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广东省
二氧化碳利用技术及潜力

Guangdong CO2 Utilization Technical Report

讨论待修改稿

Draft for Discussion and Further Revision

中英（广东）CCUS 中心
UK-China (Guangdong) CCUS Centre

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2009年，中国国务院提出2020年温室气体排放行动目标，并在2010年把广东省列为低碳试点省份。英国能源与气候变化部与广东省发展及改革委员会在广东省省长朱小丹的见证下于2013年9月在伦敦签订了推动低碳合作的联合声明,以深化双方合作,其中强调了开展碳捕集与封存（CCS）合作的重要性。2013年12月18日中英（广东）碳捕集，利用与封存产业促进与学术交流中心，即中英（广东）CCUS中心正式成立。中心致力于推动大型CCUS项目的示范，应对人类面临的温室气体排放的挑战，为中国面对的雾霾、水污染的问题提供国际合作平台，催化清洁化石能源技术产业化，以及培养相关专业人才。

In 2009, China’s State Council proposed its 2020 goal for greenhouse gas emissions, and then in 2010 made Guangdong a low carbon pilot province. Guangdong has made remarkable achievements in greenhouse gas emission control to which the UK-China low carbon cooperation has contributed significantly. In September 2013 the UK Department of Energy and Climate Change (DECC) signed a joint statement in London with the Guangdong Development and Reform Commission, witnessed by governor Zhu Xiaodan of Guangdong Province, to strengthen low carbon cooperation. The joint statement highlights the importance of collaborating in Carbon Capture and Storage (CCS). Supported by the Guangdong and UK governments, the UK-China (Guangdong) Carbon Capture, Utilisation and Storage Industry Promotion and Academic Collaboration Centre (the “Centre”) was officially founded on December 18th, 2013. The Centre is committed to promoting the demonstration of large-scale CCUS projects to tackle greenhouse gas emissions. At the same time, the Centre will also provide an international collaboration platform for solutions to other local pollution problems (such as haze, water pollution) caused by coal utilization, and to accelerate the industrialization for clean fossil energy technologies and to train qualified professionals.

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1. 引言

Introduction

1.1 CO2利用技术简介

近年来，气候变暖已严重威胁到人类可持续发展，应对气候变化成了全球共同面临的重大挑战。政府间气候变化专门委员会（IPCC）评估报告指出大气中CO2浓度的增加是气候变化的最大推手（IPCC，2013）。原则上，至少有三种方法可以减少大气中CO2：在源头减少CO2排放；CO2的捕获、封存（CCS）；CO2的利用(Wang et al.，2014)。其中，对已经产生的CO2进行捕集与封存已经逐渐被公认为一项可以实现CO2大规模减排的方法，然而这项措施目前还存在着成本高，部分地区缺乏封存能力有不确定性等局限（Sridhar and Hill，2011），制约着CCS技术的应用和发展。CO2的利用技术可以作为一个过渡方案，将捕集到的CO2附加价值，带来经济效益，补偿CCS的成本，逐渐受到人们的关注。目前，尚未有成熟的利用技术能够为人类大幅度减排二氧化碳。除了二氧化碳提高石油采收率等地质利用，其他利用能够经济地减排二氧化碳量非常有限。

具体来说，通过对排放的CO2回收利用至少可从四种途径缓解气候变化问题（Aresta，2010；Audus and Oonk，1997）：

一是二氧化碳的地质利用，如提高石油采收率，提高水的采收率；

二是通过对CO2的利用直接减少CO2的排放，例如以CO2为原料生产化工商品；

三是通过将CO2重新还原为碳氢燃料（例如，微藻养殖生成柴油技术等），循环对碳原子的利用，减少其它来源的化石燃料的燃烧，最终减少CO2的排放；

四是通过开发新的反应路径以CO2为反应试剂替代传统对气候变化有更大影响的物质，间接地缓解气候变化问题，例如在干洗业，用液体CO2替代氯化物溶剂（相同质量情况下，氯化物造成全球暖化的能力是CO2的数百至数千倍）。

Sridhar教授估计，理论上，如果各种CO2利用技术得到广泛应用，可通过前2种途径减少至少3.7 Gt/y的CO2向大气中的排放（相当于现在每年排放CO2的10%）（Sridhar et al.，2011）。

需要注意的是，即使CO2利用技术可以得到广泛地应用，它的减排潜力也是很有限的，且并不能有效抑制大气中CO2的积累，只可以减少CO2的向大气中的排放（Aresta，2010）。尤其在现阶段，典型的利用技术中CO2被利用的周期只有数天到数月，被利用的CO2储存在工业产品中，很快又会被分解、释放到大气中，很难起到减排的效果（Mikkelsen et al.，2010）。另外，一些转化过程需要消耗能源，可能会导致CO2的排放，而许多较有减排潜力（对CO2固定时间长，能耗小）的利用技术还处于R&D或者示范阶段，未能扩大规模充分发挥减排作用。除此之外，CO2技术的发展也受到多种因素的制约（Song，2010）：（1）CO2的捕集、纯化、运输费用高；（2）一些CO2的化学转化需要消耗大量能量；（3）市场相对较小，缺乏投资激励；（4）缺乏发展CO2利用技术社会经济推动力。

尽管CO2利用技术的直接减排作用小，且受到多种因素的制约，发展缓慢，CO2利用技术仍是应对气候变化问题的潜在重要措施。国际社会已经开始对CO2利用技术进行积极探索和发展。美国政府已经投资10亿美元于CO2的捕集和利用的研究；德国政府仅对一个利用CO2作为原材料的项目就投资了1.18亿欧元（Styring et al.，2011）。中国政府早就有对CO2利用相关技术开发利用的扶持，但从缓解气候变化问题的

1.1 Brief introduction to CO2 utilization technologies

The sustainable development of human beings has been greatly threatened by global warming, and the world is confronted with a big challenge to tackle climate change. The assessment report published by the Intergovernmental Panel on Climate Change (IPCC) indicated that the increase of CO2 concentration in the atmosphere is the biggest driver of climate change (IPCC,2013). In principle, there are at least three ways to reduce CO2 in the atmosphere: CO2 emission reduction from source; CO2 capture and storage (CCS); and CO2 utilization (Wang et al., 2014). Amongst these, CO2 capture and storage is recognized as a technology that can realize drastic emission reductions, though its deployment and development is constrained due to its relatively high cost and limit of CO2 storage in certain regions (Sridhar and Hill, 2011). CO2 utilization technology, however, as a potential transition mechanism, is gradually attracting people's attention because it can add value to the captured CO2, bringing economic benefits and compensating for the cost of CCS. So far, there is not yet a mature utilization technology that could contribute to a deep cut of greenhouse gas emissions of human being. Apart from CO2 utilisation through geological utilization such as enhanced oil recovery (EOR), other utilization methods could only reduce or consume very limit amount of CO2 compared to the total amount of anthropogenic emissions.

In detail, there are four pathways which help mitigate climate change issue by reusing recovered CO2 (Aresta, 2010; Audus and Oonk, 1997):

1.CO2 geological utilization, such as enhance oil recovery (EOR), enhance water recovery (EWR).

2.CO2 utilization can directly cut CO2 emissions to the atmosphere. for example, CO2 are converted to industrial chemicals and "stored" in such products;

3.The CO2 can be reduced to hydrocarbon fuels through some utilization technologies (such as microalgae breeding coupled with CO2 emission reduction technology), by which carbon is recycled, therefore reducing or replacing the use of fossil fuels, and indirectly reducing CO2 emissions.

4.By developing new reaction paths with CO2 as the reaction reagent to replace traditional chemicals which has greater influence on climate change, CO2 utilization may have an indirect contribution to mitigating climate change. For example, in the dry cleaning industry, chlorinated solvent and congeners are substituted with liquid CO2 (with the same mass, chloride has a climate change power many thousand-fold that of CO2)

It is estimated that a theoretical potential of 3.7 Gt CO2 could be prevented from entering the atmosphere every year through the first two pathways (accounting for 10% of the annual total CO2 emission) (Sridhar et al., 2011)

It should be remembered that, even if the CO2 utilization technology can be widely used, its emissions reduction potential is limited. The use of CO2 will not solve the

视角专门对 CO2 利用技术进行评估、总结和支持还是近些年的事。需要提出的是本报告中 CO2 利用技术既指利用化学和生物的方法将 CO2 转化为其它分子形态的物质并从而带来附加价值的技术，也指利用 CO2 自身的物理化学性质协助或强化其他过程（有时可以同时将 CO2 封存）的技术。

特别需要注意的是，在实际发展 CO2 利用技术的过程中，需要对技术进行综合的评估，包括整个生命周期过程中的减排潜力，能耗，环境影响，成本，原料等（Singh et al.，2014；Angunn et al.，2014；），同时还需根据 CO2 利用技术对地理位置，CO2 利用规模与纯度的要求，选择与相当的 CO2 排放源相结合，以实现真正的减排或其它社会经济收益。由于时间和专业知识的限制本报告仅对广东省几个典型的 CO2 利用技术进行初步的介绍和分析。

1.2 当今政策环境下 CO2 利用技术的意义

近些年来，中国一直努力推进低碳经济，循环经济以及二氧化碳的减排工作。2008 年通过的《循环经济促进法》积极推进资源利用减量化、再利用、资源化，从源头和生产过程减少温室气体排放（Li and Wu，2014）。CO2 利用技术可以将温室气体资源化，是促进循环经济和减排的典型技术。

随着全球对气候变化问题的日益重视，中国也加紧了对 CO2 的控制。在 2009 年的哥本哈根峰会上，中国承诺于 2020 将 CO2 排放强度较 2005 年减少 40%-45%。而现阶段，“十二五规划纲要”规定国家在 2011-2015 期间减少 17% 的排放强度（Yan and Fang，2015）该纲要还明确提出逐步建立全国碳排放交易市场，使控制温室气体排放从单纯依靠行政手段逐渐向更多地依靠市场力量转化（Zheng，2014）。为此国家发展和改革委员会于 2011 年 10 月底，批准 7 省市开展碳排放权交易试点工作。广东省作为 7 省市之一于 2013 年 11 月正式启动碳交易市场。与此同时，国家发改委和科技部在推动 CCUS 技术和政策文件均强调二氧化碳利用的重要性。在此政策环境和趋势下，可以同时兼顾经济和社会效益的 CO2 利用技术的优势将越来越明显。这是因为，一方面 CO2 利用技术是 CO CO22 潜在的“汇”，这意味着 CO22 技术的收益可能会增加，而另一方面碳市场的建立如果推动了 CCS 的发展，CO2 利用技术作为是弥补 CCS 高成本的一项方法，也可能会得到进一步的促进，但目前尚不清楚碳市场能够支持哪种利用技术。

1.3 本报告的研究方法及结构

本报告通过现场调查、访问专家和文献收集的方法对广东省 CO2 利用技术进行了调查和总结，并根据技术发展的阶段（基础研究，技术研发，中试，示范，工业化）对未商业化的技术的成熟度进行评估，同时从减排潜力等其他方面对技术进行综合评价。

本报告共分为 5 章。第 1 章主要对 CO2 利用技术进行简单的介绍并分析其在当今政策环境下的重要意义。本报告的主体部分对广东省典型的 CO2 利用技术的进行了介绍和总结。这些技术根据商业化程度、学科领域和创新度差异分以下三章进行描述：商业化 CO2 利用技术（第 2 章），CO2 的地质利用技术（第 3 章）以及创新型 CO2 利用技术（第 4 章）。其中第 2 章着重对 CO2 商业化应用的市场供求情况进行了介绍。第 3、4 章则主要从技术本身、技术成熟度和发展潜力方面进行阐述。最后，第 5 章将对未商业化的技术进行了成熟度进行比较，结合技术特点试揭示出不同技术在广东省的发展潜力。

problem of atmospheric CO2 accumulation, it might contribute to such an issue by reducing the volume of CO2 produced (Aresta, 2010). Especially at present the typical lifetime of the CO2 currently used in chemical applications is only days to months. The stored carbon is then degraded to CO2 again and emitted into the atmosphere. With such short lifetimes it is difficult to contribute significantly to the mitigation of the CO2 problem by the industrial utilization of CO2(Mikkelsen et al., 2010). In addition, some conversion of CO2 consume large amount of energy, which may introduce new CO2 emissions, and many CO2 utilization technologies with promising potential to reduce emissions are still in the R&D and demonstration stage, and have not been able to be applied on the large scale. What is worse, the barriers for CO2 utilization include(Song , 2010): (1) costs of CO2 capture, separation, purification, and transportation to user site; (2) energy requirements of CO2 chemical conversion (plus source and cost of co-reactants); (3) market size limitations, little investment-incentives and lack of industrial commitments for enhancing CO2-based chemicals; and (4) the lack of socio-economical driving forces.

Despite CO2 utilization technology leads to limited CO2 emission reduction, and its development is restricted by many factors, it is an important measures to tackle climate change. CO2 utilization technology has been actively explored and developed throughout the world. The U.S. Government has invested 1 billion US dollars in research into CO2 capture and utilization; Germany spent 118 million euros on one project using CO2 as the raw materials with (Styring et al., 2011). The development and deployment of CO2 utilization technology have long been supported by the Chinese government, while the assessment, support and conclusions concerning CO2 utilization technology from the perspective of mitigating climate change only started in recent years. Please note that the CO2 utilization technologies set out in this report refer not only to using chemical and biological methods to convert CO2 into other molecules and thus bring additional value of technology, but also using the chemical and physical properties of CO2 to assist or strengthen other processes (sometimes involving CO2 storage at the same time).

It should be noted that, in real practices, before developing CO2 utilization technologies, the technologies should be evaluated comprehensively, including the emission reduction potential, energy consumption, environmental impact, the cost and raw materials etc. in the entire life cycle (Singh et al., 2014; Angunn et al., 2014); At the same time, in order to realize the real emission reduction and other social and economic benefits, it is better to match the specific CO2 utilization technologies applications with appropriate CO2 emission points or CCS infrastructures based on its location, scale and purity of emitted CO2. Because of the limitation of time and knowledge, this report will only carry on the preliminary introduction and analysis of typical CO2 utilization technologies in Guangdong province.

1.2 The significance of CO2 utilization technologies under current policy settings

China has been working for some time

China has been working for some time on a low carbon and circular economy, and CO2 emission reduction. The "Circular Economy Promotion Law" passed in 2008 actively promotes the reduced use, reuse and recycling of resources, reducing greenhouse gas emissions from the source and the production process (Li and Wu, 2014). CO2 utilization technology is a typical method to boost the circular economy and emission reduction at the same time as utilizing greenhouse gases as a resource. Chinese government has put stronger effort on greenhouse gas control. During the 2009 Copenhagen Summit, China committed to reduce its CO2 emissions intensity by 40%-45% over the 2005-2020 period. Most recently, China's 12th 22 FYP set a national target for reducing CO2 emission intensity by 17% over the 2011-2015 period (Yan and Fang, 2015).The Outline also clearly put forward the intention to build a national carbon emissions trading market, to push for the transition from relying purely on administrative power to control greenhouse gas emissions to gradually relying more on market forces (Zheng, 2014). Consequently the National Development and Reform Committee approved 7 provinces and cities to carry out carbon emissions trading pilot work. Guangdong province, as one of these provinces, started a carbon trading market in November 2013. In addition, both NDRC and Ministry of Sciences and Technology highlighted the role of CO2 utilization in promoting CCUS technologies and demonstration projects. With these policy background, the advantage of CO2 utilization technology which can bring both economic and social benefits is becoming more and more obvious. Because the application of CO2 utilization technologies is a potential "sink" of CO2, which may bring additional profit to such practice. In addition, if the carbon market can promote the development of CCS, CO2 utilization technologies may also be popularized since these can help mitigate the high cost of CCS, although it is still unclear which CO2 utilisation technology would be qualified for support from the carbon market.

