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Creating Markets for Captured Carbon: Progress in Illinois

Kevin C. OBrien PhD*, Steve Whittaker PhD, Sallie Greenberg PhD, Yongqi Lu PhD, Lance Schideman PhD, Vinod Patel, Nandakishore Rajagopalan PhD, Brajendra Kumar Sharma PhD, Stephanie Brownstein, Les Gioja, Jason Dietsch

Prairie Research Institute, University of Illinois at Urbana-Champaign, 615 E. Peabody Drive, MC-650, Champaign, IL 61820, USA

Abstract

In previous publications/presentations at GHGT-13, a plan was outlined for the capture and storage/utilization of CO_2 within the state of Illinois. This plan has evolved significantly due to a number of technical, regulatory, and financial factors that have occurred at both the state and federal level. A combination of successful implementation of large-scale storage projects, significant investment in research and development by the US DOE, and the advent of 45Q tax credits has created a significant driver for growth in Illinois for carbon capture, utilization, and storage (CCUS) projects. This ability to either store or utilize the CO_2 creates diverse financial opportunities for CO_2 sources within the state, hence an ability to build new markets and drivers for large CO_2 emitters within the state. A major cornerstone of this effort is to have a range of capture sites in the state that can accommodate the evaluation of capture technologies that are at various levels of maturity (i.e., technology readiness levels or TRLs). The net impact is an ability to assist Illinois in achieving its goals for grid decarbonization and clean energy job creation.

Keywords: Carbon Markets; Innovative Integration; Large Pilot; Storage; CO_2 Utilization; Capture

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1. Introduction

There has been an acceleration in the development of carbon capture utilization and storage (CCUS) technologies due to the affirmation that CCUS is vital to reducing atmospheric carbon dioxide (CO_2) levels and by the continued reduction in the cost of deploying these technologies. One of the main drivers for reducing these costs has been continued research and development (R&D) funding for larger scale projects. On the storage side, this includes CarbonSAFE-Illinois. On the capture side, it includes large pilots (10 MW), front-end engineering and design (FEED) studies, and demonstration projects. In the United States (US), 45Q tax credits have stimulated and accelerated interest in CCUS projects. This confluence of events has created the opportunity for CCUS to provide regional economic development as well as aid in the decarbonization of the electric grid. Geological storage of captured CO_2 has been shown to be a viable means to manage captured CO_2. The ability to obtain tax credits at \$50/tCO_2 has become a major financial driver in many projects. Utilization of the CO_2 through either enhanced oil recovery (EOR) or other means provides a tax credit of \$35/tCO_2 plus a revenue stream from the product(s) that incorporate the captured CO_2. Various

* Corresponding author. Email *address:* kcobrien@illinois.edu

companies are now pursuing means to utilize captured carbon including incorporation into cement, use as a feedstock to produce fine chemicals or polymers, and growth of algae (subsequently used to produce biofuels and other products). The business opportunity has improved significantly due to maturation of CCUS technologies and the development of some key policies at the national level. The opportunity to form an economic cluster based on CCUS has matured and looks promising.

2. Economic Clusters

The concept of clusters has been discussed extensively by a variety of authors. Fig. 1 outlines some of the critical factors that are needed in order to enable economic clusters to grow and prosper [1-3]. These regions benefit by a concentration of complementary resources that might include leading research universities, low cost or highly trained labor, and geographic bounty [3].

Fig. 1. Factors that enable economic clusters.

Various studies have outlined the benefits of an economic clusters focused on CCUS [4-5]. In particular, the ALIGN-CCUS industrial cluster in the European Union (EU) was introduced at GHGT-14 [6]. All CCUS clusters emphasize the importance of targeted R&D activities and the coordination of large projects for both capture and storage. This approach has been enabled in the US through the CarbonSAFE program funded by the US Department of Energy National Energy Technology Laboratory (DOE/NETL) [7]. It provides a means to connect CO_2 “sources” to CO_2 “sinks”. The regional focus of the program fits well with the cluster approach. This fit is further supported through the DOE/NETL funded Regional Initiatives to Accelerate CCUS, formerly known as the Regional Carbon Sequestration Partnerships.

