中美清洁能源研究中心
清洁煤技术联盟
China-US Clean Energy Research Center
Advanced Coal Technology Consortia

郑楚光 Zheng Chuguang

华中科技大学
Huazhong University of Science and Technology

James Wood

西弗吉尼亚大学
West Virginia University

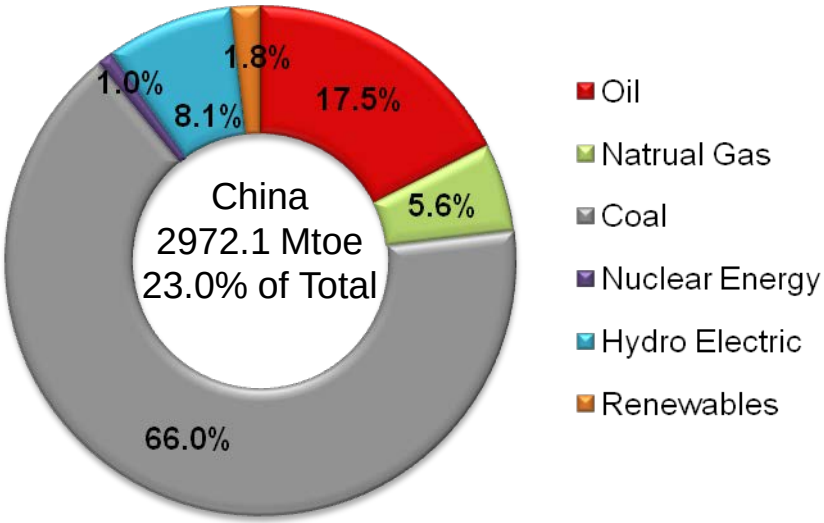
2016-07-01

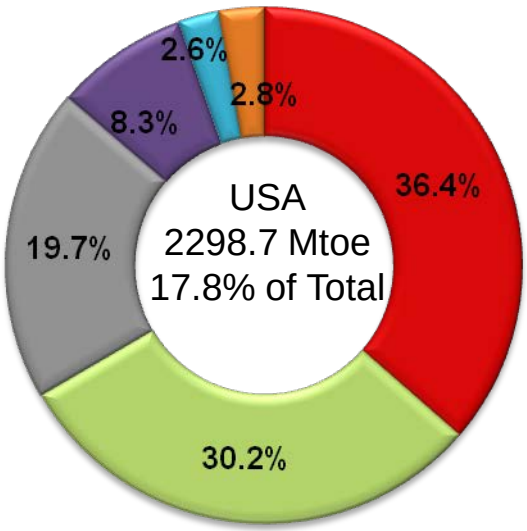
目 录 Content

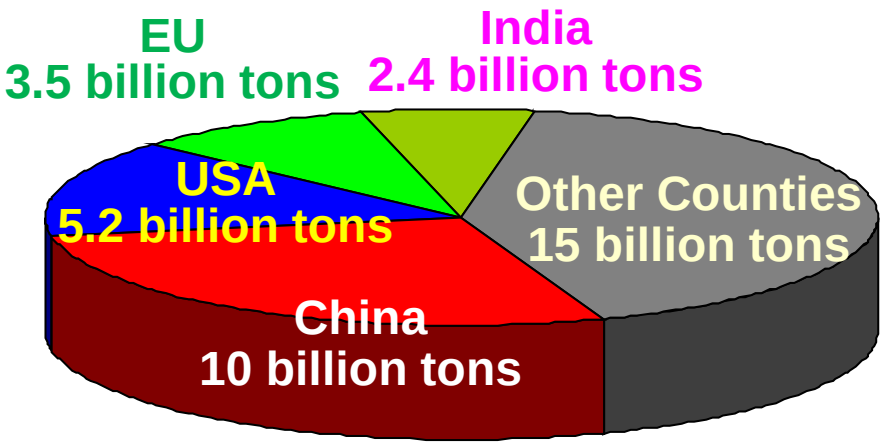
- 背景与意义
  Background
- 一期成果与亮点
  Phase I Achievements
- 二期任务与展望
  Phase II Highlights
- 感受与体会
  Future Directions

中美碳排放现状US-China CO_2 emission

Primary Energy Consumption (2014) IEA report 2014







CO_2 emission in 2013

两国肩负有巨大的减排责任

* 中美能源消耗和碳排放量均占全球总量的40%以上
* The sum of the energy consumption or CO_2 emission of China and US are over 40% respectively of the global amount.

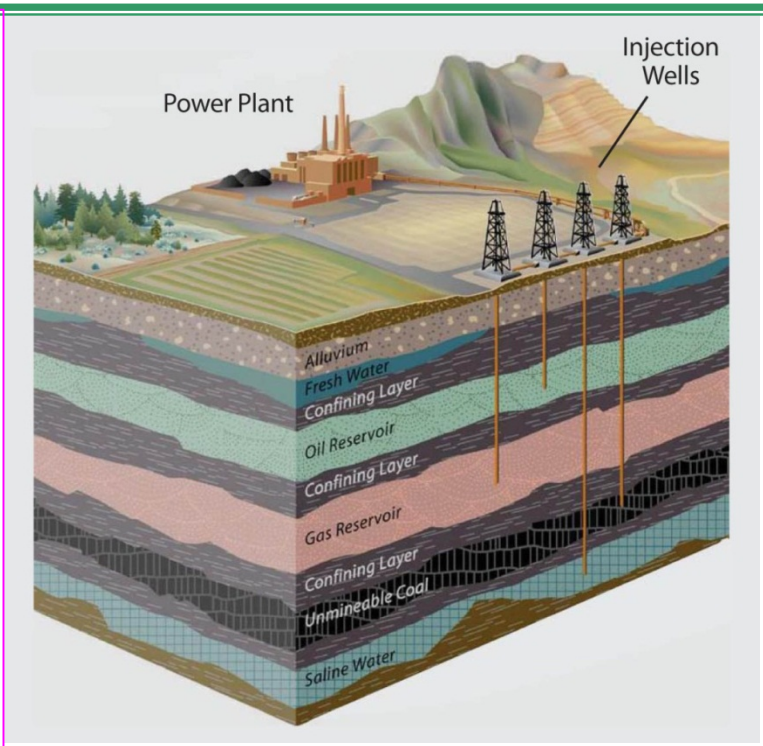
碳捕集利用与封存(CCUS)

CCUS被认为是唯一能够大幅度减少化石能源（特别是煤炭）CO_2排放的终极技术，联合国政府间气候变化专门委员会(IPCC)称，如果不采用CCUS技术，将很难完成减排任务。

中国能源革命路线图：预期2050年，全流程的CCUS系统在电力、煤炭、化工、矿物加工等系统实现覆盖性、常规性应用。

CCS is the only technology that can significantly reduce CO2 emissions from the use of fossil fuels. Delaying or abandoning CCS in the sector would increase the investment required by 40% or more in the 2DS (IEA, 2015).

China's Energy Revolution Roadmap indicates that CCUS will be widely used in all fossil based sectors by 2050.



