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The Application of CCS Technology in China: Lesson from the Sino-Italy Collaboration on Coal Fired Power Plants

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Abstract

Carbon Capture and Storage (CCS) technology is one of the most promising technological solutions to realize low-carbon utilization of fossil fuels in a large scale. Under the leadership of the Ministry of Science and Technology (MOST), China and Italy initiated the "Sino-Italy Cooperation on Application of CCS to Coal Fired Power Plants" (SICCS) project which not only promoted CCS technology exchanges and scientific research collaboration between both countries, but also conducted a pre-feasibility study on a full chain demonstration project, including capture of CO2 from coal fired power plant, CO2 transport and storage. This paper will introduce the overall R&D collaboration progress on this project. It first reports activities designed to raise CCS capacity in China and to facilitate the knowledge sharing between Chinese and Italian academe, key outcomes of the SICCS project including the first and second Sino-Italian Scientific Meetings on technology exchange, information sharing, and preliminary feasibility study for CCS demonstration project in China. Then, this paper investigates the preliminary feasibility study of a 1.0 Mt/y carbon dioxide (CO2) capture unit for an existing coal fired power station in China carried out by experts from both China and Italy. The study results obtained with reference to Chinese 600 MWe thermoelectric power plant were compared with those of Italian CCS demonstration project. Finally, this paper concludes main results of the collaboration and preliminary study, raises a new cross-boarder science and technology collaboration mechanism based on industrialization of scientific research cooperation and technology exchange by co-conducting demonstration projects. It also extracts main features

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of the processes and technologies that may be applied to the demonstrative application of CCS to the 600 MWe unit of Chinese coal power plant.

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Keywords: CCS, Coal Fired Power Plants, China, Italy

1. Introduction

The greenhouse gas most commonly produced by our activities is CO2 that is responsible for 63% of man-made global warming. One of the main sources of CO2 in the atmosphere is the combustion of fossil fuels-coal, oil and gas. Since the Industrial Revolution, the concentration of CO2 in the atmosphere has increased by around 37%, and it continues to rise. International Energy Agency (IEA) forecasts that by 2050, Carbon Capture and Storage (CCS) could become the biggest contribution to emissions reduction technology among single technologies.

China is one of the countries with the fastest growing in economy in the world and is facing a long-term challenge in meeting its energy demand. It has witnessed rapid growth in terms of its population and its per capita demand for energy. As shown in Figure 1, the demand for energy in the county has risen from 5.7 million tonnes of coal equivalent (tce) to 0.57 billion tce to 3.066 billion tce over the period from 1978 to 2009, respectively[1]. Parallel to China's rapid energy consumption, China's total emissions of CO2 have risen from 1.483 billion tonnes in 1978 to 6.9896 billion tonnes in 2008 representing an annual average growth rate of 5.2%[2]. Figure 2 gives an overview of the annual CO2-emissions in China in the period 1978-2008. Carbon Capture, Use and Storage (CCUS) technology is considered as an important technology option for clean coal utilization. Chinese government has defined clearer energy strategies to face the increasingly serious energy and environmental issues, by setting out reduction targets as intensity of carbon emissions per capita GDP reduced by 40%-45% by 2020 compared to 2005 values. China's 2011-2015 Plan aims to reduce carbon emissions intensity by 16%-17% through the development and implementation of a series of energy saving programs.

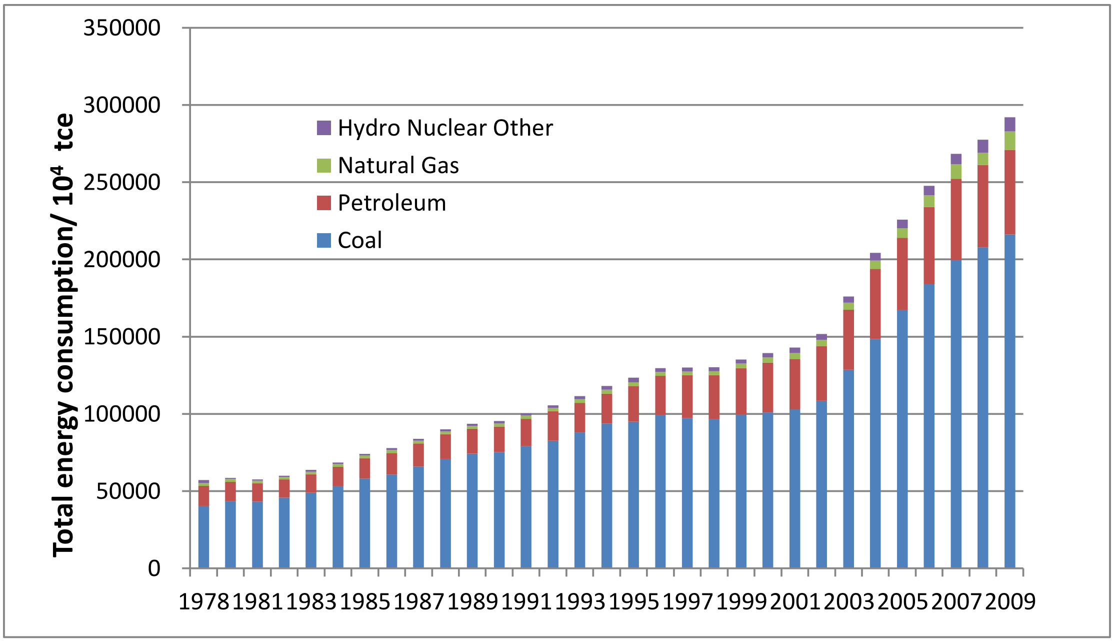

Fig. 1. Total energy consumption and composition in China in history
Source: China Statistical Yearbook, 2010.