1.3 Methodology and structure of the report

This report investigates and summarizes CO2 utilization technology in Guangdong province through field investigation, visiting experts, and literature review. It evaluates the maturity of those technologies which are not commercialized according to the technology development phase (the various phases are usually acknowledged as basic research, technology research and development, pilot test, demonstration, industrialization), and at the same time comprehensively evaluates the technologies in relation to their emissions reduction potential and other aspects.

This report is divided into five chapters. Chapter 1 makes a brief introduction to CO2 utilization technologies and analyzes their significance under today's policy environment. The main body of the report introduces and summarizes the typical CO2 utilization technologies in Guangdong province. These technologies are described according to the level of commercialization, discipline and different levels of innovation in the following three chapters: commercial CO2 utilization technology (Chapter 2), CO2 geological utilization technology (Chapter 3), as well as innovative CO2 utilization technology (Chapter 4). Chapter 2 mainly deals with market supply and demand for commercial CO2 utilization. Chapter 3 and 4 mainly explain the technologies themselves, technical maturity and their development potential. Finally, Chapter 5 compares the maturity of those technologies that are not commercialized and indicates their potential in Guangdong based on their characteristics.

2. 传统商业化 CO2 利用技术

Traditional Commercial CO2 Utilization Technologies

2.1 传统 CO2 利用技术概述

Introduction to Traditional Commercial CO2 Utilization Technologies

2. 1. 1 技术简介

CO2 作为一种利用资源具有一些重要的物理化学性质。在低浓度时，CO2 气体是无味的，但在较高浓度时会有酸性气味，它可造成窒息和刺激。在标准的温度和压力下，CO2 的密度大约是 1. 98kg/m3，是空气的 1. 67 倍。-78. 51° C 时，CO2 会凝华，固态 CO2 俗称“干冰”，一般用作冷冻。固态的 CO2（或干冰）在常温下会气化，同时吸收大量的热。CO2 用两个氧原子与一个碳原子以双键组成，结构很稳定，化学性质不活泼，没有闪点，不燃，无毒性。CO2 是植物进行光合作用必须的原料。液体 CO2 和超临界 CO2 均可作为溶剂，超临界 CO2 具有比液体 CO2 更高的溶解性（具有与液体相近的密度和高溶解性，并兼备气体的低粘度和高渗透力），但它对设备的要求比液体 CO2 高。

对 CO2 的传统利用主要基于 CO2 本身的物理化学性质，原理相对简单，下表为 CO2 的物理化学性质与对应的利用方式。

2.1.1 Technology Introduction

CO2, as a resource, has some important physical and chemical properties. CO2 gas is odorless at low concentration, but its acidic smell in relatively high concentration can cause suffocation and irritation. Under standard temperature and pressure, the density of CO2 is about 1.98 kg/m3, 1.67 times that of air. The CO2 will sublimate at minus 78.51°C, and solid CO2 is commonly known as "drikold" or "dry ice" which is usually used for freezing. Dry ice will gasify at room temperature at the same time absorbing a large amount of heat. CO2has a double molecular bond with two oxygen and a carbon atom, its structure is stable, and it is chemically inert, non-ignitable and non-toxic without flash points. CO2 is necessary for the photosynthesis of plants. Liquid and supercritical CO2 can both be used as a solvent, and the latter has a higher solubility than the former (its density and high solubility are close to liquid, and it is also of low viscosity and high penetration), but it requires more handling equipment than liquid CO2.

The traditional use of CO2 is mainly based on its chemical and physical properties, and the theory is relatively simple. The table below shows the physical and chemical properties of CO2 and their corresponding uses.

表 2.1 CO2 的物理化学性质与对应的利用方式 (Zhang, 2003; Shi et al., 2006)

性质	应用
较高浓度有窒息和刺激性	抑制细菌，食品保鲜，酿酒
密度大约是空气的 1.67 倍，且不助燃	灭火
分子结构稳定，化学惰性	焊接时的保护气体
固态 CO2（干冰）升华放热	制冷剂
植物光合作用原料	植物气肥
无色无臭；水溶液呈弱酸性，可缓冲溶液	饮料充气添加剂
液体 CO2 气化膨胀	烟丝膨胀剂
液体 CO2 和超临界 CO2 高溶解性	清洗、萃取剂

2.1.2 传统 CO2 应用行业分布

CO2 的物理和化学应用主要集中在工业级（纯度 >99.0）和食品级（纯度 >99.9）两个方向。总体上说工业级中应用包括：（1）二氧化碳气体保护焊接；（2）制冷剂（汽车空调制冷剂，干冰研磨清洗）；（3）消防气体；（4）固化硬化剂；（5）超临界萃取和超临界清洗剂；（6）植物气肥。食品级的主要应用行业有：（1）饮料行业；（2）啤酒行业；（3）烟草行业；（4）食品保鲜。

这些传统的 CO2 利用技术大多对 CO2 的存储时间在几天到几个月间不等，存储时间较长的为植物气肥。需要注意的是，由于大多是的传统利用技术并没有转化 CO2，一旦应用，CO2 就释放到了大气中，因而对 CO2 的实际存储量主要在于存货量而不在于产量。

2.1.2 Industrial distribution of traditional CO2 utilization

Physical and chemical applications of CO2 mainly include industrial grade (purity higher than 99.0%) and food grade (purity higher than 99.9%). In general, industrial applications include: (1) CO2 gas shielded welding; (2) refrigerant (automobile air conditioning refrigerants, ground dry ice cleaning); (3) fire extinguishers; (4) curing agent; (5) supercritical fluid extraction and supercritical detergent; (6) air fertilizer for plants. Food grade applications are mainly in: (1) beverage industry; (2) beer industry; (3) tobacco industry; (4) food preservation.

Most of these traditional CO2 utilization technologies could only store CO2 for a few days to a few months, air fertilizer for plant can keep CO2 captured and stored in a relatively long time. It should be noted that since most traditional utilization technologies involve no conversion of CO2, once they are the applied, CO2 is released into the atmosphere, thus for the actual storage of the CO2 mainly depends on the amount of stock rather than production.

Table 2.1 The Physical and Chemical Properties of CO2 and their Corresponding Utilization Applications (Zhang, 2003; Shi et al., 2006)

Properties	**Uses**
Cause suffocation and irritation in high concentration	Bacteria constraint, food preservation and wine or beer production
Its density is about 1.67 times that of air, and it does not support burning	Fire extinction
Its molecular structure is stable, and it is chemically inert	Weld protection
Solid CO2 (drikold) releases heat during sublimation	Refrigerant
Raw materials for photosynthesis of plants	Air fertilizer
Colorless, odorless, weakly acidic, buffer solution	Beverage filling additives
Dilation during CO2 gasification of liquid CO2	Tobacco shred swell
High solubility of liquid CO2 and supercritical CO2	Detergent and extractant

2.2 CO2 商业化应用的市场供求状况

Market supply and demand status of commercial CO2 utilization

2.2.1 中国 CO2 市场供求现状

2.2.1.1 价值链

如图 2.1 所示，中国较为典型的二氧化碳市场价值链主要分为供应商、中间商和最终需求方 3 个环节。

2.2.1 Market supply and demand status of CO2 in China

2.2.1.1 Value chain

As shown in figure 2.1, China's typical of carbon market value chain includes suppliers, intermediaries and the final consumer.

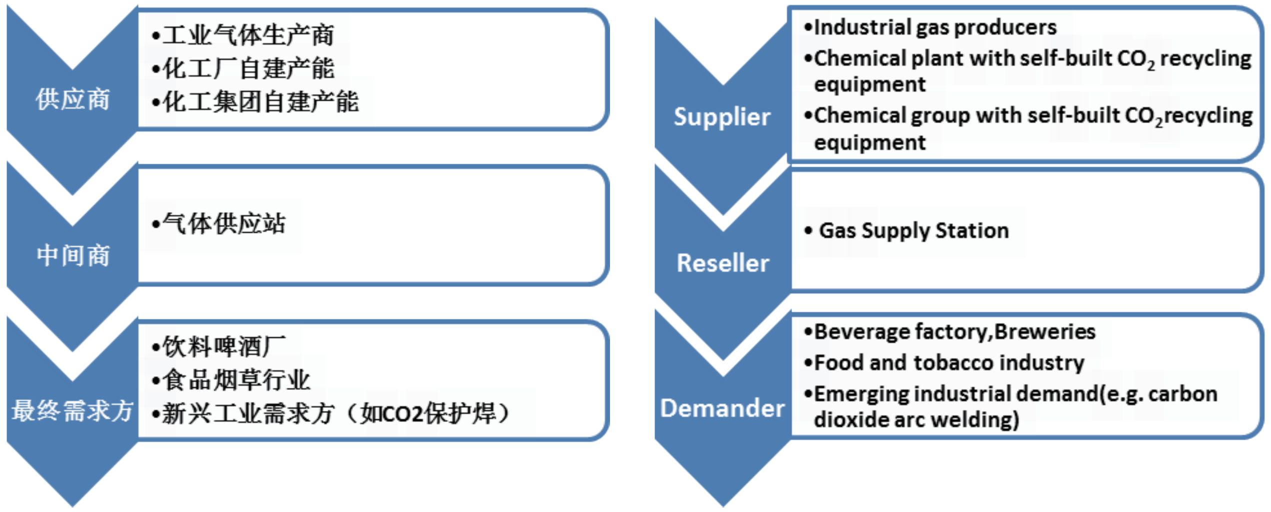


图 2.1 二氧化碳市场价值链
Figure 2.1 CO2 market value chain

2.2.1.2 供应商与成本分析

目前中国二氧化碳制造行业刚刚起步，业内约100多家生产企业可分为三类：第一类为自建二氧化碳回收设备的化工企业，如化肥厂、酒精厂等，这类企业主要利用自身的工业废气，通常规模较小，仅万吨左右，但数量较多；第二类为自建二氧化碳回收设备的大型化工集团下属公司，如中石化广州分公司华达气体厂，这类企业可利用集团下多个子公司废气资源，逐个复制二氧化碳回收模式，虽现阶段规模较小，但有依托集团成长为大规模的潜力。目前仅中石化、中海油下的几个公司有此类业务；第三类为以二氧化碳为主营业务，采购废气进行生产的专业二氧化碳生产企业，如凯美特气，具有较大规模优势、产品技术／质量优势、物流配送优势、品牌／优质客户优势。目前这类企业国内有凯美特气（年产31万吨）、普莱克斯（南京、北京合计9万吨）、重庆同辉（7万吨）等。利用废气制备食品级二氧化碳技术已经国产化。目前市场上已有杭州快凯、成都嘉禾联创、亚联高科等技术公司可提供二氧化碳生产设计服务。食品级二氧化碳生产设备投资平均约1000万元/1万吨。目前国内液体二氧化碳平均价格为500元／吨，干冰平均价格约为8500元／吨。

2.2.1.2 Supplier and cost analysis

The CO2 supply industry in China has just started, and the 100 supply enterprises in this industry can be divided into three categories. The first is self-built CO2 recycling equipment by chemical enterprises, such as chemical fertilizer and alcohol plants, which mainly make use of their industrial waste gas on a smaller scale (typically less than ten thousand tons). The second is self-built CO2 recycling equipment by large chemical group subsidiaries, such as Sinopec Guangzhou Huada Gas Factory, which can use their available waste gas resources and duplicate the carbon dioxide recycle mode one for one. Relying on the financial resources of their parent group, they have the potential to scale up their equipment. Currently, only a few subsidiary companies of Sinopec and CNOOC operate such a kind of business. The third are carbon dioxide production enterprises which purchase waste gas for production as their main business, such as Hunan Kaimeite Gases Co., Ltd. which has the advantage of scale, product technology/quality, logistics, and brand/valued customers. In China, this kind of enterprise includes Kaimeite (310 thousand tons/year), Praxair (a total of 90 thousand tons per year in Nanjing and Beijing), Chongqing Tonghui (70 thousand tons per year), etc. The technology of using waste gas to produce food-grade CO2 has been deployed throughout China. Currently, Kuaikai in Hangzhou, Jiahe lianchuang in Chengdu and Yalian Hightech can provide a CO2 production design service. An average of about 10 million yuan is invested in food-grade carbon dioxide production equipment to produce 10,000 tons of CO2. The indicative average price of liquid carbon dioxide is 500 yuan/ton, and the indicative average price of dry ice is about 8500 yuan/ton.

二氧化碳的主要生产成本包括原材料成本、电力成本、折旧费等，主要采购对象为工业废气、电力等相关能源资源（图2.2以凯美特气为例显示了二氧化碳生产成本）。

对于回收工业废气的二氧化碳企业来说，由于工业尾气中二氧化碳浓度不同，回收的能耗差异较大，成本也有巨大差异。回收不同浓度尾气每吨用电成本为150～350元，加上其他费用，总成本为250～450元。如浓度为80%的尾气，每吨总成本要超过300元。在设备投资方面，回收设备的投资巨大，二氧化碳浓度较高的尾气装置需要投入上千万元，浓度低的甚至达上亿元。

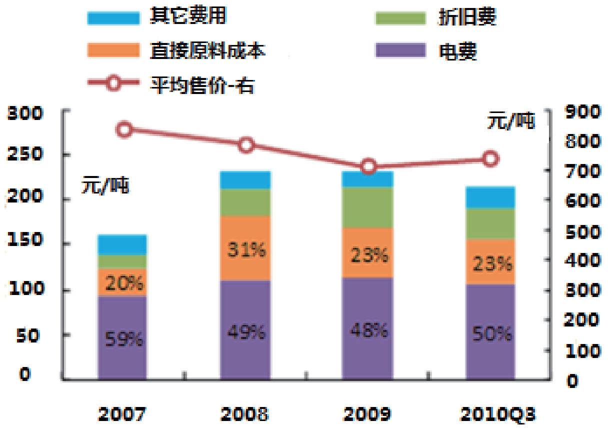


图 2.2 凯美特二氧化碳生产成本

但对于以采集地下二氧化碳气体的企业来说，生产成本却有所不同。有些二氧化碳气井的纯度高达99.9%，属于高压自喷方式采出，喷出即为气液混相，每吨电费成本仅40元，加上需缴纳的矿产资源费、管理费、矿井维护等其他费用，每吨成本接近200元。且气田气无需压缩系统，投资相对回收企业要减少一半。

The main costs of carbon dioxide production include the cost of raw materials, power, depreciation, etc. The main items procured are industrial exhaust gas, electricity and other energy resources (Figure 2.2, taking Kaimeite Gases as an example, shows the carbon dioxide production costs).

For CO2 companies which recycle industrial waste gases, there are big gaps in costs, due to wide differences in energy consumption due to the different CO2 concentrations of the various waste gases. Electricity costs between 150-350 yuan per ton of recycled exhaust gas with different concentrations, and including other costs, overall costs add up to 250-450 yuan per ton. When the concentration reaches 80%, the overall cost will be more than 300 yuan per ton. In terms of investment in equipment, with a large requirement for investment in recycling equipment, over ten million yuan need to be invested in exhaust systems for high concentrations of CO2, and more than a hundred million yuan for low concentrations.