“未来十年将是决定全球CCUS技术的关键时期”

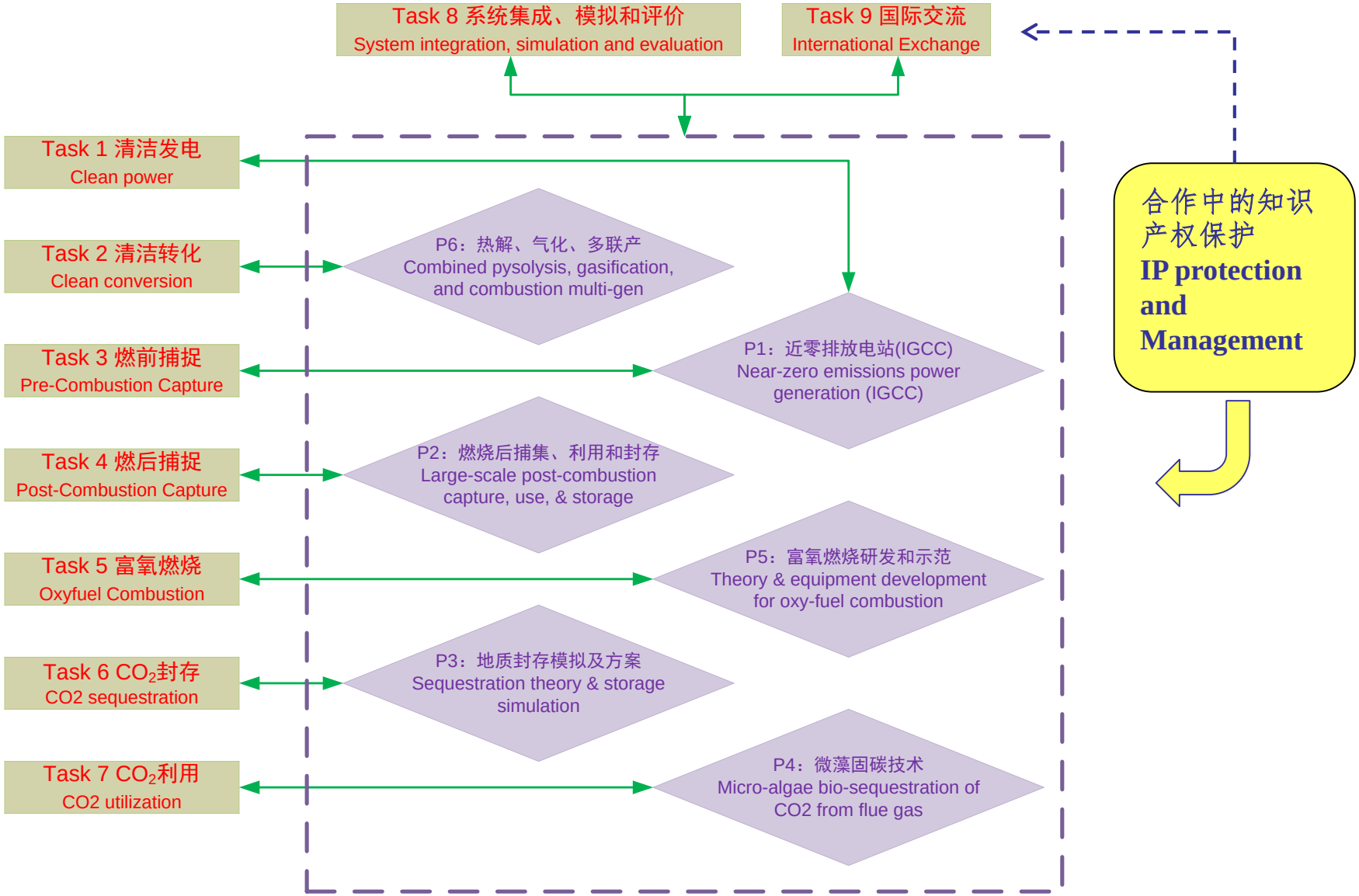
The next decade will be a critical period to determine the success of CCUS.

正由单项技术的突破向新型绿色能源系统和产业化转变—战略性新兴产业

目 录 Content

- 背景意义
  Background
- 一期成果与亮点
  Phase I Achievements
- 二期项目及成果展望
  Phase II Highlights
- 感受与体会
  Future Directions

任务与课题Projects and Tasks



涵盖了CCUS的全部内容（专门列入了IP课题）取得了一些具有影响的成果，如：

知识产权保护 Intellectual Property

TMP was originally produced by ACTC. The final TMP document of ACTC was taken as the common file for the three consortia in CERC.

TMP 由 ACTC 首先签署，其合同文本后来被纳入为CERC的共同文本。

燃前捕集 Pre-Combustion Capture *Highlights*

华能与杜克、LLNL的IGCC合作/CHNG and Duke, LLNL on IGCC

在IGCC项目**启动及运行阶段分享经验**

Share IGCC operational knowledge gained from starting up and operation

进行基于IGCC的CO_2捕集、利用与封存技术研发和示范，**建立测试平台**

Study and demonstrate the technologies of CO_2 capture, use and storage based on IGCC system and set up the test platform.

探寻双方IGCC+CCS能源战略及利益的交汇点，实现互利共赢。

Explore the intersection of the energy strategy and interest of IGCC + CCS technology of the two countries, achieve mutual benefit and win-win situation.

Edwardsport IGCC

合作内容

整体工艺情况	可用性	环境措施	成本情况
Process description and issues	Availability	Environmental Performance	cost

天津 IGCC

代表先进发展方向的整体煤气化联合循环（IGCC）具有：高效、清洁，减排潜力

燃前捕集 Pre-Combustion Capture

Highlights

中国第一个250MW IGCC电站开始商业运行

China's first 250MW IGCC power plant began commercial operation

跨入了世界仅有几台的大型商业规模的先进行业。

燃后捕集 Post-Combustion Capture *Highlights*

上海石洞口SC2400MW电厂的600MW单元机组上安装的燃烧后捕集系统（华能集团）
Post-combustion facility integrated to 600MW unit in Huaneng's Shidongkou 2400MW SC power plant.

是当时世界上容量最大的燃后捕集装置

印第安纳州吉布森SC3100 MW电厂拟建立600MW的3号机组燃烧后捕集系统（杜克能源）
Duke Energy planned to utilize unit 3 at its Gibson Station SC facility for this PCC project.

富氧燃烧 Oxyfuel Combustion

Highlights

HUST和B&W的数据共享

Data Share between HUST and B&W

- **True collaboration via open information exchange**
  通过公开信息共享达到真正的合作
- **Early creation of data exchange mechanism**
  早期建立的数据交换机制
- **MOU between HUST and B&W signed in June 2012**
  华中与巴威在2012年六月就签署了谅解备忘录
- **Monthly teleconference and regular visits**
  每月的电话会议和常规性的互访
- **Cooperation extends to outside CERC**
  合作延伸到中心之外

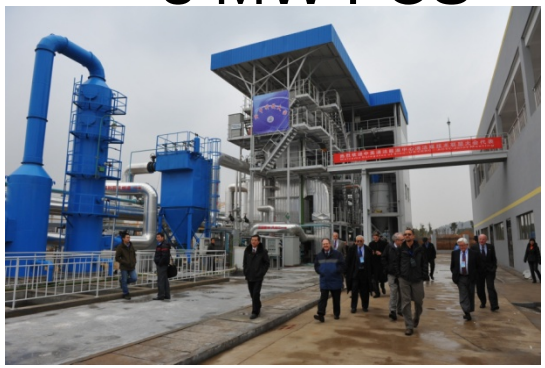
Technical Paper

Char Burnout of U.S. and Chinese Coals Under Oxy-Combustion Conditions

B&W babcock & wilcox power generation group

3篇合作论文
1 篇B&W技术报告
3 Joint Research Paper
1 B&W Technical Report

3 MW FCS



数据共享
Data Sharing

基础反应数据库 Coal Reaction Kinetics Database	中试台架数据及CFD模型 Pilot Facilities and CFD	中试试验动态及仿真 Pilot Facilities Dynamics and Process Model	大型示范经验共享 Knowledge Sharing on Large Demo

