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Enabling Technology Maturation in Carbon Capture: The Role of a University Based Power Plant as a Test Facility

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Abstract

The Abbott Power Plant at the University of Illinois at Urbana-Champaign (UIUC) provides a unique facility for testing carbon capture, utilization, and energy storage technologies. This combined heat and power (CHP) facility supplies power and electricity for the needs of the UIUC campus. Despite being an operational plant, Abbott Power Plant is actively engaged in a variety of projects. These projects range in technology readiness level (TRL) and demonstrate the ability of the plant to couple field research with operational excellence. While the plant is a fossil asset (e.g., coal and natural gas boilers), it is connected through the campus grid to renewables. This connectivity provides the ability to evaluate how new technologies (e.g., capture, utilization, and energy storage) respond to variations in the grid due to the increased penetration of variable renewables. Because the plant is located on the UIUC campus, it is also engaged in educational activities at both the undergraduate and graduate level. The ability of the plant to couple operational excellence with research and development (R&D) and education makes it an important asset for the evaluation of new technologies.

Keywords: Combined Heat and Power; Large Pilot; Small Pilot; Energy Storage; CO_2 Utilization; Capture; Load Following

1. Introduction

Abbott Power Plant (Abbott) is a cogeneration (i.e., combined heat and power or CHP) facility that supplies 70-75% of the energy demand for the University of Illinois at Urbana-Champaign (UIUC) campus [1]. The plant (shown in Fig. 1) is located on the UIUC campus and owned by UIUC. It utilizes natural gas, coal, or fuel oil in its boilers and combustion turbines. This fuel flexibility enhances system reliability and helps manage energy market financial risks. If a fuel becomes unavailable, prices climb, or campus energy demands increase, Abbott can adapt its fuel sources and ensure uninterrupted service to campus.

Abbott's maximum steam production capacity, from both coal and natural gas combustion facilities, is ~1,000,000 lb/hr (~80 MWe). There are six boilers, two heat recovery steam generators (HRSGs), two gas turbines, and nine (9)

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steam turbine generators. In Fig. 1, the tallest stack is for the three coal boilers, the three stacks to the right of that are for the natural gas boilers, and the two stacks to the right of the natural gas boilers are for the HRSGs. The block flow diagram for electricity and steam flow is shown in Fig. 2. The three coal-fired boilers are chain-grate stoker design. The downstream system of the coal-fired boilers is separate from that of the natural gas-fired boilers or gas turbines.

A schematic of the coal-fired boilers and downstream pollution abatement equipment is shown in Fig. 3. Amongst the three coal boilers, two (#5 and #6) are each capable of producing up to 150,000 lb/hr of steam and another one (#7) has a capacity of producing 190,000 lb/hr of steam. These numbers translate into 15 MWe each for Boilers #5 and #6 and approximately 20 MWe for boiler #7. All three coal boilers burn an Illinois high sulfur coal. Electrostatic precipitators (ESPs) and a wet jet bubbling flue gas desulfurization (FGD) scrubber (Chiyoda (CY-121) Limestone Forced Oxidation System) are used in conjunction with the coal boilers to remove particulate and sulfur dioxide (SO_2) from the flue gas. The total capacity of the system to treat flue gas is limited to 350,000 lbs/hr. This limitation is due to the size of the wet FGD (~35 MWe).

Fig. 1. Abbott Power Plant located on the UIUC campus.

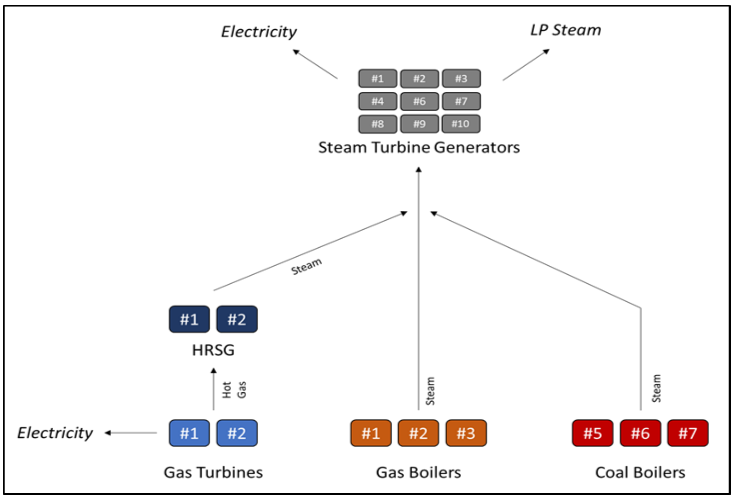

Fig. 2. Abbott Power Plant electricity and steam block flow diagram.

