Significant Research Outcomes[1]

U.S.-China Clean Energy Research Center (CERC)
Advanced Coal Technology Consortium (ACTC)

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CERC-ACTC Phase 2 was awarded in early 2016. In this short time, the project team has built on the successes of CERC-ACTC's first phase and established a strong team of research and industrial partners, while simultaneously developing new tools for data dissemination and outreach. Notable in the accomplishments in this first project year of the second phase of CERC-ACTC has been the development of a strong technical research portfolio that has drawn broad support from industrial partners, including Duke Energy, Southern Company, GE (Alstom), LP Amina, Jupiter Oxygen, Stock Equipment Company, Arch Coal, Peabody Energy, and Gas Technology Institute. In an effort to be more responsive to the needs of industry, ACTC introduced a regular webinar series where scientists present their research and inform the team about their progress, and solicit input. These webinars have been well attended since their inception in summer 2016, and provide an opportunity for direct feedback from industrial and research partners. Other accomplishments include a joint technical meeting with the U.S. and Chinese research teams in Chengdu, China, in October 2016.

1. Advanced Power Generation (Theme 1)

- ***Development of pressurized oxy-combustor:*** Researchers from Washington University in St. Louis (WUSTL) (U.S.) are completing construction of a staged, pressurized oxy-combustor (SPOC). This demonstration, initiated in ACTC's first phase, continues joint work into the second phase between WUSTL, Huazhong University of Science and Technology (Wuhan, China), and industrial input and support from Arch Coal, Peabody Energy, and Stock Equipment Company. The SPOC process is expected to provide a 7% gain in net plant efficiency, produce a concentrated stream of CO_2, and has performance benefits on widely varied coal types, allowing for application in various regions of both the U.S. and China. (CERC-ACTC Phase 1 and Phase 2)

- ***First-of-a-kind experimental system:*** Power plants equipped with advanced ultra super-critical (A-USC) boilers have the potential to dramatically improve efficiency and reduce emissions compared to existing coal-fired power plants. A survey conducted by LP Amina

[1] In addition to Significant Research Outcomes, further information about each project, including partners, research objectives, collaboration, and other details are available in the Project Fact Sheets: http://www.us-china-cerc.org/pdfs/ACTC_Factsheet_Phase1_Final.pdf

[2] This document highlights the research outcomes for CERC-ACTC from both Phase 1 and Phase 2, as of December 31, 2016. As the theme areas between the two phases have changed, this document categorizes the research outcomes according to the current (Phase 2) theme areas. CERC-ACTC partners between the two phases have also changed, and as such, partners listed under a specific project for Phase 1 does not necessarily imply that the CERC-ACTC partnership is still underway. For a current list of partners please visit www.us-china-cerc.org

and Babcock & Wilcox Company (U.S.), and Tsinghua University (China) found that subcritical power plants accounted for 78% of China's coal-fired fleet in 2009, with super- and ultra super-critical units making up the remaining 22%. CERC researchers are targeting subcritical units in China and the United States with a capacity range of 300–600 MW to maximize system-wide impacts of plant efficiency improvements and emissions reduction potential. They also developed a toolbox of technologies to enable energy conservation and emissions reduction in coal-fired power plants. Separately, the development of improved A-USC boiler technologies was adopted as a national program in China. Tsinghua University and Huaneng Clean Energy Research Institute (CERI) researchers also designed and constructed a unique experimental system to study pulverized coal combustion in counter-flow flames and used the system to investigate combustion characteristics of Xinjiang Houxun coal in A-USC boilers. (CERC-ACTC Phase 1)

- ***Crosscutting power generation and coal conversion - Demonstration of advanced coal-to-chemicals poly-generation technology:*** Gemeng International (China) cooperated with LP Amina (U.S.) in building a demonstration facility for coal-to-chemicals technology in China. LP Amina's 50 MW demonstration facility in Shanxi, China, was designed to co-produce electricity and 100,000 barrels/year of chemical intermediates. The groundbreaking design allows the power plant to co-produce electric power and high-value byproducts, increasing revenues and cutting emissions. The LP Amina- Gemeng International Energy plant could reduce greenhouse gases by more than 25% compared to conventional technology. The demonstration has completed, and the venture has ended. This project provides an example of CERC's collaborative strengths that deliver benefits and access to new markets for U.S businesses. (CERC-ACTC Phase 1)