1.8MW SBS

富氧；3-1.8MW平台上基础反应数据库、数据、模拟、仿真、大型示范经验的共享

富氧燃烧 Oxyfuel Combustion

3MW富氧燃烧全流程(3MW FCS)
3MW Oxy Demonstration

❖**Stage I: air combustion commission (2012.1~2012.2)**

- Burner work well
- Heat transfer as design
- PA, SA > 250C

❖**Stage II: oxy-combustion commission (2012.3~2012.10)**

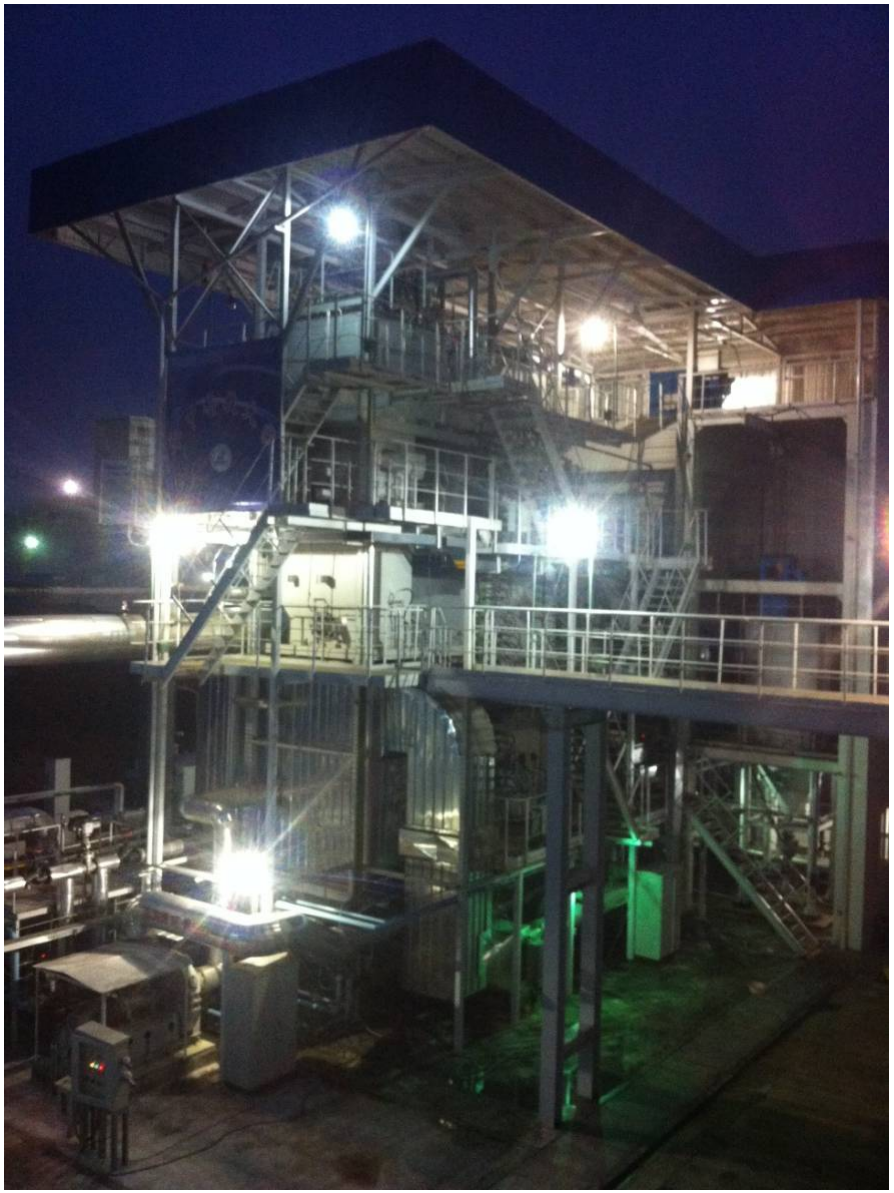
- Switch from air to oxy-fuel
- Oxygen injection safe at 300C
- CO_2 ~80%dry,vol
- Burner work well

❖**Stage III: benchmark of air combustion (2012.11)**

- Burnout ratio > 95%
- Get the detailed data of air combustion

❖**Stage IV: benchmark of oxy-combustion (2012.12-2013.6)**

- Long-time and stable operation
- Obtain the characteristic and control method of heat transfer and emission



全链条系统；结果理想

封存与驱油 Storage & EOR

Highlights

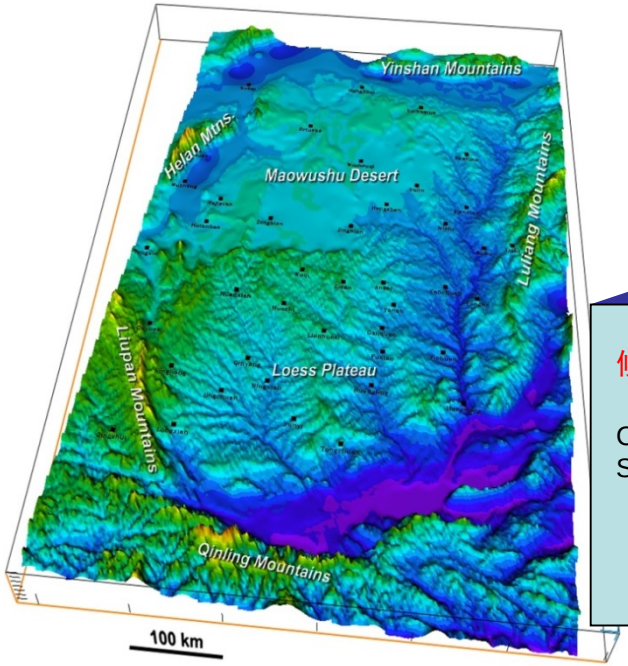
场地适宜性评价和优先级确定

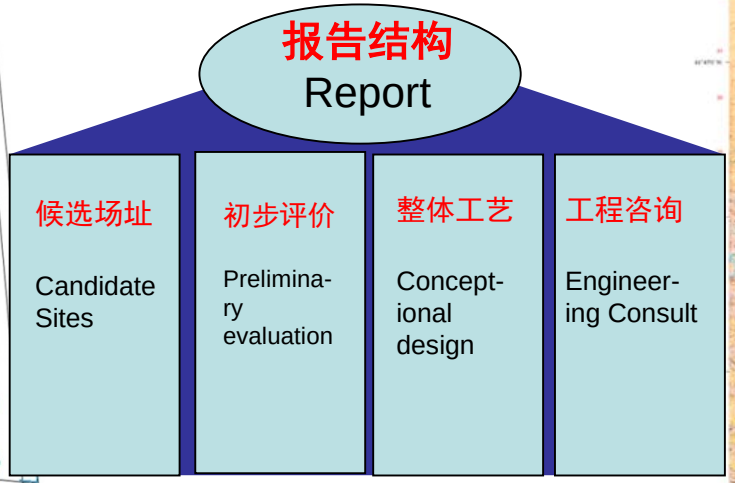
Site suitability and priority evaluations by the site screening methodology.

