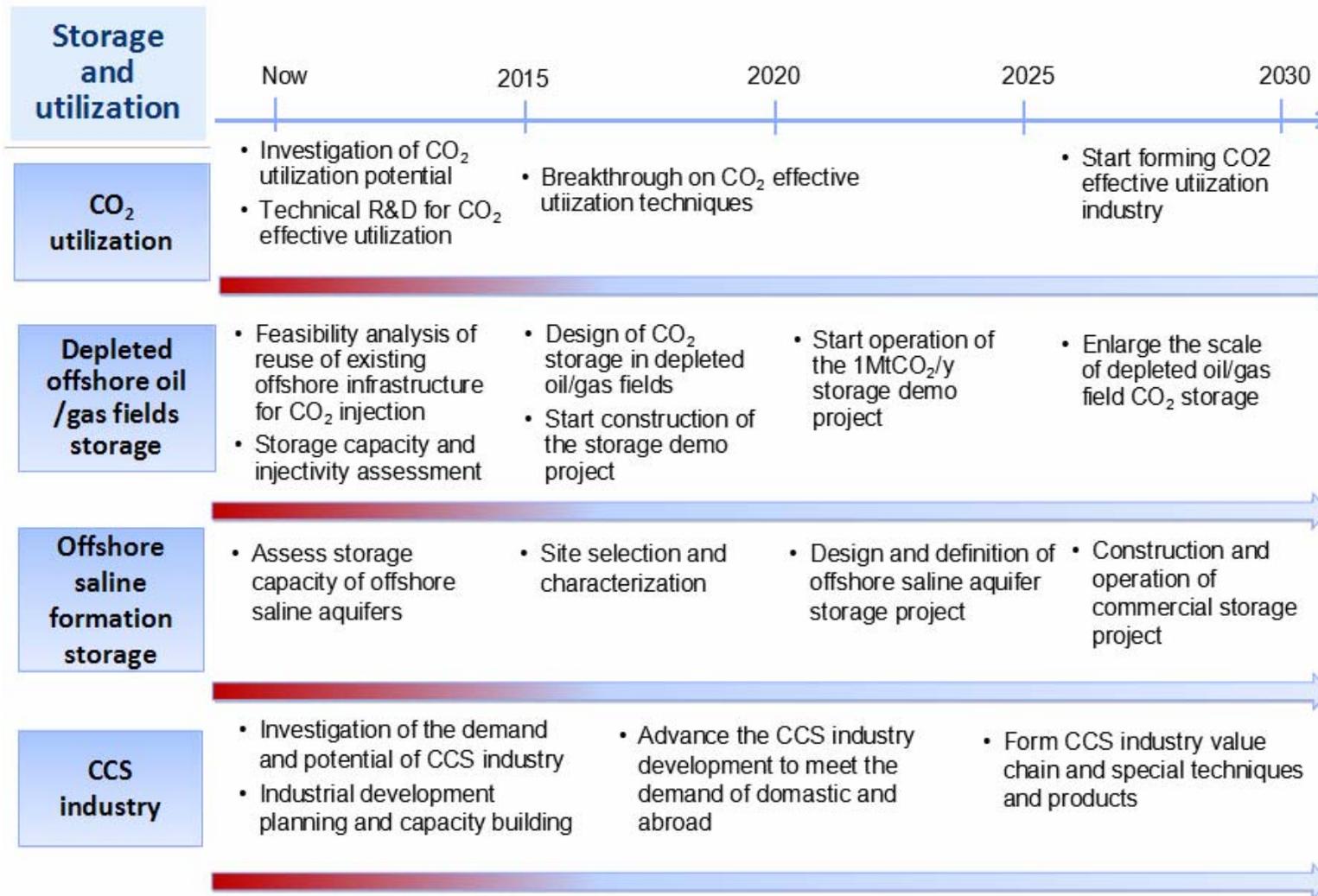


Figure 3.4 The development roadmap of CO₂ storage and utilization for Guangdong Province

4. Closing remarks

Guangdong Province needs CCUS in her low-carbon development pilot programme, because the fossil-fueled power generation is and will remain for the foreseeable future the dominant electricity source in the province, and also because CCUS is the most effective technology to realize large-scale carbon emission reductions in manufacturing and process industries that use fossil fuels.

Comprehensive studies in the GDCCUSR project have confirmed the necessity and feasibility of CCUS development in Guangdong Province and projected that CCUS development in the province would not only make a significant contribution to realizing the carbon reduction target, but also help energy security and bring business opportunities.

The technical and policy demands for CCUS development in Guangdong Province were analyzed in this report based on the features and status of CCUS technology and the natural, economic, and social conditions of Guangdong Province. Based on these analyses the CCUS Development Roadmap for Guangdong Province was prepared, which includes a general roadmap and three specific roadmaps for CO₂ capture, CO₂ transportation, and CO₂ utilization and storage, respectively. This is designed to provide a clear guideline for CCUS development in the province from now to 2030.

As Guangdong Province is the only low-carbon pilot province in southern China, and her natural and economic conditions are representative of southeastern China, we believe that the Guangdong government is able to create a favourable policy environment to encourage industry engagement in CCUS development. This will not only benefit the province in achieving her carbon reduction targets, but also lead CCUS development in southeastern China.

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