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华润电力（海丰）3 号和 4 号机组 2 x 1000 兆瓦超超临界燃煤电厂碳捕集与封存（CCS）预留报告

China Resources Power (Haifeng) Units 3 and 4:
2 x 1000MW Ultra-supercritical Coal-fired Plants
Carbon Capture Readiness (CCR) Report

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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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执行摘要

燃煤电厂是温室气体 CO2 排放的重要来源，CO2 过度排放引发的气候变化效应是当前全球广泛关注的重大问题。然而，国内针对燃煤电厂碳捕集的工程经验还较少。本报告运用国际能源署温室气体计划提出的“二氧化碳捕集预留（CCR）”概念对华润电力（海丰）3 号和 4 号机组 2 x 1000 兆瓦超超临界燃煤电厂进行了设计分析。

本报告主要包含以下内容：

- 综述目前最先进且未来有可能成为捕集大型燃烧电厂二氧化碳颠覆性技术，推荐适用于华润电力海丰电厂的碳捕集技术，并分析该技术对其他未来技术的兼容性；

- 根据选定技术工艺，推定碳捕集系统相关主要设备配置，确认碳捕集场地需求、具体接口位置和管线，规划控制系统及电力分配系统；

- 针对现有模型，对碳捕集所需能耗、物料消耗以及对电厂效率的影响进行分析评估；

- 华润电厂碳捕集实现后，对 CO2 的潜在封存地和潜在运输机制进行分析，选定相对合适的方案；

- 评估捕集预留的经济性和投资价值。

Acknowledgements & Disclaimer

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1. 引言

1.1 研究背景

广东省是中国五个低碳试点省份之一，也是中国最大的碳排放交易市场。 碳捕集、利用与封存（CCUS）是当前大型化石燃料电厂唯一可行的碳减排技术。该技术对于燃煤电厂发电量超过 80% 的中国来说尤为重要。

中国的新建电厂没有配备 CCS 装置。但是附加投资适度的设计特征，对于未来安装捕集设备有利，也可将来自电厂的碳排放锁定风险降至最低。达成此目标的一个方法示例，是英国能源与气候变化部为了支持英国 2009 年的一项政策而发布的指导性说明——所有发电容量达到或超过 300 兆瓦的新燃煤电厂的兴建都必须具有二氧化碳捕集预留（CCR）设计。另请参阅附录 1 中列出的国际能源署温室气体计划（IEA GHG）的定义。尽管英国有 CCSR 法规，澳大利亚、加拿大、欧盟和日本却均制定了自身区域的 CCSR 法规。中国也正在进行一项亚洲开发银行资助的关于其 CCSR 法规的研究。

当然，在捕集改造的时候对二氧化碳进行运输和封存也是必需的。虽然对于一个无法提供前瞻性运输与封存安排的场址来说进行电厂捕集预留设计是不适合的，但是，在未来某个时间内对电厂真实的运输与封存详情置信水平的要求，允许低于该电厂直接管制之内的碳捕集装置及其他设备建设范围的置信水平。

在许多案例中，多个潜在管道路线和封存位置的存在，对于一个特殊位置来说，降低了无一可用的风险。此外，在国家层面，一个 CCR 电厂集群（和其他大型捕集预留工业排放源）将为优化运输与封存基础设施的引入提供选择。在总体层面，即使当只有次级位置源连接用于 CCS，也将是有价值的。

本研究是 2013 年 12 月英国和广东机构之间签署的一份关于进行 CCS 技术合作地重要谅解备忘录的结果。华润电力（海丰）有限公司随后委托爱丁堡大学和广东电力设计研究院为其拟建的 3 号和 4 号机组开发此类首个 CCSR 设计。中科院南海海洋研究所，在中国海洋石油总公司的协助下规划出一条未来可能的管道连接（海上）封存，而且还指出，之前提出的可选择的运输与封存安排的范围经论证是不可行的。该项目收到了来自于英国驻广州总领事馆、豪顿集团、壳牌公司通过战略计划基金的联合赞助支持。

本研究采取了务实方针，仅当电厂处于设计和建造时，才会作出促进捕集改造的决定。当前正在采用目前最先进的知识进行 CO2 运输与封存的补充性评估。同时，本研究确认，进一步的工作，将要求用包括一份详细的管道路线调查监测和一份完整的封存位置评估报告在内的文件来界定 CCUS 改造项目的全部细节。

本报告涵盖以下主要领域：

- 一份目前最先进且未来有可能成为捕集大型燃煤电厂二氧化碳颠覆性技术的综述和一份华润电力（海丰）项目参考性捕集方法的描述；
- 对拟建项目进行该参考捕集方法改造的技术可行性评估。

从项目地点到具有足够二氧化碳封存容量的南海封存位置的可能管道线路的确定也正在进行中，由南海海洋研究所领导，并将出现在未来的报告中。

1.2 华润电力（海丰项目）

华润电力正计划在位于广东省汕尾市海丰县小漠镇的华润电力海丰项目场地上开发一个 8 x 1000 兆瓦超超临界燃煤电厂（USCPC）项目。1 号机组和 2 号机组正在建设中，预计于 2015 年 1 月和 2015 年 5 月分别开始投入运营。华润电力正试图扩建这个现有的项目并且在该场地开发两个新的燃煤电力机组。拟建的新机组（3 号机组和 4 号机组）预计达到约 2000 兆瓦的电力输出规模，而且将被称为“华润电力海丰扩建项目”。

该项目位于红海湾海岸带的西北侧，属于沿海残丘地和潮汐浅滩带。残丘地的特征是起伏的地形、散布的丘陵以及海拔为 211 米的丘陵间洼地。

海丰项目所在的汕尾市，位于北回归线的正南面，属于温和的亚热带季风气候，降雨充沛日照充足。表 1 给出了该地气象站的气象统计数据。

表 1 汕尾气象站各种气象要素统计的 1953 年至 2003 年年度和月度特征值

类别 \ 月份	1	2	3	4	5	6	7	8	9	10	11	12	全年
平均温度（℃）	14.7	15.2	18.0	21.7	25.1	27.1	28.2	28.0	27.2	24.4	20.6	16.6	22.2
平均大气压（hPa）	1019.5	1018.3	1015.7	1012.6	1008.8	1005.8	1004.9	1004.5	1008.1	1013.4	1017.0	1019.5	1012.3
平均相对湿度（%）	72	77	81	83	85	86	84	84	79	73	70	69	79
最小相对湿度（%）	3	6	12	21	12	27	37	38	20	19	13	7	3
平均降雨量（mm）	27.1	53.4	75.9	153.6	275.7	368.1	314.3	322.7	212.9	66.3	35.7	25.3	1930.9
平均风速（m/s）	3.0	3.1	3.0	2.9	3.0	3.3	3.2	3.0	3.1	3.3	3.0	2.9	3.1

2. 可能的二氧化碳捕集技术

2.1 二氧化碳捕集技术途径介绍

从化石燃料电厂捕集二氧化碳有三种主要的流程，如图 2.1 所示：

1. 燃烧后捕集：利用选择性溶剂把二氧化碳从烟气中分离出来。

2. 燃烧前捕集：燃料（即煤或天然气）通过煤气化和一种变换反应被转化为一种二氧化碳与氢气的混合物，然后氢气被用于燃烧发电。

3. 富氧燃烧捕集（也被称为氧气／二氧化碳循环）：燃料（即煤或天然气）不是与空气燃烧，而是与氧气和二氧化碳的混合物燃烧，在烟道气气流中产生较高的二氧化碳浓度（没有氮气），因此使得二氧化碳的分离较为容易。其后，当一些分离的二氧化碳被回收并与氧气混合时，二氧化碳被从烟道气气流中移除。

对燃烧粉煤的电厂来说，燃烧后捕集被认为是最佳的改造选择。燃烧前捕集技术和富氧燃烧捕集技术都将需要对电厂流程进行大幅修改，并且需要对 CCSR 设计进行大量的投资前活动。层面，即使当只有次级位置源连接用于 CCS，也将是有价值的。

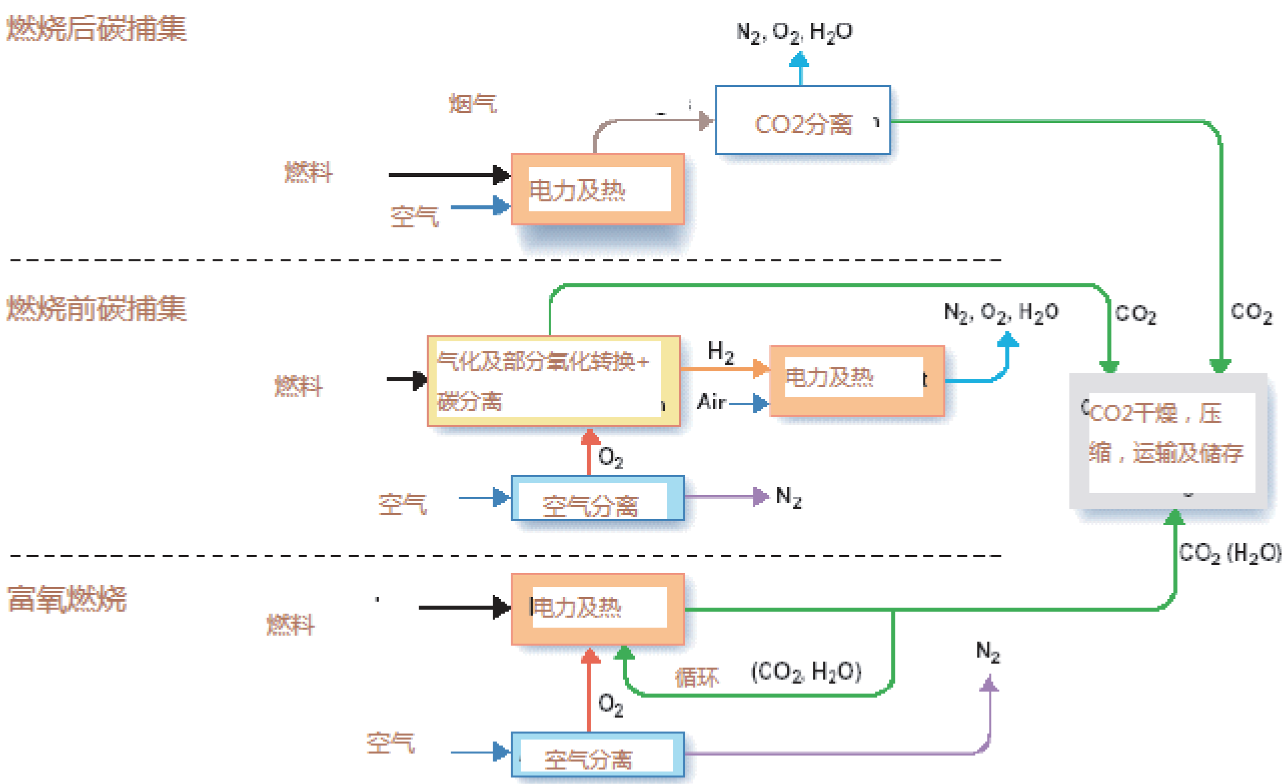

图 1 电厂三种主要的二氧化碳捕集流程选择

2.2 目前的商业燃烧后二氧化碳捕集技术

目前的商业燃烧后捕集二氧化碳捕集系统在变温流程中几乎完全使用有机胺－水溶剂。有一些是基于一乙醇胺的，但是新的胺配方和可选择的溶剂类型也正在开发用于提高性能。图 2 图给出了一种典型的溶剂变温流程。贫二氧化碳溶剂在吸收塔中吸收二氧化碳，然后被送入汽提塔（解吸塔）。在解吸塔内，富二氧化碳溶液利用低压蒸汽（对于一乙醇胺来说，通常在 120 摄氏度）加热释放出二氧化碳，释放出的二氧化碳经冷却、压缩和干燥后送去输送管道。贫二氧化碳溶液被冷却并循环回吸收塔。

目前最先进的燃烧后有机胺技术要求烟道气中的二氧化硫、二氧化氮和灰尘被降低到非常低的水平（通常要求 10 毫克／立方米，但是最佳值取决于该溶剂的成本和特性），以免污染和降解该溶剂。CCR 设计需要为安装额外的烟道气脱硫（FGD）、选择性催化还原（SCR）和除尘装置保留空间

以下推荐做法是一直在进行的概念改造研究，作为 CCR 设计评估的一部分。这假定从 3 号和 4 号机组捕集 90% 的二氧化碳，吸收剂使用 30% 重量比的一乙醇胺溶剂。这种溶剂不可能在未来使用，因为它正在被淘汰，但是一乙醇胺的性能数据是现成的，假如改良的溶剂在未来使用，它可能提供一种“安全的”设计余量。

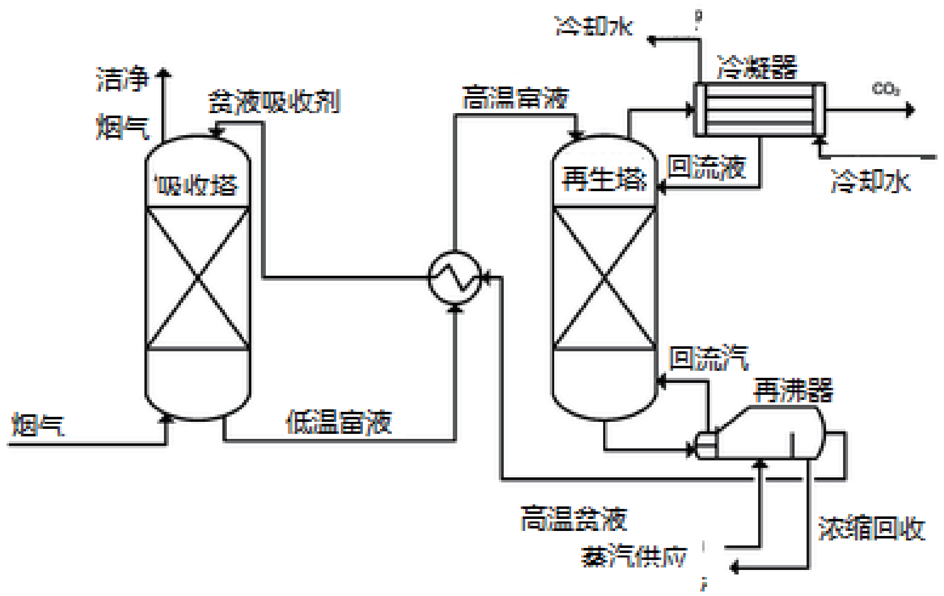

图 2 溶剂二氧化碳捕集的基本变温吸收流程示意图

2.3 新型燃烧后二氧化碳捕集技术

固体捕集或膜捕集是可选择的燃烧后捕集技术，从长远来看可以证明对捕集是有利的，因此在较长时期后可改造应用于 CCR 电厂。一个正在被开发用于固体捕集的选择是“湿层吸收”（WLA）——参见下列文本框。

这种“湿层吸收”(WLA)改为利用一种支持吸收溶剂的液态区域的多孔材料，这种材料依次吸收感兴趣的气体，在本案例中是二氧化碳。因此，这一流程是基于一种“浸渍吸附剂”的。然而，这种产品的主要新颖方面之一是吸收溶剂可以有低于其饱和压力的任何分压。这里的重点是涉及化学溶剂的一个流程，即各种各样的胺。目前的主要目标是证明这种基于化学溶剂的“湿层吸收”流程在碳捕集情况下的技术可行性。

来自于英国爱丁堡大学的 Martin Sweatman、Reader

膜法气体分离已经应用于诸如天然气脱硫和富氧空气生产等流程，而且它们有潜力在第二代碳捕集技术中扮演一种竞争性角色。由于诸如不需要再生装置、模块化和占地面积小等优势，对于燃煤电厂来说，它们可能代表其他碳捕集解决方案的一种替代选择。赵以及其他人[5]计划了一项可能的双阶段配置研究，包括基于逆流阶段、从燃煤电厂的烟道气开始的一份详细的经济与能量分析。一种最理想的膜二氧化碳/氮气的选择性（在 50 ÷ 100 范围内）被确定，而且估计的捕集成本为 31 欧元每吨二氧化碳。在 Hussain 和 Hägg 的著作中可以找到一种类似的方法[6]：提出了一种基于易化运输膜的双阶段调查研究，包括一份该捕集成本的经济评估。考虑到胺典型的 1.5 美元/MSCF 的气体处理成本(GPC)值，估计的膜成本为 0.85 美元/MSCF。

Merkel 以及其他人[7]提议了一种混合解决方案，包括将制冷阶段并入高达 150 巴的二氧化碳压缩阶段。建议的膜模块材料是 PolarisTM，而且模拟在整合逆流阶段和交叉流阶段运行。研究了涉及回收部分二氧化碳到锅炉的一种新配置：确定的捕集成本是 23 美元每吨二氧化碳。专注于美国捷能公司聚碳酸酯高通量膜的 RTI[8、9]还调查了回收二氧化碳到锅炉的可能性：报告了 30 美元每吨二氧化碳的捕集成本。