神华与LLNL、WVU的CO_2封存合作

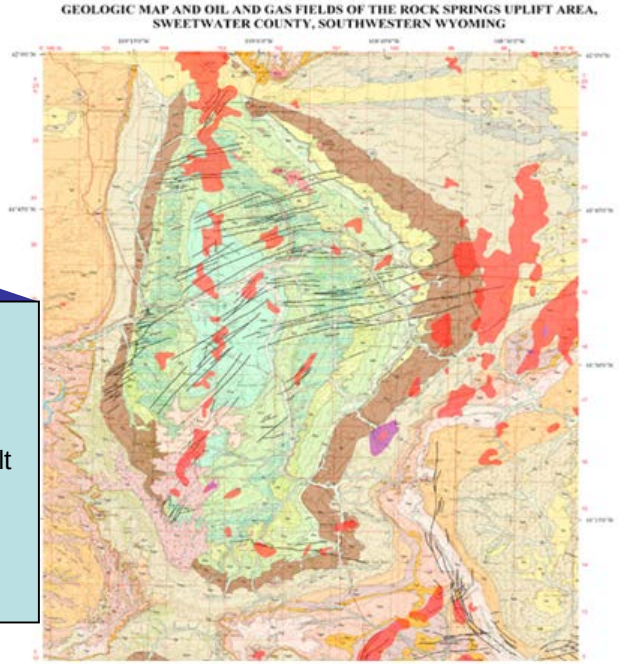
Collaboration Between Shenhua and WVU, LLNL on CO_2 storage

Ordos Basin, China
鄂尔多斯





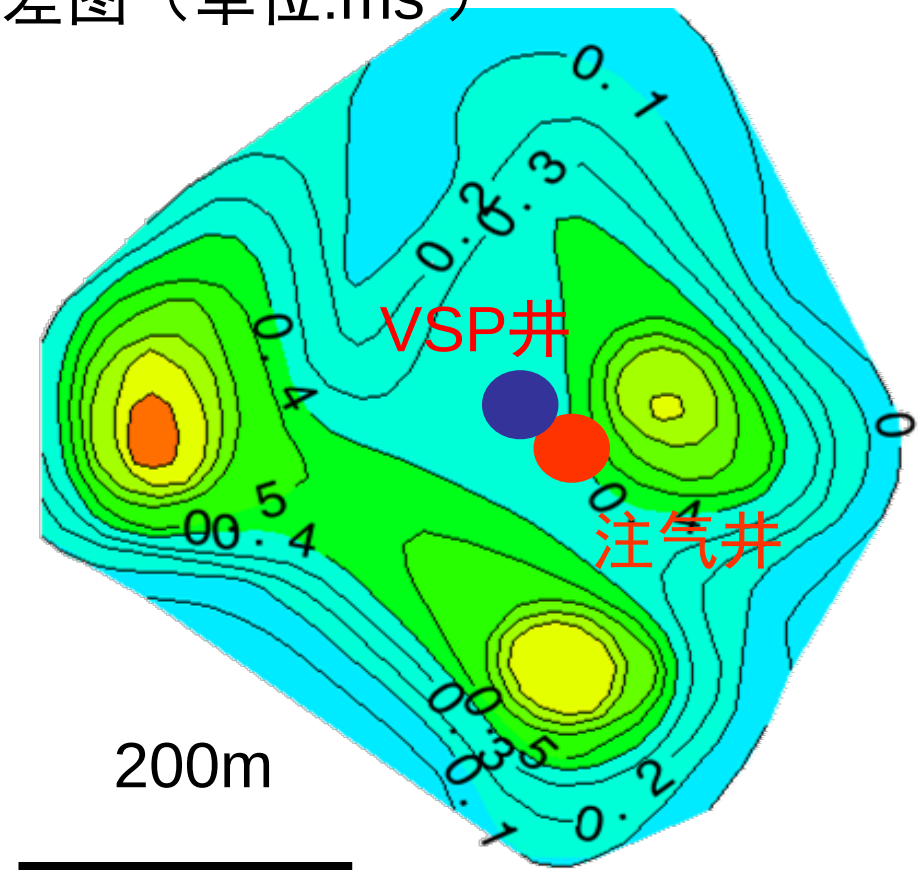
Rock Springs Uplift, USA



咸水层封存 CO_2 storage

Highlights

煤层T_0差图（单位:ms ）



神华实现了低渗透多储层同时注入，发挥各层的封存能力，具有很强的技术特色；实际注入量超过30万吨，CO_2运移350m，且均匀扩散；

Shenhua achieved CO2 injection into multiple permeability layers and exert the storage capacity of each layers; actual injection reached 300k tons, CO2 plume transports uniformly about 350m.

采油 EOR

CO_2-EOR先导试验区：开展2口井CO2注入试验

CO2-EOR pilot test region: Conduct CO2 injection test in 2 wells

(延长石油和怀俄明大学，Shaanxi Yanchang Petroleum and UWy)

Surface infrastructure

2口井CO2注入试验

CO_2储罐

注气井口

注气泵房

延长石油CO_2驱油先导试验 Shaanxi Yanchang Petroleum CO_2-EOR test

CO_2生物能源利用CO_2 Utilization with Microalgae

Highlights

利用包括基因工程在内的先进技术，筛选培育生长速度快（比大多数藻类生长快15%）、对土地要求低、含油量高（是大豆的90倍）、吸碳能力强（约为林木的5-8倍）的微藻，它既能吸附捕集电厂排放的CO_2，同时又能获得高品位的生物质能源。

Microalgae carbon-biofixation is a typical technology in exploring the utilization of CO2. In Task 7, the algae were screened and modified by some advanced methods such as genetic engineering. Then the high performance algae strains were obtained, with a high growth rate, high carbon mitigation capacity, high oil productivity, and better match with flue gas. This is a promising R&D field attracting both countries attention.

杜克能源微藻项目现场

Duke Energy's Microalgae Project at East Bend Power Plant

新奥集团的开塘种植微藻示范基地，中国廊坊

Growth System Optimization in China

发电与转化 Generation& Conversion

提高效率

超700℃超超临界锅炉特性研究 Research on issue related to super 700℃ USC boiler

煤热解气化分级转化多联产技术 Staged Coal conversion poly-generation system

- **煤中矿物质在燃烧过程中的迁移转化机制**

  Migration and transformation mechanisms of mineral during coal combustion process.

- **在1MWth试验装置上验证煤炭热解燃烧分级转化技术的可行性，具备工业示范能力**

  Coal conversion poly-generation technology combined pyrolysis, gasification and combustion is verified on 1MWt pilot plant and may be demonstrated in industry.

结渣、积灰行为对受热面热阻特性的影响
Effect of slagging and fouling behavior on heating surface thermal resistance characteristic.

热解煤气燃烧火炬
Torch of pyrolysis gas

1MWt煤热解燃烧分级转化试验装置
1MWt coal stage conversion pilot plant

一期工作的总体描述General Achievements of Phase I

五年来，通过中美两国科技人员富有成效的工作和紧密的交流合作，不仅取得了令人瞩目的研发成果，而且在CCUS领域的诸多方向上，引领和促进了该技术的发展，展示了良好的应用前景，为实现碳减排和应对气候变化，做出了我们的贡献。也为进一步的深化合作奠定了坚实的基础。

In the past 5 years, through the effective work and close collaboration of the scientists in ACTC from the two countries, achievements have been obtained. ACTC leads the way in various areas of CCUS and promotes the development of this technology which shows bright future of application. ACTC has made great contributions to realizing carbon emission reduction and corresponding to climate change.