- ***Improved modeling capabilities for oxy-combustion:*** Researchers at Huazhong University of Science and Technology (China) and Babcock & Wilcox Company (U.S.) characterized four U.S. and four Chinese coals and developed computational fluid dynamics (CFD) models for U.S. and China pilot-scale test facilities. The results show cost and performance improvements in oxy-firing combustion, a process that facilitates CO_2 capture. If policies encouraging CO_2 capture are in place, the models—once validated in larger scale demonstration projects—will help facilitate and accelerate the rate of deployment of such technology in a variety of coal regions throughout the world. (CERC-ACTC Phase 1)

2. Collaboration and Knowledge Sharing on Large Project and Demonstrations

- ***Development of a knowledge sharing platform for large-scale industrial projects:*** Theme 2 aims to assist both the U.S. and China in implementing large-scale technology demonstration projects by sharing knowledge and lessons learned among project sponsors, developers, research institutions, and other participants. Advanced coal technologies are at a critical moment in technology development, and knowledge and information sharing can play a crucial role in de-risking these projects. In this project, the team intends to help identify what drives these large scale projects to succeed or fail, and understand what those

causes can teach both researchers and the private sector for future projects. Current project partners include Duke Energy, Southern Company, Air Products, General Electric, and Jupiter Oxygen in the United States; and Huaneng, Dongfang Boiler, Shenhua Coal Company, and Yanchang Petroleum in China. (CERC-ACTC Phase 2)[3]

3. CO_2 Utilization and Storage

- ***New evaluation of saline aquifer storage and enhanced oil recovery (EOR):*** Researchers from Shaanxi Provincial Institute for Energy Resources and Chemical Engineering, Northwest University, Yanchang Oil Company, and Sinopec North China Co. (China) and the University of Wyoming Carbon Management Institute, Indiana Geological Survey, and Los Alamos National Laboratory (LANL) (United States) continue collaboration on an assessment of aquifer storage and enhanced oil recovery (EOR) potential in the Ordos Basin in China. The team has assembled the geologic, petro-physical, structural, and stratigraphic frameworks of the Ordos Basin and compared evaluation methodologies for Ordos Basin with the Wyoming and Illinois Basins in the United States. Shenhua (China) provided detailed sub-surface coding information to LANL to allow accurate modeling of areas in the Ordos Basin. This model will be useful for a number of collaborations, including exploring the potential of enhanced water recovery (EWR) and EOR projects with Yanchang Petroleum and EOR demonstrations with Shenhua. The tools and concepts developed in this research can be applied to different reservoirs in the U.S. and allows for the analysis of various technology and policy frameworks or improvements in CO_2 recovery technology, and impacts on prices and various tax and revenue frameworks based on forecasted oil prices. (CERC-ACTC Phase 1 and Phase 2)

- ***Development of low-cost, low-energy CO_2 sorbent:*** University of Wyoming (U.S.) researchers are developing a novel solution for boosting the performance of CO_2 capturing amines. This solution has shown early promise for a potentially dramatic drop in CO_2 capture cost. Bench-scale laboratory testing has proven the potential of this sorbent, and is progressing to laboratory-scale testing in CERC-ACTC Phase 2. Due to the feedback from the webinar sessions and the resulting stronger collaboration between industrial partners and researchers, this project's work plan has been closely guided by its partners. To continue to assess the commercial viability of this technology, the second year's work plan focuses on conducting life cycle analysis and understanding techniques for sorbent renewal. (CERC-ACTC Phase 2)

- ***Design configurations assessed for CO_2 utilization with microalgae:*** Researchers in the United States (Duke Energy and University of Kentucky) and China (ENN Group) examined CO_2 utilization in algal growth systems using a range of U.S. and Chinese strains and different reactor designs. In its first phase, researchers developed and demonstrated CO_2 utilization technology with microalgae and transformation of algal biomass into a

[3] Research in progress; description highlights preliminary outcomes.

sustainable source of energy or other high-value products. A mutant algae strain developed by ENN showed a 15% faster growth rate than the corresponding wild type algae. Moreover, the new strain is tolerant of aggressive environments, including high temperatures. Further assessments are ongoing at Duke Energy's East Bend power plant. The accumulated data has been incorporated in a techno-economic model that will identify potential areas for improvement and economies of scale, and has identified that development of multiple product streams to maximize the utilization of the produced algae is critical to the economic viability of this technology. Work planned in CERC-ACTC Phase 2 includes a 3-acre demonstration in Zhengzhou and continued development of technology including process optimization for algal utilization. (CERC-ACTC Phase 1 and Phase 2)