5. 赵，L 以及其他人，《用于燃烧后捕集的多级气体分离膜流程：能量与经济分析》。2010 年《膜科学期刊》359（1-2）：160-172 页。
6. Hussain，A. 和 M.-B. Hägg，《通过易化运输膜从烟道气捕集二氧化碳的可行性研究》。2010 年《膜科学期刊》359（1-2）：140-148 页。
7. Merkel，T.C. 以及其他人，《电厂燃烧后二氧化碳捕集：膜的一个机遇》。2010 年《膜科学期刊》359（1-2）：126-139 页。
8. Ramasubramanian，K. 和 W.S.W. Ho，《用于燃烧后碳捕集的膜的最新发展》。2011 年《化学工程中的当前观点》1（1）：47-54 页。

来自于 Bocciardo，D.；Ferrari，M. C.；Brandani，S.。《应用于燃煤电厂碳捕集的膜法流程的建模与多级设计》。2013 年《能源》Vol. 37，pp 932 - 940，DOI：10.1016/j.egypro.2013.05.188

3. 华润电力（海丰）3 号和 4 号机组的碳捕集预留概念改造研究

3.1 简介

本章节介绍了一个如何将一种基于一乙醇胺的碳捕集装置改装到拟建的华润电力（海丰）项目 3 号和 4 号机组烟气脱硫装置之后。目前的设备参数如表 2 所示。

3 号和 4 号机组的锅炉是超超临界、变压运行直流、一次再热、切向燃烧或对冲燃烧、烟气挡板控制再热蒸汽、平衡通风、冷灰斗、全钢结构、悬挂结构、Π 型、以及露天布置的。采用等离子点火系统。

3 号和 4 号机组采用一种直接燃烧、中速磨煤机、正压冷一次空气、粉煤系统。每台锅炉安装有 6 套磨煤机、2 套可调节活动叶片轴流一次空气（PA）风机、2 套可调节活动叶片轴流强制通风（FD）风机、以及 2 套可调节活动叶片轴流诱导通风（ID）风机。烟道气脱硫阻力由单台引风机克服，不需要额外的辅助风机。

与华润海丰电厂 3 号和 4 号机组改造分析有关的其他参数如下所示。

设计燃料：鄂尔多斯烟煤，低热值 =21250 千焦/千克

每个机组的燃料热输入：2364.3 兆瓦

悬浮微粒去除装置：每个机组提供 2 套 ESP（三室五电场），收集效率 ≥ 99.75%

选择性催化还原系统：选择性催化还原效率约为 80%

烟道气脱硫系统：石灰 - 石膏湿法烟道气脱硫，效率约为 94%

一个配备燃烧后捕集预留的超超临界粉状燃料锅炉及其附属设备的特点并没有明显不同于常规空气燃烧超超临界粉状燃料锅炉。利用燃烧后捕集技术将超超临界粉状燃料锅炉建成捕集预留设施的基本系统要求和设备要求如下文概述：

1）燃烧设备、受压部件、空气加热器、锅炉燃烧设备（磨煤机、燃烧器）、所有的受压部件和再生空气预热器都不需要为配备一个胺洗塔的二氧化碳捕集改造进行任何修改，因此，碳捕集预留对上述设备无改造要求。

表 2 锅炉主要参数（锅炉最大连续出力）

项目	单位	数值
最大持续气流	t/h	3060
过热器出口压力	MPa(a)	28.25
过热器出口温度	℃	605

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项目	单位	数值
再热蒸汽流量	t/h	2566
再热器入口压力	MPa(a)	6.15
再热器入口温度	℃	369.7
再热器出口压力	MPa(a)	5.96
再热器出口温度	℃	603
锅炉氮氧化物排放浓度	mg/Nm3	300
无辅助燃料支持的最低稳定负荷		30% BMCR
锅炉保证效率（试验性的）	%	94

华润电力海丰 3 号和 4 号机组中的冷凝式汽轮机具有 4 缸 4 排、单轴和一次再热的特征。

额定功率：1000 兆瓦

转速：3000 转 / 分钟

回热系统：3 个高压加热器、4 个低压加热器和 1 个除气器

保证热效率：7416 千焦 / 千瓦时（试验性的）

实验性的主要汽轮机参数如表 3 所示：

表 3 汽轮机主要参数（汽轮机连续最大出力）

项目	单位	数值
高压蒸汽流量率	t/h	2915
高压入口 / 出口温度	℃	600/364.4
高压入口 / 出口压力	MPa(a)	27/6.056
中压蒸汽流量率	t/h	2442
中压入口 / 出口温度	℃	600/368
中压入口 / 出口压力	MPa(a)	5.586/0.608
低压蒸汽流量率	t/h	1610
低压出口温度	℃	65
中压出口压力	kPa(a)	5.5

用于华润电力海丰电厂的煤炭性能如表 4 所示。

表 4 用于华润电力海丰电厂的煤炭性能

项目	符号	单位	设计煤种	验证煤 1
达到的碳含量	Car	%	60.13	58.6
达到的氢含量	Har	%	2.85	3.36
达到的氧含量	Oar	%	9.08	7.28
达到的氮含量	Nar	%	0.69	0.75
达到的硫含量	Sar	%	0.69	0.63
达到的水含量	Mar	%	14.9	9.61
干燥后的水分	Mad	%	8.60	2.85
达到的灰含量	Aar	%	11.66	19.77
无挥发物、无干灰	Vdaf	%	30.9	32.31
接受的低热值	Qnet,ar	MJ/kg	21.25	22.44
机组燃煤量		t/h	375	356

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3.2 电厂布局选择

为了该超超临界粉煤电厂的最佳性能能够与二氧化碳捕集装置充分整合，供应二氧化碳捕集装置辅助的热和电力要求，在本报告中已经研究了这种方法。

华润电力海丰电厂 3 号和 4 号机组碳捕集预留设计的概念改造设计原则如下：

1）二氧化碳捕集装置

对于一个容量为 1000 兆瓦的单一锅炉 / 涡轮机机组来说，锅炉最大连续蒸发量工况 BMCR 烟道气体积是 3252839Nm3 / 小时（干烟气）。二氧化碳浓度为 13.3%，进入该捕集系统的二氧化碳为 826.6 吨 / 小时。针对 3 号和 4 号机组，按 100% 碳捕集预留设计，对燃烧设计煤种可实现设计捕集率为 90%，捕集的二氧化碳总量为 743.9 吨 / 小时。

表 5 不同部位的二氧化碳量

单位：吨 / 小时	设计煤种	验证煤种
来自燃烧的二氧化碳	823.3	758.6
来自烟气脱硫的二氧化碳	3.3	2.86
进入捕集系统的全部二氧化碳	826.6	761.5
捕集的二氧化碳（90% 的捕集率）	743.9	685.3

2）溶剂选择

正如指出的那样，一乙醇胺被假定为溶剂。但是燃烧后捕集预留设计概念允许以下两种可能性中的任何一个，a）在较晚阶段升级到更好性能的溶剂，或者 b）如果该技术变得可用，转换到固体吸附剂或膜装置。选择一乙醇胺用于基础案例情景，为未来的捕集设施保留最大可能的空间和热需求量。

3）烟道气旁路系统将被设计用于电厂在未来电力市场的灵活性运营。

4）该 CCS 系统被设计每年使用 5500 小时，这与 3 号和 4 号机组的设计使用小时数相同。

3.3 装置改造和场地要求

以下论述（在 3.3 章节中）是基于以上概述的改造选择。保险起见，该改造预计将建立在应用目前最先进一乙醇胺技术的 CCP 基础之上。该 CCR 设计考虑了从原来的机组（即 1 号和 2 号机组）捕集二氧化碳。额外的场地和空间需求将被保留和保持可用，直到更小空间要求、更具成本效益的二氧化碳捕集技术商业化或监管者（例如广东发展与改革委员会）建议二氧化碳捕集改造减小空间。

3.3.1 该二氧化碳捕集预留电厂拟建的捕集流程

1）二氧化碳捕集系统

在烟道气脱硫之后，3 号和 4 号机组的清洁气体将进入该二氧化碳捕集设施。为了克服在该设施中的压力损耗，这些清洁气体的压力被一台增压风机升高。增压风机被安装在 CCP 的入口，但是以下详细设计它可能被安置在该设施的其他点位。

在进入预洗涤塔进行冷却和净化预处理之后，这些烟道气被通过冷却器进一步净化和冷却，然后在吸收塔内向上流动与逆流向下的一乙醇胺溶剂相接触。吸收塔内安装规整填料，在最小的压力降工况下促进一乙醇胺溶剂的传质过程。在吸收器的顶部设置洗涤和除雾装置，使清洁的烟道气从烟囱排出之前，将溶剂携带损失降低到最小。富含二氧化碳的胺溶液被转移到汽提塔，在其中该溶液被低压蒸汽加热，从溶液中释放出二氧化碳。二氧化碳再生后的胺溶液然后被循环到吸收塔 8。

在汽提塔的顶部，由蒸汽和二氧化碳混合物组成的气流被冷却，水蒸气冷凝回流，并且将二氧化碳处理到便于压缩机之后的管道输运封存。

解吸塔中的溶剂被收集在泥浆池中。一部分溶剂被泵入再沸器，生成用于移除二氧化碳的蒸汽。这些溶剂和蒸汽的混合物然后返回解吸塔。

为了使溶剂再生，CCS 系统设有一个回收系统。该系统能够处理解吸塔浆液池中的剩余溶液。通过添加氢氧化钠和加热该溶剂，稳定的盐类将被去除，然后溶剂将被再生重新利用。

从解吸塔的反应釜中，大部分贫溶液被泵回吸收塔。在进入吸收塔之前，这些溶剂在贫富液热交换器和一乙醇胺冷却器中被冷却。为了净化这些溶剂，在一乙醇胺冷却器 9 之后，设置机械过滤器和活性炭过滤器。

本系统将捕集 3 号和 4 号机组大约 90% 的二氧化碳。至于详细的二氧化碳捕集系统流程图，请见图 3。

2）二氧化碳压缩系统

捕集的二氧化碳将通过压缩和冷却来液化，用于随后的封存。

第一步是将二氧化碳的压力升高到 20 巴，并且冷却到 40 摄氏度的温度。第二步是干燥这些二氧化碳并且通过另一压缩级将压力升高到 110 巴。在压缩、净化和干燥后，这些二氧化碳气体通过冷凝器，然后其温度降至零下 30 摄氏度用于液化。最后，这些二氧化碳的压力被升到 110 巴，通过管道 10 或早期通过轮船运输至封存点。

二氧化碳的运输和封存将在其他报告中涉及。

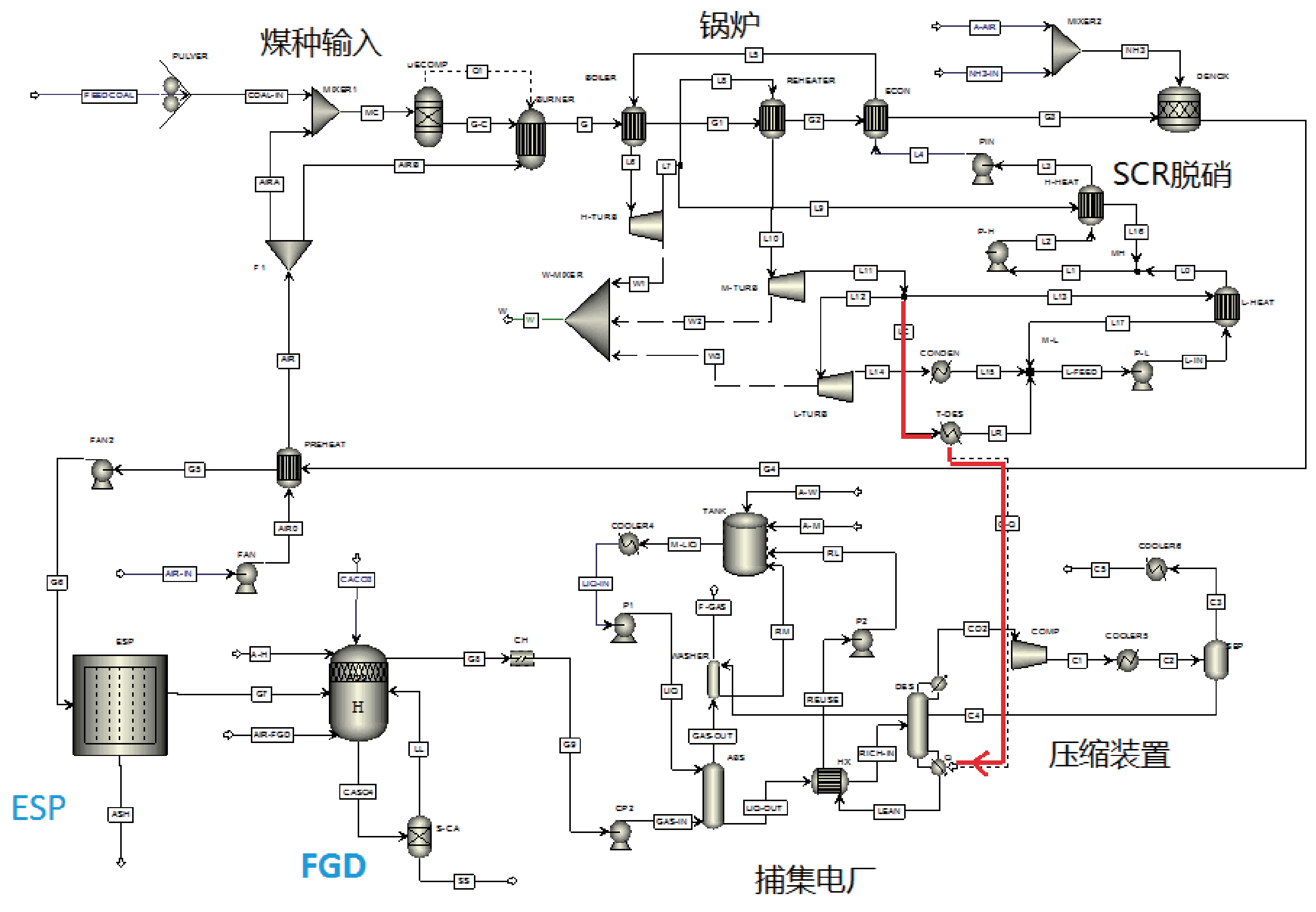


图 3 华润电力海丰电厂工艺流程图

3.3.2 空间要求

建设一个使用燃烧后捕集技术的碳捕集预留粉煤电厂的基本要求是在电厂中合适的地点留有足够的额外空间，以容纳额外的碳捕集设备和进行关键连接。另一个要求是允许扩建电厂配套设施，满足捕集设施的一些额外要求（冷却水、辅助电源配电等）。所需的空间将留给：

1）二氧化碳捕集设施。

2）锅炉岛的扩充和辅助设施（例如为连接引风机和胺洗塔的烟道设计路线所需的场地）。

3）蒸汽轮机岛的扩充和辅助设施（例如蒸汽轮机内为大型低压蒸汽管道与胺再生塔之间的线路预留空间）。

4）为满足捕集设施的额外需求的配套设施系统的扩建和补充。

5）运载工具（如胺运输）所需的额外场地。

6）基于危险性和可操作性管理学就封存以及胺类和二氧化碳的处理所进行的空间分配。

场地要求还应按照独立系统和设备要求进行商讨。

为 3 号和 4 号机组的 CCS 系统保留的区域分为两部分：吸收区和加压区。该项目将需要两套二氧化碳捕集 / 压缩设备。一套碳捕集设备所需的总面积是 1.3 万平方米