CCUS涵盖了众多的学科领域，涉及诸多的行业部门，因此ACTC的参加单位和人员都是很多的，工作量也是巨大的。

目 录 Content

- 背景意义
  Background
- 一期成果与亮点
  Phase I Achievements
- 二期项目及成果展望
  Phase II Highlights
- 感受与体会
  Future Directions

二期合作计划 Collaboration Plan for Phase II

U.S.-China Clean Energy Research Center –
Advanced Coal Technology Consortium

Phase II

2016 – 2020

Technical Narrative and Continuation Proposal

May 29, 2015

中美清洁能源联合研究中心

Clean Energy Research Center

清洁煤技术(包括碳捕集和封存)联盟

Advanced Coal Technologies Consortium

二期合作计划

Collaboration Plan for Phase II

(China Side Draft)

2015-08-05

设置5个任务 / 5 Themes Determined

与美方交流后，下一阶段拟设置5个任务：

1）先进发电技术；

2）大型示范项目合作与知识共享；

3）CO_2利用与埋存；

4）清洁转换；

5）系统分析与建模。

ACTC proposals are grouped into five categories:

1) Advanced power generation;

2) Collaboration and knowledge sharing on large scale demonstration projects;

3) CO_2 Utilization and storage;

4) Advanced coal conversion;

5) System analysis and Modeling.

亮点-路线图 Highlights & Roadmap

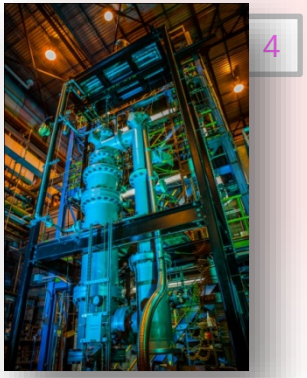
埋存与驱油
Storage & EOR

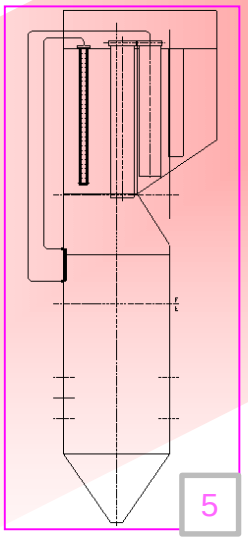
燃前捕集30MW
30 MW Pre-Comb.

300MW分级转化
300MW poly-gen. demo plant

富氧燃烧
Oxy-Comb.

先进发电





USC挂件试验
USC Test

微藻规模化养殖
Large Scale Algae cultivation

延长油田EOR示范工程 Yanchang CO_2-EOR Demo

- 延长油田与Wyoming大学达成合作协议，共同开发针对鄂尔多斯盆地内适宜低渗高非均质性油藏的CO_2-EOR技术；
- Yanchang Co. agreed with Wyoming Uni. in CO_2-EOR project in Ordos.

地质勘探、注入模型
Geo. survey, injection model

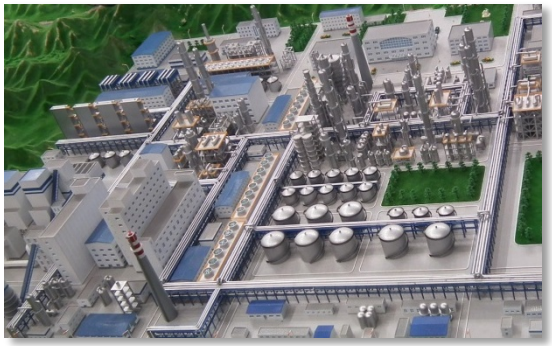
合作内容
Collaboration

规划中的 延长CO_2-EOR工程
CO_2-EOR in Yanchang Co.

怀俄明Wyoming

延长 Yanchang

ACTC



怀俄明大学与中方多家机构共同研发低渗非均质的CO_2-EOR技术，提高石油采收率。
Wyoming Uni. Collaborates with China in CO2-EOR.

CO_2提高石油采收率
CO_2 Enhanced Oil Recovery (CO_2-EOR)

Injection well index: 60

Pipeline index:200-300km

Capture index 80,000-400,000 tons

Reservoir study
- Reservoir screening
- Geological model
- Reservoir simulation

Site construction
- Increase injection well groups (60)
- Injection station construction
- Pipeline construction(200-300km)

Storage device Construction (80-400kt)
- Device construction
- Capture process innovation

Reservoir study → Construction of injection station and pipeline → Construction of storage device

2010 — CERC1.0 — 2015 — CERC2.0 — 2020

亮点-路线图 Highlights & Roadmap

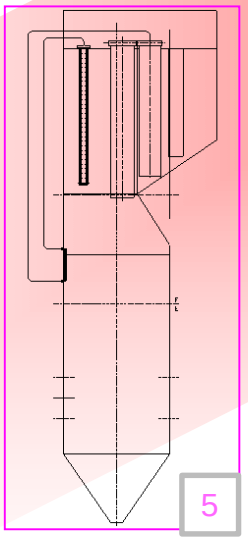
埋存与驱油
Storage & EOR

燃前捕集30MW
30 MW Pre-Comb.

300MW分级转化
300MW poly-gen. demo plant

富氧燃烧
Oxy-Comb.

先进发电



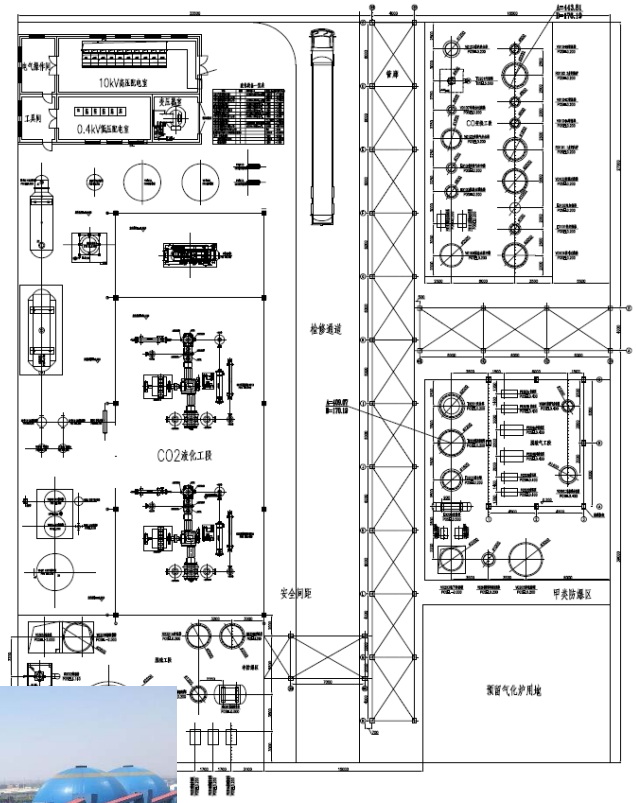
USC挂件试验
USC Test

微藻规模化养殖
Large Scale Algae cultivation

华能IGCC+CO_2捕集 IGCC+CO_2 Capture in Huaneng

- 华能在绿煤I期IGCC投运的基础上开展II期30MW燃烧前CO_2捕集项目。
- Based on the operation of IGCC, Huaneng is starting a 30 MW precombustion CO_2 capture project for syngas cleanup.

30MW_{th} pre-combustion CO_2 capture system layout



亮点-路线图 Highlights & Roadmap

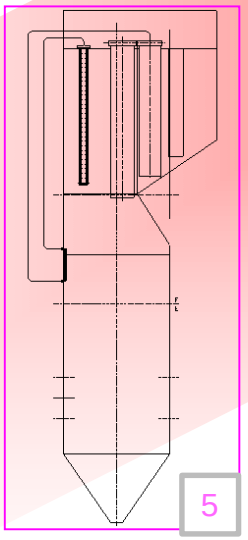
埋存与驱油
Storage & EOR

燃前捕集30MW
30 MW Pre-Comb.

300MW分级转化
300MW poly-gen. demo plant

富氧燃烧
Oxy-Comb.