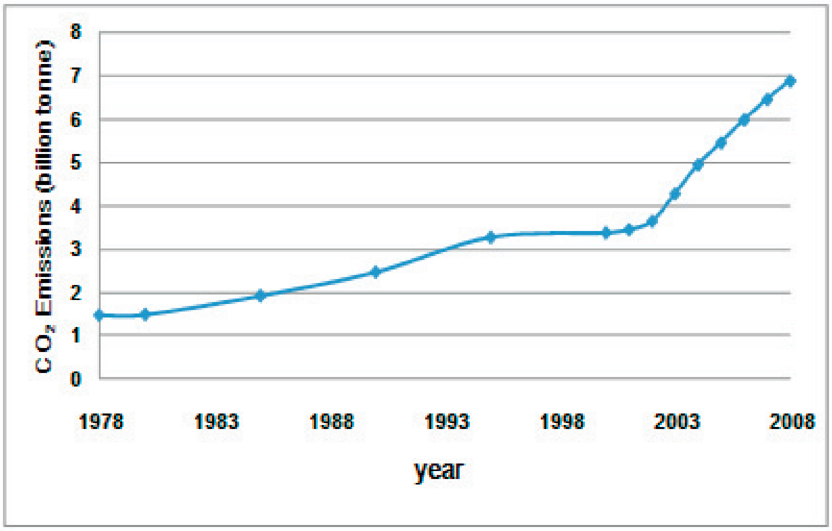

Fig. 2. Annual CO2 emissions in China from 1978 to 2008
Source: calculated based on BP data

To help fulfill the potential of CCS, the European Commission is sponsoring and coordinating the world's first network of demonstration projects, all of which are aiming to be operational by 2015. The goal is to create a prominent community of projects united in the goal of achieving commercially viable CCS by 2020. The CCS Project Network fosters knowledge sharing amongst the demonstration projects and leverages this new body of knowledge to raise public understanding of the potential of CCS. This accelerates learning and ensures that the potential of CCS can be safely fulfilled, both in the EU and in cooperation with global partners. Based on mutual interests in CCS technology, agreement on Sino-Italy Cooperation on Clean Coal Technologies including CCS and USC Power Generation was signed by Italian and Chinese partners.

2. The significance of CCS demonstration in China

2.1 The development of CCS in China

Coal based electricity generation is expected to account for the largest and rapidly growing share of power capacity in China. China's increasing involvement in CCS projects should be considered against the background of its energy-security agenda. That agenda is complex, but at its core are the targets of security of fuel supply, availability of affordable and reliable electricity supply, and access to key energy technologies. Assessing how CCS could help contribute to longer-term Chinese energy-security goals is the primary motivation behind China's CCS efforts so far.

China's CCS efforts began with a series of central-government policies supporting CCS research and development. In late 2005, the Ministry of Science and Technology signed a CCS memorandum that initiated government-sponsored CCS research. In 2006, the National Medium and Long-term Science & Technology Development Plan (2006-2020) formally designated CCS a "cutting-edge technology" in pursuit of clean and high-efficiency use of coal (a broader high-priority energy target in China). China's Science & Technology Action on Climate Change in 2007 established that CCS efforts will focus on R&D, capacity building, and demonstration of CCS technologies. China's State High-tech Development Plan, the 863 Programs[†], later allocated 300 million RMB

[†] In 1986, to meet the global challenges of new technology revolution and competition, four Chinese scientists, WANG Daheng, WANG Ganchang, YANG Jiachi, and CHEN Fangyun, jointly proposed to accelerate China's high-tech development. With

(43 million USD) to CCS technology development from 2008 to 2010 and further formalized China's pursuit of this technology. While these policies support important CCS research in China, they are not geared towards CCS deployment. Table 1 illustrates the important information of the on-going CCS projects in China:

Table 1 CCS Related National and International Cooperation Projects in China

International Cooperation Projects		
Projects	Donors	Objectives
NZEC (Phase I, II, III)	UK	final aim is to build CCS demonstration in China
COACH	EU	to prepare for large-scale use of coal for poly-generation with CCS
STRACO_2	EU	to discuss CCS Regulation, opportunities and challenges China and EU face in terms of cooperation in CCS monitoring and control and collaborative opportunities in the future
MOVECBM	EC, China	to improve the current understanding of CO_2 injected in coal and, hence, the migration of methane thus ensuring a long-term reliable and safe storage
CACHET	EC	aims to develop technologies to reduce greenhouse gas emissions from power stations by 90%
CAPRICE	EC	to promote international cooperation and exchange in the area of CO_2-capture using amine processes
GeoCapacity	EC	to investigate the CO_2 geocapacity potential, including the saline, oil fields and coal seams
China-Canada ECBM Projects	China, Canada	to build pilot plant for Coal bed methane technology and CO_2 storage project
Tianjin Dagang CCS Project	EU, China	to establish a carbon capture and storage project in China using EES Tech's carbon management and storage technology
Sino-Japan CCS cooperation	China, Japan	to jointly develop a CCS and enhanced oil recovery (EOR) project
Chinese Advanced Power Plant Carbon Capture Options (CAPPCCO)	UK, China	aims to form Carbon capture characteristics database for existing & planned plants
Developing Carbon Dioxide Capture and Storage Guidelines for China	US	focus on the guidelines for safe and effective CCS and a framework for the post-closure stewardship
China-Australia CAGS Project	to be started by 2009	to deliver the technology transfer to facilitate China's own assessment of sites for geological storage of CO_2
Chinese Government Supported Projects		
Projects	Donor/Partners	Objectives
Utilizing Green House Gas as resources in EOR and Geological Storage	MoST	to study CO_2 EOR technology and to build some EOR pilot projects
Fundamental research on the syngas production based on coal gasification & pyrolysis	MoST	to develop multi-generation system with independent intellectual property rights and satisfied with Chinese conditions and to realize low-cost & high efficiency & less pollution power generation, oil as substitute fuel, char & tar combined generation, and CO_2 emission reduction
The fundamental research on the high efficiency transfer of natural gas & syngas	MoST	aims at the catalyst objective of controlling activation & selecting conversion
Technologies and Policies Road Map for CO_2 Control in China	NSFC	to map out the blueprint of greenhouse gas control technology routes suitable for China, and recommend the advices to the government for establishing greenhouse gas control policies.
The high efficiency heat-work transfer problem study of gas turbine	MoST	to research on the energy transmission, conversion & utilization and the CO_2 removal process in the system
Development of Carbon Capture and Storage	MoST	aims at the advanced international technology to develop CO_2 capture technologies
CO_2 Injection/Sequestration in Deep Coal Seams for CBM exploitation	MoST	to study the CO_2 injection/sequestration in Deep Coal Seams for CBM exploitation in China

strategic vision and resolution, the late Chinese leader Mr. DENG Xiaoping personally approved the National High-tech R&D Program, namely the 863 Program.