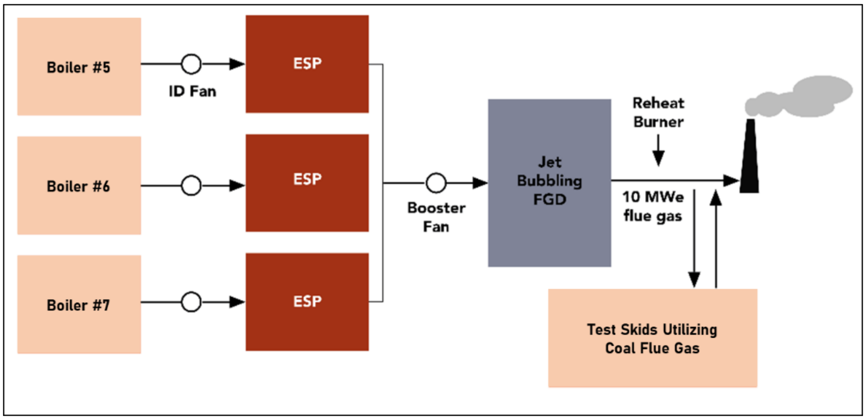

Fig. 3. Schematic of coal-fired boilers, pollution abatement equipment, and location for removal of flue gas for testing.

The overall steam cycle schematic for Abbott is shown in Fig. 4. This schematic demonstrates how Abbott provides steam and electricity to the UIUC campus for heating and power applications. The three natural gas fired boilers are each capable of producing up to 175,000 lb/hr of steam. The two HRSGs work in conjunction with the plant's two natural gas turbines. The exhaust gases from each turbine are routed with ductwork to the HRSGs. The heat provided by the exhaust gases allows the HRSGs to generate an approximate total of 45,000 lb/hr of steam. The ductwork between the gas turbine exhaust and the HRSG also is equipped with natural gas-fired duct burners. When these burners are used, the total output from the HRSGs increases from 45,000 up to 100,000 lb/hr of steam. The nine (9) steam turbines have two exhaust modes, condensing and extraction. In extraction mode, steam is exhausted from the turbine and diverted out to campus for heating.

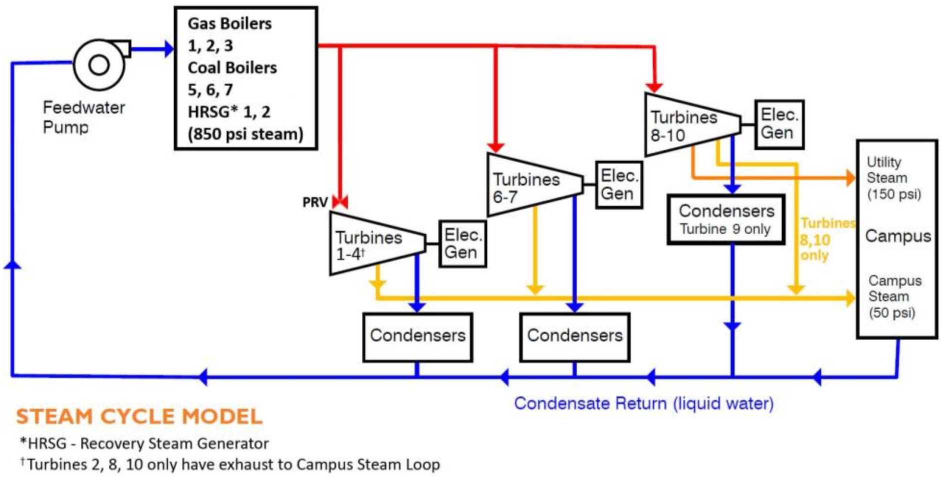

Fig. 4. Steam cycle schematic.

The UIUC campus electricity grid, steam system, and cooling water system is shown in Fig. 5. This diagram illustrates how Abbott fits in with the other campus assets. As shown in Fig. 5, UIUC generates renewable power from the campus solar farm and has a purchase agreement for wind power. The 21-acre Solar Farm-1 generates 4.68 MW power. The 54-acre Solar Farm-2 will generate 12.1 MW power by the end of 2020. The campus receives 8.6% of the wind-generated electricity from the Rail Splitter Wind Farm (~25,000 MWh). Abbott Power Plant's CHP generation is required to achieve high ramp rates and high turndown to offset the increasing renewable energy mandates of the Illinois Climate Action Plan (iCAP) [2].