先进发电



USC挂件试验
USC Test

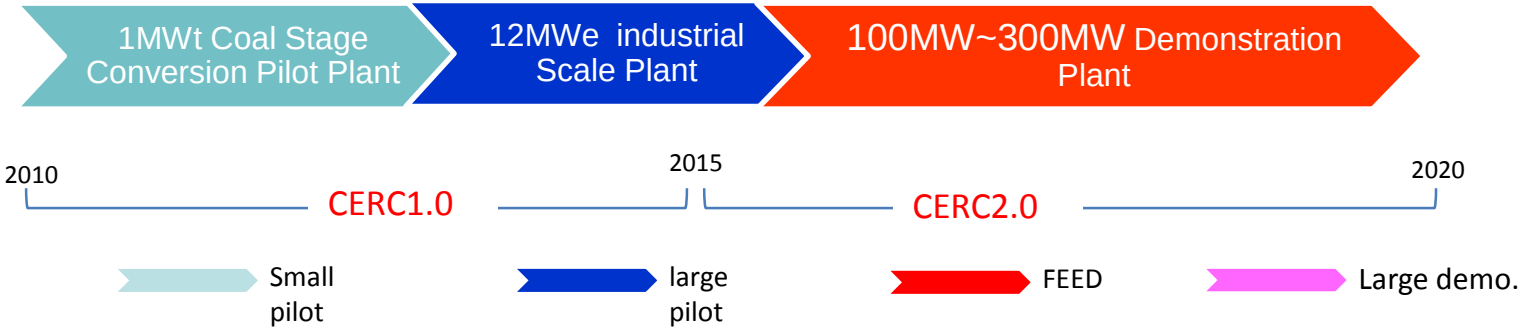
微藻规模化养殖
Large Scale Algae cultivation

300MW分级转化 300MW Conversion

1MWt Pilot Plant

12MWe Industrial Plant

-Experiments on the key conversion processes
-New synthesis processes for pyrolysis gas
-Environmental technologies
-Simulation on poly-generation system
-Design Theory and methods
-Operating the demonstration plant with a capacity between 100MW and 300MW.



LP AMINA

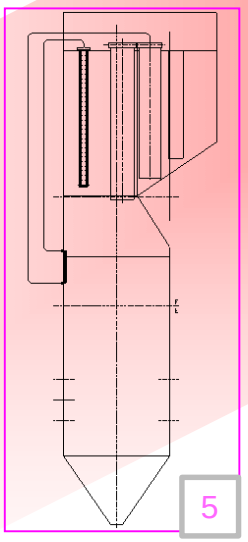
亮点-路线图 Highlights & Roadmap

埋存与驱油
Storage & EOR

燃前捕集30MW
30 MW Pre-Comb.

300MW分级转化
300MW poly-gen. demo plant

先进发电
Adv. Power Gen.



USC挂件试验
USC Test

微藻规模化养殖
Large Scale Algae cultivation

富氧燃烧
Oxy-Comb.

加压富氧燃烧Pressurized Oxy-PC

1MWt SOC Pilot 台架

10MWt POC demo 富氧燃烧示范

- Detail process modeling(Wustl) 详细流程建模
- CFD simulation (WVU) CFD模拟
- System Improvement (WVU, Wustl) 系统改进

100kWt POC small Pilot 小型中试

- Burner/boiler design (Wustl) 燃烧器/锅炉设计
- Kinetics study (HUST) 动力学研究
- Ash deposition study (THU)火山灰沉积研究
- Sub-model development (WVU, Wustl)子模型开发
- Experiments and CFD validation实验和验证
- Scale-up to 250kWt (Wustl) 规模达250kWt

Staged Oxy-PC → 100kWt Pressurized Oxy-PC → 10MWe Pressurized Oxy-PC

2010 — CERC1.0 — 2015 — CERC2.0 — 2020

Washington University in St.Louis

West Virginia University

CERC-ACTC 术联盟

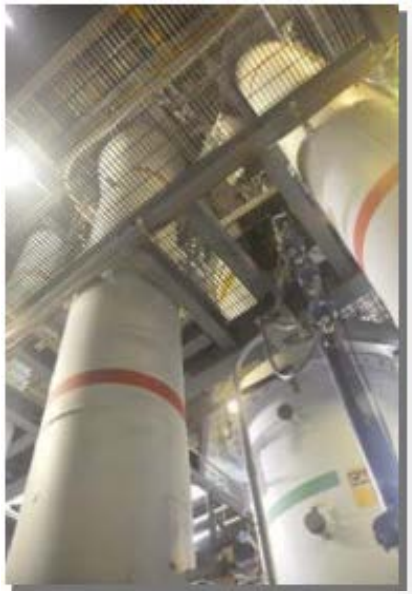
化学链燃烧 Chemical Looping Combustion

3MWt 自热维持化学链燃烧示范 Autothermal CLC demo.

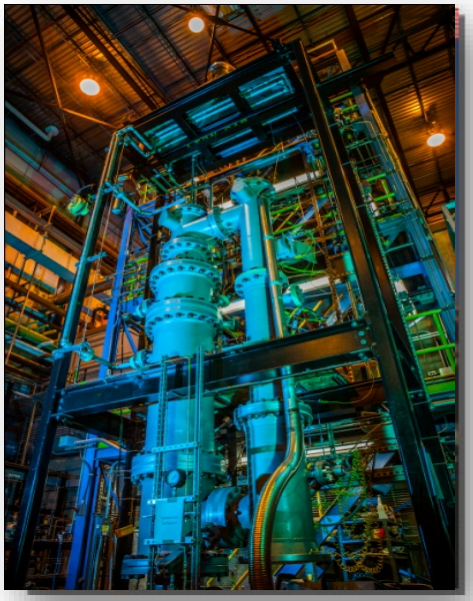
- Iron-based, calcium-based oxygen carrier R&D (Uky&HUST)
- 3D Interconnected fluidized bed CFD simulation (WVU)
- Solid particle cycle management (NETL, Alstom)

50kWt coal CLC small pilot

- Low cost oxygen carrier particle screening and reactivity upgrade (HUST);
- Redox reaction kinetics study (HUST&WVU)
- Material handling and management inside reactors (WVU);
- Oxygen carrier and its reactor compatibility study (UKy);
- Verification of 50kWth small pilot and demo. (HUST);



3MWt Autothermal CLC Facility



50kWt CLC Facility

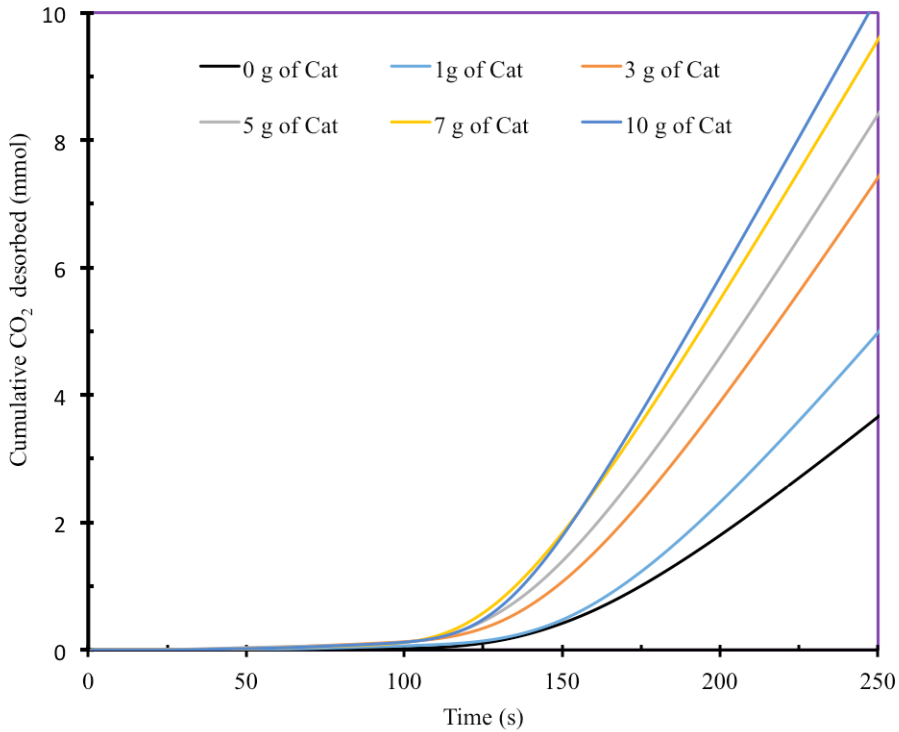
CLC concept verification and feasibility study → 50kWt **Coal CLC** → HUST and Alstom 3MWt **Autothermal CLC**