二氧化碳产品不易储存与运输，需要低温、高压环境，还需要专用槽车进行运输，所以其经济运输半径较短，约为300 km的销售半径，相对于生产成本而言，二氧化碳的储藏与运输成本较高，运输距离过长。

2.2.1.3 供求现状

尽管CO2产品利润高，再加上CO2减排指标下放、排污权有偿使用、碳交易政策指导和碳税补贴的逐步落实，中国CO2利用行业将可能进入快速发展阶段。同时，目前CO2的市场需求量相对每年的排放量极小。2013年总需求量占同年全国排放量（74.6亿吨）的0.02%以下，而部分利用技术只是暂缓二氧化碳排放，表明传统CO2利用技术很难起到减排作用。

从消费领域来看，全国二氧化碳需求的增长仍以饮料、食品保鲜、卷烟、焊接为主。从增长速度来看，预计2010-2015年间年均增长率最高为集装箱运输20%，其次为干冰19%，冷冻和冷凝16%，粮食包装16%，粮食储存12%，卷烟11%，焊接10%，啤酒8%，饮料5%，其他用途9.6%。

2.2.2 广东省CO2供应与需求概况

2.2.2.1 供应概况

根据数据，最大供应商凯美特气在广东液态CO2市场占有率为11%（2011），而2011年凯美特气在广东销售为8.3万吨，广东二氧化碳供给约为76万吨。按照30%的年增长来看大约到2015年广东的CO2供给约为150万吨。然而CO2的供给也受到需求量和政策的影响大，技术和装备的更新水平，气源的稳定性等也会影响CO2的回收供应量。

过去数据显示，广东省的CO2产业利润高，同样以凯美特气公司为例，2007-2009二氧化碳产品的平均毛利率高达73.4%，远高于国际大型气体生产企业林德（平均综合毛利率32.7%）和普莱克斯（平均综合毛利率41.5%）。

2.2.2.2 需求概况

广东工业级二氧化碳主要用于焊接和干冰研磨清洗。超临界萃取和气肥目前应用水平还不高。根据凯美特气的估计，在2015年广东二氧化碳总需求约为160-200万吨，其中工业级约100-110万吨，食品级为50-90万吨。

CO2 气体保护焊

焊接行业的分布情况：根据阿里巴巴的企业黄页，广东有大大小小62家自动焊接企业。如果算上一些也提供焊接业务的企业，可能涉及二氧化碳保护焊的企业将达到近150家。

啤酒行业

CO2不仅可以增加啤酒本身的口感和保质，且可在其生产过程中的多个环节发挥作用（如清洗和预压）。据估计，平均每生产一百升啤酒需要约1.8-2.0kg的CO2（Chen and She, 2006）。事实上啤酒在发酵过程中本身可产生大量的CO2，只是仅有很少一部分会溶解于嫩啤酒液中。尽管目前国内啤酒厂已普及CO2回收技术，回收率高达74%-84%，但每万千升啤酒实际使用量仍大于回收量，差别约为24 t（Tang, 2013）。根据2014年广东省啤酒生产的数据，厂家共生产480.79万千升，因此总需求量约为1.15万吨。

碳酸饮料行业

广东太古可口可乐有限公司，主要生产和销售世界第一品牌汽水“可口可乐”及其系列产品“雪碧”、“芬达”、“零度可口可乐”等，为广东省内十三

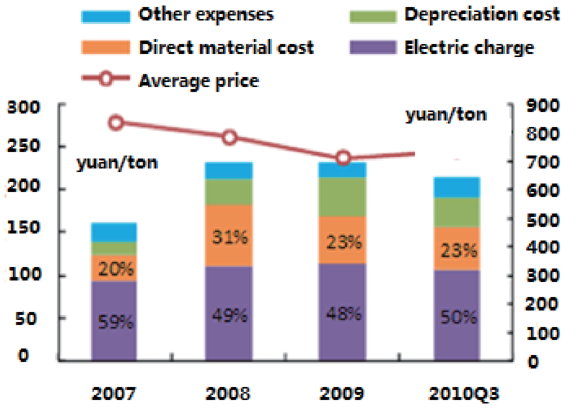


Figure 2.2 CO2 production costs by Kaimeite Gases

However, for companies which extract carbon dioxide from the ground, production costs are different. CO2 wells, whose purity reaches up to 99.9%, utilize the high-pressure spray recovery mode, spraying a mixed gas-liquid phase. Their overall costs per ton total is almost 200 yuan, of which electricity costs of only 40 yuan, but other costs include mineral resource fees, and management and mine maintenance costs. Moreover, gas wells do not need compression systems, resulting in the need for half the investment in comparison with recycling companies.

It is not easy to store and transport carbon dioxide, which needs a low temperature and high pressure environment as well as special tankers, with the result that it is only economic to transport CO2 for sale within a radius of 300 km. Compared with its production costs, costs of storage and transport are relatively high, and transport distances are too long.

2.2.1.3 Current supply and demand status

With high profits from CO2 products, the CO2 utilisation industry in China may experience a stage of rapid growth, fuelled by the gradual introduction of CO2 emission reduction targets, the need to pay for the use of pollution rights, guidelines on carbon trading policies and carbon tax subsidies. However, compared with national annual CO2 emissions, the current CO2 demand is limited. The estimated total demand in 2013 is less than 0.02% of the national annual CO2 emissions (7.46 billion tonne, which means that it is difficult for traditional CO2 utilization technologies to contribute to a massive emission reduction.

In the consumer sector, the growth of carbon dioxide consumption in China mostly occurs in the beverage, food preservation, cigarette and welding industries. In terms of growth, the highest annual average growth rate (AAGR) in 2010-2015 was 20% for container transport, 19% for dry ice, 16% for freezing and condensation, 16% for food packaging, 12% for food storage, 11% for cigarette production, 10% for welding, 8% for beer, 5% for beverage and 9.6% for other uses.

2.2.2 Overview on supply and demand of CO2 in Guangdong

2.2.2.1 On supply

Based on public data, the largest supplier Kaimeite Gas accounted for an 11% share of the liquified CO2 market of Guangdong in 2011, selling 83,000 ton the CO2 supply in Guangdong is about 760,000 ton. CO2-supply of Guangdong in 2015 will be about 1.5 million ton with a 30% annual rate of growth. However, the supply of CO2 is influenced by the demand and policy issues greatly, and the renewal of technologies and equipment and the stability of the gas sources will also affect the supply of recovered CO2.

个城市和地区多达7300万消费者提供产品和服务。广东全省2013年碳酸饮料产量约为2,926,891吨。按照每吨碳酸饮料需要0.015–0.02吨二氧化碳来计算，二氧化碳在饮料行业需求为约为44000–59000吨之间。

2.2.3 发展趋势分析

与其它种类的工业气体相比，二氧化碳行业有其独有的特色：受原料制约、运输条件制约、受政策等影响巨大。近年来，由于政府与企业的环保意识增强，CO2减排政策趋向更加严格与苛刻，许多有社会责任感的企业也主动推进本企业高CO2含量废气的回收。上述双向的推动力必然导致未来CO2产能持续上升，而CO2下游消费增长有限，中国CO2 产能经过前几年井喷式的扩张，2013年已超过800 万t/a而传统的CO2消费市场很难保证现有装置的开工率。

The history profit margins of the CO2 production in Guangdong Province is large, taking Kaimeite Gas as an example, their average gross margin in 2007-2009 reached 73.4%, much higher than large international gas production companies like Linde (its average gross margin was 32.7%) and Praxair (that figure was 41.5%).

2.2.2.2 On Demand

Industrial-grade CO2 in Guangdong is mainly used in the welding and grinding industries and for cleaning with dry ice. Supercritical fluid extraction and gas fertilizers have not been applied at a high level. According to an estimate from Kaimeite Gas, the total demand for CO2 in Guangdong in 2015 will be around 1.5-2 million ton, nearly 1-1.1 million ton for industrial-grade and 500-900 thousand ton for food-grade.

CO2 gas shielded arc welding

The distribution of welding businesses in Guangdong is as follows: according to Alibaba's company news, there are 62 automatic welding businesses in Guangdong. If companies that also provide welding services are added together, there are nearly 150 companies that could possibly be involved in CO2 gas shielded arc welding.

Beer industry

CO2 is not only needed to increase the taste and quality of beer itself, but also useful in many processes during the production (such as cleaning and preloading). It is estimated that on average the production of one hundred litres of beer requires about 1.8-2.0 Kg of CO2 (Chen and She, 2006). In fact, fermentation process can produce a large amount of CO2, but only a little will dissolve in the beer. Although currently CO2 recovery technology has been applied widely in domestic breweries with a recovery rate from 74% to 84%, the total amount of CO2 required by production of every thousand kl of beer is still greater than the recycled CO2, and the gap is about 2.4 ton (Tang, 2013). Based on 2014 data, brewers in Guangdong produced 4.8079 million kl of beer.As a result, the total demand is about -11,500 ton.

Carbonated beverage industry

The distribution of welding businesses Guangdong Swire Coca-Cola Ltd. which mainly produces and sells Coca-Cola (the NO. 1 brand of soda water worldwide) and other products like Sprite, Fanta and Coco-Cola Zero, provides products and servicesto more than 73 million consumers in thirteen cities and regions within Guangdong. The output of carbonated beverages in 2013 in Guangdong was about 2,926,891 ton. Under the standard which requires a ton of carbonated beverage to contain 0.015-0.02t CO2, it can be calculated that beverage industry's annual demand for carbon dioxide is about 44,000 -59,000 tons.

2.2.3 Development trend analysis

Compared to other types of industrial gases, the CO2 industry is unique in that it is greatly affected by limits on raw materials, transport conditions and policies. In recent years, because governments and enterprises have improved their environmental credentials, and CO2 emission reduction policies have tended to become more stringent, many enterprises with strong social responsibility now actively promote the fact that they recycle high CO2 concentration waste gases. The combination of these pressures certainly leads to continually increasing CO2 capacity, while domestic CO2 consumption has only limited growth potential. After rapid expansion for several years, the CO2 supply capacity in China in 2013 was more than 8 million t/a, but it is difficult to see how consumer demand can keep up.

3. CO2 地质利用技术

CO2 Geological Utilization Technology

3.1 CO2 驱油技术

CO2 Enhanced Oil Recovery

3.1.1 技术简介

CO2驱油（Carbon Dioxide Enhanced Oil Recovery，CO2-EOR）指将CO2注入油田，从而提高原油采收率的一项技术，也是目前唯一的能同时实现大规模CO2利用和大规模CO2封存的关键技术（Manrique et al.，2010）。石油属于不可再生能源。一次开采大概能采出原油总量的5%-20%左右（Sen，2008；Uemura et al.，2014），之后油田的储层条件会随之改变。二次开采即向油层注水来保持压力，一般能开采出15%到20%的原油，二次开采之后一般还会有60%的原油未被采出，CO2驱油作为一种三次开采技术被运用来驱油，4%到15%左右的原油有机会被采出。在美国，CO2驱油技术现如今已经成为石油生产工业的重要部分（生产总量占美国陆上石油产量的6%），并且不论在陆上还是海上产油都有强大的潜力。根据美国能源部的分析报告，全美CO2驱油产量总量预计为1370亿桶，为现有原油探明储量的三倍还多。

目前CO2-EOR技术相对成熟，但技术的应用受到地质条件和技术、经济因素的限制，不能适用于所有的油田（Ren et al.，2010）。CO2-EOR项目的开展需要大量的高纯度CO2，而CO2的分离，运输和注入设备都将消耗大量的资金。只有在CO2价格低，或者采收率高的情况下CO2-EOR技术才有经济可行性。目前CO2自然井生产的CO2最为便宜。大部分的CO2-EOR项目可以在美国进行的原因之一就是美国CO2自然资源丰富。其它降低CO2的成本的方法是将CO2-EOR项目与工业废气的捕集相结合（Uemura et al.，2014）。CO2-EOR技术其它的限制因素还有：驱油过程复杂；气体注入井的位置和数量的限制；废弃井的安全问题；在开采过程中发生的断裂（Xie et al.，2014；Alvarado and Manrique，2010）。

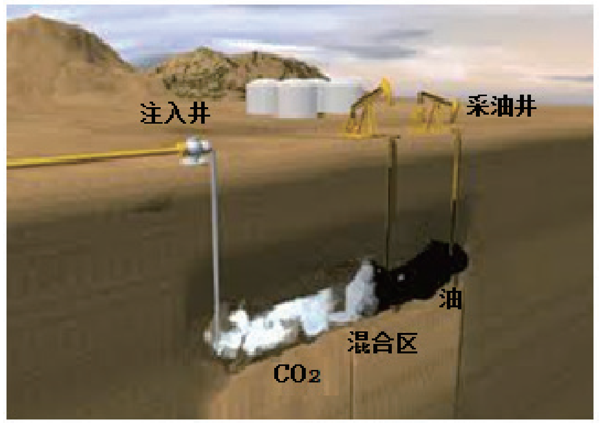


图 3.1 CO2驱油过程简图

CO2驱油的过程主要是将CO2从注入井注入油藏层，CO2作为驱替剂在油藏中经历较长时间的运移，在此过程中，部分CO2会溶解、分散在地层水和原油中，或者以自由相占据没有与井相联通的孔隙空间（Guo et al.，2014）。这样做的作用是：1、增加了油藏的能量；2、通过CO2和原油的混合降低了原油的粘度和密度，可大幅度增加原油的产量和采收率；3、部分CO2溶解在油藏的原油、地层水中或与岩石反应形成新的物质沉淀在油藏中，实现了CO2的封存。

根据CO2跟石油的混合情况，CO2驱油技术可以分为混相驱油和非混相驱油。混相驱油适合运用于轻质油驱油，CO2与原油充分混合为单相液体具有较小年粘滞阻力，原油通过CO2流体的流动而被带出储层。混相驱油适用于轻质油，深部已经接近经济生产能力极限的储层。非混相驱油是指CO2部分溶解在原油中，提取并蒸发掉轻质石油，从而导致原油膨胀并降低粘滞力。与混相驱油相比，非混相驱油适用于整个油田范围长期的驱油过程。

3.1.1 Technology Introduction

Carbon Dioxide Enhanced Oil Recovery (CO2-EOR) refers to a technology that injects CO2 into oil fields to enhance oil recovery. It is also the only key technology which currently can achieve large-scale CO2 utilization and CO2 storage Manrique et al., 2010. Oil is non-renewable resource. The first phase of oil extraction (primary recovery) can recover about 5%-20% (Sen, 2008; Uemura et al., 2014) of the oil original in the rock. After the primary recovery, the reservoir condition has been changed. The second recovery is to inject water into the oil-bearing formation to retain pressure. In this phase, 15% to 20% of extra oil might be extracted. After this phase, up to 60% of crude oil may remain in the formation. CO2-EOR is one of the methods of tertiary oil recovery technology to get more oil out. Field owners will need to consider which methods are applicable at different fields. CO2 EOR typically has a potential to recover additional 4-15% of the original oil. CO2-EOR has already been an important component of today's oil production in the US (accounting for nearly 6% of US. onshore production), it still shows significant potential for onshore and offshore production. US. Department of Energy (DOE) reported that the potential theoretical oil reserves recoverable from CO2 EOR is up to 137 billion barrels, which is more than three times the current proven reserves.

As a relatively mature technology, CO2-EOR is no longer technically challenging for the petroleum industry. However, the application of technology is limited by geological conditions, technical and economic factors, therefore CO2-EOR cannot be applied to all fields (Ren et al., 2010). When CO2-EOR is used in an oil reservoir, large amounts of pure CO2 need to be obtained, which involves substantial costs such as CO2 separation, CO2 transport, and CO2 injection installations. Unless the CO2 can be purchased cheaply, or high oil recoveries can be realized, EOR is not economically feasible. Currently, the use of natural CO2 sources is the cheapest method, and consequently CO2 EOR projects are mainly occurring in the United States because there are many CO2 gas fields. If EOR is to be linked with industrial CO2 sources, significant reductions in the cost of CO2 capture are necessary (Uemura et al., 2014).The other disadvantages are: a complex process; limitations on the quantity and location of gas injection; the safety problem of abandoned well; undiscovered fracture during oilfield exploitation (Xie et al., 2014; Alvarado and Manrique, 2010).