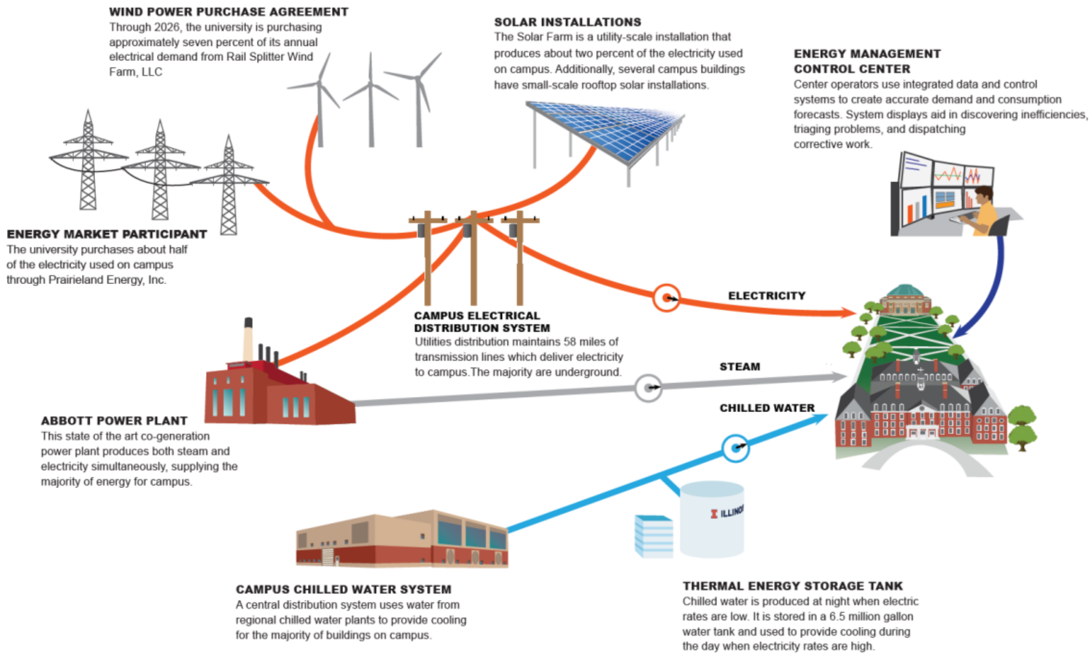

Fig. 5. UIUC campus electricity grid, steam system, and cooling water system.

2. Transitioning and Maturing Technologies at Abbott Power Plant

The technology readiness level (TRL) is often used to gauge the maturation of technologies and determine how far they are from full commercialization. TRL scales have been traditionally presented on a scale from 1 to 9, with TRL 1 implying a concept on paper and TRL 9 indicating a full commercialized technology. A modification of TRL scale for carbon capture, utilization, and storage (CCUS) was recently proposed in which the TRL scale was increased to 1 through 11 [3]. This increased scale, shown in Fig. 6, reflects the additional challenges encountered when commercializing large-scale CCUS technologies. TRL 10 and 11 indicate that the large scale of CCUS and its broad reach requires even greater integration and stability than other technologies. Note that for TRL 5 and greater, it is important to be transitioned to field-testing and evaluation.

The technology maturation process (i.e., increasing TRL) can be facilitated by having a test site that can accommodate a range of test sizes. This process is particularly intriguing when the facility is located on a university campus. Many universities focus on transitioning technologies from TRL 1 to 3 at the laboratory scale. TRLs 5 and greater require field-testing. For example, with capture technologies this means access to actual flue gas. The result is that often more advanced testing (TRL > 4) must be performed at other sites. This change in location increases research and development (R&D) costs due to traveling to the site, potential challenges in communicating with the host site, and learning how to create a more robust design that is acceptable in an actual power plant environment. Issues also arise if the host site is an operating power plant. The plant is required to achieve performance targets (financial and operational). This focus on achieving performance targets may conflict with research needs.

Abbott has been serving as a field test facility, active in carbon capture and carbon utilization (non-EOR utilization) research at a range of TRLs. Abbott has adapted its operations and procedures in order to assist in the transition of these technologies from the laboratory to field-testing. The proximity of Abbott to research facilities where laboratory tests are conducted addresses challenges outlined previously. In addition, Abbott has gained a reputation amongst power plants within the state and region as a “test bed” for emission reduction technologies. For example, Abbott was one of the first plants in Illinois to deploy flue gas desulfurization (FGD). The reputation of Abbott as being unbiased, coupled with Abbott’s willingness to share information openly with other power plants, expedites the penetration of new technologies into plants throughout the region.