2010 — CERC1.0 — 2015 — CERC2.0 — 2020

CERC-ACTC

催化剂剂量对CO2 解吸的影响

Effect of catalyst dosage on CO_2 desorption



Desorption conditions: Solution volume: 0.25 L, Flow rate of inlet gas mixture (N_2 and CO_2): 500 mL/min, Desorption temperature: 88°C; Absorption conditions: Solution volume: 0.25 L,CO_2 flow rate: 1,200 mL/min; Absorption temperature: 25°C].

- 当其他条件恒定时
  - 增加催化剂剂量可进一步增加CO_2解吸动力
  - 当剂量达到7 g时，催化剂的影响就不明显了。

With other conditions being constants

- Increase in dosage of catalyst leads to the increase in the further improvement in CO_2 desorption kinetics
- The effect of catalyst becomes insignificant when it dosage reaches 7 g

亮点-路线图 Highlights & Roadmap

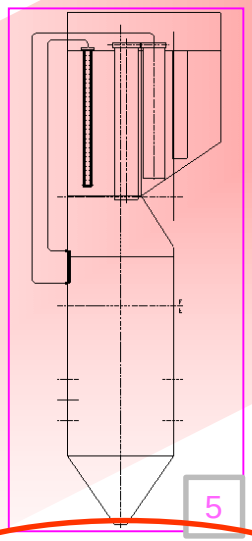
埋存与驱油
Storage & EOR

燃前捕集30MW
30 MW Pre-Comb.

300MW分级转化
300MW poly-gen. demo plant

富氧燃烧
Oxy-Comb.

先进发电
Adv. Power Gen.

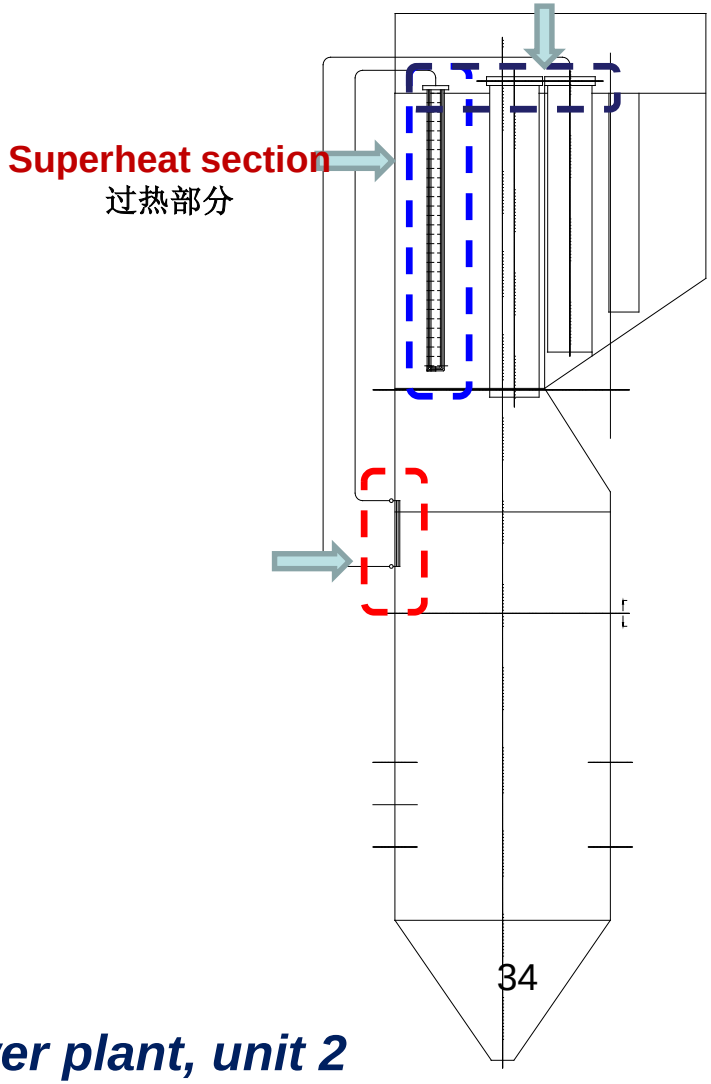


USC挂件试验
USC Test

微藻规模化养殖
Large Scale Algae cultivation

USC材料测试USC MATERIAL TESTING

- **Boiler type 锅炉类型:** ***two pass boiler***
- **Steam capacity蒸汽容量:** ***1000 t/h***
- **Production capacity生产能力:** ***320 MWe***
- **Burner type 锅炉类型:** ***wall fired System***
- **Fuel 燃料:** ***bituminous coal***
- **SH steam temperature 蒸汽温度:** ***540° C***
- **SH steam pressure蒸汽压力:** ***25 MPa***



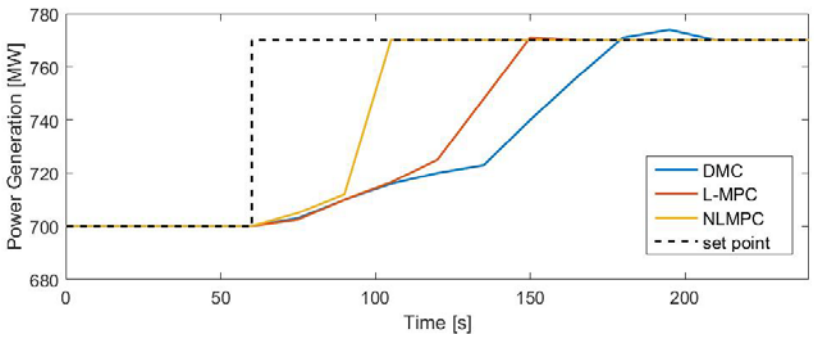
Host site : ***Huaneng Nanjing thermal power plant, unit 2***