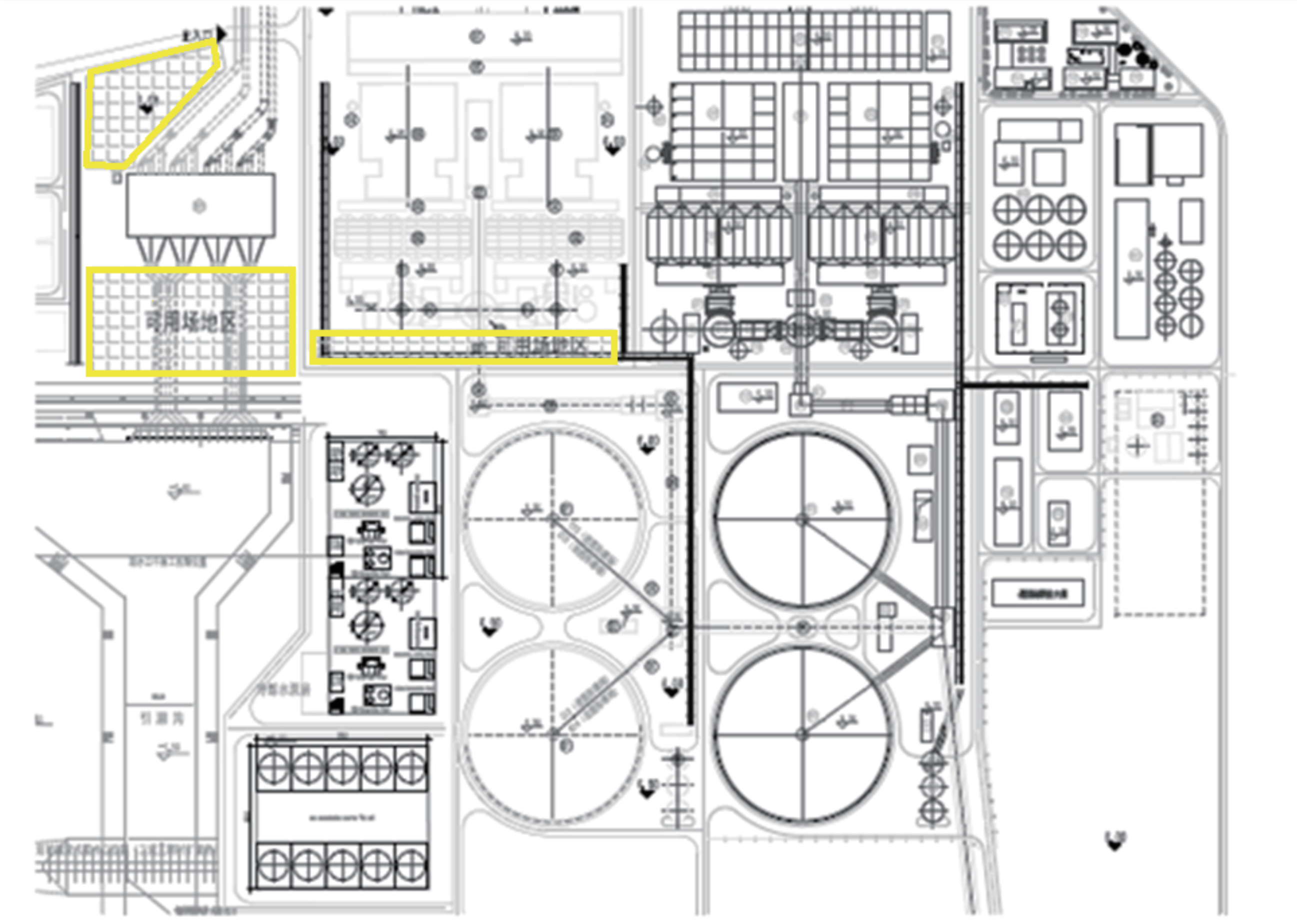


图 4 3 号和 4 号机组碳捕集预留设施分布图（可能进行改造的区域已用黄色标出）

3.3.3 二氧化碳吸收

二氧化碳的含量为 13% 的冷却后的烟道气，通过管道输送到二氧化碳吸收塔，向上流至吸收塔顶部，与质量浓度 30% 的单乙醇胺溶液逆向接触，可移除其中的二氧化碳。3 号机组的吸收区位于烟囱南面的开放空间，面积大约 7000 平方米（长度为 87.5 米，宽度为 80 米）；4 号机组的吸收区位于 3 号机组吸收区南面的开放空间，面积约为 7000 平方米。该 2 x 1 吉瓦机组的每个吸收塔的尺寸将约为直径 22 米。为了降低吸收器的成本，也有可能建造尺寸为 19 米 x19 米的混凝土立方体吸收器。

吸收器尺寸计算

每天捕集的二氧化碳量（M，吨 / 天）如方程式（3-1）中所示。

M = F * E * C (3-1)

其中，F 表示燃料消耗总量（单位：吨 / 天）

E 表示二氧化碳排放系数（单位：吨 / 天）

C 表示捕集效率

因此，

M= F * E * C = 375*1.99*90%*24= 16,119 吨 / 天

对吸收塔直径的估算以方程式（3-2）1 为基础

D= A*sqrt[te/d/%CO2] ， 其中，D（单位：米）表示吸收塔直径，

A=0.62 for 13% CO2， Te/d= 吨 / 每天回收的二氧化碳

%CO2 = 表示冷却前烟道气中的二氧化碳含量

因此，

D = 0.62*sqrt [16119/13]= 21.83 米 (3-2)

3.3.4 气路系统

1） 进气系统：使用胺洗涤剂的碳捕集改造不需要对锅炉的燃烧系统做任何改变，而且预计在这一系统中也不会存在必不可少的捕集预留要求。此外，强制通风和主气流风扇不需要在使用胺洗涤剂的碳捕集改造中进行变动。

2） 烟气脱硫系统：为了使用最小的空间安装新的风道连接锅炉烟气系统和胺洗涤剂装置，将需要引风机排气管道工程的配套设施（来接头、增加烟道调节器、隔离阀）。对此详细描述如下：

华润电力的电厂很有可能符合上述第三种情况，届时将需要进行另一阶段的化学洗涤，但在设备采购阶段，任何潜在的引风机问题都可能会得到解决。

对于没有采用烟气脱硫措施的电厂来说，必须要在合适的场地安装烟气脱硫装置，同时连接风管工程和安装增加鼓风机或改造原有引风机所需的场地。

华润电力海丰电厂 3 号和 4 号机组原有的烟气脱硫设计和施工允许其在未来进行机械性或化学性优化来达到规定的胺洗塔硫氧化物标准，因此未来对烟气系统没有必需的捕集预留要求。

1）胺洗塔硫氧化物标准限制通常对使用烟气脱硫的粉煤电厂没有附加要求。

2）如果原始的烟气脱硫装置的设计和建造允许其在未来进行机械或化学性优化以满足胺洗塔硫氧化物标准，那就不需要对烟气系统进行必要的捕集预留改造。

3）如果原始的烟气脱硫装置的设计和建造不允许其在未来进行机械或化学性优化，那么就需要一个烟气脱硫装置精处理系统来达到规定的胺洗塔硫氧化物标准。引风机可能不适应烟气脱硫装置精处理系统带来附加压力的下降，这时可能需要一个增加鼓风机或对引风机进行改造。因此，增加安装鼓风机或改造引风机所需的空间以及管道接头相关的风管工程和配套设施都要考虑到。

3.3.5 抽取蒸汽

（应提出蒸汽量的预测）

华润电力电厂汽轮机主要参数如表 3 所示。电厂进行的燃烧后捕集系统改造，将从中压 / 低压胺溶剂再生交叉管道抽取多达 50% 的蒸汽用于胺溶剂再生，如图 3 中所示（插图中显示热量沿着红色指示箭头流动）。这一管道应有配套设施，以供应汽轮机建造所需的阀门和管道接头。此外，由于低压区域大流量的减少，其在改造时应满足具体蒸汽的需求，涡轮机生产的电力将会减少。由于中压 / 低压交叉管道中流出的蒸汽供应将会减少，负荷较低时，在涡轮机选择阶段应具体考虑到可用的蒸汽供给以及碳捕集系统的要求，以此满足不同负荷下的蒸汽需求。

中压 / 低压胺溶剂再生交叉管道的蒸汽参数暂定为：0.608 兆帕（a），368 摄氏度 11。一个压力调节阀和喷水式蒸汽冷却器（利用再沸器冷凝水）将被用于将蒸汽压力和温度调节到满足二氧化碳捕集的要求。

华润海丰 3、4 号机组热力循环采用 8 级回热抽汽系统，设有 3 台高压加热器、1 台除氧器、4 台低压加热器和 1 台轴封加热器。

来自中低压缸联通管的蒸汽在二氧化碳捕集装置中进行热交换后变成饱和水，饱和水的低温热量回收到汽水混合循环系统，这样使二氧化碳捕集的热损失减到最小。

为了更好的回收低温热量，预留二氧化碳捕集装置需考虑以下方面的设计：

1）在汽水混合循环系统中要预留加热器的旁路；

2）与脱氨塔进行联合设计（例如：需增加脱氨塔回低压加热器的凝结水管）。

此外，汽机房应预留足够的空间，以保证大型低压蒸汽管道的布置需求，至少应考虑以下方面：

1）在汽轮机、管架，支撑结构安装的过程中，要考虑大型低压蒸汽管道的布置和支撑需求；

2）汽轮机和蒸汽管道疏水系统要能够处理新增管道的额外疏水。

3.3.6 电力供应（应提出对所需电量的预测）

华润电力海丰电厂 3 号和 4 号机组所使用的碳捕集系统将需要大规模扩建其辅助电力系统。扩建项目将要考虑以下因素：

1）为 10 千伏和 380 伏辅助变压器增加并留出场地。

2）为新的电力负荷、馈线和电动机控制中心所需的 10 千伏和 380 伏开关设备增加并留出场地。

3）为新的辅助变压器、配电装置和电力负荷所需的母线、电缆和电缆桥架增加并留出场地。

4）增加一个直流电系统，为新的辅助变压器和开关设备提供控制和保护电力。另外还需为二氧化碳捕集预留控制系统新增一个不间断交流电源系统。

5）为新的辅助变压器和开关设备提供控制、保护和电源开关设备。

根据上述电气内容，华润海丰电厂电气部分可能需考虑主要有：新增的厂用高压变压器，厂用低压变压器，高压、低压开关柜，母线设备，电缆，UPS，直流系统等电气设备所带来的设备及接口，需要为新增电气设备预留土建布置空间所带来的土建建设投资增加。

第三章

3.3.7 冷却水系统（需要预测所需冷却水量）

海丰电厂 3 号和 4 号机组将配备一个直流式海水冷却系统。冷却水取自电厂西边的港池，完成热交换后将被排放到该电厂东北部的海域中。根据季节温度变化是 5 摄氏度到 8 摄氏度之间。进行碳捕集改造后，中压 - 低压汽轮机交叉处低压区高达 50% 的蒸汽将会被吸取出来。因此，随着平衡转移到 CCP 冷却功率，冷凝器中的热消耗将会降低。或者冷凝器的水流保持不变降低冷凝器压力，此时一些水被转移到 CCP，冷凝器的冷却水流量也许因此而减少。因为 CCP 中大量的热消耗是处于高温的，如果可以以稍热的温度排回到大海，可能不需要增加冷却水流量。

华润电力海丰电厂 3 号和 4 号机组将采用 8 个等级的再生抽取系统，还将设置 3 个高压加热器、4 个低压加热器、1 个除氧器和 1 个密封加热器。

碳捕集系统中的热交换完成后，中压 / 低压交叉管道中的蒸汽将转化为饱和水，这些饱和水将被返回到主蒸汽循环。

为了促进上述过程的运转，捕集预留装置需要为低级别废热回收考虑到以下两点：

1）水蒸气循环所需的配套设施，可满足旁路冷凝水换热器需求。

2）与胺洗塔装置进行流程整合所需的配套设施（例如低压加热器区域吸入胺洗塔产生的冷凝水的管道工程）。

另外，蒸汽轮机岛应保留配套设施和场地，让新的大型低压蒸汽管道能在汽轮机和胺洗塔再沸器之间选择路线。在最低限度下也应考虑以下两点：

1）蒸汽轮机房中的配套设施，建造管架和支撑结构来确保布线并支撑起大型蒸汽管道工程。

2）确保蒸汽轮机房中的配套设施和蒸汽管道排水系统能处理新的管道工程的额外排水问题。

3.3.8 废水处理和海水淡化装置（需要说明胺废料的处置方案，因电厂是废水零排放要求）

由于去矿质水的要求在碳捕集改造完成后不会提高，因此在未来也没有必需的捕集预留要求。

燃烧后碳捕集所必需的胺洗塔装置、烟道气冷却器和烟气脱硫精处理装置（如果合适）将会产生额外的废水。这就意味着要为处理胺废料建设厂区外的封存和运输等配套设施，或将需要对其进行处理与回收。因此，废水处理装置区应留出场地在碳捕集改造的过程中安装附加的水处理一体化所需的扩展接口和配套设施。

3.3.9 消防系统

该 CCS 系统建设的过程中将引进一套消防系统。

3.3.10 脱硝装置

煤炭燃烧时产生的氮氧化物主要是一氧化氮，其中还会有最多 5% 的二氧化氮。一氧化氮不会与胺类发生反应，二氧化氮却正好相反。在脱胺塔中对烟道气进行进一步处理所能接受的二氧化氮浓度约为 40 毫克 / 标立方（6 v% 氧气 干烟气）。

华润电力海丰电厂 3 号和 4 号机组碳集预留改造的可行性研究在设计阶段设想采用炉内氮氧化物控制措施（采用低氮氧化物燃烧、两级燃烧系统等）和脱氮效率达 90% 的燃烧后选择性催化还原措施来使其氮氧化物排放量达到中国火力发电厂烟气脱硫污染物排放标准（GB13223-2011），即 100 毫克 / 标立方（6 v% 氧气）。根据发改能源 [2014]2093 号文规定的广东省新建电厂的尘浓度排放要求，新建燃煤电厂经过脱硝装置后，氮氧化物浓度小于 50mg/m3，烟气脱硫进气口的二氧化氮浓度预计将为 35 毫克 / 标立方，这一数值在湿法烟气脱硫的排气口会更低（湿法烟气脱硫可捕集到部分二氧化氮）。对于本项目来说，燃烧后选择性催化还原设备和湿法烟气脱硫应将氮氧化物的浓度降至所需水平。，因此本工程在实施阶段，无需特殊设计即可满足碳捕集预留对入口氮氧化物浓度限值要求。

因此，碳捕集预留没有其他要求。

3.3.11 除尘

一个传统的燃煤电厂要达到环保法规制定的微粒排放限制水平（30 毫克 / 标立方，6 v% 氧气 干烟气），根据其煤炭品质通常适合静电除尘器（ESP）或袋式过滤器。在可研阶段华润电力海丰电厂 3 号和 4 号机组可用的静电除尘器（3 室 -5 电场）有两套，其效率在试验阶段暂定为 99.75%。

根据发改能源 [2014]2093 号文规定的广东省新建电厂的尘浓度排放要求，新建燃煤电厂经过湿式除尘或高效除尘后，尘浓度小于 10mg/m3，因此本工程在实施阶段，无需特殊设计即可满足二氧化碳捕集对入口尘浓度限值要求。

在捕集改造的过程中，要满足胺洗塔烟道气进口的质量要求（5-10 毫克 / 标立方，6 v% 氧气 干烟气），就应考虑到改造除尘器的可行性以及所需的场地。一般情况下，用袋式过滤器代替原有的静电除尘器或增加一个湿式吸尘器能满足上述除尘要求，所以还应考虑改良烟气管道风机和引风机所产生的影响。

3.3.12 烟气脱硫

为了防止胺降解，将要求烟道气中二氧化硫的浓度限制在 10 到 30 毫克 / 标立方（6 v% 氧气 干烟气）。胺洗塔施加的这一要求比目前本工程可研阶段中国环保法规中规定的排放水平（也就是火力发电厂污染物排放标准所规定的 50 毫克 / 标立方，6 v% 氧气 干烟气）要低得多。

本项目采用的是石灰石湿法烟气脱硫。在项目实施阶段，根据发改能源 [2014]2093 号文规定的广东省新建电厂的尘浓度排放要求，新建燃煤电厂经过高效脱硫装置后，二氧化硫的浓度小于 35mg/m3，未来脱硫效率提高后排气口二氧化硫的浓度有望可降低至 30 毫克 / 标立方（6 v% 氧气 干烟气）以下。因此本工程在实施阶段，无需再预留特殊的脱硫装置设计。

为了让这一电厂适应极端的操作环境并为碳捕集与封存提供更清洁的烟道气以节省吸收塔单乙醇胺的消耗量，（并以此减少运营投入），我们考虑在烟道气预处理装置中加入氢氧化钠溶液，以进一步吸收二氧化硫。这也将降低烟道气中二氧化氮的浓度以及粉尘的含量。

3.3.13 化学剂量与封存

由于在碳捕集改造前后对冷凝和供给水化学的要求没有变化，因此未来对化学剂量控制系统也没有捕集预留的要求。随着增加捕集设施后整个流程的一体化，未来需要对热交换器排放口处的冷凝液水质进行监测，因为部分的冷凝液加热工作将由冷凝器上方的胺洗塔来完成。但这在以后也不是一个硬性要求。

3.3.14 控制系统

确保安全、可靠的运行，碳捕集系统将要配备可与电厂控制系统进行沟通的控制系统和携带式仪表。

预计的自动化程度要达到以下几点要求：

1）该系统在一些当地员工的检查和援助下可在控制室完成启动、关闭、监控和控制操作。

2）操作人员可以监督该系统的运行条件，并通过液晶显示屏或键盘控制制动器。确保达到所有的卫生与安全要求。

3）实现调制和程序控制系统的优化设计，减轻操作人员的工作量。在非常规的运行条件下，联锁保护控制系统可以让相应的系统或设备投入或停止运行，以安全地运行或关闭系统。

为达到上述自动化水平，华润海丰电厂的集中控制室为四机一控，位于 1 号机汽机房旁，远离 3、4 号机将来新建的二氧化碳捕集装置。就地设置专用控制室，当后期运行条件熟练后，再与考虑与集控室合并。因此需在二氧化碳捕集装置旁预留控制室和电子设备间的场地。

3.3.15 额外的管道工程

因为在胺洗塔再生器中使用了大量的低压蒸汽，冷凝液需要回到水－蒸汽－冷凝液循环中，再加上碳捕集设备与水－蒸汽－冷凝液循环的一体化都要求改造后安装额外的管道。额外的管道工程大致包括：

- 连接再生塔和低压加热器区域的再生塔冷凝水回水管路。
- 连接脱胺塔回流冷凝器和低压加热器区域的水－蒸汽－冷凝液管路。
- 从大型低压蒸汽管道向再生塔的引流管道。
- 通向烟气冷却器和二氧化碳压缩机中间冷却器的冷却水管道。
- 胺溶液吸收设备回流冷凝器和低压加热器区域之间的汽水凝结循环系统管道。