Integrated Research on CO_2 Emission Reduction, and its Resource Recycling, Low NO_x Combustion, SO_x Control and multi-pollutants removal	MoST	study on integrated control of eliminating multiple pollutants in coal-fired power plants

Chinese Enterprise Actions		
Projects	Donor/Partners	Objectives
Pilot program in Jilin oilfield established by Petro China	Petro China	to build EOR pilot program in Jilin oilfield
Huaneng's Greengen Project	Huaneng	aims at the development and demonstration & popularization of hydrogen production by coal gasification, hydrogen gas turbine combined power generation, fuel cell power generation and coal based energy system with CCS
Huaneng's CO_2 capture demonstration project	Huaneng	to build demonstration plant of CO_2 capture by post-combustion
ENN Resource Recycling of CO_2	ENN Group	focus on gas distribution and the exploitation of coal-based clean energy, explores hydrogen energy and bio-energy by recycling of treatment of CO_2 (CO_2) to realize zero emission and clean utilization of coal-based energy during its whole lifespan
enShhua's CCS project	Shenhua	work on research and development of the carbon capture and storage (CCS) project at its coal-to-liquids plant

2.2 The reason for demonstrating CCS projects in China

CCS is a technical option to contribute to achieving greenhouse gas emission reductions. Chinese government and industry are together taking a very positive approach to CCS deployment. The technical maturity of specific CCS system components varies greatly. Some technologies are extensively deployed in mature markets, primarily in the oil and gas industry, while others are still in the research, development or demonstration phase. An overview of the status of all CCS components is shown in Table 2.

Table 2 Current maturity of CCS system components

The X's indicate the highest level of maturity for each component. For most components, less mature technologies also exist

CCS component	CCS technology	Research phase[a]	Demonstration phase[b]	Economically feasible under specific conditions[c]	Mature market[d]
Capture	Post-combustion			X	
	Pre-combustion			X	
	Oxyfuel combustion		X		
	Industrial separation (natural gas processing, ammonia production)				X
Transportation	Pipeline				X
	Shipping			X	
Geological storage	Enhanced Oil Recovery (EOR)				X[e]
	Gas or oil fields			X	

	Saline formations			X	
	Enhanced Coal Bed Methane recovery (ECBM)[f]		X		
Ocean storage	Direct injection (dissolution type)	X			
	Direct injection (lake type)	X			
Mineral carbonation	Natural silicate minerals	X			
	Waste materials		X		
Industrial uses of CO_2					X

a Research phase means that the basic science is understood, but the technology is currently in the stage of conceptual design or testing at the laboratory or bench scale, and has not been demonstrated in a pilot plant.

b Demonstration phase means that the technology has been built and operated at the scale of a pilot plant, but further development is required before the technology is required before the technology is ready for the design and construction of a full-scale system.

c Economically feasible under specific conditions means that the technology is well understood and used in selected commercial applications, for instance if there is a favourable tax regime or a niche market, or processing on in the order of 0.1 Mt/y CO2, with few (less than 5) replications of the technology.

d Mature market means that the technology is now in operation with multiple replications of the technology worldwide.

e CO2 injection for EOR is a mature market technology, but when used for CO2 storage, it is only economically feasible under specific conditions.

f ECBM is the use of CO2 to enhance the recovery of the methane present in unminable coal beds through the preferential adsorption of CO2 on coal. Unminable coal beds are unlikely to ever be mined, because they are too deep or too thin. If subsequently mined, the stored CO2 would be released.

The widespread application of CCS would depend on technical maturity, costs, overall potential, diffusion and transfer of the technology to developing countries and their capacity to apply the technology, regulatory aspects, environmental issues and public perception.

CCS has not yet been applied at a large (e.g.,600 MW) coal fired power plant, and that the overall system may not be as mature as some of its components. Therefore it is cruel to promote studies on large scale CCS systems, as well as demonstration.

China is one of the main county that produce and use coal, and pay special attention to innovation of CCUS.

In order to address some of the technical and economical issues mentioned above, a preliminary feasibility study on 1 Mt/y CO2 capture from an existing 600 MW coal-fired power station with post-combustion technology was conducted by Italian and Chinese experts.

3. Description of Cooperative Research Project

In May 2008, the Ministry of Science and Technology of China (MOST), the Italian Ministry for the Environment, Land and Sea, and the Italian national power company, Enel signed a MoU on Cooperation on Clean Coal Technologies, including Carbon Capture and Storage Technology and Ultra-supercritical Thermal Power Technology. The parties agreed to build a constructive dialogue mechanism and identify specific areas of cooperation and potential partners to promote cooperation on clean coal technology and CCS technology and thus to lay a foundation to promote substantive bilateral technical cooperation. Under this cooperative framework, the first scientific meeting was held in Beijing in December 2008, during which preliminary consensus on cooperation was reached. In April 2009, the Department of International Cooperation of MOST organized the visit of Chinese enterprises and experts in CCS-related to Enel headquarters, R&D centers, laboratories and related demonstration projects, and reached a clear consensus on cooperation in the field of CCS technology.

In September 2009, China's Ministry of Science and Technology, the Italian Ministry of Environment, Land and Sea (IMELS), and the Italian Enel signed an "Agreement on Clean Coal Technology including CCS and Ultra-Supercritical Coal-fired Power Plants Technologies", an event which marked the formal launch of SINO-ITALY CCS Technology Cooperation Project Preliminary Feasibility Study on Engineering Application of CCS Technology in China.

3.1 Research Aim

The project aims to strengthen exchanges and cooperation among companies and research institutions between China and Italy in the field of CCS and promote the research, development and application of such technology. The project will focus on a potential CCS project in China, carry out pre-feasibility study, hold a series of technical seminars, personnel exchanges and other forms of activities, and thus, will promote the exchange and experience sharing in CCS engineering and technical fields. Learning Italian experience in pre-feasibility study and engineering of the CCS project through bilateral cooperation will be of great benefit for the improvement of the technical capacity of China's CCS technology.