The process essentially pumps CO2 into injection wells and uses the CO2as a displacement agent to prolong the replacement of oil in the reservoir. In the process, part of the CO2 will dissolve and disperse in formation water and crude oil, or will occupy the pore space that has no connection with wells in free phase(Guo et al., 2014)The effects of this are: 1. To increase the energy of the oil reservoir; 2. To decrease the viscosity and density of the crude oil through mixing it with CO2, which can significantly increase crude oil production and the recovery factor; 3. To achieve CO2 storage, as part of the CO2 dissolves in the crude oil and the formation water in the oil reservoir, or react with rocks to form new matter which gets deposited in the oil reservoir.

根据油藏地理位置的不同又可以将 CO2 驱油技术分为陆上 CO2-EOR 和离岸 CO2-EOR。美国能源部的报告指出离岸 CO2 驱油在资源利用和环境保护方面更有优势，因为：CO2 的封存地远离人口密集地区，避免了其他地表与地下资源开采权的纷争，并且使得地下饮用水免受污染。

然而离岸 CO2-EOR 工程面临许多挑战，包括采样平台面积相对于采油设备过小，钻取新的 CO2 注入井成本高以及需要将 CO2 从陆上 CO2 源运输到离岸平台等（Godec et al.， 2013）。因而离岸 CO2-EOR 可行性低于陆上 CO2-EOR（Manrique et. al.， 2010）。在未来，离岸 CO2-EOR 的发展需要技术的开发和革新（Godec et al.， 2013），目前缺乏海上提高石油采收率的经验。

3.1.2 技术成熟度

CO2 驱油技术相对其它地质利用技术较为成熟，但国内与国外，陆上与离岸发展进度不一。在美国陆上的油田已使用了四十余年，在中国的吉林、胜利等油田也有近十年的规模化试验。虽然海上油田设施和作业的成本和技术难度都比陆上油田高得多，随着全球 CO2 减排压力的增大，海上油田的 CO2-EOR 也在近年来提上日程，国际上离岸二氧化碳驱油案例包括计划有：

a. 巴西深海区 Santos 盆地的 Lula 油田项目

b. 北海 Draugen /Heidrun 油田和 Don Valley 项目

c. 阿布扎比波斯湾油田项目

d. 越南 Rang Dong 油田试注项目

e. 马来西亚 Dulang 油田试注项目

f. 墨西哥湾和路易斯安那湾试注项目

除此之外，许多国家对离岸油田的 CO2 驱油和封存潜力进行了评估。美国能源部与能源技术实验室对墨西哥湾 CO2 驱油潜力评估结果表明，墨西哥湾的总共离岸 CO2 驱油潜力估计为 149.2 亿桶，用于驱油的 CO2 约为 35.5 亿吨；苏格兰二氧化碳捕集与封存中心报告估计英国北海地区的 CO2 驱油可封存约 10 亿吨 CO2。

在这些海上油田 CO2-EOR 技术的实践中，巴西 Lula 油田项目是国际知名的大型深水二氧化碳驱油项目，很多先进的技术在此项目中都得到了应用。Lula 油田由巴西石油公司开发，注入深度为 2000 至 3000 米，距离里约热内卢 180 英里。储层为碳酸盐，上覆有 6000 英尺厚的盐岩盖层，原油密度为 28-30 API，高气油比，高二氧化碳含量（8% 至 15%）。

巴西石油在第一阶段进行了一系列的短期试注实验，以期提高资本利用效率。很多新一代的 CO2 驱油技术在这次项目中得以实现：智能完井技术，动态井下监测技术，大规模 CO2 循环回注技术等。在储层描述阶段，扩展井测试技术应用于定义储层的连通性。现有的井以及其他设备都经过了防腐蚀改造。Lula CO2 驱油项目运用了一口注气井，两口水气交替注气井，以及多口生产井。2013 年起项目的大规模运用启动后，每年的 CO2 注入量预期达到约 71 万吨。从 Lula 项目经验得出，项目之前的试注环节对于 CO2 的影响预测是很有效用的。

3.1.3 中国南海北部 CO2-EOR 潜力分析

珠江口盆地面积近 20 万平方公里（图 3.2），是一个新生代含油气沉积盆地，包含南海北部到目前为止已发现的所有油田，近年来在陆坡区域陆续发现一些天然气田。据 2008 年评估，珠江口盆地的地质资源量为 2200 百万吨（160 亿桶）油和 7430 亿立方米天然气（Ministry of Land and Resources, 2008），其中已探明储量为 583 百万吨

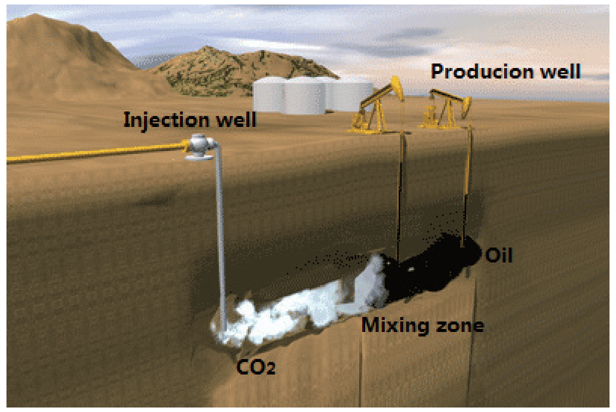


Figure 3.1 Diagram of the Process of CO2-EOR

According to the situation of mixture between CO2 and oil, the methods used for CO2-EOR could be miscible and immiscible CO2-EOR. In miscible CO2-EOR-CO2 is fully mixed with oil, forming a single-phase liquid with less viscosity. Oil could be extracted by the CO2 flow. This method could be applied to light oil, deep reservoirs that are close to the economic productivity limit. Another method is immiscible CO2-EOR, which means CO2 partially dissolved in heavy oil and boils off light oil, causing oil to swell and reducing the viscosity. Comparing to miscible CO2, this method is normally for whole field and longer time scale (up to 10 years).

CO2-EOR can also be divided into onshore CO2-EOR and Offshore CO2-EOR based on the geographical location of oil reservoir. Offshore CO2-EOR is recognized to have several advantages in terms of resource utilization and environmental protection by U.S. DOE (Litynski, 2011): the storage sites are far away from heavily populated area, that avoiding storing material beneath populated area, reduces difficulty of establishing surface and mineral rights for storage sites, and reduces risks to pollute drinking water. However, there is very limit commercial deployment experiences in offshore CO2 EOR.

However, the deployment of CO2-EOR technology in offshore oil fields faces many challenges, including limited platform space for CO2 recycling equipment, the expense of drilling new CO2 injection wells, and the need to transport CO2 from onshore sources to offshore platforms (Godec et al., 2013). Therefore, EOR applicability in offshore fields is limited compared to onshore fields (Manrique et. al., 2010).In the future, advances in technology are required for undertaking the challenge of deploying innovative designs and advanced CO2-EOR technology in offshore oil fields (Godec et al., 2013).

3.1.2 Technology Maturity

CO2–EOR technology is relatively mature compared to other geological utilization technologies, but the development progress differs at home and abroad as well as onshore and offshore. The onshore oil fields in the US have used CO2–EOR for more than 40 years, whereas oil fields such as Jilin Oil Field and Shengli Oil Field have been carrying out small-scale tests for about 10 years. With the increase of pressure to reduce global CO2 emissions, CO2-EOR in offshore oil fields has been put on the agenda in recent years, though the costs of offshore oil facilities, operations and technical difficulties are much higher than those of onshore oilfields. International offshore fields where CO2-EOR has been evaluated and planned include:

a. Offshore Brazil, Lula Oil Field

b. North Sea, Draugen /Heidrun Oil Fields and Don Valley Project

c. Offshore Abu Dhabi, Persian Gulf Oil Fields

d. Offshore pilot in Vietnam, Rang Dong Oil Field

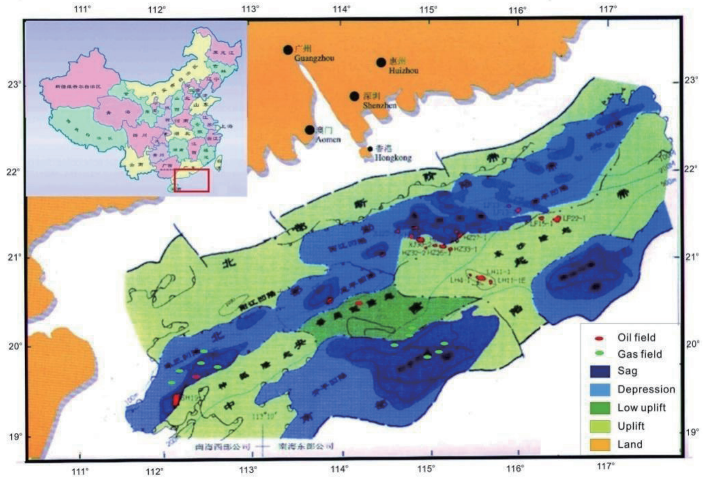


图3.2 珠江口盆地地质简图

（42.5亿桶）油和585亿立方米天然气。珠江口盆地的石油开采始于1990年，盆地中有16个油田已经投入生产。自1996年以来盆地年产原油一直保持在63百万桶以上，至2007年底累计产量155百万吨（11.3亿桶）原油，仅占已探明储量的18%。迄今，已有一个油田在2009年停采废弃，其余油田仍在高速开采，同时通过探边摸底力求扩大储量。

珠江口盆地应用CO2-EOR的有利条件是：原油为具有低密度和低粘度的轻质油；储层有高－中孔隙度和高－中渗透率；深度一般大于1500米，这些都有利于高效率的混相驱油。另外，油田大多在浅水陆架区，离广东沿岸的大型CO2排放点源（煤电厂、石化企业等）距离较近，形成良好的源汇匹配。

不利条件之一是该盆地的大多数油田具有强大的天然水动力条件，能保持油藏压力，连注水二次采油都不需要就能保持较高的采收率。目前大多数油田的预期采收率40-60%，残余油饱和度较低，这些都会影响驱油效果。另外，与北海、墨西哥湾和巴西海外相比，珠江口盆地的油田小得多，除流花11-1油田的探明储量为155百万吨（11亿桶）外，其他都是小油田，探明储量在60~10百万吨（4.4~0.7亿桶）范围内；这就会大大降低CO2-EOR的经济性。

不过，上述不利条件并不能排除在珠江口盆地应用CO2-EOR的可能性。珠江口盆地油田的原油采收率与北海和墨西哥湾油田大致相当，因而也同样不能因此否定采用CO2-EOR进一步提高采收率的可能性。美国能源部2014年（DOE，2014）在对墨西哥湾油田的评估中，认为储量小于1千万桶（1.4百万吨）的油层肯定不具备实施CO2-EOR的经济性，而取为5千万桶（6.8百万吨）为被评估油层的储量下限，符合这种条件的储层在珠江口盆地是存在的。

CO2-EOR项目的经济性除了与地质条件有关之外，还与多种技术、经济、甚至政治条件有关。CO2减排压力的增大、原油价格的升高、以及驱油方法技术的改进，都会提高项目的经济性。因此，有必要对珠江口盆地的油田全面进行CO2-EOR应用的技术经济可行性评估，筛选出可行的油田，估计其应用CO2-EOR可能产生的驱油效益和CO2减排效益，提出CO2-EOR的部署意见，为政府和石油企业的战略决策提供依据。

e. Offshore pilot in Malaysia, Dulang Oil Field

f. Offshore pilot projects in the Gulf of Mexico's coastal waters and bays of Louisiana.

In addition, many countries have evaluated the potential CO2-EOR offshore resource.In the CO2-EOR offshore resource assessment commissioned by DOE and NETL, the estimated oil recovery from GOM is estimated to be up to 14,920 Million Barrels in total, and the CO2 demand is 3.55 billion tons. The estimated CO2 storage capacity of all fields of UK North Sea is up to around 1 billion tons by Scottish Carbon Capture and Storage Centre.

In the field of offshore CO2-EOR technology, Lula Field project is the leading and only example of offshore commercial application of CO2 injection and EOR. Lula field is a remote deep water supergiant oilfield that was discovered by Petrobras where oil production started in 2009, about 180 miles from Rio de Janeiro. The field is a carbonate reservoir with 6,000 ft salt column, holding oil of 28-30 API, high GOR, and high CO2 composition in the solution gas (8% to 15%). CO2 is separated from the associated gas and reinjected into the producing oil formation at a depth of between 2,000 to 3,000 m below seabed. CO2 injection and EOR has been incorporated in the initial phase of oilfield development, rather than as a tertiary stage of production. This avoided the need for retrofit and conversion of pre-existing facilities and wells which is required in other fields.

In the early implementation phase (started at 2011), Petrobras operated a series of short-term CO2 injection and EOR pilot tests at Lula to improve capital efficiency. "Next Generation" CO2-EOR is planned for use in the project: intelligent well completions, dynamic down hole monitoring, tracer injections, extensive CO2 recycling, etc. for deep water. In reservoir characterization phase, Extended Well Tests (EWTs) is used to define reservoir connectivity. The CO2 content from associated gas is recycled for miscible CO2-EOR. The existing wells and infrastructure are required for retrofit for corrosion resistant. Lula EOR includes one gas injector, two WAG (Water alternating gas injection) injectors and multiple producers. From 2013, the commercial scale CO2-EOR was opened. When the platform reaches full production, it could re-inject about 710 thousand tons of CO2 per year. From Lula case study, it comes to the conclusion that piloting phase is important in test how oil recovery will be effected by CO2-EOR.

3.1.3 CO2-EOR Potential Analysis of Northern South China Sea

Encompassing nearly 200,000 square kilometers (Figure 3.2), the Pearl River Mouth Basin is a Cenozoic oil and gas sedimentary basin, which includes all the oil fields which have been found so far in the northern South China Sea. Some natural gas fields have been found on the continental slope area in recent years. According to the 2008 assessment, the geological resources in the Pearl River Mouth Basin are 2.2 billion tons (16 billion barrels) of oil and 743 billion cubic meters of natural gas, of which the proven reserves are 583 million tons (4.25 billion barrels) of oil and 58.5 billion cubic meters of natural gas (Ministry of Land and Resources, 2008). Oil production in the Pearl River Mouth Basin began in 1990, and 16 oilfields have been put into production. Since 1996, the basin's annual output of crude oil has remained at more than 63 million barrels, and up to the end of 2007, the total output was 155 million tons (1.13 billion barrels) of crude oil, accounting for only 18% of the proven reserves. So far, only one oil field stopped extraction and was abandoned in 2009, the rest are still extracting, and efforts continue to expand reserves through exploration.