碳捕集预留电厂应在合适的地方（特别是蒸汽轮机房）留出铺设新管线的场地，以容纳上述的管道工程。

3.3.16 其它的电厂基础设施

对于其它的基础设施来说，需要考虑下列基本要求：

1）在合适区域留出的扩宽道路以及建设新道路的场地（以处理运输车辆增加的问题），

2）扩建办公大楼所需的场地（容纳电厂改造后增加的新职员），

3）还必须留出未来扩建仓库的场地。

3.3.17 压缩空气（需给出预估量）

预留二氧化碳捕集装置的改造工程需要增加压缩空气用量（包括检修用气和仪表用气）。为满足今后压缩空气用量增加的需要，电厂压缩空气系统需要做如下改造要求：

1）为空压机及压缩空气系统工程预留（如空气干燥器、储气罐）的安装空间和位置;

2）对压缩空气的配气支管进行分级，以满足因脱碳需要增加的压缩空气用量需求，同时设备配置需增加；

3）为压缩空气系统的配套设施进行其它改造准备。

3.3.18 控制仪表系统

大多数现代化控制系统的更换周期都是 15 年 12。本电厂如在 15 年后实施改造，目前还不需要额外投入。但是预期的改造时间小于 15 年，应考虑为捕集电厂专门设计一个独立的控制窗口或程序包，还应在控制室为其划出额外的场地或在现场设置一个独立的控制室。

3.3.19 单乙醇胺运输与储存

假定单乙醇胺将会以浓缩的形态储存在现场。若碳捕集所要求的是新鲜溶剂，单乙醇胺的浓度将会被稀释到 30%。我们还未对捕集过程所需的单乙醇胺进行估算，因为随着技术的进步，所需量也会相应减少。计算出的单乙醇胺消耗率为 86 千克 / 小时。

3.3.20 废弃单乙醇胺的处理

废弃的单乙醇胺将被送往一家废弃化学物质处理公司。

3.3.21 员工管理

华润电力将依照电厂安全条例对捕集电厂的员工进行管理。但是，我们也有可能会请一家专业公司来运营捕集设施，届时将由该公司的员工进行操作。无论华润电力采用哪种运营模式，所有的地面员工都将遵照华润电力最初的指导方针来开展工作。

3.3.22 二氧化碳捕集电厂的运营管理

如果改造要在电厂建成 10 年之内进行，建议授权本地区在二氧化碳领域有着丰富经验的专业公司管理碳捕集电厂。如果改造要在 2025 年之后进行，预计电力行业将获得一定的运营 CCS 电厂的信心，届时建议对该电厂实施内部管理。

4. 潜在的投资前选择：基于胺洗技术的燃烧后碳捕集

本章节将从定性的角度讨论电厂以及二氧化碳捕集电厂的投资影响。

4.1 超超临界煤粉锅炉及配套设备

一个具备燃烧后捕集预留的超超临界粉煤锅炉及配套设备的特点与粉煤空气燃烧超超临界锅炉相比，没有明显的不同。锅炉本体（燃烧设备、炉膛、对流传热面）和空气加热器是基本相同的。将超超临界粉煤锅炉建设成利用燃烧后捕集技术的捕集预留设备的基本系统设备要求如下文概述：

燃烧设备、受压部件、空气加热器、锅炉燃烧设备（磨煤机、燃烧器）、所有的受压部件和再生空气预热器都不需要为配备一个胺洗塔的二氧化碳捕集改造作出任何更改，因此，预知没有基本的捕集预留要求。

4.2 烟气预处理

目前的大多数碳捕集技术要求较低水平的硫氧化物、氮氧化物和颗粒。这将要求要么对新系统进行升级，要么采用辅助设备以减少烟气中的杂质含量。对于此次捕集预留设计，我们将在华润电厂未来进行电厂改造时增加辅助设备。然而，有的技术，例如壳牌 Cansolv 公司的技术，在烟道气进入捕集设施之前，不需要额外的洗涤。因此，目前阶段不需要额外的投资。

4.3 原水预处理设备

在原水预处理设备区域应考虑预留场地和资金，以便在需要时增加额外的原水预处理流。

4.4 去矿化 / 海水淡化装置

由于碳捕集改造后对去矿化水的要求将不会提高，因此未来也不会有必需的捕集预留要求。

4.4 蒸汽轮机的选择

二氧化碳捕集系统需要大量的抽汽，这将对汽轮机的安全运行产生巨大影响。从涡轮机工厂提供的初步数据来看，这些蒸汽可从胺溶剂再生中压 / 低压交叉管道中抽取，低压涡轮机入口处应安装节流调节阀以保持气压稳定。这样可达到碳捕集系统的运行要求，但会导致低压区域的效率降低。碳捕集抽汽系统如图 5 所示：

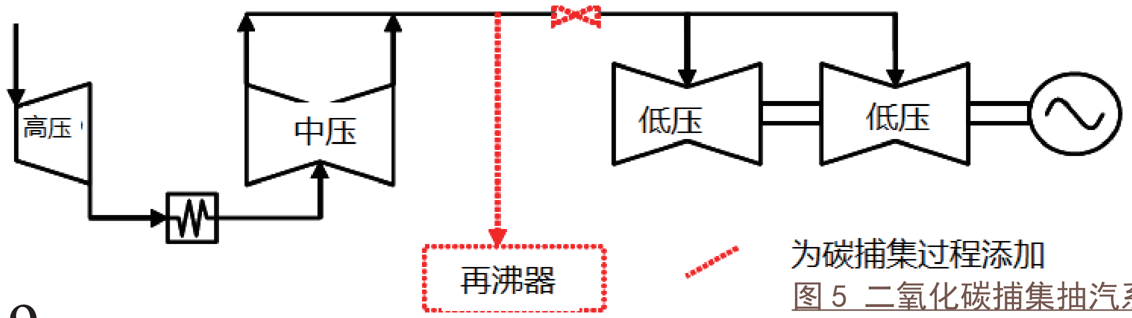


图 5 二氧化碳捕集抽汽系统

每个机组的燃料热输入为 2364.299 兆瓦，该电厂预计产生 1000 兆瓦（THA）总电力和 964.8 兆瓦（THA）净电力。厂用电率为 3.52%。

4.4.1 对捕集预留粉煤电厂性能的影响

表 6 对电厂性能的影响

（传统粉煤电厂 VS 采用碳捕集的粉煤电厂，一个机组）

项	单位	传统粉煤电厂	采用碳捕集的粉煤电厂（提取出将近 50% 的蒸汽）	采用碳捕集的粉煤电厂（提取出将近 40% 的蒸汽）	采用碳捕集的粉煤电厂（提取出将近 30% 的蒸汽）
额定功率	兆瓦	1000	779.6	823.68	867.76
燃料输入	千克 / 秒	111.26	111.26	111.26	111.26
MEA 消耗率	千克 / 小时	0	86	86	86
煤碳热值（低热值）	兆焦 / 千克	21.25	21.25	21.25	21.25
燃料热量输入	兆瓦	2364.299	2364.299	2364.299	2364.299
冷凝器压力	兆帕	0.0057	0.0057	0.0057	0.0057
厂用电率	百分比	3.52	27.92	26.43	25.09
涡轮机耗热率	千焦 / 千瓦时	7416	9512.57	9003.50	8546.14
涡轮机效率	百分比	48.54	37.84	39.98	42.12
锅炉效率	百分比	94	94	94	94
管道效率	百分比	99	99	99	99
电厂总效率	百分比，低热值	45.17	35.22	37.21	39.20
净功率输出	兆瓦	964.8	561.9	605.98	650.06
额定功率	兆瓦	1000	779.6	823.68	867.76
二氧化碳损耗	百分比	100%	10%	10%	10%

4.4.2 设备配置差异：传统电厂对比捕集预留粉煤电厂

下列清单显示了设备的修改。

表 7 设备清单（传统电厂对比捕集预留粉煤电厂）

项	传统粉煤电厂	捕集预留粉煤电厂
超超临界粉煤锅炉和配套设备	基本标准	应为烟气系统预留接口和场地
悬浮微粒清除装置	静电除尘器，效率不低于 99.75%	应将原有的静电除尘器改造为袋式过滤器或增加湿式除尘器
蒸汽涡轮发电机和辅助设备	基本标准	涡轮机改造以及蒸汽管道的增加将提高投资
水－蒸汽－冷凝水循环	基本标准	额外的水－蒸汽－冷凝水和土木系统将提高投资
压缩空气系统	基本标准	增加的压缩机和压缩空气系统将增加投资，其新增中 CO2 压缩系统包括：压缩机、换热器、干燥器、管路及 CO2 泵。
胺洗脱碳装置	无	直接接触冷却器及泵 胺泵 吸收塔 储罐 再沸器 换热器 再生塔 配液装置 过滤器 引风机

4.5 结果总结

对于进行燃烧后捕集改造的粉煤电厂来说，至多 50% 的蒸汽将从胺溶剂再生中压 / 低压交叉管道中抽取。虽然锅炉与汽轮机在燃烧时所需的燃料量一致，涡轮机的热效率将提高，但其功率输出和电厂总效率将会因低压区域流动的减少而降低。同时，碳捕集系统将消耗 18.25 万千瓦的厂用电力，因此厂用电率将增加，进行捕集改造的粉煤电厂的电力供应也将减少。此外，还应考虑为华润电力海丰电厂 3 号和 4 号机组的捕集改造留出额外的场地以及改造装置。

5. 捕获 CO2 的潜在封存地和运输途径

5.1 潜在封存地

经对多个封存地的对比分析，本设计的潜在封存地暂定为惠州 21-1 油气田，详细分析如下：

5.1.1 广东省 CO2 地质封存潜力

本研究对广东省主要的陆域和海域沉积盆地 CO2 地质封存潜力进行了评估，分析了封存地质条件，估算了有效封存容量。“有效封存容量”为卢纶封存容量乘以反映一系列地质和工程因素的有效封存系数 E（对于咸水层）或 Ce（对于油气田）。除了估算了各盆地的有效封存容量之外，还对各盆地的浅水区（<300m）和主要油气田的有效封存容量。得出的主要结论如下：

（1）广东省陆上 CO2 封存潜力很小，且由于人口稠密，不建议实施 CO2 封存工程。

（2）在广东省东南海外的南海北部海域具有巨大的 CO2 地质封存潜力（表 8）。保守估计（概率分布的 P15 分位数），其咸水区的有效封存容量约 205Gt CO2，其中包括油田中的 0.142Gt CO2 和气田中的 1Gt CO2。在水深小于 300m 的浅水区域，保守估计的咸水层有效封存容量为 163Gt CO2，是广东省 2010 年大型点源排放量（252Mt CO2）的 600 倍。因此南海北部浅水区 CO2 封存潜力足够满足广东省 CO2 封存的需求。广东省实现 CO2 封存将以离岸封存为特色。（2）

根据地质地理条件，珠江口盆地珠一凹陷以及东沙隆起北部为最有利的 CO2 地质封存区（图 6）。该区域面积约 400 km2，水深较浅（大部分 <200m），中 - 下中新统地层厚度大，且含有优质储盖组合。保守估计该区域有效封存容量为 77 Gt CO2，是广东省 2010 年大型点源排放量的 300 多倍。这里汇集了珠江口盆地的大多数油气田，有一部分已经枯竭或即将枯竭。

（4）CO2 地质封存潜力绝大部分在咸水层中，是将来规模化 CO2 封存的主要防水。珠江口盆地的油田基本都属于小型油田，由于这些油田的水驱能力充足，一次采收率普遍较高（>40%），因此开展 CO2 驱油提高采取率利用的前景较低。但是，在油田开采枯竭后，油田开发工程设施可再利用于 CO2 注入，将会大大降低海上封存成本，因此是实现 CO2 封存的早期机会。主要的不足是这些油田的封存容量较低，因此必须考虑相邻咸水层储层的联合利用。由于海上油气田开发工程设施再利用于 CO2 注入封存的可行性评估必须在油气田废弃之前完成，因此此项任务显得尤为紧迫。

（5）第二个有利的 CO2 封存区域为北部湾盆地的涠西南凹陷，其面积约为 3000 km2，新生界地层厚度为 9000m 以上，具有良好的储盖层组合，已发现 8 个小型油田，其中 5 个油田正在开发中，1 个已经废弃。涠西南凹陷咸水层的 CO2 有效封存容量为 2~8 Gt CO2，平均 5Gt CO2。该区水深较浅（<30m），距离陆地非常近。因此，该区域将是广东省西部以及广西省 CO2 工业排放源的潜在的封存区。该区域进行 CO2 封存的

（5）不利因素为相对较为强烈的新构造运动，包括火山活动、地震等，但 6 级以上地震主要发生在涠西南凹陷的东部。另外已有钻井的完整性也是确保封存安全性的一个重要因素，需进行详细的评估。

琼东南盆地和莺歌海盆地具有巨大的 CO2 有效封存容量，但它们距离陆上大型点源相对较远。这两个盆地的共同特征是其大型气田中通常含有较高比例的 CO2 含量。如琼东南盆地的崖 13-1 大气田，天然气地质储量为 97.85*109 m3，CO2 含量 ~8%；莺歌海盆地的东方 1-1 大气田，天然气地质储量为 87*109 m3，CO2 含量 55%~71%. 目前，从这些气田采出的 CO2 除了少量用于化肥生产外，大部分直接排放到大气中。这些高含 CO2 的气田在将来可能考虑开展 CO2 捕集与封存。

表 8 南海北部咸水层[1]（Gt CO2）和油气田[2] CO2 有效封存潜力

咸水层 CO_2 有效封存容量（$GtCO_2$） （范围[3] 的计算去有效系数 E=0.01～0.04，均值取 E=0.026 根据 IEAGHG(2009))						
有效封存容量		北部湾盆地	琼东南盆地	莺歌海盆地	珠江口盆地	Total
全盆地	范围	20.2~80.9	12.8~63.3	62.0~247.9	110~443	205~835
	均值	52.6	41.1	161.1	289	544
浅水区 (<300 m)	范围	20.2~80.9	3.5~17.4	62.0~247.9	77~310	163~656
	均值	52.6	11.3	161.1	201	373
油气田 CO_2 有效封存容量（$GtCO_2$） 对于油田，“范围”计算取 Ce=0.12～0.4，“均值”取 Ce=0.25； 而对于气田，“范围”计算取 Ce=0.47～0.9，“均值”取 Ce=0.6；相关解释见本报告 2.3 节						
		BBWB	QDNB	YGHB	PRMB	Total
油田	范围	0.011~0.035	0.070~0.024	-	0.061~0.205	0.142~0.264
	均值	0.022	0.015	-	0.128	0.165
气田	范围	-	0.620~1.190	1.300~2.490	1.093~2.093	3.013~5.773
	均值	-	0.790	1.660	1.395	3.845
油气田	范围					3.149~6.016
	均值					3.997
YA13-1 气田	范围		0.055~0.104			
	均值		0.070			
DF1-1 气田	范围			0.087~0.166		
	均值			0.111		

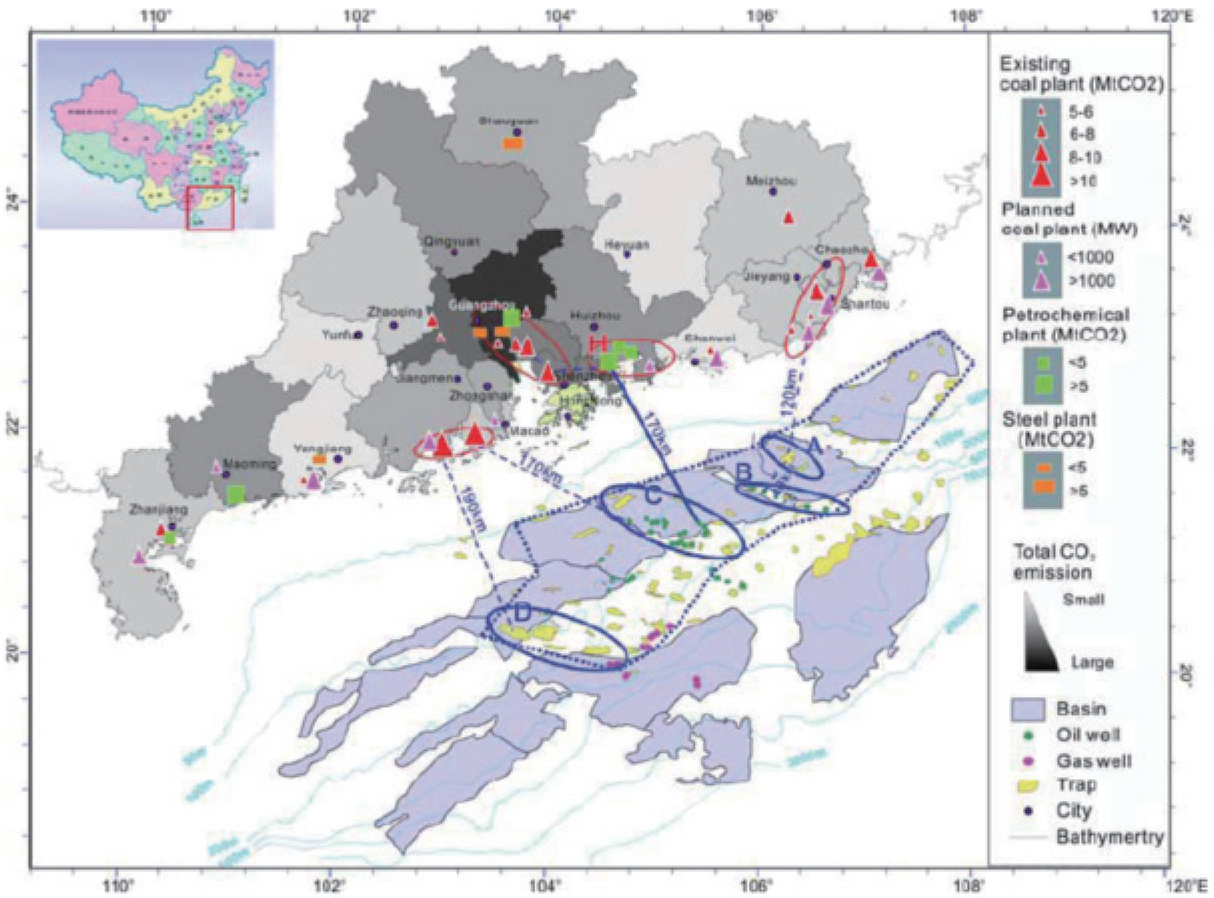
1] 有效封存容量为理论（最大）封存容量乘以有效封存系数 E 或 Ce，反映一系列的地质和工程方面的限制因素。
2] 包含未开采的油气田。
3] 本表中“范围”指概率为 P15~P85 的分位数；“均值”指概率为 P50 的分位数。