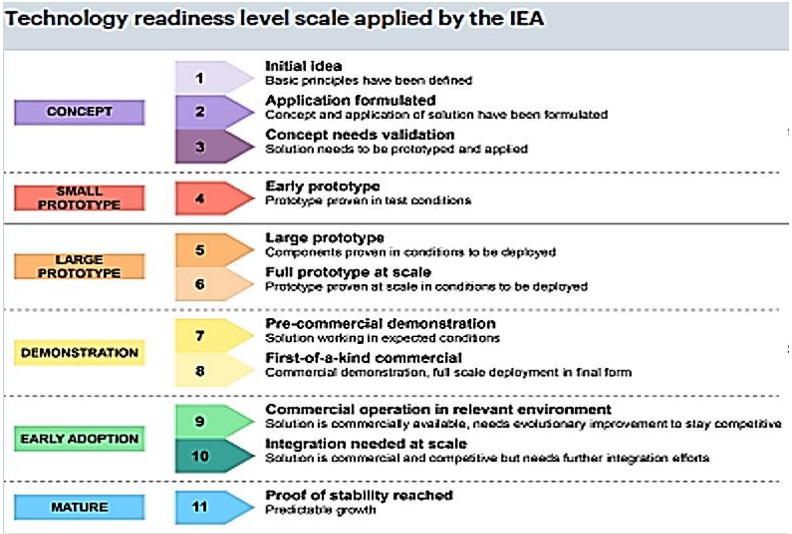

Fig. 6. Technology Readiness Level (TRL) scale proposed for Carbon Capture Utilization and Storage (CCUS) technologies.

Abbott has demonstrated the ability to bridge a range of TRLs. The facility has the ability to accommodate testing with flue gas from the kWe level to the MWe level. It has also demonstrated the ability to conduct multiple projects on-site. The ability to test with both natural gas and coal provides a means to cost-effectively conduct experiments on both types of fuels. All these factors provide a means to accelerate the transition of technologies from the laboratory to the field and then scale-up the technology. It is vital that these transitions can be accomplished while using the same host site. These advantage reduces R&D costs and reduced development time and have enabled Abbott to apply to join the International Carbon Capture Test Network [4].

3. Carbon Capture Projects at Abbott Power Plant

Various carbon capture related technologies are being tested at Abbott and the status of those projects can best illustrate space availability and accessibility to flue gas feed streams. These technologies have all matured to the point that the systems are ready to be tested with actual flue gas. All projects were funded by the U.S. Department of Energy / National Energy Technology Laboratory (DOE/NETL). Due to funding restrictions, they were tested using only flue gas derived from the coal boilers.

3.1. Biphasic Solvent-Enabled Absorption Process for Post-Combustion Carbon Capture

Abbott is the host site for testing of a transformational biphasic solvent CO_2 absorption process. The biphasic solvent is superior in CO_2 capacity and has high thermal and oxidative stability. The biphasic absorption process features a unique process configuration that allows for maintaining low solvent viscosity and a fast absorption rate. The overall project objective is to demonstrate the progression toward DOE’s transformational capture goals (95% CO_2 purity at a cost of ~\$30/tonne of CO_2 captured).

This project is a perfect example of transitioning from TRL 1 to 5 in one location and the value of being able to make the transition in a seamless fashion. Fig. 7 outlines the development of the technology from a proof-of-concept (performed as part of dissertation research) to a 40 kWe test utilizing coal-based flue gas. Because of Abbott’s ability to test with flue gas, the entire testing was done on the UIUC campus.

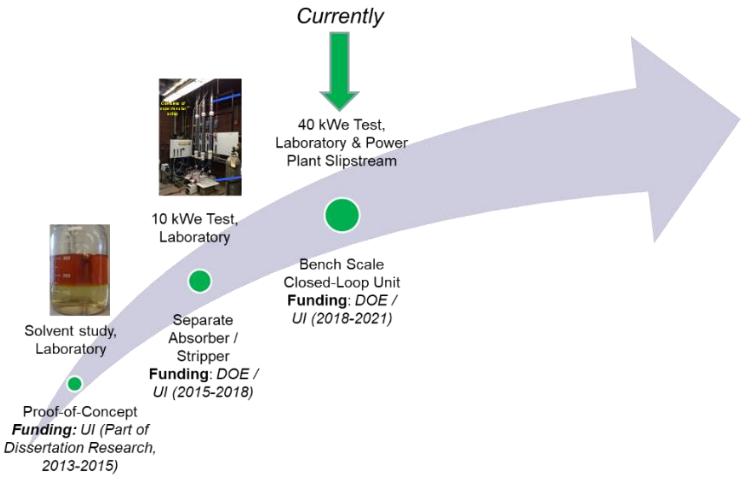

Fig. 7. Pathway to scale-up of Biphasic solvent-based capture system.