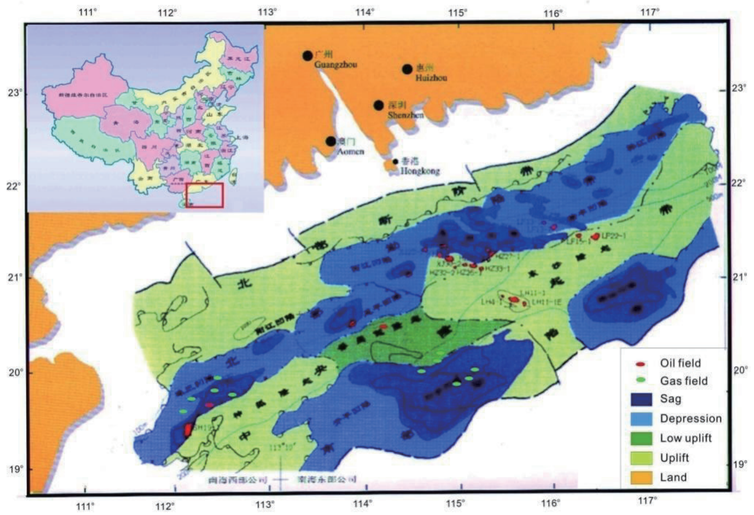


Figure 3.2 Geological sketch of the Pearl River Mouth Basin

The favorable conditions for applying CO2-EOR to the Pearl River Mouth Basin are: the crude oil is light with low density and viscosity; the reservoir has a high-medium porosity and permeability; the depths are generally greater than 1500 meters, which favor efficient miscible-phase EOR. In addition, most oil fields are located on the continental shelf in shallow water, close to large CO2emission point sources on thecoast of Guangdong (coal power plants, petrochemical enterprises, etc.), meaning good source-sink matching.

One of the adverse conditions for CO2-EOR in the basin is that most of the oilfields have strong natural water dynamic conditions, which can maintain reservoir pressure, and keep the recovery efficiency high, meaning that even water injection for secondary oil recovery might not be needed. Currently, the expected recovery rates of most oilfields are 40-60%, and residual oil saturation is low, all of which mitigate against EOR. In addition, compared with the North Sea and the Gulf of Mexico and Brazil, the oil fields in the Pearl River Mouth Basin are much smaller; the Liuhua 11-1 Oil Field has proven reserves of 155 million tons (1.1 billion barrels), others are small oil fields with proven reserves in the range of 60 ~ 10 million tons (4.4 ~ 70 million barrels), which significantly reduces the economics of CO2-EOR. A further challenge for offshore fields is the sutiability and viability of conversion and retrofit of facilities and wells for use in CO2 EOR.

However, the above-mentioned disadvantages cannot rule out the possibility of the application of CO2-EOR in the Pearl River Mouth Basin. Oil recovery from fields in thePearl River Mouth Basin is about the same as from oil fields in the North Sea and the Gulf of Mexico, so the possibility of using CO2-EOR to further improve oil recovery cannot be ruled out. The 2014 evaluation of oil fields in the Gulf of Mexico by US Department of Energy (DOE, 2014) stated that implementing CO2-EOR in fields with reserves less than 10 million barrels (1.4 million tons) would certainly not be economic (estimated when the crude oil price was between US$ 80 and 100), and it took as an economic floor level 50 million barrels (6.8 million tons). Reservoirs in the Pearl River Mouth Basin conform to these conditions.

In addition to geological conditions, the economics of CO2-EOR projects also depend on a variety of technical, economic and even political conditions. The increase in pressure for CO2 emission reductions, and the improvement in oil displacement techniques could enhance the economics of the project. Therefore, it is necessary to carry out a comprehensive technical and economic evaluation of the feasibility of CO2-EOR applications for the oil fields in the Pearl River Mouth Basin. This would identify feasible oil fields, estimate the efficiency of possible EOR and CO2 emission reductions, and present options for CO2-EOR deployment to provide the basis for governments and oil enterprises to make strategic decisions.

3.2 CO2 增强地热系统技术

CO2 Enhanced Geothermal Systems Technology

3.2.1 技术简介

地热资源是一种稳定持续的清洁可再生资源，是未来能源利用的热点。由于目前主要开采利用的中低温，水热型地热资源有发电效率地热田规模小的特点，人们逐渐开始广泛关注地底深层 3-10 km，以干热岩热能为主的增强型地热系统（Guo et al.，2014）。仅保守估计，地壳中干热岩所蕴含的能量相当于全球所有石油、天然气和煤炭所蕴含的能量的 30 倍（Xu et al.，2012）。人们最初开采干热岩地热是通过以水作为工作介质的增强型地热系统完成的。CO2 增强地热系统（Carbon Dioxide Enhanced Geothermal Systems，CO2-EGS）在该技术的基础上发展而来，即使用超临界 CO2（压力 >7.382MPa，温度 >31.04˚C）替代水作为增强型地热系统中的传热流体，来开采地热资源（Brown，2000）。其过程是将 CO2 注入深层热储，通过生产井回采来收集热能如图 3.3。

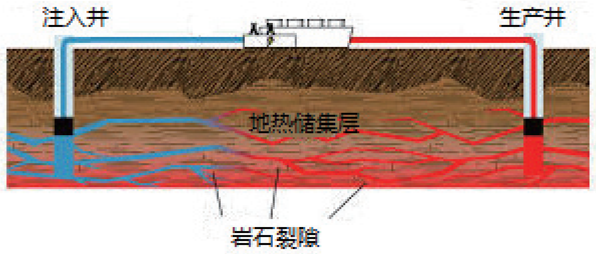


图 3.3 CO2 增强地热系统过程示意图

3.2.1 Technology Introduction

Geothermal resources are stable,constant, clean and renewable;they represent a hot spot in future energy use.Because theefficiency of small scale water-type geothermal fields(which are mainly exploited at present) is similar to that of power generation, public concern is gradually growing over deep (3 to 10 km underground) , mainly hot dry rock thermal enhanced geothermal systems(Guo et al., 2014). At only a conservative estimate, the energy contained in hot dry rocks in the earth's crust is equivalent to 30 times all the oil, gas and coal energy in the world (Xu et al., 2012). People first started extracting hot dry rock geothermal energy through enhanced geothermal systems with water as a medium. Carbon Dioxide Enhanced Geothermal Systems (CO2-EGS) derives from this technology, i.e. using supercritical CO2 (pressure > 7.382 MPa, and temperature > 31.04 ˚C) instead of water as the heat transfer fluid in the enhanced geothermal systems, to exploit geothermal resources(Brown, 2000).The process of injecting CO2 into deep thermal storage, to recover heat energy from production wells, is shown in figure 3.3.

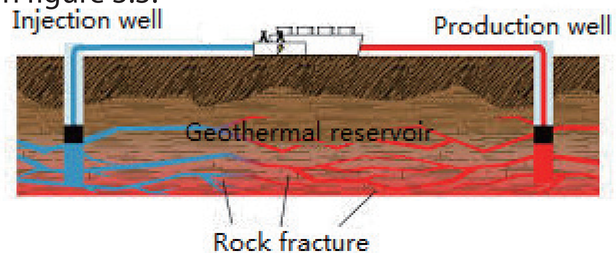


Figure 3.3 Process Diagram of CO2 Enhanced Geothermal Systems

相对于较为传统的工作介质水作为增强地热系统，其优势是（Pruess，2006）：

1、CO2 作为工作介质既可实现减排，又可以节省水这种较为稀缺的资源。

2、CO2 不易溶解地层矿物质，破坏岩石裂隙的渗透性。

3、CO2 有较大的膨胀系数，使得注入井的冷的 CO2 与生产井热的 CO2 密度差异大，因而可以提供较强的浮力驱动（虹吸效应），减少热流循环系统能量的消耗。

4、CO2 有较低的粘稠系数，可以产生较大的流速和渗透系数。

基于以上，CO2 增强地热系统技术是一项非常有前景的技术。

3.2.2 技术成熟度

在国际上，以水做为工作介质的增强地热系统技术已经趋于成熟，总体上处于示范阶段（Guo et al.，2014）。CO2-EGS 技术与其有相似之处，但也存在差异，现阶段主要处于技术开发的早期阶段，开展较为多的主要是 CO2 增强型地热系统的模拟研究（Zhang et al.，2013）。但也有国家已经开始推动示范工程的建设，如美国 GreenFire Energy 公司正推动在亚利桑那和新墨西哥边境附近建立一个 2MW 的 CO2 增强地热系统示范电厂（Peng et al.，2014）。

中国的 EGS 研究还处于起步阶段，目前尚未开展野外试验研究，只进行了一些陆上 EGS 资源评价和前景分析方面的研究工作（Guo et al.，2014；Feng et al.，2014，33），但正日益受到重视。

The advantages of enhanced CO2 geothermal systems over using the more traditional water as the working medium, are (Pruess, 2006):

1.Using CO2 as a working medium can not only realize emission reductions, but also save water, a relatively scarce resource.

2.CO2 does not easily dissolve to form minerals, and affect the permeability of the rock.

3.CO2 has a larger expansion coefficient, which means there is a big difference in density between cold CO2 in the injection wells and hot CO2 in the production wells. It can thus provide a strong buoyancy drive (siphon effect), to reduce the energy consumption of the heat circulation system.

3.2.2 Technology Maturity

Internationally, enhanced geothermal technologies that use water as a working medium are maturing, and are mainly at the demonstration stage (Guo et al., 2014).CO2-EGS technology has similarities, but also differences, and is currently mainly at the early stages of development, and more simulations of CO2 enhanced geothermal systems need to be carried out (Zhang et al., 2013).Countries have begun to promote the construction of demonstration projects, such as GreenFire Energy in the United States which is promoting the establishment of a 2 MW CO2 enhanced geothermal system demonstration power plant near the border of Arizona and New Mexico (Peng et al., 2014).

EGS research(on-shore) in China is still in its infancy, has yet to develop research in the field, and only some resource evaluation and prospect analysis research work has been implemented (Guo et al., 2014). However it is being taken more and more seriously.

3.2.3 广东发展地热系统的潜力

广东省是一个地热资源较为丰富的地区（如图 3.4）。广东省处于环太平洋地热带上，地质构造存在多条断裂带，例如：电白—龙川带、广州—从化—海陵带、北东向的莲花山带等。其中，莲花山断裂带横贯深圳、珠海、中山等珠江三角洲地区。在中山横栏的西南、新会南部、珠海斗门东南、沙湾南部等地都是形成较大型地热田的远景规划区（Mao and Ma，2011）。

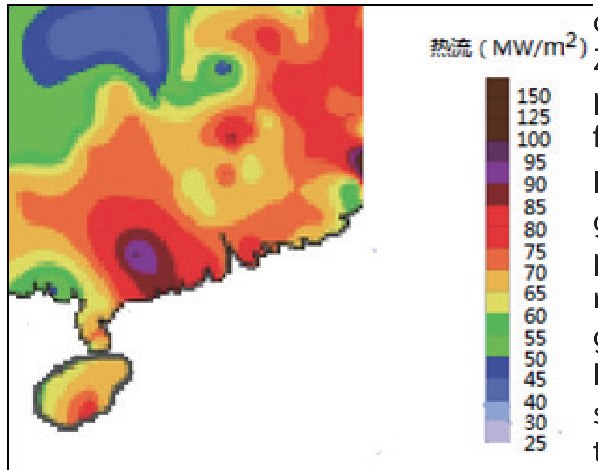


图 3.4 广州及周边地区热流分布图（Wang et al.，2012）

除此之外，广东省地热的开发利用一直走在全国的前列。1970 年，广东丰顺第一台 86 kW 地热发电试验机组发电成功，1982 年，在广东省科委和电力局的支持下，中国科学院广州能源研究所等单位再建了一台 300 kW 机组（3 号机），1984 年电站移交丰顺当地电力部门。发电站目前仍能正常运转，这是我国第一座地热试验发电站（Mao and Ma，2011）。而且最近研究发现，尽管理论上中国地热资源丰富，EGS 可以在全国各地应用，但受到钻井技术和经济等因素的限制，EGS 只能在少数地热梯度高的地区得到开发利用，其中就包括广东省（表 3.1）其它的有较大潜力的

3.2.3 The Potential for Guangdong Developing Geothermal Systems

Guangdong province is an area relatively rich in geothermal resources (as shown in Figure 3.4). Guangdong province is in the Circum-Pacific geothermal bel, and there are several fracture zones in geological structure, such as: Dianbai-Longchuan zone, Guangzhou-Conghua-Hailing zone, Lianhua mountain zone in northeast, etc. Lianhua mountain fracture zone traverse Shenzhen, Zhuhai, Zhongshan and other Pearl River Delta Region, in which the southwest of the Zhongshan, the south of Xinhui, the southeast of Doumen in Zhuhai and the south of shawan are potential large geothermal field in the future(Mao and Ma,2011).

In addition, the development of geothermal utilization in Guangdong province take its place in the front ranks of China. In 1970, The first 86 kW geothermal power plant of Fengshun Fuxing in Guangdong Province is successful in its generating units trial test. In 1982, with the support of the Guangdong Department of Energy and the Science and Technology Committee, Guangzhou institute of energy conversion and other institutes built a 300 kW generating unit, which is still in normal operation. (Mao and Ma, 2011). What's more, recent research found that,

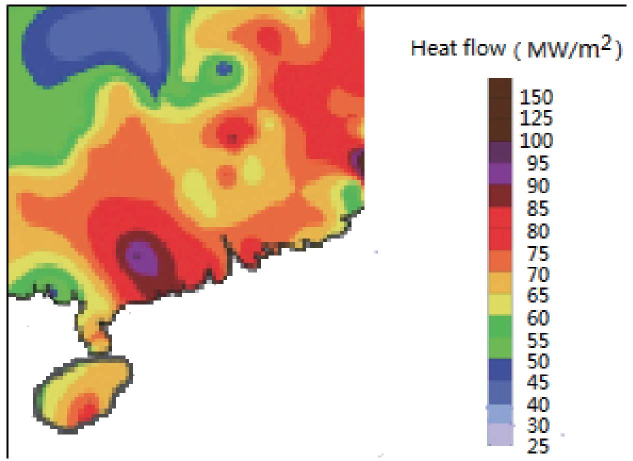


Figure 3.4 Heat Flux Distribution of Guangzhou and the Surrounding Area(Wang et al., 2012)

表 3.1 广东省 EGS 开发潜力

地质特征	地热数据	地热利用历史	位置
地热资源呈带状分布且受岩浆岩和断层结构控制	300m 处 92 C	地热电厂（2008 年停产）	市区

Table 3.1 Potential site for EGS in Guangdong.

Geological characteristics	Geothermal data	Pre-existing hydrothermal plant	Potential site location Location
Geothermal resources in Guangdong Province is in zonal distribution and is controlled by magmatic rocks and faults	The temperature is 92 C in 300 m	Suspended in 2008	In urban area The spas are abundant

地区包括西藏羊八井，云南腾冲和海南等（Feng et al.， 2014）。

目前，技术研究和发展仍然是 CO2-EOR 限制的主要因素。广东作为改革开放的前沿省份，不应坐等所有技术都完全成熟再去发展，而应参与到技术发展的研发中，以推动该技术早日实现商业化。建议国家及广东省相关部门及时立项开展增强型地热资源潜力评价、开采模式、产能分析和技术、经济可行性评价工作；着重研究深部人工热储形成、裂隙特征描述、高温测井仪等关键技术（Mao and Ma，2011）。

although theoretically EGS can be applied throughout the continent with rich geothermal resources around China, in fact, EGS can only be exploited commercially in certain places with high geothermal gradients. This is mainly because of limitations in the drilling technology and economic factors. One of these places is Guangdong province (Table 5), and other potential places for EGS are Yangbajing in Tibet, Tengchong in Yunnan province and Hainan province(Feng et al., 2014).

At present, the main restricting factors in CO2-EOR application are still technology research and development. As one of most developed province in China's reform and opening up, Guangdong should not develop CO2-EOR application until all the technology is mature, and should be involved in the research and development of related technology, to promote the commercialization of the technology. Therefore it is recommended that the relevant departments of state and Guangdong province should carry out the evaluation of potential resources, research on exploitation mode, capacity analysis and the evaluation of technical and economic feasibility without delay (Mao and Ma,2011).