3.2 Participating Parties and Organization Structure

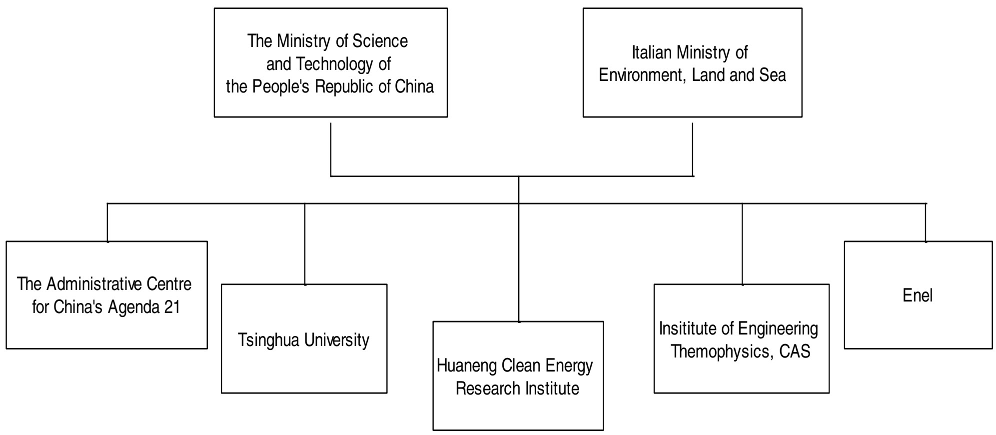

Fig. 3. The framework of organization management

3.3 Research Task

The project consists of cooperative research, personnel and technical exchanges, and other elements. The project is divided into the following three work packages:

3.3.1 Research, information exchange and sharing on CO2 capture in Coal fired power plants

To enhance the CCS-related technical and engineering level of both sides through workshops, information and personnel exchanges, as well as experience sharing and other activities based on existing CCS experimental and engineering test devices; and to support relevant basic research of China on the capture and storage technology and the development of pre-feasibility study.

3.3.2 Pre-feasibility study of the application of CCS technology in China

To conduct pre-feasibility study on potential CCS project, including CO2 capture, compression and transportation and on such aspects including systems integration, safety, environmental impact, and economic evaluation after the project site and technology are selected; and to carry out comparative study with the pre-feasibility study of Enel's CCS demonstration project in Porto Tolle.

3.3.3 Cooperation scheme for the future joint feasibility study

To make preliminary preparation for joint feasibility study as a possible next step: on the basis of the completed pre-feasibility study, to draft the activity plan and budget for both sides to cooperate in the future.

4. Project Activities and Major outcomes

4.1 The 1st Scientific Meeting: R&D and Technical Progress on CCS

On March 11, 2011, SICCS project held its first scientific meeting under the theme of CCS R&D and technical progress. Participants made a comprehensive introduction to the progress of project implementation, and exchanged views and deliberated on the development and engineering demonstration of CCS technology in both China and Italy. Opening address was given by representatives from the Department of International Cooperation of MOST and the Italian Ministry of Environment, Land and Sea (IMELS). About 60 people participated the meeting, who were representatives from project executive agencies, namely, ACCA 21, China Huaneng Group, Institute of Engineering Thermophysics of China Academy of Sciences, Tsinghua University, and Enel, and experts from such institutions as Peking University, China University of Petroleum, Yanchang Oilfield, etc.

After the meeting, experts from both sides visited Huaneng Group' Shidongkou (Shanghai) demonstration plant with a capture capacity of 120,000 tons of CO2 per year.

Outcomes: Proceedings of the 1st Scientific Meeting on Research and Development Activities on Carbon, Capture and Storage.

4.2 The 2nd Scientific Meeting: Recommendations to Design and Operate a Coal-fired Power Plant Integrated with CC Units and CO2 Storage

From Dec. 11 to Dec. 15 2011, SICCS held its second Scientific Meeting in Italy, under the theme of Recommendations to Design and Operate a Coal-fired Power Plant Integrated with CC Units and CO2 Storage. The meeting was aimed at strengthening bilateral technical exchanges and exploring the possibility of further deepening cooperation and broadening its scope. Representatives from government authorities of the two countries, including China MOST, Italian Ministry for the Environment, Land and Sea, Italian Ministry of Economic Development and Italian Parliament addressed at the opening session. At the meeting, participants from both sides carried out thematic discussions on topics including CCS-related policies of China and Italy, post-combustion CO2 capture technology and process design, design and construction standards for CCS projects and its integration with power plants, and environmental impact assessment measures of CCS projects.

During the meeting, the Chinese delegation visited Enel's R&D center and CO2 capture demonstration devices at the local power plant in Brindisi, and a series of thematic discussions were conducted.

Outcomes: Proceedings of the 2nd Scientific Meeting on Recommendations to Design and Operate a Coalfired Power Plant Integrated with CC Units and CO2 Storage

4.3 Preliminary Feasibility Study for Application of CCS Technology in China

This pre-feasibility study has considered possible pathways towards large-scale CO2 capture technologies in China, by an assessment of the available CO2 capture technologies, their development status in China and the potential for early applications of these technologies in greenhouse gas emission reduction context.

Huaneng Clean Energy Research Institute (CERI), Institute of Engineering Thermophysics, Chinese Academy of Sciences (IET) and Tsinghua University (THU), with the support from ENEL and Administrative Centre for China's Agenda 21 (ACCA21), conducted the studies to evaluate the technical and economic feasibility of a 1 Mt/y CO2 capture unit retrofit to an existing 600MW coal-fired subcritical power generation unit in Huaneng Tongchuan Power Station with post-combustion technology. The design and operation guidelines for Power Unit (PU), Carbon Capture Unit (CCU), Compression and Transportation system (C&T) are studied by modelling and analyzing its pros and cons based on knowledge and experience in CO2 capture, aiming to better understand and apply this technology in a realistic way. Features of the preliminary feasibility study include:

- The capture system of the pre-feasibility study was conducted based on self-owned intellectual property rights as well as design and operation experience by Chinese participating organizations;

- Efforts were given to the comparison and optimization among multiple steam supply programs for the integration of capture unit and the thermal system in power plants, and the team conducted innovative technical and economic analysis on the capture system coupled with solar energy;
- Initial calculations were conducted on the investment and operation costs for the entire capture system based on existing experience;
- Comparative analysis was carried out in the pre-feasibility study with Italian CCS demonstration project.