It is important to note that there is ample space at Abbott for performing multiple field tests. This area is illustrated by examining the space allocated for the 40 kWe skid mounted capture unit for the biphasic solvent testing. The space allocated for testing is shown in Fig. 8. This location provided easy access to coal-based flue gas. The ducting of the flue gas from the plant to the 40 kWe skid was also important. Fig. 9 depicts the modifications made to provide ducting for the flue gas from the plant to the unit. It was convenient to modify an existing access door to enable feeding the flue gas to the unit and then returning it to the stack. The two different size ducting are designed to accommodate the 40 kWe biphasic capture testing and the larger 0.45 MWe for the aerosol testing (described later in this document). The proximity of the test unit to the flue gas source reduced ducting and hence reduced overall costs for the project.

Fig. 10 compares the system tested in the laboratory at 10 kWe (Fig. 10a) with simulated flue gas and the scaled-up system tested with actual flue gas from the coal boilers at Abbott (Fig. 10b). One of the challenges was transitioning from columns in the laboratory (height of approximately 9 feet) to columns in the field (height of approximately +60 feet). This change required air quality dispersion assessment to assure that health and safety requirements could be met based on very conservative exposure limits for solvent emissions.

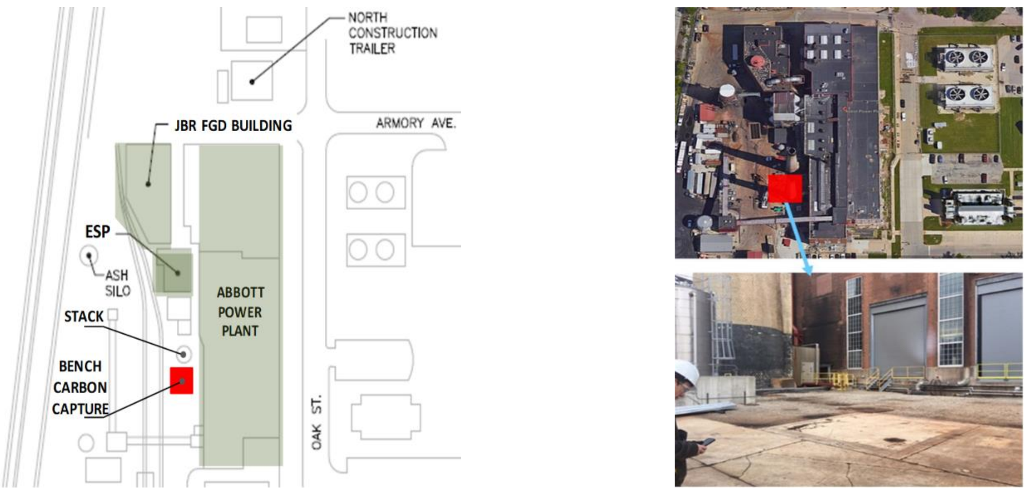

Fig. 8. (a) Schematic for location of biphasic capture site; (b) View of location prior to build.

(a) (b)

Fig. 9. Flue gas ducting for coal-based flue gas. (a) Routing of ducting from access door. (b) Side view of Biphasic unit and ducting.

(a) (b)

Fig. 10. Comparison of (a) 10 kWe system tested in laboratory with simulated flue gas and (b) 40 kWe unit evaluated with coal-based flue gas.

3.2. Aerosol Mitigation Technologies

The loss of amine-based solvents used in carbon capture has become a critical concern as the solvent-based process has scaled up. The mechanism for the loss of the amines is through the formation of aerosols. Aerosol formation and the subsequent loss of solvent has become a concern from a techno-economics perspective as well as an environmental, health, and safety concern. One of the major factors that contribute to the formation and concentration of these aerosols is the concentration of aerosol particulates in the flue gas. Flue gas is a feed stream to the capture unit. Standard ESPs and fabric filters (baghouses) are typically used to remove aerosol particulates from flue gas. However, a minimum particle collection efficiency exists for ESPs and fabric filters.