5.1.2 源－汇匹配和早期机会

广东省的大多数大型 CO2 工业排放点源都分布在东部沿海，尤其集中于珠三角地区（图 6）。这些大型点源与离岸的珠江口盆地潜在封存场地形成良好的匹配关系。

广东省的源汇匹配方案有很多，本次研究提出源中枢与汇中枢相匹配的方案，中枢间的直线距离为 120km 到 200km 之内（图 6）。沿海岸线设立的配备处理设备的源中枢，而汇中枢则利用废弃油气田的已有工程设施或在大型空构造之上建立。需要对输气管线进行区域性规划，以实现排放点源与源中枢、源中枢与汇中枢、以及汇中枢与封存场地之间的高校和经济的 CO2 输送。

本研究提出了惠州项目作为广东省全流程 CCUS 示范项目的早期机会。惠州项目包括从计划待建的炼化厂的高纯度 CO2 开展低成本捕获，以及利用珠江口枯竭油气田已有工程设施开展低成本地质封存，源－汇间直线距离约为 170km，如图 6 中蓝色实线所示。计划待建的炼化厂位于惠州市沿海，建成后每年将从制氢装置排放 2.6 Mt 高纯度 CO2。近枯竭油田为一穹隆构造，储层为下中新统海相砂岩，埋深 2820m~3000m。初步的注入模拟研究表明，虽然该油田的 CO2 封存容量非常小，但可利用其周围邻近的咸水层进行封存，可以满足以 1Mt CO2/ 年的速率注入 20 年的需要。当前的紧迫任务是展开惠州项目的技术和经济可行性评估，在油田枯竭之前查明油田设施利用于 CO2 注入的可行性。



图广东省 CO2 源汇匹配方案

灰色区域为广东省市级行政区划的 CO2 排放相对强度；红色和蓝色圈为排放源点群和封存汇点群；蓝色线为源汇的联络线，标注了实际距离；插图为中国大陆行政区划图，显示研究区位置。

5.2 运输途径

5.2.1 运输方式

二氧化碳从捕集地点到封存地点之间的运输是二氧化碳捕集与封存（CCS）链条中的一个必要环节。管道和船舶运输是目前主要的海上运输系统，都有着成熟的技术和可以借鉴的经验。根据运输量、运输距离、地理条件、灵活性需求、投资决策的时间等的不同，这些运输方式有着不同的优势。

当需要比较灵活的二氧化碳的封存地点和持续时间时，船舶运输也许是一种更好的运输方式。跟管道运输相比，船舶运输所需的首次投资额较少；如果是长途运输，它可能比管道运输更经济。

5.2.2 运输成本

欧盟执委会零排放平台的研究表明：

1）管道运输的成本主要由资本成本组成（通常 >90%），大致与距离成正比，因此显著受益于规模经营和全产能利用。

2）航运的成本较少取决于运输距离及规模。航运的资本成本所占例（通常 <50%）要低于管道运输，然而运营成本却比管道运输高得多。此外，船舶还有运输其他气体的剩余价值，因而有可能降低金融风险。

3）将管道和船舶相结合起来的海上运输网络可以提供既具有成本效益又低风险的解决方案，特别适用于集群的早期发展。

对于本设计而言，二氧化碳气体源位于海丰小漠镇，而潜在的二氧化碳封存地点在惠州 21-1 油气田，直线距离低于 100km。

管道运输　据中科院岩土所魏宁等研究指出，100km 的管道，设定输量范围在 3Mt/a ～ 20Mt/a 的情景下，总建设投资范围是 7.8 亿～ 13.9 亿 RMB，平准化成本为 0.10 ～ 0.41 RMB.t-1.km-1。假定海丰电厂 3、4 号机组同时脱碳，假定年工作 250 小时，输量在 9Mt/a 左右，显然运输量在设定范围。

船舶运输　按 1000MW 燃煤机组捕集的二氧化碳总量为 743.9 吨 / 小时计算，假设租用船为 35000m3 LPG 船， 每天则需要 24 船，市场租价为 100 万美金每月，折算成本为 0.12RMB.t-1.km-1。考虑运输调配，价格可进一步降低。

相较而言，船舶运输更为经济。

第六章

6. CCS 资本和运营成本估算

6.1 初投资

据估计，华润电力海丰电厂 3 号和 4 号机组的进行 CCS 改造将增加 27% 的资本成本，其中包括 CCS 装置和改变现有系统所需的成本。

表 9 预计华润电力海丰电厂 3 号和 4 号机组的进行 CCS 改造对其资本成本的影响

项目	单位	传统粉煤电厂	捕集粉煤电厂（抽取将近 50% 的蒸汽）
静态资本成本	元	基本标准	+27%
单位成本	元 / 千瓦	3689	4658

6.2 运营成本

根据工程师的输入及相关研究，华润电力海丰电厂 3 号和 4 号机组碳捕集的运营成本约为 275 元 / 吨二氧化碳，其中包括人力资源、管理和维护成本，厂房电力和化学品消耗以及水处理费用等。

6.3 机会成本

CCS 设施的机会成本是指电力销售收入损失，这来自 CCS 设施的蒸汽消耗。假定低压区域的蒸汽消耗是 50%，那么华润电力海丰电厂 3 号和 4 号机组的电力输出将从 2000 兆瓦下滑至 1559.2 兆瓦。虽然工作时间的增加可抵消部分损失，但每年的电力销售损失仍将达到 8.9487 亿元。因此，碳捕集的机会成本预计将为 95.67 元 / 吨二氧化碳。

6.4 总结

1）由于首个商业规模的 CCS 燃烧后捕集燃煤电厂将在 2014 年 10 月才开始运营，世界上还没有任何将 CCS 技术应用到 1000 兆瓦机组上的实践经验，因此，本研究是理论上的。本研究旨在为大规模燃煤电厂建设成为捕集预留电厂提供一种简单的解决方案。

2）从我们的研究可得出，使用胺溶剂作为吸收剂的燃烧后 CCS 技术最有可能用于华润海丰电厂 3 号和 4 号机组，然而，这项技术存在一些问题，例如能耗较高以及所需投资较大。未来需对低能耗的新型吸收剂做更多的调查，以开发出更先进的胺吸收方法以及替代性技术。我们的目的是让 CCS 技术更有效且环保，同时还

能节省能源、投资和占地面积。

3）实现电厂碳捕集预留可以较低的成本降低新建电厂的碳锁定效应，并实现向 CCS 可行的平稳过渡。在未来 10 年内，这是一种不存在风险的低成本政策选择。广东省应积极实行捕集预留技术研究、开发捕集预留示范项目，并为大型新建电厂进行捕集预留起草相关政策。

4）电力行业作为主要的二氧化碳排放源，是未来实施 CCS 技术的关键领域。因此，广东省应重视 CCS 技术的研发并尽快建立及设计一个燃烧后 CCS 示范项目，以积累在广东省热电厂应用 CCS 技术的经验并推动中国温室气体减排技术的进步。

附录 1 CCS 预留的定义

应格伦伊格尔斯八国峰会 13 的要求，国际能源署温室气体计划（IEA GHG）14 发布了定义以下 CCR 电厂要素的研究：

1. 二氧化碳捕集预留电厂，是当必需的监管或经济驱动力出现时，可以包含二氧化碳捕集的电厂。建设捕集电厂的目的是减少闲置资产和碳锁定的风险。

2. 捕集预留电厂的开发商应当对确保已经确定和消除的所有妨碍二氧化碳捕集安装和运行的已知因素在其控制下负责。这可能包括：

3. 二氧化碳捕集改造和潜在预投资的选择研究

4. 包括足够的空间和获得额外的设施

5. 确定合理的二氧化碳封存路线

6. 涉及审批电厂的主管当局应当具备能够判断开发商是否满足这些标准的足够信息。

自从 IEA GHG 的定义被采用以来，许多研究已经进行了碳捕集预留 15 工程要求、其经济和政治可行性 16 的研究。2010 年，在 IEA GHG 的碳捕集预留定义基础上，一次国际能源署 / 碳封存领导人论坛 / 全球碳捕集与封存研究院的联合会议和其后的工作小组准备了一个国际上一致认同的碳捕集与封存预留定义，最初的总结如下：

“碳捕集与封存预留设施，是当必需的监管和经济驱动力出现时，能够并打算进行 CCS 技术改造的大规模工业或电力二氧化碳来源。将新的设施建设成碳捕集与封存预留或将现有的设施改造成碳捕集与封存预留的目的，是减少未来碳锁定或无法完全使用没有配备 CCS 的设施（闲置资产）的风险。虽然 CCSR 不是一直二氧化碳减排选择，但是是一种在未来帮助二氧化碳减排的方法。CCSR 不适用于那些必需的驱动力已经出现或曾经出现的司法管辖区。”

1.Introduction

1.1 Background for the Study

Guangdong is one of five pilot low-carbon provinces and the largest emission trading market in China. Carbon capture, utilisation and storage (CCUS) is the only viable large-scale technology to decarbonise fossil fuel power plants. The technology is particularly important for China where more than 80% of electricity is generated through coal-fired power plants.

New power plants in China are not being built with CCS. But design features that, for moderate additional investment, could facilitate the subsequent installation of capture equipment can help to minimise the risk of a carbon emission lock-in from these plants. One example of an approach to achieve this is the guidance notes released by the UK Department for Energy and Climate Change (DECC)[1] in support of a 2009 UK policy that all new combustion plants with a capacity of 300MWe and above need to be built with a CO2 Capture Ready (CCR design). See also the International Energy Agency Greenhouse Gas Programme (IEA GHG) definition in Appendix 1. Despite the UK regulations on CCSR, Australia, Canada, EU and Japan have its own regulation on CCSR[2]. China is also undergoing a study funded by the ADB on its CCSR regulation.

be proposed, but the level of confidence with which actual T&S details, at some distance in the future, can be specified is less than for the construction scope for the capture plant and other equipment lying within the power plant's direct control.

In many cases, however, the existence of multiple potential pipeline routes and storage sites reduces the risk of none being available for a particular site. And at a national level, a CCR power plant fleet (and other large capture ready industry emitters) would provide options for optimising the introduction of a T&S infrastructure that, at an aggregate level, would be valuable even when only a sub-set of sites sources were connected for CCS.

This study follows on from a major MoU[3]signed between institutions in UK and Guangdong to collaborate on CCS technologies, in December 2013. The China Resources Power (Haifeng) company subsequently appointed the University of Edinburgh and Guangdong Electric Power Design Institute to develop a first-of-a-kind CCR design for its proposed Haifeng Units 3 and 4 and

[1] Carbon Capture Readiness (CCR): a guidance note for Section 36 Electricity Act 1989 consent applications. available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/43609/Carbon_capture_readiness_-_guidance.pdf

[2]CCS Ready policy and regulations - the state of play. GCCSI.

[3] The MoU was signed on 27 Sep 2013 witnessed by the governor of Guangdong province Mr Zhu Xiaodan and the Minister of State of Climate Change in the UK Mr Gregory Barker.

the South China Sea Institute of Oceanology, with assistance from CNOOC, propose a likely future pipeline connection to (offshore) storage and also to indicate the scope for alternative T&S arrangements should the former prove to be infeasible. The project received co-funding support from the British Consulate General to Guangzhou, Howden, Shell, through the Strategic Programme Fund.

The study therefore takes a pragmatic approach. Decisions to facilitate capture retrofit are planned to be made at the only opportunity, when the plant is being designed and built. The best available knowledge is being used for the complementary T&S assessment, but it is recognised that further work, including a detailed pipeline route survey and a full storage site assessment, would be required to define the full details of a CCUS retrofit project.

This report covers the following key areas:

- A review of current state-of-the-art and future potentially disruptive technologies for capturing CO2 from large combustion plants, and a description of a potential current-technology CCR approach at the China Resources Power (Haifeng) project.
- Assessment of the technical feasibility of retrofitting the indicative capture method to the proposed project.

The identification of possible pipeline routes to storage locations in the South China Sea with sufficient capacity to store CO2 is also underway, led by SCSIO, and will be in a future report.

1.2 China Resources Power (Haifeng Project)

China Resources Power is planning to develop an 8 x 1000MW ultra-supercritical coal-fired power project (USCPC) on the China Resources Power Haifeng project site near Xiaomo Town, Haifeng, Shanwei in Guangdong, China. Units 1 and 2 are in construction and are expected to be put into operation in Dec 2014 and Jan 2015 respectively. China Resources Power is seeking to expand the existing project and develop two new coal-fired power units at the site. The proposed new units (3 and 4) are expected to be deliver around 1000 MW electricity output each and will be known as the China Resources Power Haifeng Expansion Project.

The project lies on the northwest side of Red Bay Coastal Zone, in the coastal monadnock land and tidal shallow zone. The onshore monadnock is characterised by undulating terrain, scattered with low hills and interdune depressions with an elevation of is 211.0m.

Shanwei City, where Haifeng project is based, is located just south of the Tropic of Cancer, and has a subtropical mild monsoon climate with abundant rainfall and adequate light and heat. Table 1.1 below shows meteorological statistics from the site weather stations.

Table 1.1 Yearly and monthly characteristics value of various meteorological elements of the statistics for the Shanwei meteorological station (1953-2003)

Item \ Month	1	2	3	4	5	6	7	8	9	10	11	12	Whole year
Average temperature (˚C)	14.7	15.2	18.0	21.7	25.1	27.1	28.2	28.0	27.2	24.4	20.6	16.6	22.2
Average barometric pressure (hPa)	1019.5	1018.3	1015.7	1012.6	1008.8	1005.8	1004.9	1004.5	1008.1	1013.4	1017.0	1019.5	1012.3
The average relative humidity (%)	72	77	81	83	85	86	84	84	79	73	70	69	79
Min. relative humidity (%)	3	6	12	21	12	27	37	38	20	19	13	7	3
The average rainfall (mm)	27.1	53.4	75.9	153.6	275.7	368.1	314.3	322.7	212.9	66.3	35.7	25.3	1930.9
The average wind velocity (m/s)	3.0	3.1	3.0	2.9	3.0	3.3	3.2	3.0	3.1	3.3	3.0	2.9	3.1

2. Potential CO2 Capture Technologies

2.1 Introduction to CO2 Capture Technology Pathways

There are three major processes to capture CO2 from fossil fuel power plants, as shown in Figure 2.1:

1.Post-combustion: CO2 is separated from the flue gas using selective solvents.

2. Pre-combustion: the fuel (i.e. coal or gas) is converted into a mix of CO2 and hydrogen through gasification and a shift reaction and then hydrogen is burned to generate electricity.

3. Oxyfuel (also called ‘O2/CO2 cycle’): the fuel (i.e. coal or gas) is burnt with a mix of oxygen and CO2 instead of air, which produces a higher CO2 concentration (without nitrogen) in the flue gas stream, thus making CO2 separation easier. Thereafter, CO2 is removed from the flue gas stream while some separated CO2 is recycled and mixed with oxygen.

Post-combustion capture is considered as the best retrofit option for pulverised coal-fired power plants[4]. Both pre-combustion and oxyfuel technologies would require substantial modifications of the power plant process and demand significant pre-investment for a CCR design..