4. 创新型 CO2 利用技术

Innovative Carbon Dioxide Utilization Technologies

4.1 CO2 合成可降解塑料

Biodegradable plastics synthesized by CO2

4. 1. 1 技术简介

CO2 合成可降解塑料的原理是 CO2 和环氧丙烷（PO）在催化剂的作用下聚合形成聚碳酸丙烯脂（C4H6O3），如图 4.1 所示。

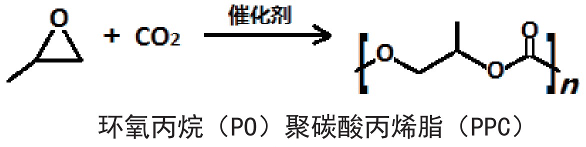


图 4. 1 CO2 和环氧化物的共聚反应

CO2 和环氧化合物共聚技术的关键点和难点之一是催化剂的设计。CO2 是一种相对稳定的化学物质，如何将化学惰性的 CO2 活化并获得较高转化率是其资源化利用的关键，也是全世界科学家的研究的重要科学问题。

由 CO2 和环氧丙烷的聚合而成的聚碳酸丙烯脂是一类脂肪族聚碳酸酯，具有较好的阻氧能力和一定的强度、透明性，还有良好的生物降解性能（Luinstra andBorchardt， 2012），6 个月内能完全堆肥降解，而传统的塑料通常不具备这种特性（Du et al.， 2004）。

CO2 和环氧化合物共聚技术发展近五十年来，其产业化规模（千吨～万吨）远小于聚烯烃产业。但是，世界范围内对可降解塑料的需求却日益增加（Wang et al.， 2012）。最新的调查报告显示，在可再生和可降解趋势的推动下，仅全球包装市场对可降解塑料的需求量将在 2023 年达到 945 万 t，年均复合增长率高达 33％（Huicong website， 2014）。

4.1.1 Technology Introduction

The theory of biodegradable plastics synthesized from CO2relies on carbon dioxide and propylene oxide polymerized as C4H6O3 using a catalyst, as shown in Figure 4.1.

Figure 4.1 copolymerization between CO2 and epoxide

One critical and difficult point in copolymerization between CO2and epoxide is the design of catalysts. As a relatively stable chemical, how to activate chemically inactive carbon dioxide and get high conversion efficiency is the key to its use as a resource, and also a significant scientific issue being studied across the world.

C4H6O3 polymerized by CO2and epoxide is a form of aliphatic polycarbonate with good oxygen barrier properties, some intensity, transparency and biodegradability (Luinstra and Borchardt, 2012), which can be completely composted and degraded within six months, while conventional plastic does not have this property (Du et al., 2004).

Since copolymerization between CO2and epoxide was developed almost 50 years ago, the scale of this industry is far smaller than that of the polyolefin industry. But the demand for degradable plastic around the world is growing

4.1.2 技术成熟度及示范工程

CO2 合成可降解塑料的催化合成技术已经进入了产业化示范阶段，由广东省研发机构研发的技术应用于工业生产的示范工程主要有河南天冠集团有限公司和江苏金龙绿色化学有限公司的 CO2 基塑料生产线（表 4.1）。

其中中山大学孟跃中团队通过发明高效催化剂，根据其发表资料显示，成功利用工业废气 CO2 合成了完全生物降解的塑料并开发出了中低压本体聚合工艺和无污染、全循环、三级脱挥后处理工艺。这些工艺在河南天冠企业集团建成全球首个年产 25000 吨 CO2 基全降解塑料工业化生产线（图 4.2），并实现了长期稳定运转。生产的 CO2 全降解塑料经国家塑料制品质量监督检验中心检测，产品性能完全符合全生物降解塑料的 IS014855 标准。

(wang et al., 2012). According to the newest survey, the demand for degradable plastic in the packaging market alone across the world will reach 9.45 million tons in 2023 with the compound annual growth rate (CAGR) approaching 33% under the impetus of the trend towards renewable and degradable products (Huicong website, 2014).

4.1.2 Maturity of technology and demonstration projects

Catalytic CO2 synthesis technology of biodegradable plastic is at the industrialized demonstration stage. Demonstration projects in industrial production in which technologies developed by R&D organizations in Guangdong have been applied include the CO2-based plastic production line (Figure 4.1) of Henan Tianguan ltd. and Jiangsu Jinlong Green Chemical ltd.

公司	产量	应用	技术来源
河南天冠企业集团有限公司	25000 吨	塑料袋等包装（袋、盒）	中山大学
江苏金龙绿色化学有限公司	10000 吨	聚氨酯原料	中国科学院广州化学研究所

表 4.1 CO2 基塑料示范工程举例

Company	Production	Application	Technology sources
Henan Tianguan ltd.	25000t	Packages like plastic bags/boxes	Sun Yat-sen University
Jiangsu Jinlong Green Chemical ltd.	10000t	Raw materials for polyurethane	Guangzhou Chemistry Institute of CAS

Figure 4.1 CO2-based plastic demonstration project

在该团队主要技术发明点和获得的系列专利的支撑下，不仅整个生产工艺过程流程短、能耗小，投资少、无污染，还应用到了 CO2 废气捕集回收、高效负载催化剂生产和下游应用产品等产业链的其它环节，初步形成的完整产业链。

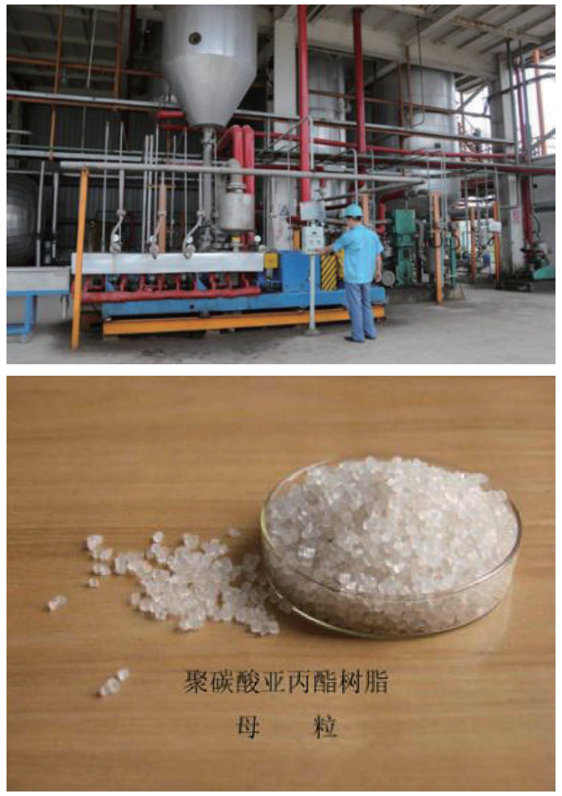


图 4.2 河南天冠企业集团有限公司塑料生产线及产品母粒[1]

[1] 图片来源于河南天冠企业集团有限公司官方网站

4.1.3 减排潜力及环境社会效益

直接合成聚合物材料技术可以同时实现 CO2 的直接减排和间接减排。直接利用量：如反应方程式所示（图 4.1），CO2 与环氧丙烷共聚生成 CO2 基塑料 PPC，生产每吨产品大约消耗 0.43t CO2，理论直接利用量为 0.43t CO2。除此之外，生产过程中 CO2 替代了化石原料，还实现了间接减排。

Among those developing efficient catalysts, Yuezhong MENG's team from Sun Yat-sen University, according to their publication, successfully synthesized completely biodegradable plastic with industrial waste carbon dioxide, and developed a bulk polymerization process under medium and low pressure, together with a comprehensively cycled treatment process after three levels of devolatilization without pollution. Henan Tianguan Ltd. used those processes to build the first industrialized production line of CO2-based completely biodegradable plastic with 25000 tons of annual production across the world(Figure 4.2), and managed to achieve long-term stable operations. The production of CO2-based completely biodegradable plastic is overseen by the National Quality Supervision and Inspection Center of Plastic Products with product performance in full compliance with ISO14855 standard for completely biodegradable plastic.

Figure 4.2 The plastic production line (Figure 4.1) of Henan Tianguan Ltd. and product masterbatch[1]

4.1.3 Emission reduction potential and environmental and social benefits

Technology for the direct synthesis of polymer materials can achieve both direct and indirect CO2emission reductions. Direct: as demonstrated in the reaction equation (Figure 4.1), carbon dioxide and propylene oxidecan copolymerize CO2-based plastic-PPC,

[1] Picture 1 from the official website of Henan Tianguan ltd.

该技术由于以工业废气为原料，大大降低了合成塑料工业的原料成本，随着研发技术的日趋成熟，这种优势会越来越大，其带来的经济效益也将会逐年增加。总之，该技术的环境社会效益有以下几点：

（1）实现了工业废气 CO2 的资源化利用，有利于 CO2 减排；

（2）合成的生物全降解塑料有利于解决 " 白色污染 "；

（3）用工业废气合成塑料，开发了新碳源，减少了对石油资源的依赖。

（4）产品附加值高，原料成本低，有利于推动经济发展和调整塑料产业结构。

consuming about 0.43t CO2/t. Indirect: in addition, CO2 takes the place of fossil fuel and indirect emission reductions are achieved during the production.

Owing to the use of industrial waste gases as raw material, this technology significantly cuts raw material costs in the synthesized plastic industry. With increasingly mature technologies in R&D, this advantage is becoming more obvious, which brings more and more economical benefits. In summary, the environmental and social benefits are as follows:

(1)Using industrial waste carbon dioxide reduces its emission;

(2)Synthesizingcompletely biodegradable plastic helps solve “white pollution”;

(3)Synthesizing plastic with industrial waste gases develops carbon as a new resource thus reducing dependence on oil;

(4)High added values and low raw material costs are conducive to boosting the economy and the structural adjustment of the plastic industry.

4.2 CO2 合成汽油添加剂

CO2 Synthetic Gasoline Additive

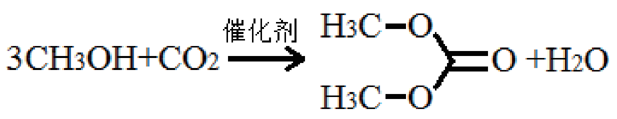
4. 2. 1 技术简介

碳酸二甲酯（Dimethyl Carbonate，DMC）作为一种化学原料没有毒性，被称为绿色化学品。近年来，美国已提出用 DMC 逐步替代甲基叔丁基醚作为汽油添加剂，提高辛烷值（其具有 3 倍于甲基叔丁基醚的含氧量、高辛烷值、低挥发性以及生物可降解性）（Li and Zhong，2002；Pacheco and Marshall，1997）。简单来说，只需在汽油中加入 6% 的 DMC 即可将 90# 汽油

4.2.1 Technology Introduction

As a chemical raw material with no toxicity, dimethyl carbonate (DMC) is called a “green chemical”. In recent years, the United States proposed its use, gradually replacing Methyl Tertiary Butyl Ether as a gasoline additive to increase the octane value (it has an oxygen content three times that of Methyl Tertiary Butyl Ether together with low volatility and biodegradability.) (Li and Zhong, 2002; Pacheco and Marshall,

优化为 98# 汽油。合成碳酸二甲酯的方法有光气法、甲醇氧化羰基化法、酯交换法和 CO2 和甲醇直接反应法（Tundo and Selva，2002）。前三种方法分别有环境污染，不安全，和高成本的缺点。由 CO2 和甲醇直接合成 DMC 不仅在合成化学、碳资源利用和环境保护方面具有重大意义，而且可使生产过程简化，生产成本显著降低，它是发展 DMC 生产的一条新途径（Zhou et al.,2003），其反应方程式如图 4. 3。



$$3CH_3OH+CO_2 \xrightarrow{催化剂} (H_3C-O)_2C=O + H_2O$$

图 4. 3 CO2 和甲醇直接反应法合成碳酸二甲酯

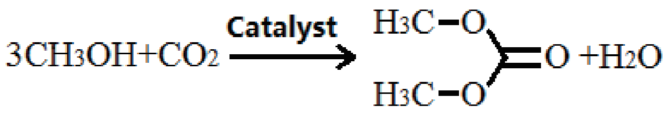
该技术的难点是设计有效的催化剂和反应条件以打破二氧化碳的惰性及热力学平衡限制，另外产物分离也具有一定难度。

4. 2. 2 技术成熟度

目前，文献记录国内外 CO2 和甲醇直接反应合成 DMC 的技术还处于基础研究阶段（Peng et al.，2014）。

图 4. 4 CO2 和甲醇直接合成 DMC 连续式固定床催化反应器（左）与中试设备（右）

1997). Simply speaking, adding 6% DMC to gasoline can increase the octane number from 90# to 98#. There are methods for synthesizing DMC, such as phosgenation, oxidative carbonylation of methanol, transesterification and direct reaction between carbon dioxide and methyl alcohol (Tundo and Selva, 2002). The first three methods have their own weaknesses: namely environmental pollution, safety issues and high costs. DMC directly synthesized from carbon dioxide and methyl alcohol not only has great significance in synthetic chemistry, carbon utilization and environmental protection, but also can simplify production processes and aggressively cut production costs, which is a novel way to develop DMC production (Zhou et al.,2003), as demonstrated in the reaction equation of Figure 4.3 as follows:



$$3CH_3OH+CO_2 \xrightarrow{Catalyst} (H_3C-O)_2C=O + H_2O$$

Figure 4.3 carbon dioxide and methyl alcohol directly synthesized to dimethyl carbonate.

The difficulty of this technology is to design efficient catalyst and reaction conditions to overcome the inactivity of carbon dioxide and break through the thermodynamic equilibrium limit. There is also difficulty in separating products.

4.2.2 Technology maturity

So far, according to literature home and abroad, the technology for directly synthesizingDMC from carbon dioxide and methyl alcohol is under basic research (Peng et al., 2014).

Figure 4.4 Continuous fixed-bed catalytic reactor of DMC directly synthesized from carbon dioxide and methyl alcohol (on the left side) and pilot equipment (on the right).

中山大学孟跃中团队掌握的合成 CO2 和甲醇直接合成碳酸二甲酯技术走在了世界的前列，其开发的电辅助催化二氧化碳和甲醇直接合成 DMC 的规模化制备技术已经在河南南阳中聚天冠低碳科技股份有限公司进行中试（图 4.4）。

4.2.3 减排潜力

CO2 和甲醇直接合成 DMC 可以同时实现 CO2 的直接减排和间接减排。直接利用量：如反应方程式所示（图 4.3），生产每吨 DMC 可以约消耗 0.5t CO2，理论直接利用量为 0.5t CO2。除此之外，该技术较传统的酯交换和氧化羟基化合成 DMS 技术，CO2 替代了化石原料，实现了间接减排。其中需要注意的是，如果对 DMC 进行生命周期评价， 可以发现 DMC 最终燃烧又变成 CO2 释放到大气中，所以其减排效果主要体现在间接减排。

The technology to synthesise DMC from carbon dioxide and methyl alcohol is owned by Zhongyue MENG's team at Sun Yat-sen University and who are world leaders in this field. A pilot to begin preparations to scale up their technology through electrical auxiliary catalysis of carbon dioxide and methanolis being conducted by Zhongju Tianguan low carbon Technology Co., Ltd., Nanyang, Henan (Figure 4.4).

4.2.3 Potential to cut emissions

Synthesizing DMC by carbon dioxide and methyl alcohol can achieve both direct and indirect emission reductions of carbon dioxide. Direct uses: as demonstrated in the reaction equation (Figure 4.3), to produce a ton of DMC can consume about 0.5t CO2, which is equivalent to direct uses in theory. In addition, in comparison between this technology and conventional synthesis technology of DMC through transesterification and oxidation hydroxylation, CO2 replaces fossil fuel and indirect emission reductions are achieved. It should be noted that at the end of life cycle, DMC will be combusted and released into the atmosphere as CO2, so the emission reduction effect is mainly reflected in the indirect reduction.