3. Illinois as a CCUS Economic Cluster

3.1. Elements or Building Blocks that Enable Cluster Formation

The Prairie Research Institute (PRI) within the University of Illinois at Urbana-Champaign (UIUC) is driving the vision to build markets for carbon in Illinois and an economic cluster focused on CCUS. PRI is one of the largest research institutes within UIUC and is focused on applied R&D. As with any industrial cluster, there needs to be a combination of physical, financial, policy, and intellectual resources focused on the issue. Illinois has this combination of factors that enable it to be perform as a CCUS economic cluster.

Fig. 2 outlines the elements necessary to build a CCUS economic cluster. One of the basic elements is having excellent pore space for geological storage of CO_2. This storage is critical because geological storage of CO_2 is much more mature than non-EOR means of CO_2 utilization. CarbonSAFE-Illinois is enabled by this geological feature. Fig. 3 illustrates how DOE/NETL funded R&D programs have supported the systematic maturation of CO_2 storage within the State of Illinois.

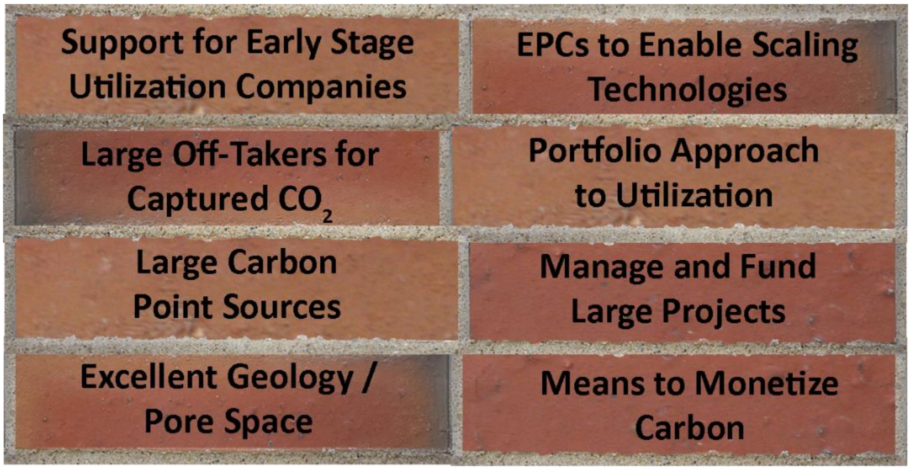


Fig. 2. Vital elements that enable the formation of CCUS based economic cluster within Illinois.

The other basic element is the ability to monetize carbon. The advent of 45Q tax credits has encouraged investors to explore CCUS projects based on the ability to gleam tax credits ($50/t$CO_2$ for storage, $35/t$CO_2$ for utilization including EOR). Building on these basic elements, Illinois and its surrounding region also has large point sources that generate CO_2 emissions. These sources emanate from both power generation and industrial sources. These CO_2 sources are outlined in Fig. 4. CarbonSAFE-Illinois has examined how to connect these sources with the appropriate geological CO_2 sinks. These plans have demonstrated the logistics and feasibility of constructing CO_2 pipelines to transport CO_2 from these large point sources to the appropriate geological storage locations.

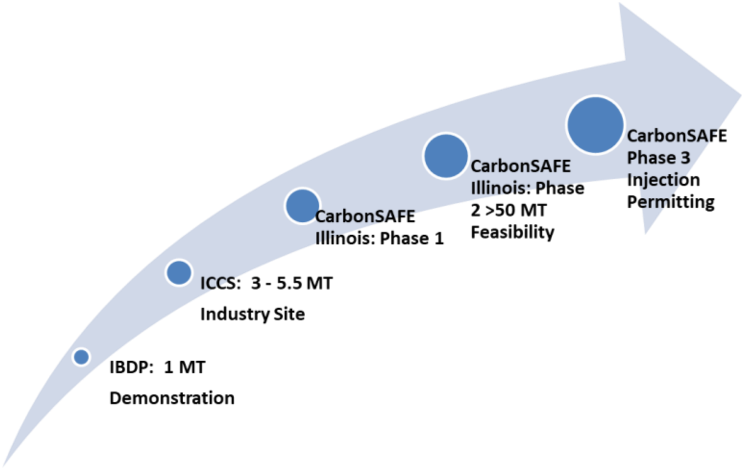


Fig. 3. Roadmap of technology maturation of CO_2 storage in Illinois.