- ***Pre-feasibility work on saline aquifers near GreenGen:*** Lawrence Livermore National Laboratory (LLNL), Los Alamos National Laboratory (LANL), and West Virginia University (WVU) performed a pre-feasibility study on a saline aquifer adjacent to the Bohai Basin near Tianjin, China, using subsurface data supplied by Chinese researchers, and the results are promising. The purpose of the pre-feasibility study was to clear the way for a feasibility study and enhanced water recovery (EWR) project in conjunction with the CO_2 capture system currently being constructed at the GreenGen project site. The study led to discussions between U.S. and Chinese researchers on formation pressure management during injection, which will be an important consideration when using saline aquifers for CO_2 storage. There is a high feasibility of useful water production and the ability to actively manage formation pressures. This has multiple positive outcomes, relevant for potential applications in U.S. and China, for reducing risk in saline aquifer storage and in production of low-salinity water that could be utilized for municipal or agricultural use. (CERC-ACTC Phase 1)

- ***Membrane fabrication:*** As a means to separate CO_2 from post-combustion gases, researchers at Los Alamos National Laboratory (LANL) (U.S.) fabricated a 100-nm thin CO_2-selective layer on commercially attractive support material, using LANL's Ultrasonic Spray Coating Technique (USCT). This resulted in the development of a novel polymer/ionic liquid (IL) hybrid-membrane that can achieve high-permeability in a mechanically robust platform. Such hybrid polymer/IL systems benefit from liquid-like CO_2 permeability and solubility in the IL, resulting in enhanced perm-selectivity. Polymer molecular manipulations were applied to dramatically improve IL additive retention and hybrid membrane permeability. The ultra-thin composite membrane fabrication method is now under continuous development and optimization. Large scale membrane fabrication appears to be readily achievable. (CERC-ACTC Phase 1)[4]

4. Advanced Coal Conversion

- ***Validated co-generation technology at pilot plant:*** CERC researchers from the United States (LP Amina and West Virginia University) and China (Zhejiang University) jointly

validated the modeling results of a 1 MW pilot plant for coal co-generation technology. The design combines pyrolysis, gasification, and combustion. The co-generation technology is expected to reduce maintenance costs and greenhouse gas emissions by more than 25% compared to conventional technology. Based on the validated model, researchers are now developing a co-generation system and advanced coal gasification process technology and will demonstrate the technologies at industrial scale for deployment in the United States and China. (CERC-ACTC Phase 1)

- ***Novel coal-to-chemicals polygeneration simulated and ready for testing:*** Researchers from China (ENN Group) and the United States (Lawrence Livermore National Laboratory and LP Amina) completed experiments and simulations of a coal-to-chemicals polygeneration scheme for LP Amina's calcium-carbide reactor. The simulation findings will be used to design and build a very high-temperature polygeneration reactor at laboratory scale. The results set the stage for improved operation and commercialization, with potential for scale-up in China's coal-to-chemicals markets. New polygeneration technologies are expected to dramatically reduce waste heat, water use, and greenhouse gas emissions, while improving thermal efficiency of power generation and chemical by-products production. (CERC-ACTC Phase 1)

- ***Direct synthetic natural gas (SNG) production from coal:*** ENN Group (China) and Lawrence Livermore National Laboratory (U.S.) built and tested a bench-scale, high-pressure, constant-volume reactor. Coal gas with high-concentration methane was obtained, validating the possibility of direct SNG production from coal. The team has constructed a circulating high-pressure, constant-volume reaction system for coal-to-SNG. If successful, this work will result in the development of a new approach for direct SNG production from coal with high-efficiency, low-pollution, and low-cost. (CERC-ACTC Phase 1)

5. Systems Analysis and Modeling

- ***Modeling the impact of power plant cycling and development of model-based optimal mitigation strategies:*** As the deployment of renewable energy sources increases, fossil-fuel power plants that were designed to operate at base-load conditions will need to be able to cycle their load. The purpose of this research is to quantify the effects of cycling on fossil-fuel power plants in terms of increased operating and maintenance (O&M) costs and the accompanying changes in efficiency and emissions that cycling operation will cause. This information will be utilized to develop optimal control strategies and to identify retrofit solutions to existing power plants to allow their continued efficient and cost-effective operation under these new operational conditions. Industrial partners, including Duke Energy, Southern Company, and General Electric, are providing operational and component data to guide this research, which has significant potential in increasing the competitiveness of fossil generation in the commercial sector. (CERC-ACTC Phase 2)[5]

[5] Research in progress; description highlights preliminary outcomes.