Outcomes: Report on Preliminary Feasibility Study on CCS Application in China. Completed Interim Technological Reports include:

IR1: Scope and main contents of the pre-feasibility study
IR2: Power Unit selection and characteristics
IR3: Power Unit - Steam cycle modeling and characteristics of flue gas treatment
IR4: Preliminary design of flue gas treatment system modifications
IR5: Summary of power unit research findings
IR6: Selection of capture technology and parameters for Carbon Capture Unit
IR7: Defining engineering criteria for CCU integration
IR8: CCU layout and preliminary findings of P&ID
IR9: Summary of Capture Unit research findings
IR10: Selection of CO2 compression and transportation system
IR11: Summary of compression and transportation unit research findings
IR12: Report of the comparison study of the pre-feasibility study with the Enel demo project

4.3.1 Aim and scope of Preliminary Feasibility Study

The pre-feasibility study, was developed by coupling CCS design experiences matured by ENEL, which designed the advanced power stations Torrevaldaliga North and Porto Tolle and those of prominent Chinese Institutions CHNG-CERI, Tsinghua University, IET-CAS coordinate by MOST-ACCA21 had, as scope and main objectives, the following:

- Description of the existing power plant where the CCS unit will be integrated;
- Definition of the general criteria for the CCS unit design and specification of energy and mass balance (IN/OUT of capture section);
- Evaluation about different solutions for the CCS unit integration with the power plant and definition of the arrangements for the thermal cycle and exhaust flue gas treatment plant;
- The knowledge and experience on research, development and demonstration of post combustion CO2 capture technologies, and the reason for the selection of the capture technology;
- Description of the reasons for the technological choices and evaluation about storage site;
- Preliminary design for the CO2 treatment and compression system and for the transport section;
- Preliminary investment estimation of the CO2 capture project;
- Suggestions and next steps towards development of a 1 Mt/y CCS demonstration project.

4.3.2 Description of the selected base plant

The principles for selection of the base case were very comprehensive, such as the demonstration effect, space availability for construction area and for plant extension for the carbon capture unit, environmental constraints, subsidy of electricity price in local government etc.

The site selection criteria for different type of power plant are listed in Table 3, which illustrates the specialties of PC+CCS power plant compared to the regular power plant.

Table 3 Site selection criteria for different type of power plant

Criteria for selecting site	Regular power plant	PC+CCS power plant

Load	Heat Load Electricity Load	Heat Load Electricity Load
Economic performance	Investment Cost O&M Cost Payback time(PBT) -	Investment Cost O&M Cost Payback time (PBT) Subsidy of electricity price Incentive of el. price Additional Cost
CO_2 Capture	-	Tolerability of the plant Additional Water consumed
CCS	-	Distance of transportation Cost of transportation Safety of transportation Capacity of storage Geological conditions of storage site Risk of storage Cost of storage
Fuel	Fuel Conditions (Availability, Quality)	Fuel Conditions (Availability, Quality)
Environmental Impact	Local environment conditions Environmental Impacts	Local environment conditions Environmental Impacts
Construction condition	Traffic conditions Local space Construction conditions Geologic hazard Hydro meteorological conditions	Traffic conditions Local space Construction conditions Geologic hazard Hydro meteorological conditions

	Water source	Water source
	Legal and regulations	Legal and regulations
Social impacts	-	Support from local government
		Public acceptance

Huaneng Tongchuan Power Plant (HT) of China Huaneng Group (CHNG) is selected as the base power plant, located in Potou town, Yaozhou district, Tongchuan city of Shaanxi Province, covering an area of 435 Mu (~0.29 km2) in total. It is 70 km away from Xi'an, the capital city of Shaanxi province, as shown in Figure 4.

Fig. 4. Location of Huaneng Tongchuan Power Plant

Sufficient space is available for capture plant and related modifications, no space limitation was revealed for the installation and integration of a capture plant.

Tongchuan and its surrounding areas abound in coal mines. HT is 60 km away from Tongchuan coal mine. The subordinate collieries of the Tongchuan mineral bureau include Yuhua、Xiashijie、Chenjiashan. In addition, there are many local collieries as supplement. On one hand, abundant coal can be guaranteed in long-run supply, on the other hand, coal mine is potential reservoir for CO2 through the application of ECBM.

HT is 400 km away from Yanchang Oil field, owned by Yanchang Petroleum which is the 4th largest crude oil enterprise in China. Its major oil fields are in the middle and north part of Shaanxi Province with more than 12 million tons of crude oil production per year. Its major oil production facilities are distributed in Dingbian, Jingbian, Hengshan and Wuqi, where the potential storage place for EOR is located:

- Dingbian Oil Production Company holds 1518 oil wells which can produce more than 1.2 million tonnes crude oil per year;

- Jingbian Oil Production Company possesses 2293 oil wells at present, which can produce more than 1 million tonnes crude oil per year;
- Hengshan Oil Production Company have 1000 oil well approximately at the moment with an annual crude oil production of about 300,000 tonnes;
- Wuqi Oil Production Company – an oil drilling and production base with oil E&P, crude oil production, gathering and purification, storage and marketing in one piece, has an annual crude oil production over 2 million tonnes.

Experiments on EOR have been carried out in Yanchang Oil field, at various oil wells in Yulin and Yan'an. The oil recovery of the test wells are enhanced by 45% at maximum.

The installed capacity of HT Phase I project is 2 600 MW, funded by Huaneng Power International, Inc. The project started officially on Mar.1, 2006 and lasted about 21 months. Unit 1 and 2 finished the 168-hour continuous trial operation test under full capacity on Nov.8 2007 and Dec.12 2007, respectively. Both were put into operation by the end of 2007. The three major equipments applied in Phase I projected were provided by Harbin Boiler Company, Dongfang Turbine Co., Ltd and Dongfang Electric Machinery Co., Ltd. The single-row direct air-cooling system provided by Harbin Air Conditioning Co., Ltd worked on the main engines. Indirect air-cooling systems provided by SPX were used on small engines. Three-phase double-winding step-up transformer was selected as the main voltage transformer. It has the highest parameters of domestic equipments as a 600 MW subcritical unit with air-cooling system.

4.3.3 General design criteria for CCS unit

The choices of design are defined by general criteria according to:

- The operation of the thermo-electric power plant must be independent by operation of CCS unit. The power plant should be operated as same as the state before being retrofitted by CCS. Meanwhile, the operation of CCS unit should follow the operation of power plant.
- Minimize the energy and material consumption and optimize the integration of the CCS island, minimizing the loss of performance. The integration (especially the steam integration) between the CCS island and power plant should be the focus of system optimization.
- Minimize the footprint of the capture unit and optimize the system efficiency.
- Simplify the supervising system, minimize the requirement of maintains and operation. The existing workers of the power plant should be able to operate and maintain the CCS equipments after being trained.
- Design in accordance with the state and local Health, Safety and Environment regulations.
- Minimize of waste flows modifying the flue gas characteristics at the inlet of CCS unit (pollutant concentration, temperatures, etc.), according to the best performances of the flue gas treatment train.
- To perform calculations a typical flue gas composition must be considered, fixing a coal of reference (typical coal used in the selected power plant).
- NOx, PM and SO_2 concentrations must be consistent with the values of the power plant technical specifications. In particular, SO_2 content in the flue gas at the inlet of the CCS unit must be evaluated according to the specific adsorbent technology that will be used.