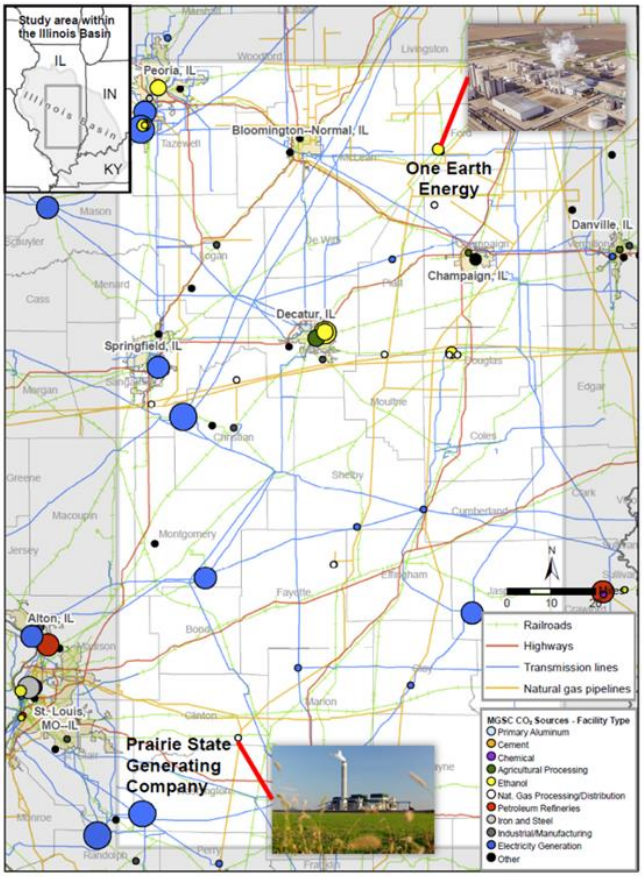


Fig. 4. Major point sources for CO_2 emissions in Illinois and surrounding regions.

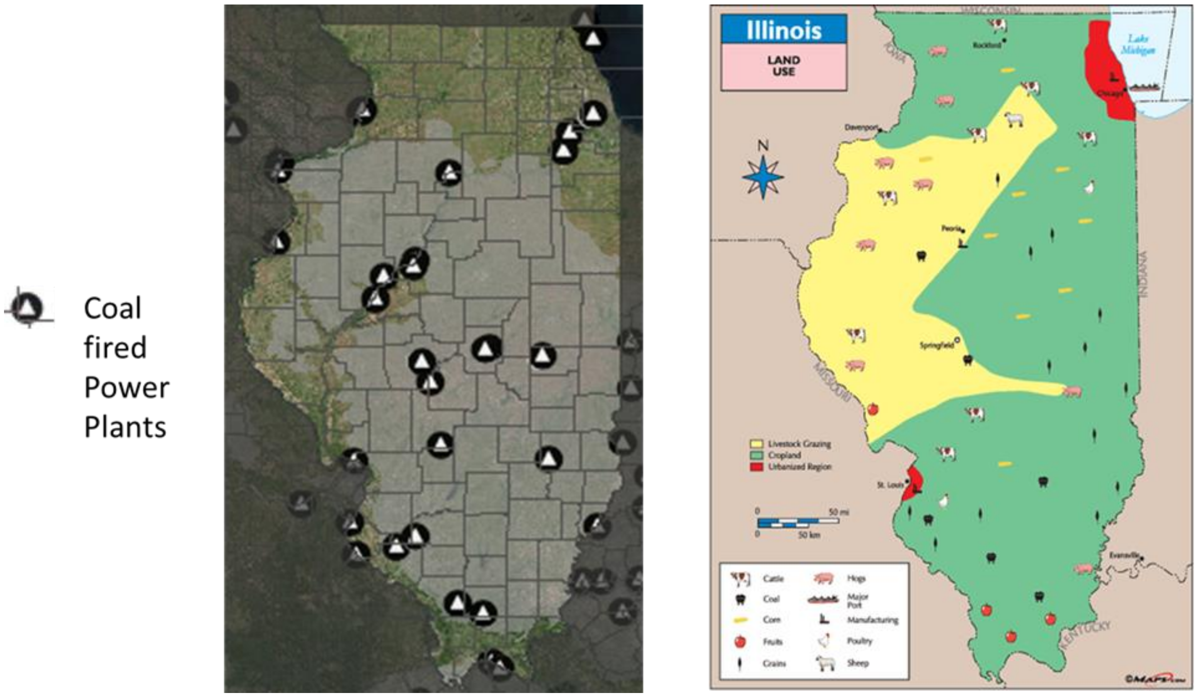
As pointed out in previous publications, it is vital to be able to construct large CCUS projects in order to make the economic cluster financially attractive. This requires the ability to bring together multiple stakeholders, build coalitions that include a variety of industries, and then provide project management and technical guidance to assure the large projects are completed on time and within budget. Because these projects are funded by DOE/NETL, it is important to have the experience and infrastructure to manage the technical and financial reporting required by DOE/NETL sponsored projects. PRI/UIUC has a history of forming teams and managing large projects on the capture and storage side. PRI/UIUC's reputation as a "neutral third party" that focuses on benefitting Illinois and its constituents plays a critical role in making these projects successful.