- ***Advances in simulation modeling lead to new optimal designs for CO_2 source-sink matching in Chinese and U.S. basins:*** Researchers in the United States (Los Alamos National Laboratory (LANL) and the Indiana Geological Survey (IGS)) and China (Institute of Rock and Soil Mechanics, Chinese Academy of Sciences (IRSM)) built the first-ever cost surface for linking CO_2 sources to geologic sinks for the Ordos Basin. The cost surface—which is used to identify potential CO_2 pipeline routes—was built using multiple geographic layers including topography, population, and land use. The cost surface was then used to develop carbon capture, utilization, and storage (CCUS) infrastructure that connects hundreds of existing CO_2 sources to a set of nine potential reservoir regions provided by the Chinese partners. CO_2 source data, including industry type (e.g., coal-fired power plants, iron and steel industry) and emission quantity, were used to optimize CO_2 management schemes for targeted capture scenarios ranging from 10 $MtCO_2$/yr to more than 250 $MtCO_2$/yr. The LANL-IGS-IRSM project team is currently working on the next-generation CCUS infrastructure advancements such as electricity generation targets and CO_2 utilization opportunities including CO_2-enhanced oil recovery (CO_2-EOR). Similar system analyses have been performed in the Illinois basin for the Gibson Generating Station in cooperation with Duke Energy (U.S.). In addition, LANL, IGS, and the University of Wyoming, working in both the Illinois basin and the Rock Springs Uplift (RSU) in Wyoming, have also demonstrated that inclusion of reservoir uncertainty is key to developing realistic estimates of CO_2 storage capacity and injectivity. Results from this work are being examined by local and regional leaders in China who are planning for implementation of CCUS. (CERC-ACTC Phase 1 and Phase 2)

- ***Further utilization of post-combustion simulations:*** Lawrence Livermore National Lab (U.S.) is modeling a solvent developed by Babcock & Wilcox Company (U.S.) to conduct comparisons with research performed earlier by CERC scientists from Huaneng (China) and Duke Energy (U.S.). This research will generate additional data points on the cost of capture while leveraging existing work to yield further benefits that were not initially anticipated. In CERC–ACTC Phase 2, the model will be reconfigured to include Duke Buck Station (a 600 MW combined cycle gas turbine) and re-run to compare cost and performance data on a gas fired power plant. (CERC-ACTC Phase 1 and Phase 2)

- ***Modeling of Huaneng Shidongkou post-combustion capture system:*** Researchers from Lawrence Livermore National Laboratory (U.S.) and Huaneng CERI (China) used operational data from the 600 MW Shanghai Shidongkou Power Plant to build and validate a simulation model for the post-combustion capture mixed-amine absorption process. The model allows process performance assessments under varying decision-making environments. Researchers completed the conceptual simulation of a 1-million ton per year post-combustion CO_2 capture system in Duke Energy's Gibson-3 station using technology developed by China Huaneng and demonstrated it at the Shanghai Shidongkou Power Plant. This effectively advances new capture and solvent technologies for the development of efficient CO_2 capture in existing coal plant retrofits. The simulation model revealed a number of design advances and suggested a cost of US$61–$68 per metric tonne versus

previous estimates of US$100 per metric tonne, if the same system were installed at Duke's Gibson 3 plant in Indiana. Laboratory research conducted at the University of Kentucky (U.S.) and Tsinghua University (China) under this theme identified a two-phase solvent and new catalyst family with record activity levels. (CERC-ACTC Phase 1)

- ***Reduced energy penalty from post-combustion CO_2 capture:*** Researchers from Tsinghua University (China) and West Virginia University (U.S.) simulated a steady-state scenario for CO_2 capture from a super-critical pulverized coal power plant using a monoethanolamine (MEA) solvent. Optimizing the design and operating parameters, researchers were able to reduce the simulated net energy penalty by 2.5%—from 12.7% to 10.2%. Application of advanced modeling and simulation tools enable improvements in technology and systems integration not otherwise possible, due to the complex nature of the many interacting processes present in large-scale power generators with carbon capture. Such improvements are expected to guide designs that will decrease cost and improve performance of CO_2 capture technologies. (CERC-ACTC Phase 1)