Linde corporation previously analysed both literature studies and aerosol measurements during the testing of their Linde/BASF carbon capture system at the National Carbon Capture Center (NCCC). A summary of these results is shown in Fig. 11. Experimentally, it was determined that if aerosol concentrations are equal to or less than 10^7 particles/cm^3 for particles ranging in diameter from 70 nm to 200 nm (denoted by a red dotted line on Fig. 11), there is no need for pre-treatment of the flue gas feed stream to the capture unit. It is also important to note that it has been empirically observed that power plants that are equipped with a baghouse typically will have aerosol concentrations lower than 10^7 particles/cm^3. Additional studies have shown that high concentrations (>10^7 particles/cm^3) of very fine aerosol particles with particle diameters below 200 nm cause the most severe amine losses because demister systems in direct contact coolers (DCC), scrubbers, and CO_2 absorbers are most effective at capturing particles with diameters above 200 nm along with any entrained amine in the gas phase [5].

Abbott is an excellent host site for evaluating ways to mitigate aerosol formation and hence solvent loss. Fig. 11 demonstrates that the coal-based flue gas from Abbott has an aerosol concentration that exceeds 10^7 particles/cm^3 in the particle size range of <200 nm. As a result, a test skid was fabricated to evaluate three different approaches to mitigating aerosols in flue gas. The three approaches are (1) spray tower and heat exchanger; (2) a filter developed by InnoSepra; and (3) a specially designed electrostatic precipitator (ESP). Fig. 12 depicts the skid constructed for evaluating these technologies and its location at Abbott. The flue gas feed stream for the unit is equivalent to 0.45 MWe.

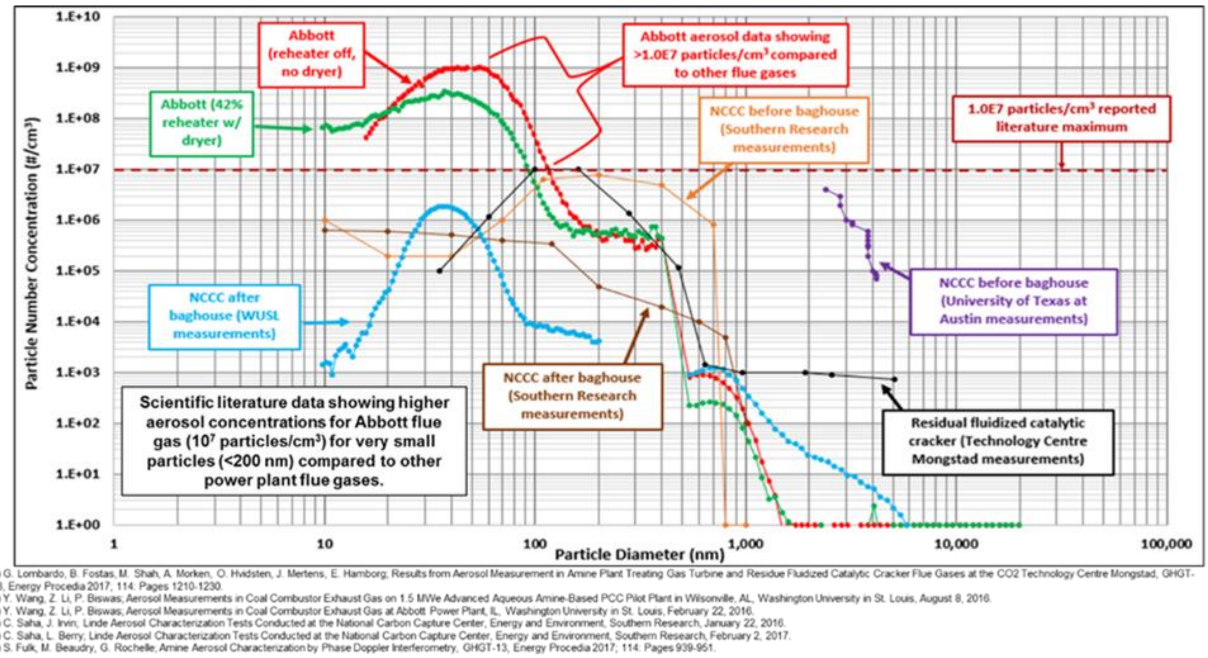

Fig. 11. Aerosol concentration as a function of particle diameter at various plants.

(a) (b)

Fig. 12. Three aerosol mitigation tested: (a) spray tower & heat exchanger, (b) InnoSepra filter and ESP.