Once captured it is important to have "off-takers" for the captured CO_2. These off-takers include entities that will manage the geological storage of the CO_2 or entities that will utilize the CO_2 for EOR or other means. As discussed previously, geological storage is viable in Illinois and attractive for the 45Q tax credits. CarbonSAFE-Illinois has provided a forum for discussions with organizations that will manage the transport and storage of the CO_2. As with any investment, diversification is important. DOE/NETL funded studies have examined the potential for EOR applications within the state. It is important to acknowledge that the potential for EOR is much lower in Illinois than in other states. Non-EOR utilization is a much more attractive option.

Many CO_2 utilization methods have been proposed and are being developed. While there are many options, it has often been asked how economically feasible are these approaches? In many of these cases, CO_2 is a feedstock for a product in which the CO_2 is incorporated. Could the large volume of CO_2 being captured result in large quantities of the product being produced and hence depress the market price of the product? It would seem best to co-locate the facility that produces the product that incorporates the CO_2 close to the CO_2 point source. Also, it would be important to select utilization methods that will produce products that match well with the demands of the regional economy. For example, if the regional economy were primarily agriculturally focused, it would make sense to select a CO_2 incorporated product that is designed for agricultural applications.

The first step in this matching process is outlined in Fig. 5. This analysis focuses on coal-fired power plants, but the analysis could be adapted to industrial sources of captured CO_2 as well. Illinois has a significant amount of agricultural land use. Many of the coal-fired power plants are in agriculturally focused regions. This implies that if products that incorporate the captured CO_2 from the power plants were designed for agricultural applications, there would seem to be a good match between the CO_2 incorporated products and the demands of the region. This suggests that applications that generate fertilizer or produce algae that can be latter transformed into animal feed, biochar, or biofuels could match well with the demands of the region.

In order to drive innovation within the CCUS economic cluster, it is important to not only have large projects, but also a portfolio of new developing technologies. 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, while TRL 9 indicates a full commercialized technology. A modification of TRL scale for CCUS was recently proposed in which the TRL scale was increased from 1 to 11 [10]. 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.



(a) (b)

Fig. 5. Correlating (a) coal-fired power plant locations with (b) agricultural land use in Illinois.