华能集团南京热电厂，2号机组

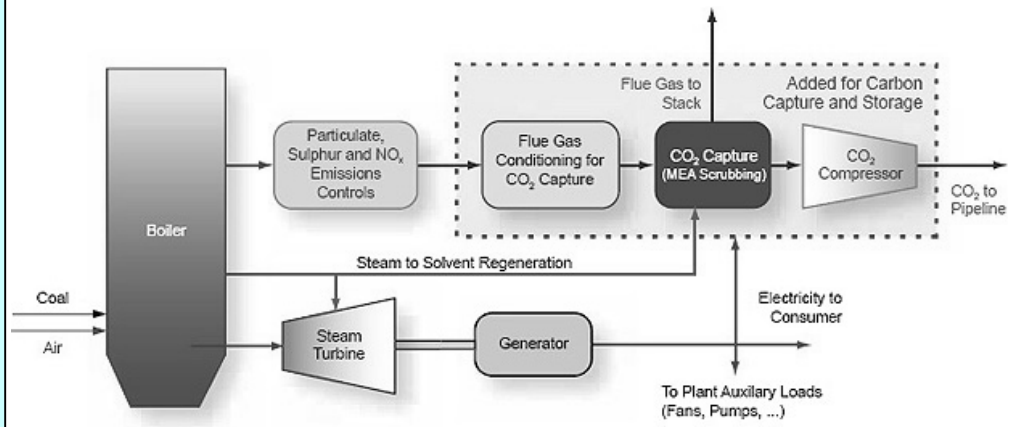
用于改进电厂循环的控制策略实施

Implementation of Control Strategies for Improved Power Plant Cycling

- 研发先进模型预测控制（MPC）算法
  - 线性MPC：动态矩阵控制（DMC）
  - 两个非线性MPC: 所提 NLMPC及文献MPC (L-MPC) 作为检验标准
- 根据要求，对带碳捕集的IGCC电厂用于发电控制实施策略
- 目前重点是将开发的方法延伸到带碳捕集和不带碳捕集的超临界煤粉(SCPC)电厂
- Developed advanced model predictive control (MPC) algorithms
  - Linear MPC: dynamic matrix control (DMC)
  - Two nonlinear MPC: proposed NLMPC and literature MPC (L-MPC) as benchmark
- Implemented strategies for integrated gasification combined cycle (IGCC) plant with carbon capture for power generation control according to the demand
- Current focus is on extending developed methods to address cycling of supercritical pulverized coal (SCPC) plants with and without carbon capture



IGCC电厂发电选点踪迹



超临界煤粉(SCPC)电厂示意图

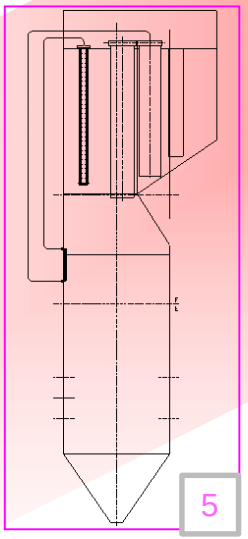
亮点-路线图 Highlights & Roadmap

埋存与驱油
Storage & EOR

燃前捕集30MW
30 MW Pre-Comb.

300MW分级转化
300MW poly-gen. demo plant

先进发电
Adv. Power Gen.



USC挂件试验
USC Test

微藻规模化养殖
Large Scale Algae cultivation

富氧燃烧
Oxy-Comb.

微藻碳捕集与生物固碳
CO_2 Sequestration and Fixation with Microalgae

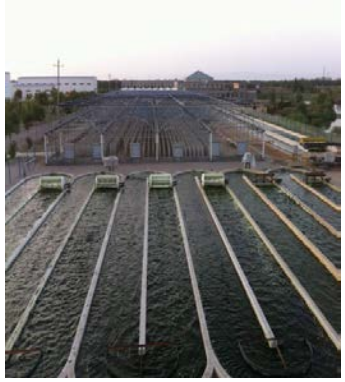
微藻实验室与小规模室外实验

Lab and small scale outdoor experiments

1000平方米小型中试

1000m² small Pilot

- Achieve long term stable operation
- Obtain a CO_2 fixation rate at 30g/m²/d
- Improve biomass yield by 30% compared to SERC 1.0
- Separation and purification for product such as EPA
- Develop contamination control approaches



3英亩微藻养殖中试示范

3 acre large pilot demonstration

- Set up a 3-acre cultivation facility
- Biomass productivity 18 g/m²/d
- Conduct Techno-economic and lifecycle analyses of CO_2 capture and recycling
- Develop multiple high-value algal products

200平方米微藻养殖 200m² algae cultivation → 1000平方米微藻养殖 1000m² algae cultivation → 3英亩微藻养殖中试实验 3 acre pilot algae cultivation

2010 — CERC1.0 — 2015 — CERC2.0 — 2020

基础研究 Basic research → 室外试验 Outdoor testing → 小型中试 Small pilot → 大型中试 large pilot

ENN新奥 用我所能 善待明天

浙江大学 ZHEJIANG UNIVERSITY

DUKE ENERGY

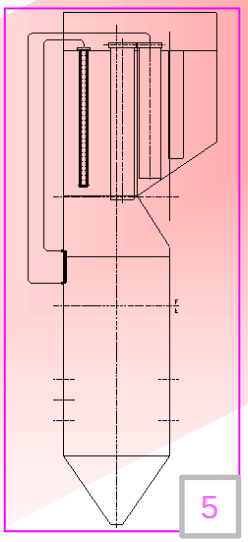
亮点-路线图 Highlights & Roadmap

埋存与驱油
Storage & EOR

燃前捕集30MW
30 MW Pre-Comb.

300MW分级转化
300MW poly-gen. demo plant

先进发电
Adv. Power Gen.



USC挂件试验
USC Test

微藻规模化养殖
Large Scale Algae cultivation

富氧燃烧
Oxy-Comb.

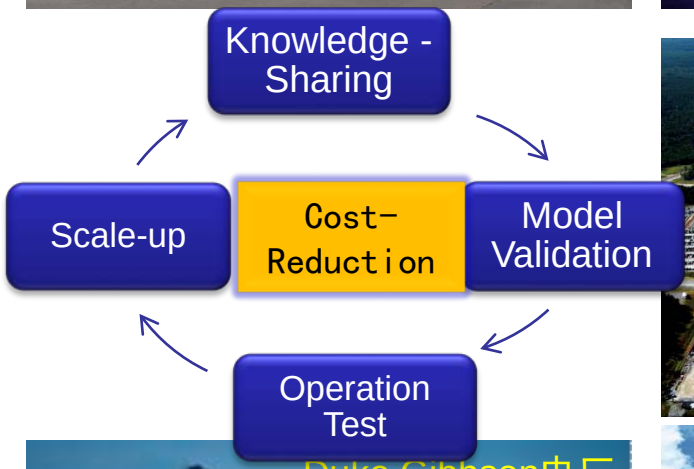
富氧燃烧工业及大型示范Oxy Demonstration

- 华中科技大学等在应城建设35MW富氧燃烧工业示范装置，并对神木200MWe富氧燃烧大型示范开展预可行性研究；
  HUST leads the 35MW oxy demo project in Yingcheng and the 200MWe oxy plant pre-feasibility study in Shenmu.
- 采用化学链制氧与富氧燃烧耦合，使富氧燃烧的发电成本降低35%；
  Combine CL oxygen production with Oxy-combustion to reduce the generation cost by 35%.

目 录 Content

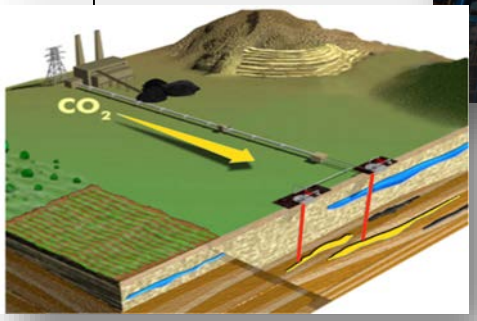
- 背景意义
  Background
- 一期成果与亮点
  Phase I Achievements
- 二期项目及成果展望
  Phase II Highlights
- 感受与体会
  Future Directions

大型示范及经验共享-促进第一代技术的商业化
Knowledge Sharing on Large-scale Demo is Critical



二期合作研究目标

在一期的基础上，再经过五年的合作努力，使现有CCUS技术完善和成熟，特别是为规模化放大和商业化应用开拓新的局面；并为新一代CCUS技术的发展和推进展现出新的亮点。



Thank you for your attention