4.3.4 Basic design of CO_2 capture Unit

The design of the CO_2 capture and compression sections are based on the flue gas data. The capture process is simulated using an unclosed flow sheet to make the flow sheet much easier to converge, while keeping the overall water and MEA balance to zero, and the lean loading of solvent out of stripper and into the absorber the same. The parameters and results of the simulation are shown in Table 4 and Table 5. The energy requirement was 3.69 GJ/ton CO_2, which agrees well with the numbers reported in industry today. Depending on the state-of-the-art technology of column manufacturing, the column diameter is chosen as 12 m.

Table 4 Absorber parameters and results of CO_2 capture unit

Packing type	Structured, 250Y
Stage	35

Column height m	20
Column diameter m	12
Top pressure kPa	125
Bottom pressure kPa	130
Inlet flue gas temperature °C	40
Inlet lean solvent temperature °C	40
MEA (wt.%)	30
Solvent/Gas ratio(mole flow)	4
Lean solvent loading(mole CO_2/mole MEA)	0.24

Table 5 Stripper parameters and results of CO2 capture unit

	Parameter
Stage	13
Reboiler pressure kPa	180
Condenser pressure kPa	170
Reboiler heat duty MW	529
Heat duty per ton recovered CO2(GJ/tCO2)	3.69
Rich solvent loading(mole CO2/mole MEA)	0.50
CO2 removal efficiency	0.8

4.3.5 Preliminary investment assessment

The capture costs have been based on the experience obtained as result of the design, construction and operation of CHNG CO2 capture demonstration plants, using commonly accepted scale-up rules. An overview of these costs is given in Table 6. It indicates that the levelised capital costs and the energy costs are dominated the overall cost.

Table 6 Overview of capture and compression costs for 1 Mt/y capacity CO2 capture plant

	Costs estimation
Total capital cost (10^6 RMB)(*)	1200
Levelised capital cost(**) (RMB/ton CO2)	180
Levelised O&M (RMB/tonCO2)	18
Energy costs (RMB/tonCO2)	152
Total (RMB/tonCO2)	350

**15% capital recovery factor*
*** costs CO2 transportation and storage systems are not included being such data influenced by site and CO2 reuse if there are any CO2*

4.3.6 Main results from prefeasibility study

The prefeasibility study can be preliminarily summarized with reference of HT power plant that:

- The initial inspection of the plant site has not revealed space limitations for the installation and integration of a 1 Mt/y CO2 capture plant.
- Based on the knowledge and experience obtained from pilot plants, amine based process is the most reliable, economic and efficient one at this stage for the development and demonstration of a 1 Mt/y scale capture plant.
- The analyses have shown that penalties with CCS application to power station may reduce performance of Tongchuan power plant, the overall efficiency is about between 28.8-33.7% depending on steams from different pressure turbines. This comes up to an efficiency loss of about 12.2-7.3% compared to a state-of-the-art power plant without CO2 capture. Solar energy is a possible way to reduce the energy penalty of CO2 capture.
- Indicative investment costs are estimated to be 1200 million RMB (±20%) for the proposed amine based CO2 technology 1 Mt/y capture project. The total specific costs are 350 RMB/ton CO2. These costs were based on initial assessment of the capture, compression costs, which can be only mitigated by further development of the technologies (solvent innovation, gas cleaning technologies, thermal integration design) and CO2 utilizations, for instance: CO2 EOR, chemical synthesis and ECBM. The overall development of CCUs can be achieved in the framework of international cooperation, sharing knowledge, facilities, experiences and communications among energy companies and stake holders to accelerate the introduction of the technologies suitable to create conditions for sustainable developments.

4.3.7 Technical results from prefeasibility study

- Power plant selected for CCS Demo-Plant

The Power Plant (location to be defined) will have a capacity of 3x660 MWe, with the high efficiency of the thermal cycle (44% net). The USC boilers will be of “once-through” type, with spiral tubes furnace water walls and will be operated in “sliding pressure” mode (see Table 7).

Table 7 Main characteristics of Chinese and Italian Power Plants (without CCU)

	Tongchuan Power Plant (China)	**Power Plant (Italy)**
Power Plant Capacity	2x600 MW_e	3x660 MW_e
Boiler type	Subcritical	Supercritical
Steam Cycle	Single Reheat	
Steam Parameters	16.7 MPa/538 °C 3.43 MPa/538 °C	25.3 MPa/604±4 °C
Condenser	Direct Air Cooling 13.5 kPa/48.31 °C TRL 28 kPa/66.5 °C	
Net Efficiency	41.1 %	44 %
FGD SO_2 out	200 mg/Nm^3	<100 mg/Nm^3
DeNOx NO_x out	200 mg/Nm^3	<100 mg/Nm^3
FF PM out	not available	< 15 mg/Nm^3

The unit at the power plant on which the demo CCS plant will be installed is designed to be powered by pulverized coal or to co-fire coal and biomass (biomass co-firing up to 5% of the total heat input, e. g. wood chips).

Regarding coal, the power plant will be designed to utilize a variety of different qualities. Only as reference in the Table 8 the main coal characteristics are reported.

The power plant will be designed and constructed to assure an environmentally compatible use of coal for power production, satisfying the more stringent regulation on emissions, effluents and residues.

Table 8 Coal Properties

Proximate analysis (weight % as received)	**Tongchuan Power Plant (China)**	**Power Plant (Italy)**
Moisture	11.4	6.53-15.53
Ash	18.31	3.53-16.00

Volatile Matter	36.87	24.6
Fixed Carbon	33.42	54.4

	Tongchuan Power Plant (China)	Power Plant (Italy)
Heating Value LHV (MJ/kg)	21.42	24.93-28.93

Ultimate Analysis (Weight % Dry Ash Free)	Tongchuan Power Plant (China)	Power Plant (Italy)
C	86.86	63.39-71.93
H	3.55	3.54-4.81
N	0.64	1.19-1.69
S	0.73	0.3-1.0
O	8.22	5.92-11.47

Key factors of the new power units will be the high efficiency thermal cycle (44% net), and extremely low pollutant emissions. The net specific CO2 emissions of the plant will be about 790 g/kWh for the design coal.