3.3. Coordinating Biphasic Capture Solvent and Aerosol Testing

One of the challenges was coordinating location, construction, and operation of the biphasic capture solvent system and the aerosol mitigation system. Both were located close to the flue gas source and each had separate flue gas feed pipelines (see Fig. 9). This was due to the difference in size between the two systems (i.e., biphasic 40 kWe while aerosol 0.45 MWe). In addition, a field analytical laboratory (trailer) is in place and was used to house personnel and equipment for both tests. The trailer (shown in Fig. 13) is already located at a site adjacent to both the aerosol and biphasic solvent test systems. The coordination and site layout for both projects is shown in Fig. 14. Space usage has been designed to enable ease of access to equipment. Utilities are shared (when appropriate) between projects. In addition, ducting runs are minimized from Abbott to the test systems.

Fig. 13. Location of analytical trailer. Concrete pad is where aerosol testing system is located.

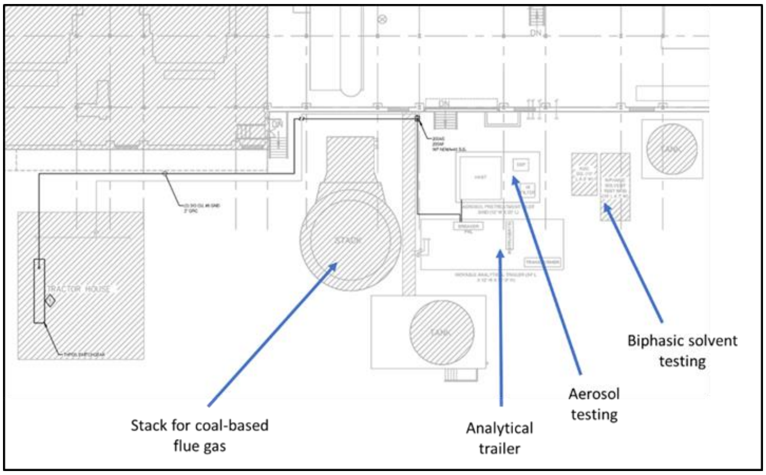

Fig. 14. Layout of aerosol and biphasic test facilities.

3.4. Other Carbon Capture Testing Locations

Previous proposals examined the installation of a Linde/BASF 15 MWe large pilot, carbon capture facility at Abbott. This system was to be located north of the facility in an area that is currently being used for lay down and storage of extra materials (see Fig. 15). This system was designed to extract flue gas from the coal-fired portion of the plant, but the design of the flue gas ducting system could have enabled testing of natural gas-based flue gas as well. Ducting was planned to run over the roof of the plant to the capture plant.

Abbott will also be the host site for the engineering scale testing of a mixed-salt process (MSP) based on ammonium and potassium salts for CO_2 capture from coal-based power stations. This system was developed by SRI International. UIUC/Abbott will be responsible for the detailed engineering, fabrication, construction, and operation of the system. The objective of the research project includes performing integrated MSP testing at engineering scale for long-term periods under dynamic and continuous steady-state conditions with a real flue gas stream to address concerns relating to scale-up and integration of the technology to coal-based power plants. The flue gas feed stream is equivalent to 0.5 MWe.

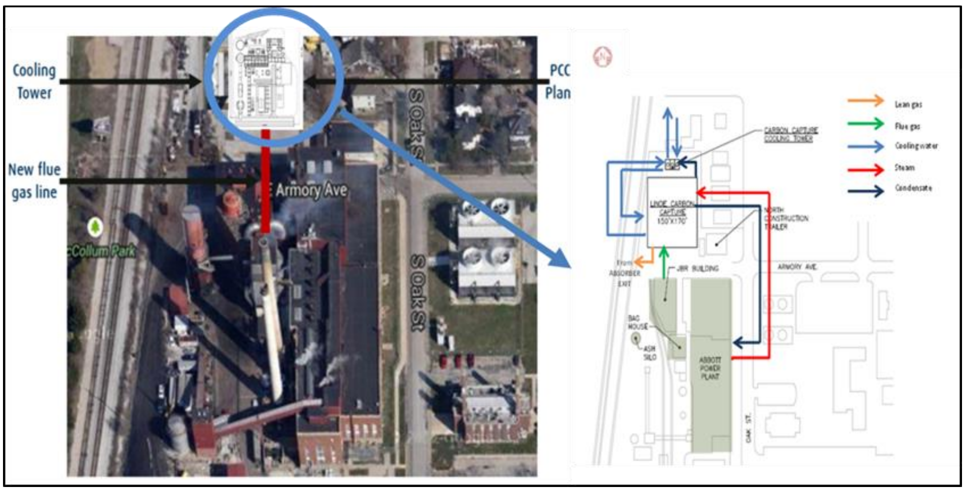

Fig. 15. Proposed location for a 15 MWe capture facility at Abbott.