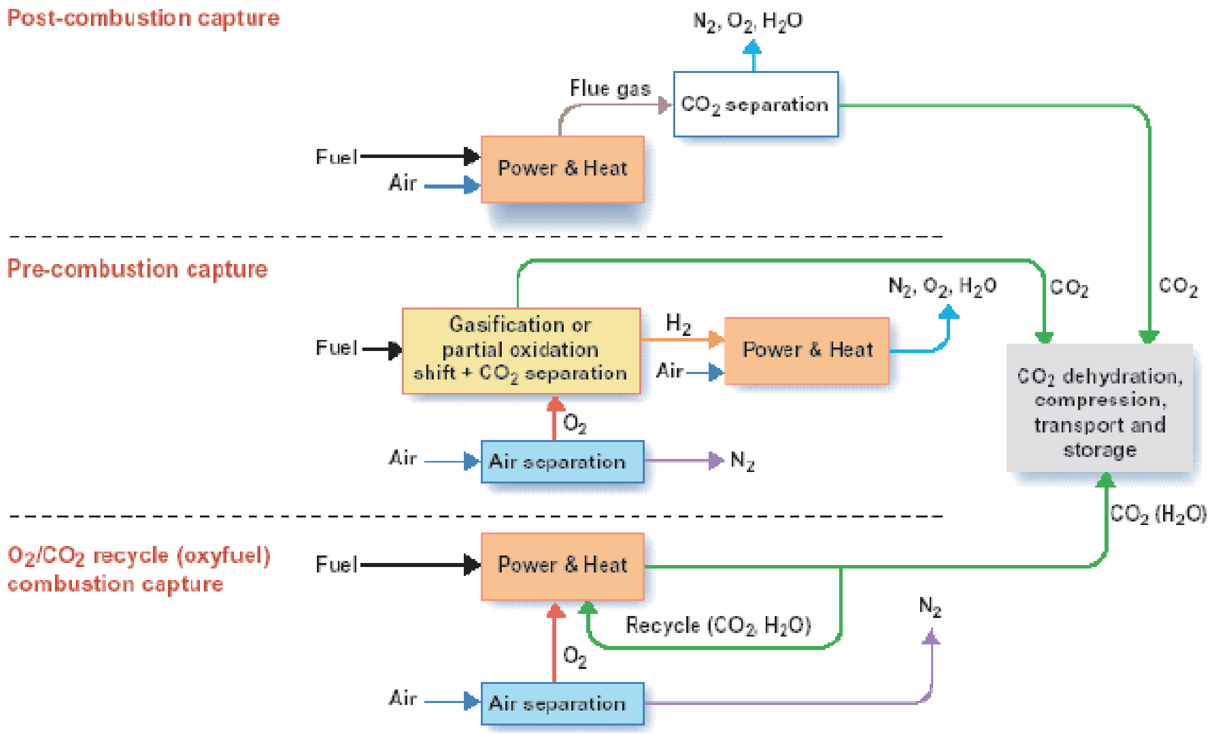


Figure 2.1 Three main options for CO2 capture from power plant[5]

[1]*Li, J. & Liang, X.CO2 Capture Modelling for Pulversied Coal-fired Power Plants: a case study of an existing 1GW ultra-supercritical power plant in Shandong, China., Separation and Purification Technology (2012). 94, p. 138-145*

[2]*VGB Power Tech, 2004. CO2 Capture and Storage: VGB Report on the State of the Art. http://www.vgb.org/vgbmultimedia/Fachgremien/Umweltschutz/VGB+Capture+and+Storage.pdf*

2.2 Current Commercial Post-combustion CO2 Capture Technologies

Current commercial post-combustion CO2 capture systems almost exclusively use aqueous amine solvents in a thermal swing process. Some are monoethanolamine (MEA)-based, but new formulations of amines and alternative types of solvents are also being developed for improved performance. Figure 2.2 illustrates a typical solvent thermal swing process. The CO2 lean solvent absorbs CO2 in the absorber and is then sent to a stripper column (desorber). There CO2 rich solvent is heated with low-pressure steam (typically at 120°C for MEA) to release the CO2, which is cooled, compressed and dried. The CO2 lean solution is then also cooled and recycled to the absorber.

The current state-of-the-art post-combustion amine technologies require oxides of sulphur and nitrogen and dust in the flue gases to be reduced to very low levels (typically order 10-30 mg/m3, but optimum values depend on the cost of the solvent and specific properties) to avoid contaminating and degrading the solvent. A CCR design therefore requires space to be reserved for installing additional flue gas desulphurisation (FGD), selected catalytic reduction (SCR) and dust removal units.

Following recommended practice a conceptual retrofit study has been undertaken as part of the CCR design assessment. This was assumed to involve 90% CO2 capture from Units 3 and 4 using 30% w/w MEA solvent. It is highly unlikely that this solvent will be used in the future, since it is already being superseded, but property data for MEA is readily available and it is likely to give a ‘safe’ design margin if improved solvents are used in the future.

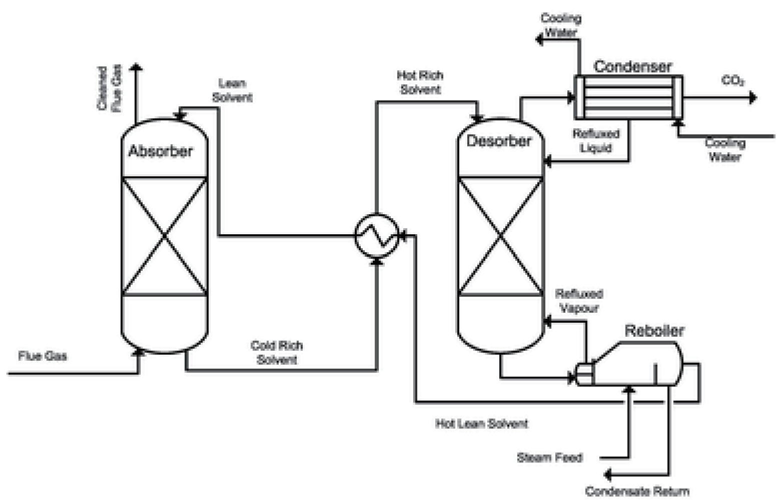


Figure 2.2 Schematic diagram of a basic thermal swing absorption process for solvent CO2 capture[6]

[6]*Herzog, H., Meldon, J., Hatton, A., 2009. Advanced Post-combustion CO2 Capture. https://mitei.mit.edu/system/files/herzog-meldon-hatton.pdf*

2.3 Novel Post-combustion CO2 Capture Technologies

Solids or membrane capture are alternative post-combustion capture technologies that might prove advantageous for capture in the longer term and therefore be retrofitted to a CCR plant in a longer term. One option being developed for solids capture is 'wetting layer absorption' (WLA) – see Boxes below.

From Martin Sweatman, Reader, University of Edinburgh, UK

In 'wetting layer absorption' (WLA) a porous material is used to support liquid-like regions of absorbing solvent, which in turn absorb the gas of interest, in this case carbon dioxide. So this process is based on a kind of 'impregnated sorbent'. However, one of the key and novel aspects of this work is that the absorbing solvent can have any partial pressure below its saturation pressure. Here the focus is on a process involving chemical solvents, namely kinds of amine. The main objective, at the moment, is to demonstrate the technical feasibility of the WLA process based on chemical solvents in the context of carbon capture.

From Bocciardo, D.; Ferrari, M. C.; and Brandani, S. Modelling and Multi-Stage Design of Membrane Processes Applied to Carbon Capture in Coal-Fired Power Plants. Energy Procedia. Vol. 37, pp 932 - 940. 2013. DOI: 10.1016/j.egypro.2013.05.188

Membrane gas separations are already applied for processes like natural gas sweetening and production of oxygen-enriched air and they have the potential of playing a competitive role in second generation carbon capture technologies. Thanks to strengths such as absence of regeneration apparatus, modularity and small footprint, they may represent an alternative to other carbon capture solutions for coal-fired power plants. Zhao et al. [5] propose a study of the possible dual-stage configurations including a detailed economic and energetic analysis based on countercurrent stages, starting from the flue gas of a coal-fired power plant. An optimal membrane CO2/N2 selectivity (in the range 50 ÷ 100) is identified and a capture cost of 31 €/tCO2 is estimated.
A similar approach can be found in the work of Hussain and Hägg [6]: a dual-stage countercurrent investigation based on facilitated transport membranes is presented, including an economic evaluation of the capture costs. Considering a value for the Gas Processing Cost (GPC) of 1.5 $/MSCF typical for amines, a cost of 0.85 $/MSCF is estimated for membranes.

Merkel et al. [7] propose a hybrid solution including a refrigeration stage integrated into the compression of the CO2 up to 150 bars. The material suggested for the membrane modules is PolarisTM and simulations are run integrating countercurrent and cross-flow stages. A new configuration involving the recycle of part of the CO2 to the boiler is investigated: the identified capture costs are 23 $/tCO2. The possibility of recycling the CO2 to the boiler is also investigated by RTI [8, 9] focusing on the Generon polycarbonate high flux membrane: a capture cost of 30 $/tCO2 is reported.

5. Zhao, L., et al., Multi-stage gas separation membrane processes used in post-combustion capture: Energetic and economic analyses. Journal of Membrane Science, 2010. 359(1-2): p. 160-172.
6. Hussain, A. and M.-B. Hägg, A feasibility study of CO2 capture from flue gas by a facilitated transport membrane. Journal of Membrane Science, 2010. 359(1-2): p. 140-148.
7. Merkel, T.C., et al., Power plant post-combustion carbon dioxide capture: An opportunity for membranes. Journal of Membrane Science, 2010. 359(1-2): p. 126-139.
8.. Ramasubramanian, K. and W.S.W. Ho, Recent developments on membranes for post-combustion carbon capture. Current Opinion in Chemical Engineering, 2011. 1(1): p. 47-54.

3. Carbon Capture Ready Conceptual Retrofit Study for CRP (Haifeng) Units 3 and 4

3.1 Introduction

This section describes how an MEA-based the CO2 capture plant (CCP) could be retrofitted to the proposed China Resources Power (Haifeng) project Units 3 and 4 after the FGD plant. The current power plant parameters are shown in Table 2-4.

Units 3 and 4 boilers are ultra-supercritical, variable pressure operating once through, single reheat, tangential or opposed wall firing, flue gas damper control reheat steam, balanced draft, dry bottom, completely steel structure, and hanging construction, Π type , outdoor arrangement. A plasma ignition system is used.

Units 3 and 4 adopt a direct firing, medium speed mill, positive pressure cold primary air, pulverized coal system. There are 6 sets of mills, and 2 sets of adjustable moving blade axial flow primary air (PA) fans, 2 sets of adjustable moving blade axial flow forced draught (FD) fans and 2 sets of adjustable fixed blade axial flow induced draft (ID) fans (steam turbine driven) are mounted for each boiler. The FGD resistance is overcome by an ID fan, with no extra booster fan.

Other parameters relevant to the retrofit analysis for CRP Haifeng Units 3 and 4 are as follows.

Design Fuel: Ordos bituminous coal, LHV=21250 kJ/kg

Fuel heat input of each unit: 2364.3MW

Particulate removal unit: 2 sets ESP (three chambers five electric fields) are provided for each unit , collection efficiency η≥99.75

SCR system: Selective Catalytic Reduction, efficiency is about 80%

FGD system: Limestone-Gypsum Wet FGD, efficiency is about 94%

The features of a USC PF boiler and auxiliaries for post-combustion CCR are not noticeably different from a conventional air-fired USC PF boiler. The essential system and equipment requirements for the construction of USC PF boilers as CCR plants to utilize post-combustion capture technology are outlined below:

1)None of the combustion equipment, pressure parts, air heater, boiler combustion equipment (mills, burners), all pressure parts and the regenerative air pre-heater requires any modifications for CO2 capture retrofit with an amine scrubber and hence no essential capture-ready requirements are foreseen.

Table 3-1 The boiler major parameters (BMCR)

Item	Unit	Value
Maximum continuous flow	t/h	3060
The outlet pressure of superheater	MPa(a)	28.25
The outlet temperature of superheater	˚C	605
The reheat steam flow	t/h	2566
The inlet pressure of reheater	MPa(a)	6.15
The inlet temperature of reheater	˚C	369.7
The outlet pressure of reheater	MPa(a)	5.96
The outlet temperature of reheater	˚C	603
Boiler NOx emission concentration	mg/Nm3	300
The minimum stable load without auxiliary fuel support		30% BMCR
Boiler guaranteed efficiency (tentative)	%	94

The condensing type turbine design for CRP Haifeng Units 3 and 4 is characterized by four cylinders and four exhausts, single shaft, and single reheat.
Rated power: 1000MW
Rotating speed: 3000 r/min
Regenerative system: three HP heaters, four LP heaters and one deaerator
Guaranteed heat rate: 7416 kJ/kW.h(tentative)
The tentative major turbine parameters are shown in Table 3-2:

Table 3-2 The turbine major parameters (TMCR)

Item	Unit	Value
HP steam flow rate	t/h	2915
The inlet/outlet temperature of HP	˚C	600/364.4
The inlet/outlet pressure for HP	MPa(a)	27/6.056
IP steam flow rate	t/h	2442
The inlet/outlet temperature of IP	˚C	600/ 368
The inlet/outlet pressure for IP	MPa(a)	5.566/ 0.608
LP steam flow rate	t/h	1610
The outlet temperature of LP	˚C	65
The outlet pressure for LP	kPa(a)	5.5

The properties of the coal for the CRP Haifeng plant are shown in Table 3-3.

Table 3-3 Coal properties for the CRP Haifeng plant

Item	Symbols	Unit	Design coal	Verification coal
Carbon as arrived	Car	%	60.13	58.6
Hydrogen as arrived	Har	%	2.85	3.36
Oxygen as arrived	Oar	%	9.08	7.28
Nitrogen as arrived	Nar	%	0.69	0.75
Sulphur as arrived	Sar	%	0.69	0.63
Moisture as arrived	Mar	%	14.9	9.61
Moisture as dried	Mad	%	8.60	2.85
Ash as arrived	Aar	%	11.66	19.77
Volatile matter, dry ash free	Vdaf	%	30.9	32.31
Lower heating value as received	Qnet,ar	MJ/kg	21.25	22.44
Coal consumption		t/h	375	356

3.2 Plant configuration option

For optimum performance the USCPC plant would be able to be fully integrated with the CCP, supplying its auxiliary heat and power requirements, and this approach has been investigated in this study.

The design principles for the conceptual retrofit of the CRP Haifeng Power Station Units 3 and 4 with CCR designs are as follows:

1)CO2 capture plants (CCP)

Each unit will be associated with a train of capture units; therefore, two trains of post-combustion capture units are planned at this stage. Each capture unit is described in this report.

For a single boiler/turbine unit with the capacity of 1000MW, the BMCR flue gas volume is 3252839Nm3 / h (dry). CO2 concentration is 13.3% with 826.6t/h of CO2 entering the capture system. The designed capture rate is designed at 90%, and the total amount of CO2captured will be 743.9t/h for the design coal.

Unit: t/h	Design Coal	Verification coal
CO2 from combustion	823.3	758.6
CO2 from FGD	3.3	2.86
Total CO2 entering capture system	826.6	761.5
Captured CO2 (90% capture rate)	743.9	685.3

2)Solvent selection

As noted, MEA has been assumed as the solvent. But the concept for a post-combustion capture ready design allows the possibility to either, a) upgrade to a better performing solvent at a later stage, or b) switch to a solid adsorbent or membrane unit if the technology were to become available. Selecting MEA for the base case scenario probably reserves the maximum possible space and heat requirement for the future capture plant.

3)The flue gas bypass system will be designed for power plant flexibility operating in future electricity markets.

4) The CCS system is designed to be utilised 6500h[7] annually, which is the same as the designed utilization hours for Units 3 and Unit 4.

[7]*Average operating hour is around 6000 hours per year.*

3.3 Plant Modification and Site Requirements

The following discussion (within section 3.3) is based on the retrofitting option outlined above. Following a conservative approach, the retrofit estimates will be based on a CCP applying current state-of-the-art MEA technology. The CCR design considers capturing CO2 from Units 3 and 4. The extra site and space requirements will be reserved and kept available until more cost effective CO2 capture technologies with less space requirements are commercialised or the regulator (e.g. Guangdong Development and Reform Commission, GDDRC) advises that less space is required for CO2 capture retrofit.

3.3.1 The proposed capture process in the retrofitted CO2 capture ready plant

1) CO2 capture system

After the FGD units the clean gas of Units 3 and 4 will enter the CO2 capture plant. The clean gas pressure is then boosted by a booster fan, in order to overcome the pressure losses within the plant. This fan is shown at the inlet to the CCP but following detailed design it could be located at other points in the plant.

After entering the pre-scrubber for cooling and cleaning pre-treatment, the flue gas is further scrubbed and cooled by the cooler, then flows up the absorber with a counter-current flow of MEA solvent down. The absorber is equipped with structured packing to enhance mass transfer to the MEA solvent with minimum pressure drop. At the top of the absorber there is wash and demister section to minimise solvent carryover before the clean flue gas is emitted from the stack. The amine solution, rich in CO2, is transferred to the stripper column, in which the solution is heated with low pressure steam to release the CO2 from the solution. The stripped amine solution is then recycled back to the absorber[8].

At the top of the stripper, the vapour stream, comprising a mixture of steam and CO2, is cooled to condense the water vapour and to leave the CO2 available for compression and for subsequent sequestration by the pipeline transportation.

The solvent in the desorber is collected in the sump. A portion of the solvent is pumped into the reboiler to generate steam for the removal of CO2. The solvent and steam mixture is then returned to the desorber.

In order to regenerate the solvent, the CCS system has a recovery system. By adding NaOH and heating the solvents, stable salts will be removed and the solvent will be regenerated for reuse.

From the sump of the desorber, most of the lean solution is pumped back to the absorber. Before entering the absorber, the solvent is cooled in the cross flow heat exchanger and the MEA cooler. In order to clean the solvent, mechanical filters and activated carbon filters are provided after the MEA cooler[9].