The optimized combustion system is designed to comply with 445 mg/Nm3 NOx concentration at boiler outlet, to be reduced to less than 100 mg/Nm3 peak concentration at the stack through ammonia injection in an “high dust” SCR equipment (see Table 1-3).

Particulate is reduced to less than 15 mg/Nm3 (see Table 1) peak concentration at the stack through the installation of fabric filters; this equipment is considered to be the most efficient way for the abatement of both the total and the fine particulate (PM10 and PM2,5).

SOx are reduced to less than 100 mg/Nm3 (see Table 1-3) peak concentration at the stack through a wet FGD equipment using limestone-gypsum process. The gypsum produced will be sold being in compliance with chemical and physical characteristics of Euro Gypsum Specifications.

Much care has been adopted to reduce the liquid discharge close to zero by treating WFGD liquid blow-down in a crystallizer.

- ◆ Capture Process
- ● Design Basis

The demo plant will be able to treat a flue gas flow rate of 0.81 MNm3/h, corresponding to 40% of the flue gas coming out from Unit (660 MWe) and to a power capacity of 250 MWe net. The design CO2 capture efficiency on mass basis of the CCU is 90% of the treated flue gas, producing about 4500 t/day corresponding to approximately 1 Mt/y of CO2. In Figure 3, a typical process scheme is shown.

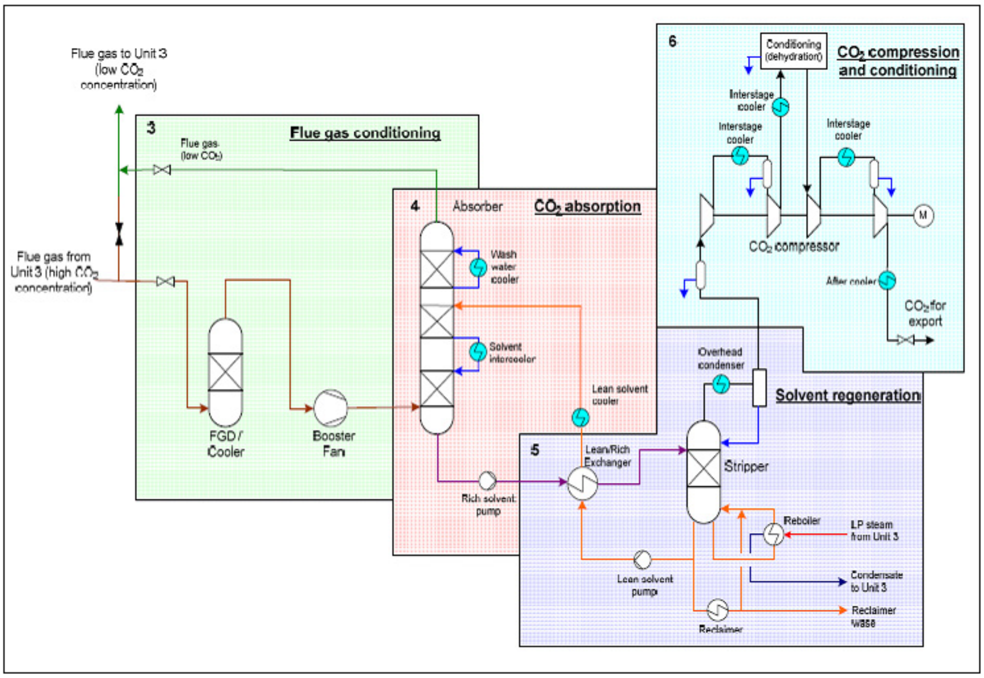

Fig. 5. Process scheme for CCU

The plant configuration for the carbon capture unit is of the "side stream" type. The Carbon Capture Unit is fed with desulphurized gas taken before the Gas - Gas Heater of the Unit, after the existing wet-FGD.

The flue gas are routed to a pre-treatment section, in which the cooling and SOx removal will be carried out, in order to minimize the degradation of the solvent to be used for the absorption process and to reach the adequate temperature for the absorption process. Approximately, > 95% of the SOx is absorbed from the flue gas; the temperature of the flue gas will be reduced to a value in the range 35-45°C according to the process used in the selected technology. The cooling and the desulphurization could be realized into a single equipment or in a 2-Stage DCC, depending on the selected technology.

The fan is located downstream the DCC and is used in order to overcome the pressure drop through the entire capture plant. The fan will be a single stage type, equipped with flue gas flow rate control device. Adequate systems aimed at noise emission reduction will be provided.

The flue gas are then sent to the absorber column, designed to remove 90% of the carbon dioxide contained in the flue gas. The absorber is made up of two/three packed beds, realized with structured packing. Detail size of the absorber will depend on the final technology selected.

The flue gas enters the bottom of the absorber and flows upward, reacting with the solvent solution, in a counter-current mode. The structured packing provides a high interfacial area, low pressure drops and minimal overall column size. Solvent is distributed across each bed with channel type liquid distributors. Intercooling between the beds could be provided in order to remove heat generated by the exothermic absorption reaction, increasing the solvent CO2 carrying over capacity.

On the top of the absorber, one or more water washing packed bed sections will be provided, in order to cool the treated gas leaving the absorber, to recover entrained solvent and to remove solvent degradation components.

The treated flue gas at about 40 to 50°C, through the Gas-Gas Heater (GGH) and to the stack for the discharge to the atmosphere, while the carbon dioxide-rich solvent leaves the absorber and is pumped by the rich solvent pump, to the regeneration section (stripper), in which the CO2 chemical absorption process is reversed.

The carbon dioxide-rich solvent that leaves the bottom of the absorber is sent to one or two lean/rich heat exchangers, in which the temperature of the rich solvent rises up to about 100°C, in exchange with the lean solvent, that is re-circulated back to the absorber, after a further cooling to a temperature of about 40 to 45°C, needed for the absorption process.

The stripper is made up of two packed beds, with random or structured packing; a washing section on the top of the stripper is provided. The operating pressure of the stripper is about 1.8 bar(a), while temperature will be about 120-122°C

The CO2 rich solvent from the lean/rich heat exchanger enters the stripper below the wash section and flows down through the packed beds, in counter-current to stripping steam, which removes CO2 from the rich solvent. The solvent is distributed across each bed with channel type liquid distributors. The semi-lean solvent is collected on the bottom and is sent to the reboiler, where it is heated by condensing low pressure steam and where the stripping steam, mainly consisting in water and CO2, with traces of solvent, is generated. The vapour flows up the stripper through the packed beds and exchanges heat with the falling rich solvent liquid, promoting the CO2 desorption and solvent regeneration.