4. Energy Storage Interest and Capabilities

Fig. 5 demonstrates the diversity of UIUC campus grid. Because of the increased penetration of renewables onto the campus grid, UIUC is an excellent location to evaluate the impact of incorporating energy storage with fossil assets and renewables. Abbott is an ideal asset for testing energy storage technologies because it includes a variety of fossil energy and variable renewable energy assets. It is a relatively contained system because it serves the campus grid. It has traditionally been a "testbed" for new technologies and has developed simulation programs to evaluate the impact of increased variable renewable energy assets on the power plant and the campus grid.

"Inside the fence locations" for energy storage systems are available and designated in Fig. 16. Abbott has been included as a host site in a variety of different energy storage proposals. In those proposals, the minimum size of the energy storage unit is 10 MWh. The locations indicated in Fig. 16 would meet the requirements for at least 10 MWh energy storage system design for a wide range of technologies.

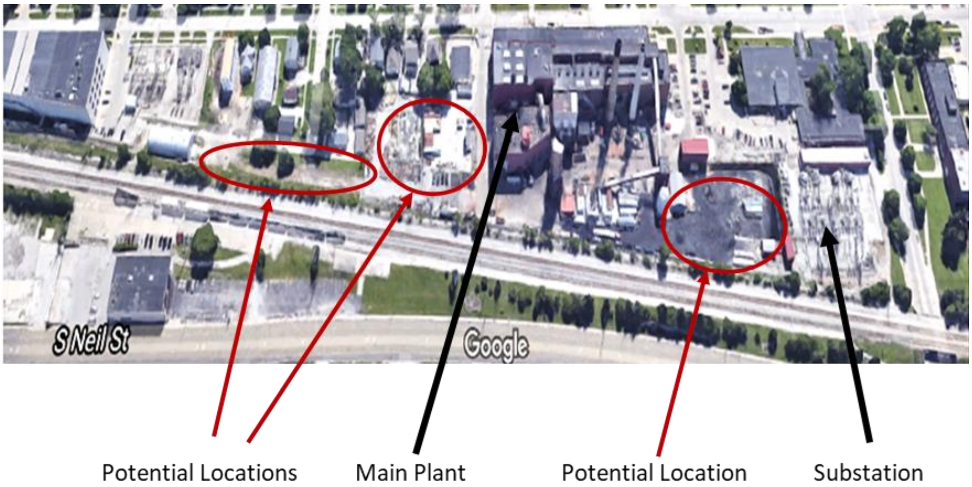

Fig. 16. View of Abbott Power Plant and potential locations for energy storage system.

5. Workforce Development, Education, and Outreach

One of the major advantages of Abbott is that it is located on the UIUC campus and has a history of being an unbiased evaluator of new technologies in the power generation industry. Abbott interacts with the Institute for Sustainability, Energy, and Environment (iSEE) as they work with academic departments to develop relevant curriculum that engage with Abbott [6]. The ability to have field testing at large scales provides a means to involve students in field testing, designing experiments, and evaluating results from testing. This affords students a unique and practice-based learning environment. Abbott has also engaged with other training groups to help train plant operators.

Abbott actively engages with the local and university communities. This engagement involves tours and discussion with Abbott professional staff. The groups Abbott interacts with ranges from engineering students to girl scout troops.

6. Summary

Abbott Power Plant on the UIUC campus offers a variety of advantages as a host site for carbon capture, CO_2 utilization, and energy storage related projects. The plant has been proposed and used as a host site for project sizes ranging from the kW level to the MW level. Space is available to simultaneously construct and evaluate technologies on site. An additional advantage is the ability to span ranges of TRLs and especially aid in the transition of early stage technologies from the laboratories on campus to field-testing with actual flue gas. Another advantage offered by

Abbott is that the campus grid continues to add variable renewable energy assets to complement the existing fossil asset (i.e., Abbott). Simulation models have been developed to examine the impact on fossil assets and the grid as these renewable assets are added. This modeling provides another metric to examine when evaluating capture, utilization, and energy storage technologies. The reputation of Abbott as a non-biased evaluator of technologies, its ability to aid in workforce development and education, along with its outreach to the local community enables the plant to further the education of the future workforce and to educate stakeholders on future trends in the power industry.

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