This system will capture approximately 90% of CO2 for Units 3 and 4. For a detailed CO2 capture system flow chart, see Figure 3-1.

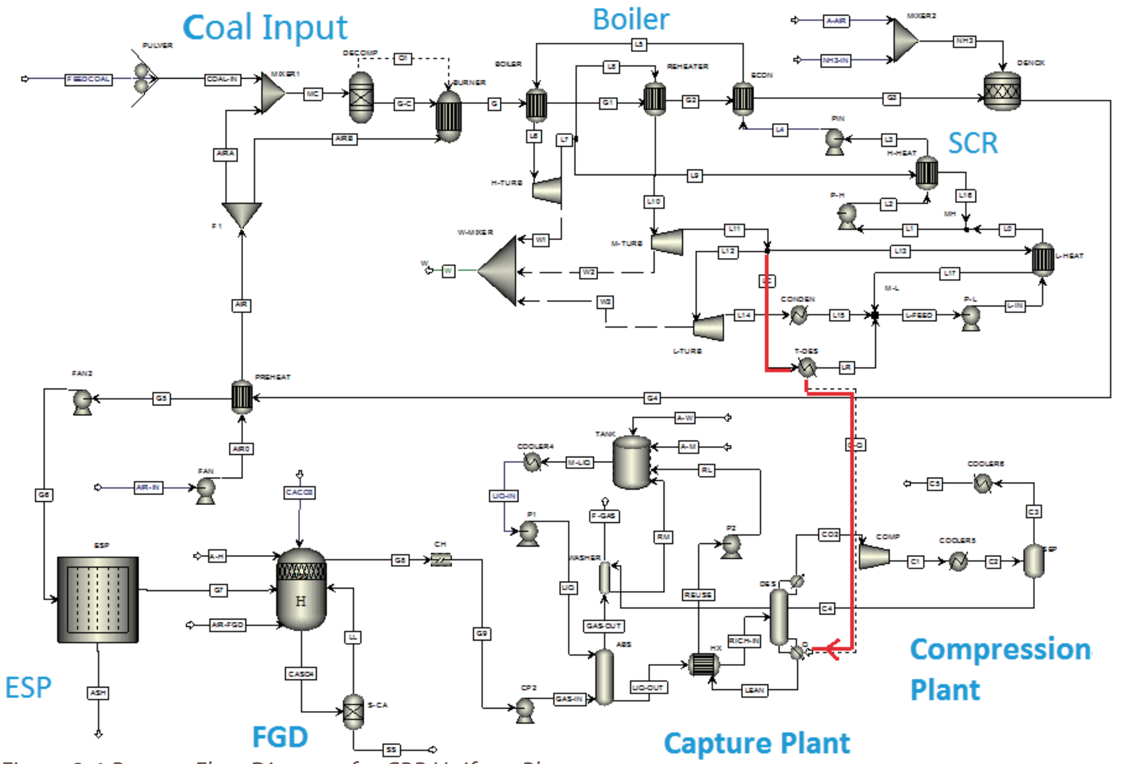


Figure 3-1 Process Flow Diagram for CRP Haifeng Plant

[8]*Xu Shisen , Gao shiwang. capture , utilization and storage technology of CO2 in Coal-fired power plant [J]. Shanghai Energy Conservation , 2009, (9) : 9 - 13.*

[9]*IEA.CO2 capture and storage -a key carbon abatement option [R]. Paris, France: IEA / OECD, 2008.*

2)CO2 compression systems

The captured CO2 will to be liquefied by compression and cooling for subsequent storage.

The first step is to raise the pressure of the CO2 to 20 bar with one compressor, and then to cool to 40 ˚C . The second step is to dry the CO2 and increase the pressure to 110 bar by another compression stage. Finally, the pressure of the CO2 is raised to 110 bar for transport to the storage site by pipeline[10] or ship at the early stage.

CO2 transport and storage will be covered in other reports.

[10] *Same as footnote 6.*

3.3.2 Space Requirements

The prime requirement for building a CCR PF power plant utilising post combustion capture technology is the allocation of sufficient additional space at appropriate locations on the site to accommodate the additional CO2 capture equipment and make critical connections. A further requirement is to allow for extensions to balance of plant equipment to cater for any additional requirements (cooling water, auxiliary power distribution etc.) for the capture equipment. Space will be required for the following:

1) CO2 capture equipment.

2) Boiler island additions and modifications (e.g. space for routing a flue gas duct between the ID fan and the amine scrubber).

3) Steam turbine island additions and modifications (e.g. space in the steam turbine building for routing a large low pressure steam pipe to the amine stripper unit).

4) Extension and addition of balance of plant systems to cater for the additional requirements of the capture equipment.

5) Additional vehicle movements (amine transport etc.).

6) Space allocation based on hazard and operability (HAZOP) management studies, considering storage and handling of amines and handling of CO2.

The space requirements are also discussed under individual system and equipment requirements.

The area reserved for the CCS system for Units 3 and 4 is divided into two parts: the absorption area and the pressurization area. Two sets of capture/compression CO2 capture equipment will be needed for this project. The total area of one single set of CO2 capture equipment is 13000 m2.

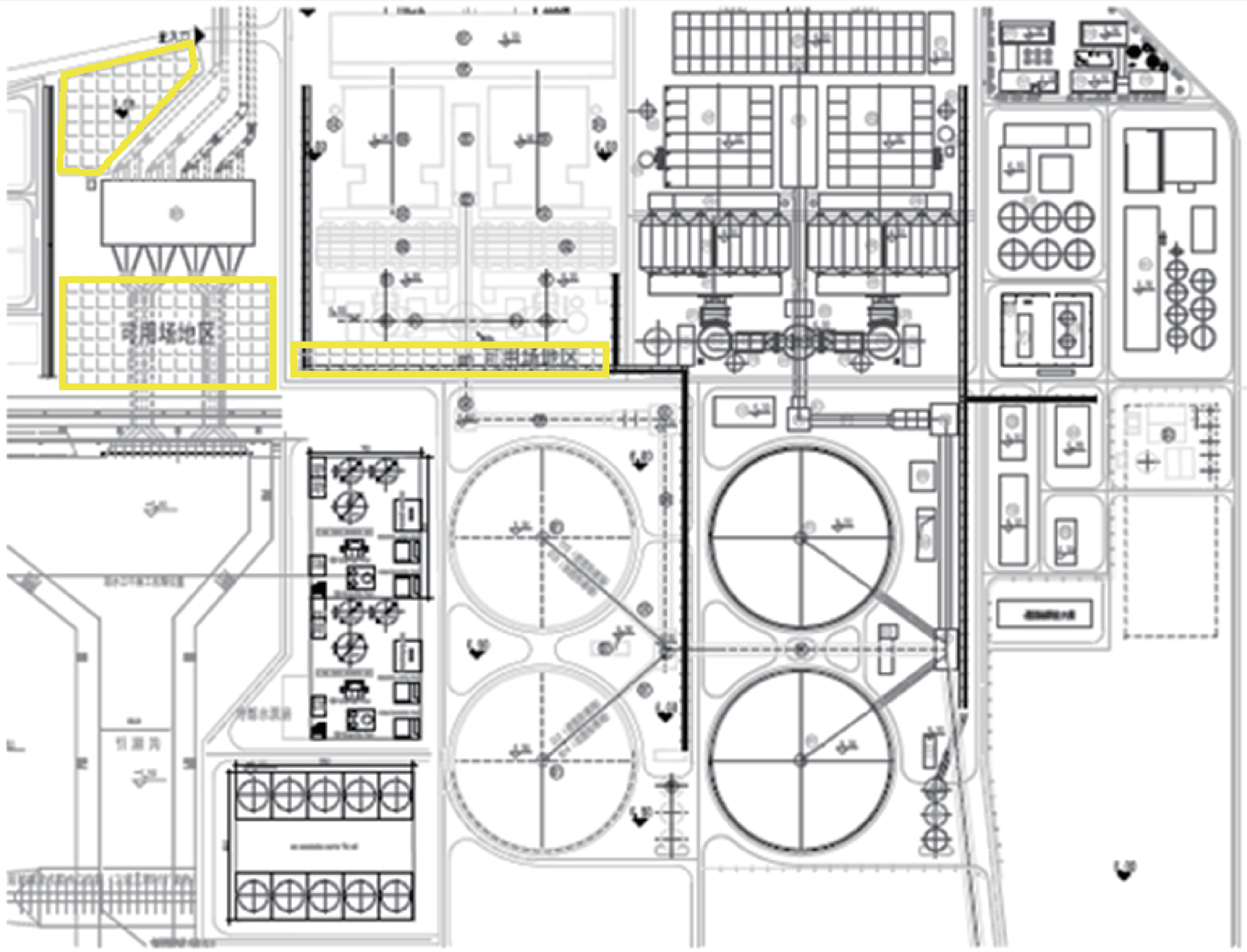


Figure 3-2 Layout of CO2 ready-plant for Unit 3 and 4 (Possible retrofitted site is highlighted in yellow)

3.3.3 CO2 Absorption

The cooled flue gas, with CO2 content of 13%, is ducted to CO2 absorbers and the CO2 is removed from the flue gas by passing the gases up the absorber against a counter flow of 30% MEA solution. The absorption area for Unit 3 is located in the open space on the south side of the chimney, with an area of approximately 7000 m2 (the length is 87.5m, the width is 80m); The absorption area for Unit 4 is located in the open space on the south side of the absorption area for Unit 3, with an area of approximately 7000 m2.The dimensions of the absorber for each of the 2 x 1GW units will be approximately 22 meters in diameter. There is also the possibility to build a cuboid absorber out of concrete with a size of 19m*19m in order to lower the cost for the absorber.

Calculation for Absorber size

The quantity of CO_2 capture per day (M, tonne/day) is given by equation (3-1) as below.

$$M = F * E * C \quad (3-1)$$

Where F = the total fuel consumption (tonne / day)
E = CO_2 emission factor (tonne CO_2 / tonne fuel)
C = Capture efficiency
Therefore,
M= F * E * C = 375*1.99*90%*24= 16,119 tonne / day
The estimation of absorber diameter is based on equation (3-2).
D= A*sqrt[te/d/%CO2] , where the absorber diameter (D, meter),
A=0.62 for 13% CO_2, Te/d=tonnes/day of CO_2 recovered
%CO2 = volume of CO_2 in flue gas before cooling
Therefore,
D = 0.62*sqrt [16119/13]= 21.83 metres (3-2)

The total area of the absorber is 305m2 and the calculated height is 45meter, with SS steel.

The pressurization areas for the two units are located on the south side of the absorption areas, with an area of 12000 m2 (the length is 120m, the width is 100m). The possible area for future retrofit is highlighted in yellow in Figure 4. From the analysis of the current master plan, the area is available to meet the space needs of the CCS systems. As carbon capture technology develops, in the detailed design phase it might be possible to reduce the required area.

3.3.4 Gas path system

1) Inlet Air system: CO_2 capture retrofit with amine scrubbing does not call for any changes to the combustion air system of the boiler and no essential capture-ready requirements are foreseen in this system. In addition, the forced draught (FD) fans and the primary air (PA) fans do not need any modifications for CO_2 capture retrofit with amine scrubbing.

2) FGD system: As a minimum space for installing new duct work to enable interconnection of the boiler flue gas system with the amine scrubbing plant and provisions in the ID fan discharge duct work (for tie-ins, addition of bypass dampers, isolation dampers) will be required. These are discussed below:

a) For PF power plants with modern advanced FGD, normally no additional requirement is foreseen to meet the amine scrubber SOX level limits.
b) If the original FGD plant design and construction allows mechanical or chemical enhancement in the future to meet the amine scrubber SOX level limits, no essential capture-ready requirement is foreseen in the flue gas system.
c) If the original FGD plant design and construction do not allow mechanical or chemical enhancement, then an FGD polisher to meet the amine scrubber SOX level limits will be required. The ID fan may not be able to accommodate the additional pressure drop introduced by the FGD polisher and a booster fan or reform of ID fan may be required. Hence space to install the booster fan or reform the ID fan and associated duct work and provisions for tie-ins shall have to be considered.

The CRP plant is likely to fit the c) scenario above, where another stage of chemical scrubbing is required, but any potential ID fan problem can be resolved at the equipment purchase stage.

For power plants without any FGD measures: space at an appropriate location for installing a FGD plant along with connecting duct work and space to install the booster fan or reform the ID fan would be essential.

The original FGD plant design and construction for CRP Haifeng Units 3 and 4 allows mechanical or chemical enhancement in the future to meet the amine scrubber SOX level limits, so no essential capture-ready requirement is foreseen in the flue gas system.

3.3.5 Steam Extraction

CRP plants retrofitted with post combustion based capture systems will extract up to 50% of the steam from the IP/LP cross-over pipe for amine solvent regeneration as shown in Figure 3-1 (heat flow indicated by a red arrow for illustration purpose). The pipe should have provisions to accommodate the required valves and tie-ins in the turbine building. Furthermore, due to the major flow reduction in the LP section, it should be reformed to meet the requirement to extract steam, and the power produced by the turbine will reduce. As the steam supply flow from the IP/LP cross-over pipe will be reduced when the load is low, during the turbine selection stage the available steam supply and the requirements of carbon capture system should be considered in detail to meet the steam requirement at varying loads.

The steam parameters from the IP/LP cross-over pipe for amine solvent regeneration is tentatively: 0.608MPa (a), 368 °C [11]. A pressure control valve and spray desuperheater (using reboiler condensate) will be used to regulate steam pressure and temperature to meet CO_2 capture requirements.

[11] The pressure can be reduced to 0.9MPa.

Chapter 3

3.3.6 Electricity Supplies

The carbon capture system will require a significant expansion of the auxiliary power system of the CRP Haifeng Power Station Units 3 and 4. The expansion project needs to consider the following factors:

1) Adding and making space for 10kV and 380V auxiliary transformers

2) Adding and making space for 10kV and 380V switchgear for the new power loads, feeders and MCC;

3) Adding and making space for bus bar, cable and cable tray for the new auxiliary transformers, switchgears and power loads.

4) Adding a DC power system to provide control and protection power for the new auxiliary transformers and switchgear. Also adding an AC UPS system for a CO2 Capture-Ready control system.

5) Adding control and protection and power switch equipment for the new auxiliary transformers and switchgear.

3.3.7 Cooling Water System

Units 3 and 4 of Haifeng power plant will be equipped with a once through sea water cooling system. The cooling water is taken from the harbour basin to the west of the plant, and discharged after heat exchange to the sea area to the northeast of the plant. Temperature change is between 5oC to 8 oC depending on season. After CO2 capture retrofit, up to 50% of steam will be extracted from the low pressure sections of the IP-LP turbine crossover. Consequently, there will be a decrease in the heat rejection in the condenser. The condenser cooling water flow may therefore be reduced, with the balance being diverted to CCP cooling duties, or alternatively the condenser flow may be maintained in order to reduce condenser pressures and some of the water then be diverted to the CCP. Since much of heat rejection in the CCP is at elevated temperatures it may not be necessary to increase cooling water flows if it can be returned to the sea slightly hotter.

An eight stage regenerative extraction system will be adopted for CRP Haifeng Units 3 and 4. Three HP heaters, four LP heaters, one deaerator and one sealing heater will be provided.

After heat exchange in the carbon capture system, steam from the IP/LP cross-over pipe will change to saturated water, which will be returned to the main steam cycle.

To facilitate the above, a capture-ready plant should consider the following for low grade heat recovery:

1) Provisions in the water steam cycle enabling bypass of the required number of condensate feed water heaters.

2) Provisions for process integration with the amine scrubber plant (e.g. provision in the condensate pipe work in the LP heater area for admission of condensate from the amine scrubber).

Furthermore, provision and space should be kept in the steam turbine island to enable routing of the new large LP steam pipe between the steam turbine and amine scrubber plant reboiler. This should consider the following as a minimum:

1) Provisions in the steam turbine building, building pipe racks and building support structures to enable routing and supporting the large steam pipe work.

2) Provisions in the steam turbine and plant steam piping drain systems to handle additional drains from this new pipe work.

3.3.8 Waste Water Treatment and Desalination plant

No essential capture-ready requirements are foreseen, as the demineralised water requirement is not expected to increase after the CO2 capture retrofit.

The amine scrubbing plant along with flue gas coolers and an FGD polishing unit (if appropriate) necessary for post combustion CO2 capture will result in the generation of additional effluents. This means provision should be made for the amine waste, e.g. storage and transport offsite, or treatment and recycling may also be required. Hence, the waste water treatment plant area should have space for expansion and provisions for integration with the additional treatment stream(s) to be installed during the CO2 capture retrofit.

3.3.9 Fire System

A fire fighting and fire protection system will be introduced to the CCS system.

3.3.10 SCR

NOx produced from coal firing is mainly NO and with up to 5% NO2. NO does not react with amines, but NO2 does. NO2 concentration of around 40 mg/ Nm3 (@ 6% O2 v/v dry) is considered acceptable for further processing of the flue gas in an amine scrubbing plant.