The reboiler return pipework delivers the heated two phase mixture at a temperature about 121-122°C to the stripper below the packed bed; the remaining liquid is separated by gravity from the steam and CO2 vapours. The lean solvent liquid is then then extracted from the bottom of the stripper and passed through the lean/rich exchanger to recover heat to the incoming rich solvent flow.

In order to remove impurities from the circulating solvent, a small percentage of the lean solvent flow is routed to a cleaning system to remove particles (introduced from the flue gas), pollutants, trace elements and degradation products.

A reclaimer is installed in order to maintain solution quality. A slipstream of the lean solvent leaving the bottom of the stripper is send to the reclaimer to remove heat stable salts and high molecular weight degradation products. The reclaimer system will be brought into service when degradation product concentrations in the circulating solvent exceed 1% w/w, operating in a discontinuous basis.

In the reclaimer unit also caustic soda (NaOH) is injected in stoichiometric amounts to react with Heat Stable Salts (HSS) to recover the molecular amines. Amine is liberated by boiling the solution utilising condensing high pressure (HP) steam and is returned to the main solvent loop. At the end of the reclaiming cycle, demineralised water is fed to the reclaimer to improve the amine recovery and reduce the quantity of amines remaining in the unit. The waste will contain organic and inorganic sodium salts, non-volatile impurities such as fly ash, small amounts of amine and high molecular amine degradation products, and water. Waste volume is reduced by utilising as HP steam at highest available pressure.

In the washing section of the stripper, water is used to wash entrained solvent out of the vapour stream and remove some of the vapour phase solvent from the overhead. The resulting vapour from the top of the stripper, containing CO2 saturated with water, is then cooled and water is partially condensed in a condenser, down to 40-50°C, using cooling water, or, if suitable, vacuum condensate from Unit, that could optimise energy integration. The two phase mixture from the condenser is sent to the overhead accumulator, where the CO2 is separated from the condensed water.

The CO2 rich vapour is sent to the CO2 product compressor; in case of high pressure in the stripper, or when the CO2 is out of specification it can be vented to the absorber stack ducting return to Unit.

- Integration between the Power Plant and the Capture Process

The power plant Unit provides steam (both low and high pressure) needed for the operation of the CCU.

Low pressure steam is necessary in the stripper unit, in which the rich solvent is regenerated through the removal of the CO2. The LP steam provides heat to the semi-lean solvent at the bottom of the stripper column; the resultant vapour passes upwards through the packed beds, providing sufficient heat to strip the CO2 from the downward flowing rich solution.

High pressure steam from Unit is used to heat a slip stream of the lean solution leaving the bottom of the stripper in the reclaiming section, in which heat stable salts and high molecular weight degradation products are removed.

The steam condensate from reboiler and reclaimer is recovered to the Unit steam cycle without sub-cooling, in order to recover all the sensible heat of the condensate.

To optimize the heat integration between Unit and the CCU, vacuum condensate from Unit steam cycle condenser is available and will be used as cooling medium to recovery low grade heat at the CCU.

Unit will also provide the electric power needed for all the auxiliaries and the CO2 compressors.

- Compression and Conditioning Units

As described in the previous section, CO2 will be extracted from the exhaust stream of the Power Plant by a CCU. In order to transport the CO2 to the storage location it is necessary to compress and condition the gas. These functions will be carried out by a new compression plant, which will be located in the existing turbine hall made available by the removal of power generation Unit. The turbine hall will be renovated and refurbished for this purpose.

Detailed development of the design of the compression plant will be carried out during the FEED, in which several options concerning the plant process operation and types of equipment will be developed. The final compression pressure of the CO2 will be defined later according to the final CO2 reservoir storage study. However, at this time certain expectations of the compression plant's form and function can be stated.

Untreated CO2 gas will exit the CCU at approximately 1.5 bara and 37-50°C. The compression plant will compress the CO2 for transport via onshore/offshore pipeline to the injection site. predominantly dense phase transportation is expected. From pre-FEED study of the overall project conditions, for the options of 10" and 12", 120 km export pipeline, it is estimated that the CO¬2 will need to be compressed to around 127 bar and 105 bar respectively. The final optimization of route length and pipeline sizing will be performed in the CTS-FEED to be undertaken in the next phase; for the gas compressors system an indicative outlet pressure of 140bara is used.

The CO2 compression will be performed by 2x50% compressors. The number of compression stages will be dependent on the selected technology, but on the basis of the preliminary information obtained, it is expected that 7 ÷ 8 stages will be required. Depending on the final delivery pressure, it is possible that the last compression stage will be replaced by a pumping stage, as an option for energy saving.

4.4 Plans and Schemes for Future CCS Cooperation

The CCS integration in power station provides a number of questions that must be evaluated during Feasibility study and during Front End Engineering Design execution and many of these are emerging from D4 report which opens a variety of possibilities that are requiring, for a final decision, very detailed analyses on processes and components. Expertise from several companies should be involved and fully integrated to the feasibility study team since the beginning of SICCS Phase 2 for a better development, for instance of the Enhanced Oil Recovery (EOR) and CO2 storage in oil field, modification of steam turbine, integration of solar systems to limit the steam flow rate derived from steam cycle, as well as carbon and capture unit and its integration to power unit. For the reasons mentioned above, the Phase 2 plan proposed in the following should be considered as preliminary proposal to be used as base for discussion at the kick-off meeting of the phase 2. Phase 2, being a feasibility study, will be necessarily subject to a new Agreement, according to the China authority procedures for energy, should include terms and conditions to allow strategic approval of feasibility study, FEED, plant construction as well as CCUS demonstration, even though it will be subjected to the final investment decision.

The report, focused to map out the possible next steps of the Sino-Italy cooperation on CCS technology development and demonstration, is based on the pre-feasibility study, for planning and budgeting mainly feasibility study of CCUS application to a coal fired power plant to be jointly inspired by Enel and CHNG as part of the project outcome.

Outcome: Report on Phase 2 Planning and Budgeting: Plan and Budget for a Feasibility Study on CCS Application to a Coal-fired Power Plant.

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