4.3 微藻养殖耦合 CO2 减排

Microalgae Breeding Coupled with CO2 Emission Reduction

4.3.1 技术简介

微藻固碳技术通常是指自养型微藻利用太阳能吸收 CO2 转化为自身物质的过程（Yang et al.， 2009）。如图 4.5 所示，CO2 通常以气态形式存在于大气中，而当 CO2 由气相进入到培养液中后，其转变为 CO2、HCO3^{-}、CO3^{2-} 等形式，培养液中 CO2 和 HCO3^{-} 经被动扩散和主动运输进入细胞叶绿体中，在一系列酶的作用下（Calvin 循环），利用光反应产生的能量（ATP）和还原力（NADPH），实现对碳的固定。

4.3.1 Technology Introduction

Microalgae carbon sequestration technologies often refer to the process whereby autotrophic microalgae uses solar energy to absorb CO2and converts it into its own material (Yang et al., 2009 . As shown in Figure 4.5, CO2 usually exists in the atmosphere as a gas, and when CO2 enters into a nutrient solution in the gas phase, it converts into forms such as HCO3^{-} and CO3^{2-} in the nutrient solution. It then enters into the chloroplasts of cells by passive diffusion and active transport, under the action of a series of enzymes (Calvin cycle), using the energy produced by light reaction (ATP) and reducing power (NADPH) to achieve the carbon storage.

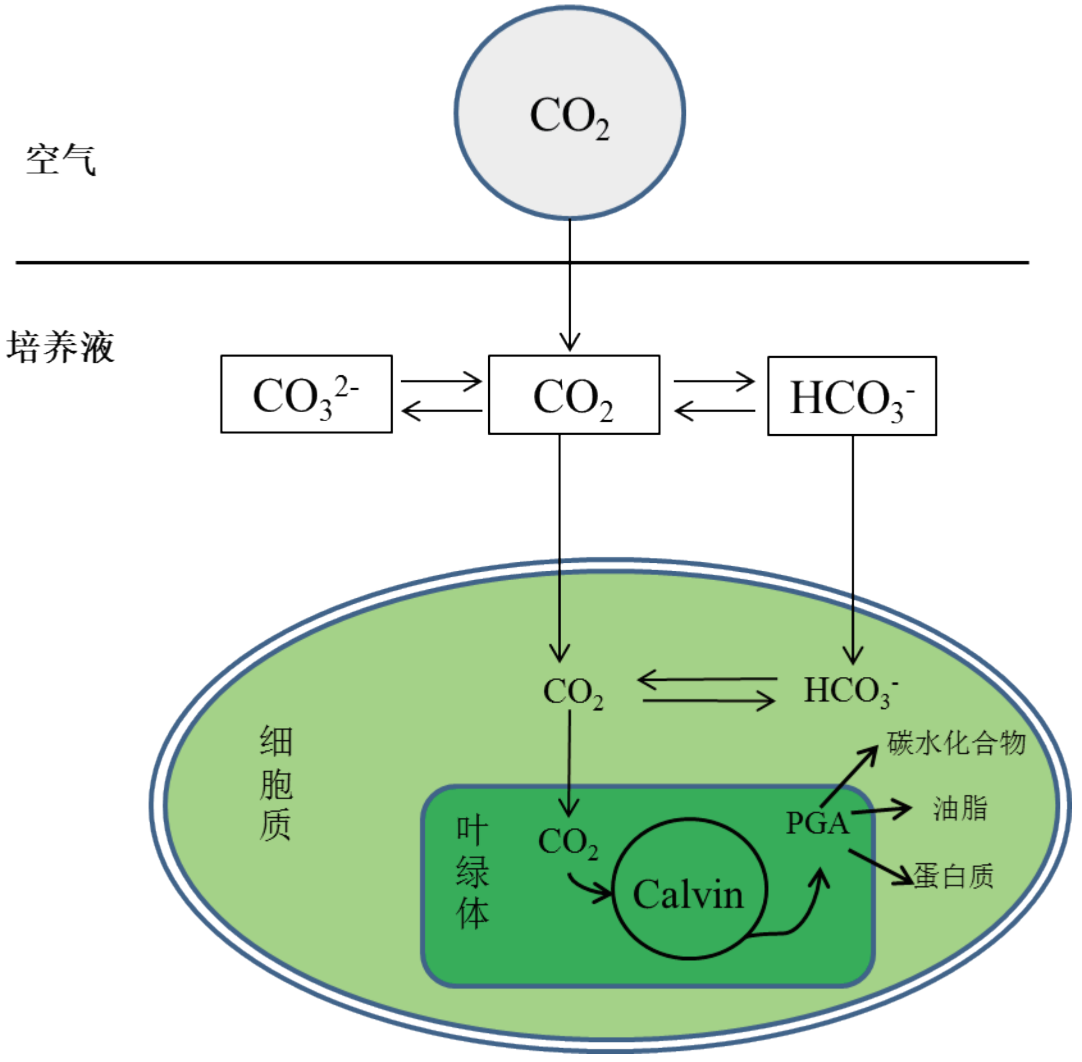


图 4.5 微藻 CO2 固定机制

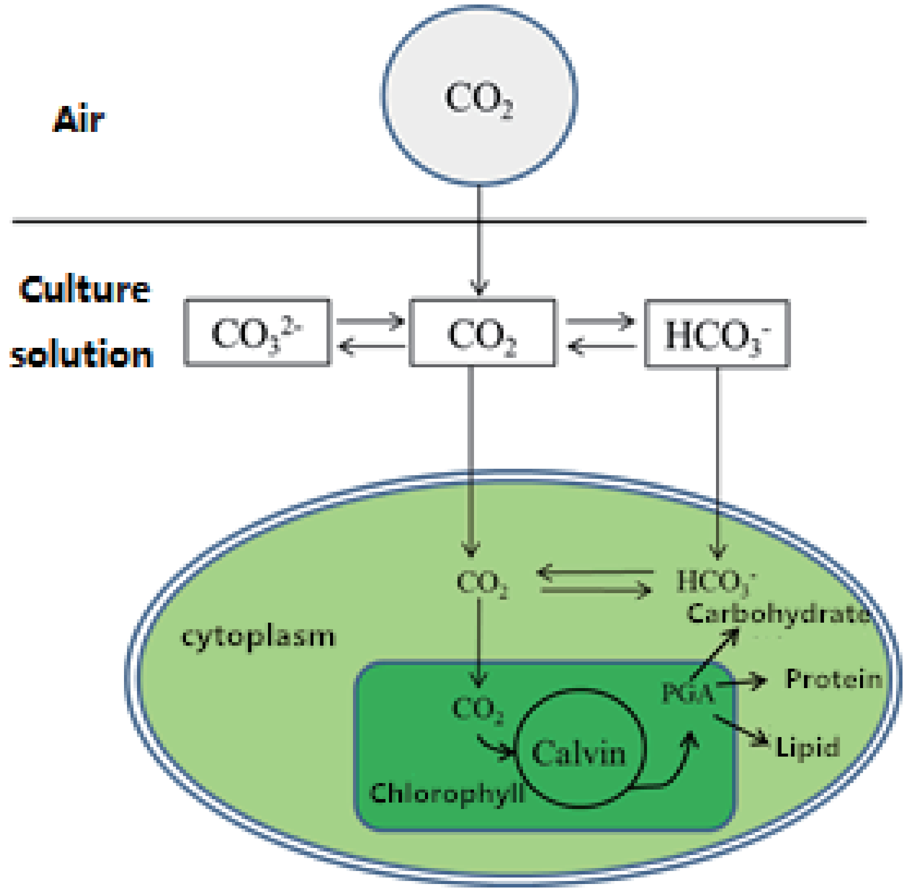


Figure 4.5 Microalgae CO2StorageMechanism

微藻固碳的技术环节主要包括：1 耐高 CO2 浓度、高固碳率和耐抗污染藻株的筛选，优良藻株是微藻高效固碳的基础；2 微藻规模化培养（培养条件优化以及光生物反应器设计），实现 CO2 的高效固定以及微藻的高密度养殖；3 微藻采收，收获微藻生物质用于下游产品的开发（微藻生物柴油、食品、保健品、饵料、饲料等）。

如果结合烟气作为 CO2 的来源还可以吸收烟气中的 NO 和 SO2，起到净化烟气的作用（Lam and Lee，2012）。

The technical requirements for microalgae carbon storage technology mainly include: 1 The selection of high-concentration-CO2-endured, high-carbon-storage-rate and anti-pollution algae, (good algae is the basis of efficient microalgae carbon storage); 2 Microalgae scale cultivation (culture conditions optimization and optical bioreactor design), to achieve efficient CO2storage and high-density breeding of microalgae; 3 Microalgae recovery, to gain microalgae biomass and use it for the development of downstream products (microalgae biodiesel, food, health food, fish bait, feed, etc.).

If the CO2 is contained in flue gas, it can be purified by absorbing the NO and SO2 (Lam and Lee, 2012).

4. 3. 2 技术成熟度

目前微藻养殖耦合 CO2 减排生成食品的技术已经进入了产业化示范阶段。中国科学院南海海洋研究所向文洲教授团队已经将微藻固碳技术应用于多个生产食品的示范工程上来，如表 4. 2

4.3.2 Technology Maturity

Technology for microalgae breeding to produce food coupled with CO2 emission reductions is currently in the industrialization demonstration stage. Wenzhou XIANG’ team in the South China Sea Institute of Oceanology of the Chinese Academy of Sciences has applied microalgae carbon storage technology to multiple food production demonstration projects, shown in Table 4.2.

公司名称	养殖面积 /m2	应用	技术来源
三亚海王海洋生物科技有限公司	约 3 万	食品	中科院南海海洋研究所
中山市蓝藻生物食品开发有限公司	约 2 万	食品	中科院南海海洋研究所
北海生巴达生物技术有限公司	约 3 万	食品	中科院南海海洋研究所
深圳市绿得宝保健食品有限公司	约 2 万	食品	中科院南海海洋研究所

表 4. 2 微藻固碳示范工程举例

Company	Culture area(m2)	Application	Source of technology
Sanya Neptunus MarineBiological Technology Co., LTD	About 30,000	Food Production	South China Sea Institute of Oceanology, Chinese Academy of Sciences
Zhongshan Cyanobacteria Biological Food Co., LTD	About 30,000	Food Production	South China Sea Institute of Oceanology, Chinese Academy of Sciences
Beihai SBD Biosicence Technology Co.,LTD	About 30,000	Food Production	South China Sea Institute of Oceanology, Chinese Academy of Sciences
Shenzhen Ludebao Health Food Co., LTD	About 30,000	Food Production	South China Sea Institute of Oceanology, Chinese Academy of Sciences

Table 4.2 Illustration of Microalgae Carbon Storage Demonstration Projects

目前，中科院南海海洋研究所正关注更大规模的微藻固碳产业化示范，新技术创新点的中试以及新藻种的培育和实验。其中正在培育的藻种之一嗜碱绿球藻 MC-1（图 4.6）具有极具潜力的减排产油藻种：诱导培养下油脂含量能超过55%；能进行室外大规模培养，适应烟气培养条件；培养后期有自动下沉特性，便于采收；除能产油外还富含虾青素、亚麻酸，可用于生产高值化产品。

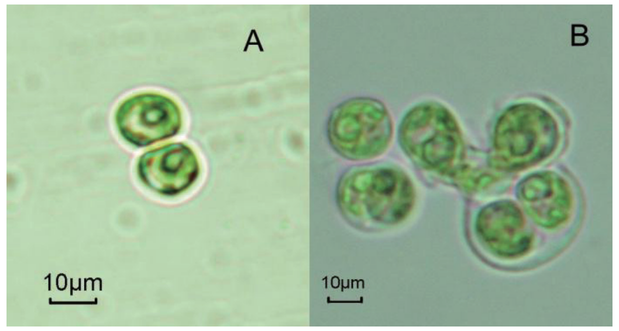


图 4.6 嗜碱绿球藻 MC-1 的光学显微镜照片

Figure 4.6 Optical Microphotographs of Chlorococcum Alkaliphilus MC-1

以丰富的优势藻种为支持，不断地对培养技术进行优化，加开发和放大高效光生物反应器（Huang et al.， 2010），提高产油率和 CO2 利用效率（Chen et al.， 2009）缩小微藻生物柴油与石化柴油成本差距的重要手段，该项技术将前景广阔。

The Institute has been focusing on demonstrating larger-scale industrialized microalgae carbon storage, pilots of new technologies and cultivation and testing of new algae breeds. One of the algae breeds being cultivated, chlorococcum alkaliphilus MC-1(Figure 4.6), has great potential for emission reduction and oil production. Under domesticated cultivation, its oil content (which is rich in astaxanthin, linolenic acid, and can be used in the production of high value products) can exceed 55%. It is susceptible to large-scale outdoor cultivation and can adapt to cultivation in flue gas conditions. Finally, it has an automatic sinking characteristic in the later period of culture, which makes it easier to recover.

With abundant superior algae breeds available, the constant optimizing of culture techniques, and the accelerated development and enlargement of effective optical bioreactors (Huang et al., 2010), the resulting improvement in oil production rates and the efficient use of CO2 (Chen et al., 2009) are important means to reduce the cost gap between microalgae biodiesel and petroleum diesel, giving this technology great potential.

4.3.3 Emission Reduction Potential and Environmental and Social Benefits

The efficiency of microalgae in storing CO2 from the flue gas of a power plant can reach 75.6%(75.6% of the total CO2 in the flue gas is utilized by microalgae) under specified conditions, calculated on the basis that the carbon content of microalgae accounts for 50% of the biomass, and 1 kg of biomass can store 1.83 kg of CO2. It should be noted that the products will finally be combusted or decomposed through respiration into CO2, so the emission reduction effect is temporary.

开展微藻固碳技术还可以带动中国多个技术领域的发展，对中国经济发展具有重要的推动作用：1 与沙荒地综合利用结合，在实现 CO2 固定的同时，缓解中国土地压力；2 可与绿色循环经济发展相结合，利用农业 CO2 废气 （沼气中的 CO2）、废水进行微藻规模化养殖，生产动物饲料，形成区域性绿色循环经济；3 与现有发电厂、炼钢厂、化工厂等 CO2 排放大户结合，利用工业 CO2 废气进行微藻规模化养殖生产生物能源（无需捕集分离和纯化）（Yao et al.， 2010）。

Developing microalgae carbon storage technologies can also drive the development of China's other many technology fields, and play an important role in China's economic development: 1 by the comprehensive use of desert and wasteland, realizing CO2 storage could mitigate the pressure on China's land; 2 using agricultural waste CO2 (CO2 separated from biogas) and wastewater to implement large-scale microalgae breeding and produce animal feed, would develop a regional green circular economy; 3 , using industrial waste CO2 emissions(without CO2 capture, separation and purification)from existing big CO2 emitters such as power plants, steel mills, chemical plants for microalgae scale cultivation can produce energy (Yao et al., 2010).