The design phase of the feasibility study for Units 3 and 4 of CRP Haifeng Power Station envisaged incorporating in-furnace NOx control measures (low NOx burners, two stage combustion air systems) and post combustion SCR measures with the denitrification efficiency of 90%, to limit NOx to the Chinese emission standard for pollutants from thermal power plants (GB13223-2011) FGD of 100 mg Nm3 @ 6% O2 v/v. The NO2 concentration is expected to be about 35mg/Nm3 at the FGD inlet and lower still at the wet FGD outlet (NO2 can be part-captured in a wet FGD). For this project, the post combustion SCR equipment and wet flue gas desulphurisation (WFGD) should reduce the NOx concentration to required levels.

Hence no essential capture-ready requirements are foreseen.

Chapter 3

3.3.11 Dust Removal

A conventional PF power plant is normally fitted with an electrostatic precipitator (ESP) or bag filter depending upon the coal quality to meet the particulate emission level limits imposed by environmental regulations (30 mg/Nm3 @ 6% O2 v/v dry). 2 sets of ESP (three chambers - five electric fields) are provided for each unit in CRP Haifeng Units 3 and 4; the efficiency is tentative believed to be 99.75%.

During capture retrofit, to meet the amine scrubber flue gas inlet quality requirements (5~10 mg/Nm3 @ 6% O2 v/v dry), the feasibility of and space for a reforming dust remover should be considered. Normally, replacing the original ESP with a bag filter or adding a wet ESP can meet the above dust requirement, hence the impact of reconfiguring on the flue gas duct and ID fan should also be considered.

3.3.12 Flue Gas Desulphurisation

SO2 concentration in the flue gas limited to the order of 10 to 30 mg/Nm3 (6% O2 v/v dry) will be required to avoid amine degradation. This requirement imposed by the amine scrubber, is very much lower than the emission levels imposed by current Chinese environmental regulations i.e. the emission standard for pollutants from thermal power plants (50 mg/Nm3 t @ 6% O2 v/v dry).

This project uses limestone-gypsum WFGD. Unit 3 and Unit 4 have already been covered. The desulfurization system can be designed with sufficient space set aside so that as the desulfurization efficiency improves in the future, the outlet concentration can reduce to 10-30 mg / m3 standard (at 6% O2 v/v dry).

In order to adapt the plant for extreme operating conditions, as well as to provide cleaner flue gas for CCS to save the absorber MEA consumption, (and therefore reduce the operating investment), we are consider adding NaOH solution to the gas pre-treatment device for further absorption of SO2. This will also have the effect of reducing the concentration of NO2 and dust in the flue gas.

3.3.13 Chemical Dosing and Storage

As there are no differences in the requirements before and after CO2 capture retrofit in the condensate and feed water chemistry, no capture-ready requirements are foreseen in the chemical dosing systems. With process integration after the addition of capture equipment, monitoring of condensate water quality at the outlet of heat exchangers is foreseen, as part of the heating of the condensate will be undertaken by the amine scrubber plant overhead condenser. However, this is not foreseen as an essential requirement.

3.3.14 Control system

To ensure safe and reliable operation, the CO2 capture system will be equipped with a control system and field instruments, which can communicate with the plant control system.

The level of automation expected to be reached is as follows:

1) With checks and assistance from a few local staff, the system could be started, shut down, monitored and controlled in the control room.

2) Operators can supervise the operating conditions of the system and control most actuators via LCD/keyboard. If necessary, remote manual control functions will ensure safe and economic operation.

3) Optimal design of the modulation and sequence control systems reduces the work for operating staff. Under abnormal operating conditions, interlocking protection control systems can put corresponding systems or equipment into or out of service so that the system can operate or shut down safely.

In order to reach such an automation level, space for a control room and an electronic equipment room must be reserved next to the CO2 capture system.

3.3.15 Additional pipe work

Installation of additional pipework after retrofit will be required due to the use of a large quantity of LP steam in the amine scrubbing plant reboiler, return of condensate into the water-steam-condensate cycle, and process integration of capture equipment with the water-steam-condensate cycle. Additional pipework broadly includes:

- A large LP steam pipe between the steam turbine and reboiler.
- Reboiler condensate return piping between the reboiler and the LP heater area.
- Water-steam-condensate piping between the amine scrubbing plant reflux condensers and the LP heater area.
- Drain piping from the large LP steam pipe to the reboiler.
- Cooling water piping to the flue gas cooler and CO2 compressor inter cooler(s).

To accommodate the above pipe work, the capture-ready plant should have space at appropriate locations (in particular the steam turbine building) to route the new piping.

3.3.16 Other plant infrastructure

The following basic requirements need to considered in relation to other infrastructure:

1) Space at appropriate zones to widen roads and add new roads (to handle increased movement of transport vehicles),

2) Space to extend office buildings (to accommodate additional plant personnel after capture retrofit)

3) Space to extend stores building are foreseen as essential requirements.

Consideration should also be given to how, during a retrofit, vehicles or cranes will access the areas where new equipment will need to be erected.

3.3.17 Compressed Air

Two extra compressed air required will be provided by the existing compressors on sites.

3.3.18 Control and Instrumentation

Most modern control systems will be replaced every 15 years. If it is likely the power plant will be retrofitted after 15[The retrofit time is subject to change with operation condtions.] years, no current input is required. If the anticipated time to the retrofit time is less than 15 years, a separate controlling window or software package designed specifically for the capture plant should be considered. Extra space should also be allocated in the control room or a separate control office provided onsite.

3.3.19 MEA deliveries and Storage

It is assumed that MEA will be stored onsite in a concentrated state. When fresh solvent is required, the MEA will be diluted to around 30% for carbon capture. We have not estimated how much MEA is required for the capture process, as when technology improves, the quantity will tend to reduce. The MEA consumption rate is calculated to be 86kg/h.

3.3.20 Handling of Waste MEA

Waste MEA will be taken away to a waste chemical treatment company.

3.3.21 Staff Management

The capture plant staff should be managed by CRP under the power plant safety rules. However, there is a possibility that a specialist company will run the capture facilities, and provide their own staff. No matter which operating method CRP aims for, all staff on the ground should follow the site rules from CRP.

3.3.22 CO2 Capture Plant Contract

The CO2 capture plant is proposed to be managed by specialist company that has experience on CO2 within the region if the retrofit will happen within 10 years of the construction of the power plant. If the retrofit happen after 2025, it is expected some level of confidence against operating CCS plant will be gained by the power industry, then managing the power plant internally will be recommended.

4. Possible Pre-Investment Options: Post Combustion Amine Scrubbing Technology based CO2 Capture

This section discusses the power plant and the investment impact of the carbon dioxide capture unit from a qualitative point of view.

4.1 USC PF Boiler and Auxiliaries

The features of a USC PF boiler and auxiliaries with post-combustion capture-ready are not noticeably different from a pulverised coal air-fired USC PF boiler. The boiler proper (combustion equipment, furnace, convection heat transfer surfaces) and air heater are essentially the same. The essential system and equipment requirements for the construction of USC PF boilers as capture-ready plants to utilize post-combustion capture technology are outlined below:

None of the combustion equipment, pressure parts, air heater, boiler combustion equipment (mills, burners), all pressure parts and the regenerative air pre-heater requires any modifications for CO2 capture retrofit with an amine scrubber and hence no essential capture-ready requirements are foreseen.

4.2 Flue Gas Pre-treatment

Most of the current carbon capture technology requires low SOx, NOx and particle level. This will require either an upgrade to the new system, or additional equipment to reduce the impurities level in the flue gas. For this capture ready design, we will aim at adding additional equipment when CRP is going to retrofit the plant in the future. And some technology, for example, Shell Cansolv technology, does not need additional scrubbing before the capture plant to reduce SO2 contents. Therefore, no additional investment is required at this stage.

4.3 Raw water pre-treatment plant

Space and investment shall be considered in the raw water pre-treatment plant area to add additional raw water pre-treatment streams, if required.

4.4 Demineralisation / Desalination Plant

No essential capture-ready requirements are foreseen, as the demineralised water requirement is not expected to increase after CO2 capture retrofit.

4.4 Selection of steam turbine

The CO2 capture system needs a large amount of extracted steam, and has a great impact on the efficiency of the turbine. From preliminary data provided by the turbine factory, the steam can to be extracted from IP/LP cross-over pipe for amine solvent regeneration, and a throttling regulating valve in the LP turbine inlet should be installed to make the pressure stable. Hence the operating requirements of CO2 capture system can be achieved, but the efficiency of LP section will reduce. The CO2 capture steam extraction system is shown in Figure 5:

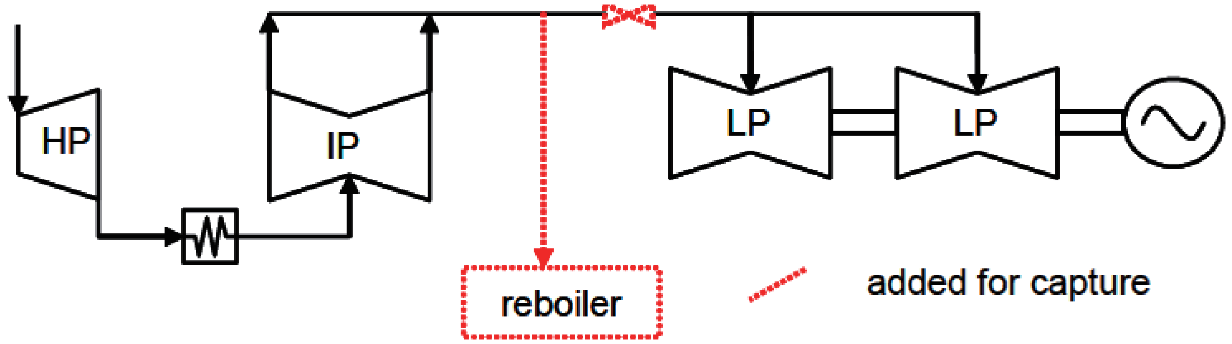


Figure 5 CO2 capture steam extract system

With 2364.299MW fuel heat input for each unit, the power plant is estimated to generate 1000 MW (THA) gross power and 964.8 MW (THA) net power. Auxiliary power rate is 3.52%.

4.4.1 Impact on capture-ready PF power plant performance

Table 5 Impact on plant performance

(Conventional vs capture-adopt PF power plants, one unit)

Item	**Unit**	**Conventional PF power plants**	**Capture- adopt PF power plants (extract almost 50% steam)**	**Capture- adopt PF power plants (extract almost 40% steam)**	**Capture- adopt PF power plants (extract almost 30% steam)**
Case No.		Case 1	Case 2	Case 3	Case 4
Rated power	MW	1000	779.6	823.68	867.76
Fuel input	kg/s	111.26	111.26	111.26	111.26
Coal heating value(LHV)	MJ/kg	21.25	21.25	21.25	21.25
Fuel heat input	MW	2364.299	2364.299	2364.299	2364.299

Condenser pressure	Mpa(a)	0.0057	0.0057	0.0057	0.0057
Auxiliary power rate	%	3.52	27.92	26.43	25.09
Heat rate of turbine	kJ/kW·h	7416	9512.57	9003.50	8546.14
Turbine efficiency	%	48.54	37.84	39.98	42.12
Boiler efficiency	%	94	94	94	94
Pipe efficiency	%	99	99	99	99
Gross plant efficiency (LHV)	%,LHV	45.17	35.22	37.21	39.20
Net power output	MW	964.8	561.9	605.98	650.06
Item	Unit	Conventional PF power plants	Capture- adopt PF power plants, extract almost 50% steam	Capture- adopt PF power plants, extract almost 40% steam	Capture- adopt PF power plants, extract almost 30% steam
Rated power	MW	1000	779.6	823.68	867.76
Loss of CO2	%	100%	10%	10%	10%

4.4.2 Equipment Configuration difference: conventional vs capture-ready PF power plants

Table 6 Equipment List (conventional vs capture-ready PF power plants)

The list below shows the modification for the equipment.

Item	Conventional PF power plants	Capture-ready PF power plants
USC PF Boiler and Auxiliaries	Basic standard	TP and space should be considered for flue gas system
Particulate Removal Unit	ESP,efficiency≥99.75%	Original ESP should be reformed to bag filter or add wet dust collector
Steam Turbine Generator and Auxiliaries	Basic standard	Reforming of turbine and adding steam pipe will increase the investment.
Water - Steam - Condensate Cycle	Basic standard	The additional water-steam-condensate and civil system will increase the investment.
Compressed Air System	Basic standard	The additional compressors and compressed air system components will increase the investment.

4.5 Summary of Results

For PF power plants retrofitted with post combustion based capture systems, up to 50% steam will be extracted from the IP/LP cross-over pipe for amine solvent regeneration. While the boiler burns the same amount of fuel, the turbine heat rate will increase but the power output of turbine and the gross plant efficiency will reduce due to the reduction of flow in the LP section. At the same time the CO2 capture system will consume 180MW auxiliary power, so the auxiliary power rate will increase and the power supply will reduce for Capture retrofit PF power plants. Furthermore, additional space, and device reforming should also be considered for Capture retrofit in CRP Haifeng Units 3 and 4.

5. CCS capital and future operating cost estimate

5.1 Capital Cost

It is estimated that there would be a 27% increase in the capital cost in HR Power Haifeng Units 3 and 4 if CCS is retrofitted, including the cost of the CCS plant and modifications to the existing system.

Table 7 Estimated Impact of CCS retrofitting on capital cost of HR Power Haifeng Units 3 and 4

ITEM	**UNIT**	**Conventional PF power plants**	**Capture- adopt PF power plants (extract almost 50% steam)**
Static Capital Cost	Yuan	Basic standard	+27%
Unit Cost	Yuan/kW	3689	4658

5.2 Operating Cost

According to the engineer's input and relevant research, the operating costs of carbon capture for CRP Haifeng Unit 3 and 4 is approximately 275 Yuan/tCO2, which includes manpower, management and maintenance costs, house power and chemicals consumption, and water processing fees, etc.

5.3 Opportunity Cost

The opportunity cost of CCS plant refers to the lost sales revenue of the electricity, which could otherwise be produced using the steam consumed by the CCS plant. Assuming 50% steam consumption from the LP, the output of Haifeng Units 3 and 4 would slide from 2000MW to 1559.2MW. Though partially offset by the increased working hours, lost electricity sales would still amount to 894.87 million Yuan annually. Thus, the opportunity cost of CO2 capture is estimated at 95.67 Yuan/tCO2.

5.4 Conclusion

1 Since the first commercial scale CCS post combustion coal-fired power plant will start operation in Oct 2014, and there is no experience of CCS applied to a 1000MW unit anywhere in the world, this research is theoretical. The research aims to provide a simple solution for large scale coal fired power plants to be built capture ready.

2 From our research, post combustion CCS technology using amine solution as the absorbent has the greatest potential for CRP Haifeng power plant Units 3 and 4 in the next 3-5 years. However, this technology has problems, such as high energy consumption and a large investment requirement. More research needs to be made on new absorbents with low energy consumption in future to develop more advanced absorption amine processes, as well as alternative technologies. All of the assumptions in this report is on post-combustion amine capture.

3 Making plant CCR can reduce the carbon lock-in effect of newly built power plants at low cost and make a stable transition to CCS realizable. It is a no risk policy choice with less than 1% increase in capital investment in the next 10 years. Guangdong should actively carry out research on CCR technology, develop CCR demonstration projects, and draft relevant policy for CCR for large new-build power plants.

4 As the major producer of CO2 emissions, the power industry is the key area to implement CCS in the future. Therefore, Guangdong should attach importance to R&D of CCS and set up and design a post combustion CCS demonstration project as soon as possible, to accumulate experience of CCS application in Guangdong's thermal power plants and promote technical progress of reduction of China's greenhouse gas emissions. For China Resource Power, the need to spread out awareness of the CCS technologies to its power, natural gas and cement sector is also discussed with the management level within the company.

Appendix1 Definition of CCSReadiness

At the request of the Gleneagles G8 summit[13], the International Energy Agency Greenhouse Gas Programme (IEA GHG)[14]published a study which identified the following key elements for CCR power plants:

>A CO2 capture ready power plant is a plant which can include CO2 capture when the necessary regulatory or economic drivers are in place. The aim of building plants that are capture-ready is to reduce the risk of stranded assets and carbon lock-in.

>Developers of capture ready plants should take responsibility for ensuring that all known factors in their control that would prevent installation and operation of CO2 capture have been identified and eliminated. This might include:

>A study of options for CO2 capture retrofit and potential pre-investments

>Inclusion of sufficient space and access for the additional facilities

>Identification of reasonable routes to storage of CO2

>Competent authorities involved in permitting power plants should be provided with sufficient information to be able to judge whether the developer has met these criteria.

Since the IEA GHG definition was adopted, a number of studies have been conducted to investigate the engineering requirements of CCR[15], its economic and political feasibility[16]. In 2010, building on the IEA GHG CCR definition, a joint IEA/CSLF/GCCSI meeting and subsequent working party prepared an internationally-agreed definition of CCSR, with an initial summary as follows:

"A CCSR facility is a large-scale industrial or power source of CO2 which could and is intended to be retrofitted with CCS technology when the necessary regulatory and economic drivers are in place. The aim of building new, or modifying existing, facilities to be CCSR is to reduce the risk of carbon emission lock in or of being unable to fully utilise them in the future without CCS (stranded assets). CCSR is not a CO2 mitigation option, but a way to facilitate CO2 mitigation in the future. CCSR ceases to be applicable in jurisdictions where the necessary drivers are already in place or once they come in place."

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