4.4 太阳光催化转化 CO2 技术

Sunlight Catalytic Conversion CO2 Technology

4. 4. 1 技术简介

光催化还原 CO2 是基于模拟植物的光合作用。其原理是它利用太阳能激发半导体光催化材料产生光生电子－空穴，以诱发氧化－还原反应将 CO2 和 H2O 合成碳氢燃料，其反应方程式如图 4.7。

$$CO_2+H_2O \xrightarrow[\text{催化剂}]{\text{光}} \text{碳氢化合物} + O_2$$

图 4.7 光催化还原 CO2 为碳氢燃料

光催化还原 CO2 是固定转化 CO2 的途径之一，其它的途径还包括热化学转化、电化学转化等。在大多技术途径中，CO2 转化都需要较苛刻的条件，而光催化反应可以在较温和的条件和较低能量输入下完成（Li et al.， 2012）。光催化转化 CO2 技术其它的优势还包括（Wu et al.， 2011；Li et al.， 2012）：

4.4.1 Technology Introduction

Photocatalytic reduction of CO2 is based on the simulation of plant photosynthesis.Its principle is that it uses solar energyto stimulate semiconductor photocatalytic materials to produce photoproduction electron-holes to induce oxidation-reduction reaction, converting CO2 and H2O into hydrocarbon fuels. The reaction equation is shown as Figure 4.7.

$$CO_2+H_2O \xrightarrow[\text{Catalyst}]{\text{Light}} \text{Hydrocarbon} + O_2$$

Figure 4.7 Photocatalytic Reducing CO2 to Be Hydrocarbon Fuels

Photocatalytic reduction of CO2 is one way of storing and converting CO2; other ways include thermal chemical

直接以清洁可再生能源----太阳能作为驱动力无需耗费辅助能源；原料简单易，可真正实现碳材料的循环使用；可将CO2转化为甲烷、甲醇等高附加值的燃料及其它化学品。

基于以上优点，该技术因而被认为是最具前景的 CO2转化方法，但同时也是极具挑战性的前沿方向。

4.4.2 技术成熟度及难点

太阳光催化还原CO2技术还处于在研发阶段，其技术难点之一在于太阳能的利用效率低（Wu and Lin，2005）。以现有的可应用的光催化材料TiO2，ZnO，SrTiO3为例，反应只能利用占太阳能4%的紫外光，而要实现高效地利用太阳能，必须使用占太阳光能43%左右的可见光部分。目前已有一些报道高效可见光催化还原CO2反应体系的建立（Pan and Chen，2007；Woolerton et al.，2010）。其它的技术难点有光催化材料对CO2吸附性能差以及对CO2活化和光生电子-空穴分离效率考虑不足等问题（Wu et al.，2011）。

4.4.3 前景展望

光催化还原CO2的研究与开发面临着许多问题。但是在持续不变的政策与经费的支持下，随着新型体系、新型结构的高效光催化剂的开发，光吸收、气体吸附、气体活化与光生载流子基本行为等诸多因素的最佳匹配的物理参数的调控，光催化材料纳米尺度的多功能化集成式设计，以及太阳能高效利用、超强气体吸附与高效的气体转化的光还原反应体系的最终建立，那么未来光催化还原CO2技术的大规模商业化应用并不是梦想（Wu et al.，2011）。

conversion, etc. In most technological approaches, conversion of CO2 needs demanding conditions; however, light catalytic reaction can be completed in relatively mild conditions with low energy input (Li et al., 2012). Other advantages of photocatalytic CO2 conversion technology include (Wu et al., 2011; Li et al., 2012):the direct use of clean and renewable energy (solar energy being the driving force, there is no need to consume auxiliary energy); its raw materials are simple and easy to find, and it genuinely recycles carbon material since it can convert CO2 into high value-added fuel such as methane, methanol and other chemicals.

Based on the above advantages, the technology is considered as one of the most promising CO2 conversion methods, but it will also be very challenging to take forward.

4.4.2 Technology Maturity and Difficulties

Technology for the catalytic reduction of CO2 by sunlight is still in the development stage, one of its technical difficulties being the low efficiency in the conversion of solar energy (Wu and Lin, 2005).Based on existing applicable photocatalysis materialse.g. TiO2, ZnO, and SrTiO3, the reaction only uses 4% of the solar ultraviolet light, and to achieve greater efficiency, the reaction must use the visible spectrum which accounts for about 43% of sun light energy. There have been some reports about the establishment of efficient visible light catalytic reduction of CO2 systems (Pan and Chen, 2007; Woolerton et al., 2010).Other technical difficulties include photocatalytic materials for CO2with poor adsorption performance and the insufficient consideration of CO2 activation and photoproduction electron-hole separation efficiency (Wu et al., 2011).

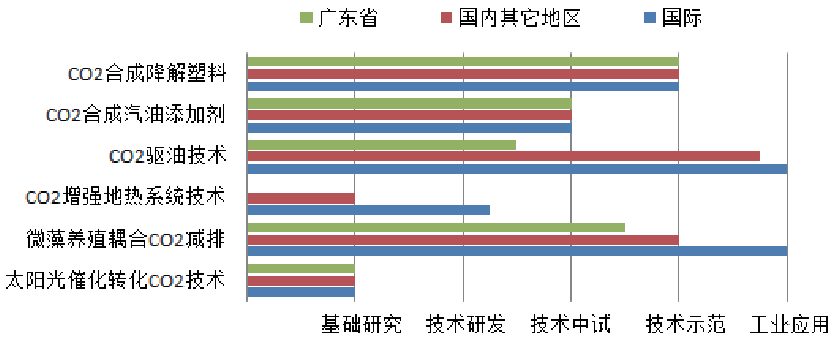
4.4.3 Prospect Outlook

The research and development of photocatalytic reduction of CO2 is faced with many problems. These include (i) the development of high efficiency photocatalysts with new systems and new structures,(ii) regulating and controlling the best match of physical parameters formany factors such as light absorption, gas adsorption, gas activation and the basic behavior of photon-generated carriers, (iii) multi-functional integrated design of photocatalytic materials on the nanometer scale, (iv) as well as the efficient utilization of solar energy, super strong gas adsorption and the final establishment of light reduction reaction systems with highly efficient gas conversion. However, under sustained policy and funding support, the large-scale commercial application of photocatalytic reduction of CO2 technology in future may not be a dream(Wu et al., 2011).

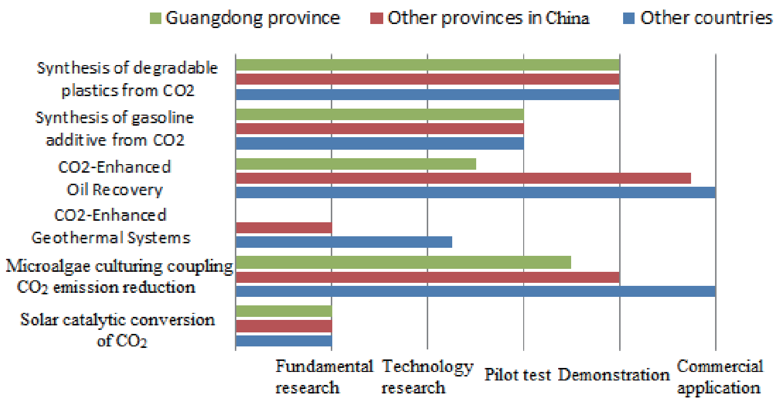
5. 结论与讨论

Conclusion and Discussion

调查结果表明，广东省从技术的掌握程度和发展条件上具备进一步发展 CO2 利用技术的潜力，但目前利用技术对碳减排效果不明显。广东省 CO2 利用技术涵盖从传统的商业化 CO2 利用技术到地质利用技术，再到一些创新型的利用技术，覆盖类型广，层次多。已经商业化的利用技术在广东省主要分布焊接和饮料业，已形成成熟的市场价值链，但技术主要利用 CO2 自身性质，较少涉及对 CO2 的转化等深层次的利用，产品附加值小，且典型的利用技术 CO2 被利用的周期只有数天到数月，应用规模小，减排的效果小。未实现商业化的 CO2 利用技术主要集中在对 CO2 的化学生物转化和地质利用上，总体上减排潜力相对传统技术大，且产品附加值高，但不同 CO2 利用技术成熟度不同如图 5.1。



~~图 5.1 CO2 利用技术成熟度~~



~~Figure 5.1 Maturity of Carbon Dioxide Utilization Technologies~~

The results of this report show that Guangdong has potential to realize further development of CO2 utilization technologies in the terms of coverage of technologies and development conditions, but current CO2 utilisation technologies have limited potential in achieving carbon reduction. Studies at multiple levels are ongoing for technologies from conventional commercialized carbon dioxide utilization, through geological application, to innovative utilization. The wide application - for commercialized technologies in Guangdong come mainly from the welding and beverage industries, and these have had mature market value chain. However, the typical lifetime of the CO2 currently used in commercialized applications is usually a few days to a few months. With such short lifetimes and limited scale of utilization, it is difficult to contribute significantly to the mitigation of the CO2 problem by the industrial utilization of CO2. CO2 utilizations mainly deploy the characteristics of CO2 itself involving little of conversation and further exploitation therefore have limited added value. CO2 utilization technologies which have not been commercialized mainly concentrated in the chemical or biological conversion of CO2 and geological utilization. Overall these technologies have relatively higher emissions reduction potentials and added value to products compared with traditional technologies, but these technologies are currently at different stages of maturity.

具体来说，两种化工应用 CO2 利用技术（CO2 合成降解塑料、汽油添加剂）发展的较为成熟，已经到达技术中试以及以上水平。这是因为技术本身发展的积累外，还由于相关科研机构科研团队自主研发能力强。两种在广东省最有潜力的地质利用技术成熟度差异较大。CO2-EOR 技术在国际上已经工业化，中国其他地区也有较为丰富的经验，广东省虽然未有具体的实践，但技术问题不会制约其应用，目前比较急迫的是对珠江口盆地的油田进行 CO2-EOR 可行性分析。广东省有良好的发展 CO2-EGS 技术的条件如有高地热梯度地热资源，目前首要的任务是对技术的研发和试验。微藻养殖耦合 CO2 减排生产食品的技术已经发展到示范阶段，但最新的研究成果和技术的革新需要进一步的中试。太阳光催化转化 CO2 技术是被认为是最具前景的 CO2 转化方法，同时也是极具挑战性的前沿方向，需要大力推进基础研究和技术研发。

广东省发展二氧化碳利用技术还有一定的紧迫性。这是因为一些技术的应用有最佳时期，一旦错过就无法挽回。例如 CO2-EOR 技术，必须在油田废弃之前若干年完成评估工作，因为从作业成本考虑，海上油田的开采速度一般较高，而一旦油田枯竭就要及时废弃，那时再考虑 CO2-EOR 就不再可能。另一方面从 CO2 利用技术的成熟度来看，广东省掌握着一些技术走在全国前列甚至是世界前列，加快促进这些技术的规模化和商业化，才能保持竞争力，带来较大的经济效益。而随着全世界对 CO2 利用技术的逐渐增加的关注度来看，一些前沿的创新型的科技正在越来越受到科学家重视，需要把握时机，学习和自主创新发展这些技术，以增加广东省减排和可持续发展的潜力。

Thanks to continued technological improvement through independent research and the development of related scientific research organizations and teams, two kinds of chemical technologies applied to carbon dioxide utilization are relatively mature, reaching pilot level and above. There are big gaps in the maturity of the two kinds of geological technologies with the potential in Guangdong. Onshore CO2-EOR has already been internationally industrialized and other regions are also gaining wide experience. Although there are no specific examples of this technology in Guangdong, technological issues cannot restrict its application. There is now an urgent need to conduct a feasibility analysis of CO2-EOR in the Pearl River Mouth Basin. There are good development conditions for CO2-EGS applicaton in Guangdong province such as geothermal resources with high geothermal gradient, , and R&D and testing of this technology should be the first priority. Technologies for microalgae cultivation for food production coupled with carbon dioxide reductions have been developed through to the demonstration stage, but the newest research findings and technological innovations need further piloting. The technology for catalytic CO2-conversion by sunlight is considered a potentially promising CO2-conversion method, but it is still at the cutting edge, and needs basic research and technological R&D to be aggressively promoted.

Since some technologies are time-limited and once missed are gone forever - it is urgent for Guangdong to develop carbon dioxide utilization technologies. For example, evaluation of CO2-EOR must be completed before fields are depleted several years hence. Offshore fields,

通过以上对广东省 CO2 利用技术的综合分析，还可以得到以下启示：

1. 二氧化碳地质利用为最有减排潜力的利用技术，但需要进行更深入的可行性研究。另一方面，目前在广东尚未有成熟利用技术能够取代二氧化碳离岸地质封存技术的碳减排潜力。

2. 发展 CO2 利用技术，需要对技术进行综合的评估。包括整个生命周期过程中的减排潜力，环境影响，能耗，成本，原料等。其中对减排潜力的估计需考虑到各个环节潜在的“源”和“汇”，例如能量消耗。但也无需局限于减排潜力，只要综合评价可以实现较高的社会经济收益，都可以纳入发展的对象。

3. 结合其它环境治理项目，共同推进可持续发展。一些技术的发展面临成本高的屏障，如果能结合其它治理项目，共同发展即可达到降低成本，多方面、多层次增加社会环境效益的效果。例如微藻养殖耦合 CO2 减排与废水处理相结合。

4. 增加科技创新，提高产品附加值。科技的创新是 CO2 利用技术发展的“催化剂”，不仅可以提高 CO2 利用率又可以增加经济效益。因而大力推动创新型和一些亟待研究开发的 CO2 利用技术的发展，可起到事半功倍的效果。

5. CO2 不易储存与运输，其经济运输半径较短（约为 300 km）。那些需要对 CO2 进行预先捕集的利用技术如果根据技术对地理位置，CO2 利用规模与纯度的要求，选择适当的 CO2 排放源或 CCS 项目相结合，可大大降低运输成本，提高经济效益。

because of high operating costs are depleted rapidly and then abandoned, making them unlikely to be considered for CO2-EOR.Guangdong leads China, and even the world, in the level of maturity of certain carbon dioxide utilization technologies. Their scale-up and commercialization need to be accelerated, so as to maintain a competitive advantage and bring great economic benefits. With the world's growing attention on carbon dioxide utilization technologies, leading edge novel scientific technologies are attracting the interest of more scientists, so we must catch the opportunity to learn from them and develop these technologies through independent innovations so that the potential to cut emissions and achieve sustainability can be improved.

Further comprehensive studies of carbon dioxide utilization technologies might achieve the following:

1. CO2 geological utilization has the highest potential in carbon reduction, but it requires further feasibility study in Guangdong. On the other hand, there is not yet a mature utilization technology that could potentially achieve a deep cut of carbon emissions in Guangdong. CO2 offshore geological storage technology remains the most important abatement technology.

2.To develop CO2 utilization technologies, the technologies should be evaluated in a lifecycle method, including the emission reduction potential, energy consumption, environmental impact, the cost and raw materials etc. in the entire life cycle. During the estimation of emissions reduction potential, every potential "source" and "sink" for CO2 in different process of application should be considered, such as energy and products consumption. But emissions reduction potential should not be the only criteria, any CO2 utilization technology which can achieve overall higher social and economic benefits could be listed among the objects of development.

3. To combine other projects on environmental management so as to promote sustainability. Because some technological developments are facing high cost barriers, cost cutting and social and environmental benefits can increasing be achieved if development is promoted in combination with other environmental management projects. For instance, microalgae cultivation coupled with carbon dioxide emission reductions could be integrated with waste water treatment.

4. To increase scientific and technological innovations so as to enhance the added value of products. Scientific and technological innovations are catalysts for carbon dioxide utilization technologies, which can not only improve the efficiency of carbon dioxide utilization but also increase economic benefits. Therefore, progressively promoting innovative carbon dioxide utilization technologies with those which urgently await R&D can have a multiplier effect.

5. It is not easy to store and transport carbon dioxide which has a short radius for economic transport (about 300km). Thus, it is better to match the specific CO2 utilization technologies applications, which are reliant on CO2 capture with appropriate CCS infrastructures based on its location, scale and purity of emitted CO2.

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