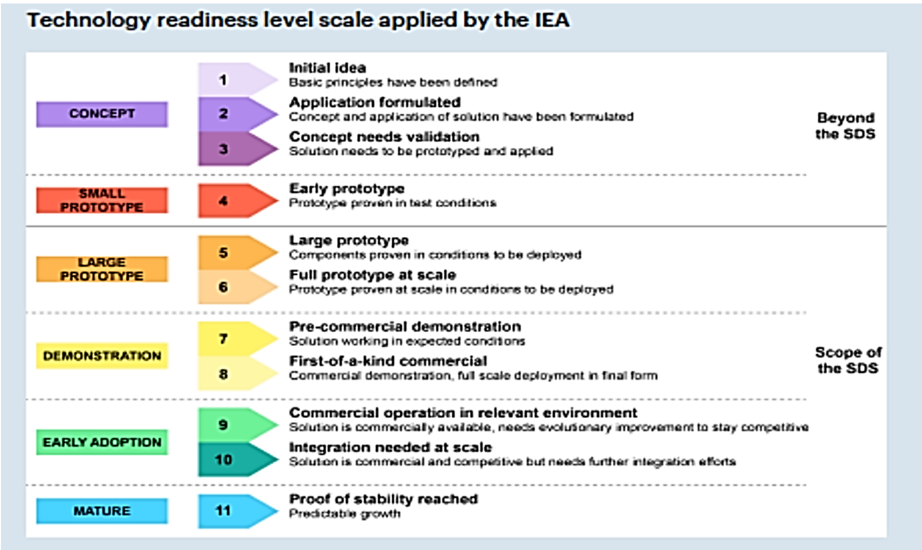


Fig. 6. Proposed expanded TRL scale for CCUS technologies.

The challenge from a research, design, and development (RD&D) management perspective is to have a diversified portfolio of projects that span as much of the TRL scale as possible. It is important to be developing early stage concepts (TRL 1-3), but critical to have technologies being tested in the field at a range of scales. It is especially important to be able to transition to the demonstration stage and beyond as soon as possible because many unknown issues that would not occur at lower TRLs will appear during these stages. This need for a diverse R&D portfolio relates to the top row of elements outlined in Fig. 2.

Within the CCUS economic cluster, it is critical to have a support structure for early stage companies. These companies will drive technology development at the TRL 1-5. This support is especially important as it relates to CO_2 utilization for non-EOR applications. Utilization for non-EOR is a developing field where a variety of approaches are being explored. Part of the important support infrastructure is access to testing with actual flue gas. The cluster should have host sites that are able and willing to evaluate these novel approaches. It is best to have hots sites that are also large point sources for CO_2 emissions.

As the TRL increases, other organizations need to be engaged. Engineering, procurement, and construction (EPC) firms take on a critical role as the technology is scaled-up. These types of partners must be part of the economic cluster development team. Host sites that are willing to evaluate technologies at the 10 MW level and above again play a critical role in the development process of the CCUS economic cluster. In a sense, host sites become an "anchor" that attract technology developers and investors to the region. Region specific business models can now be developed based on large scale testing at the host sites. It is a much more fluid process as compared to testing at host sites from other regions outside the economic cluster. The results obtained in this case must be translated and adapted to the unique needs of the economic cluster region. Technical and business risks increase significantly due to the need to translation and adaptation process.

3.2. Projects and Educational Organizations in the Illinois CCUS Economic Cluster

R&D projects and organizations are vital to the on-going growth of the CCUS economic cluster. The goal is to have a portfolio of projects that spans the range of TRLs listed in Fig. 6. As mentioned previously, it is important to have host sites in the cluster to facilitate maturation of the technology. Educational organizations also play a critical role. They are a source for human resources (engineers, operators, etc.) and for innovative approaches. They can also create, nurture, and support early stage companies.

Fig. 7 outlines the projects and research organizations engaged in the Illinois CCUS economic cluster. Large storage projects based on storing CO_2 captured from ethanol plants were the first types of projects to be initiated. The educational component of this project was UIUC and Richland Community College. The success of this work has resulted in the CarbonSAFE effort outlined Figs. 3 and 4. Large capture projects have also started over the past two years. These projects are located at large point sources: Prairie State Generating Company (PSGC) and City Water, Light, and Power (CWLP). Educational resources on the capture projects include UIUC, Southern Illinois University, and Illinois Eastern Community Colleges. These large capture projects are in regions called out for potential geological storage as defined by CarbonSAFE in Fig. 4.

Three host sites are available within the cluster and are listed in Fig. 8. The range of facilities enables evaluation of CCUS technologies at various sizes. All facilities have coal-fired power generation, but Abbott Power Plant has natural gas-fired generators as well. This variety creates the opportunity to evaluate technologies with coal and natural gas and perform a side-by-side comparison.

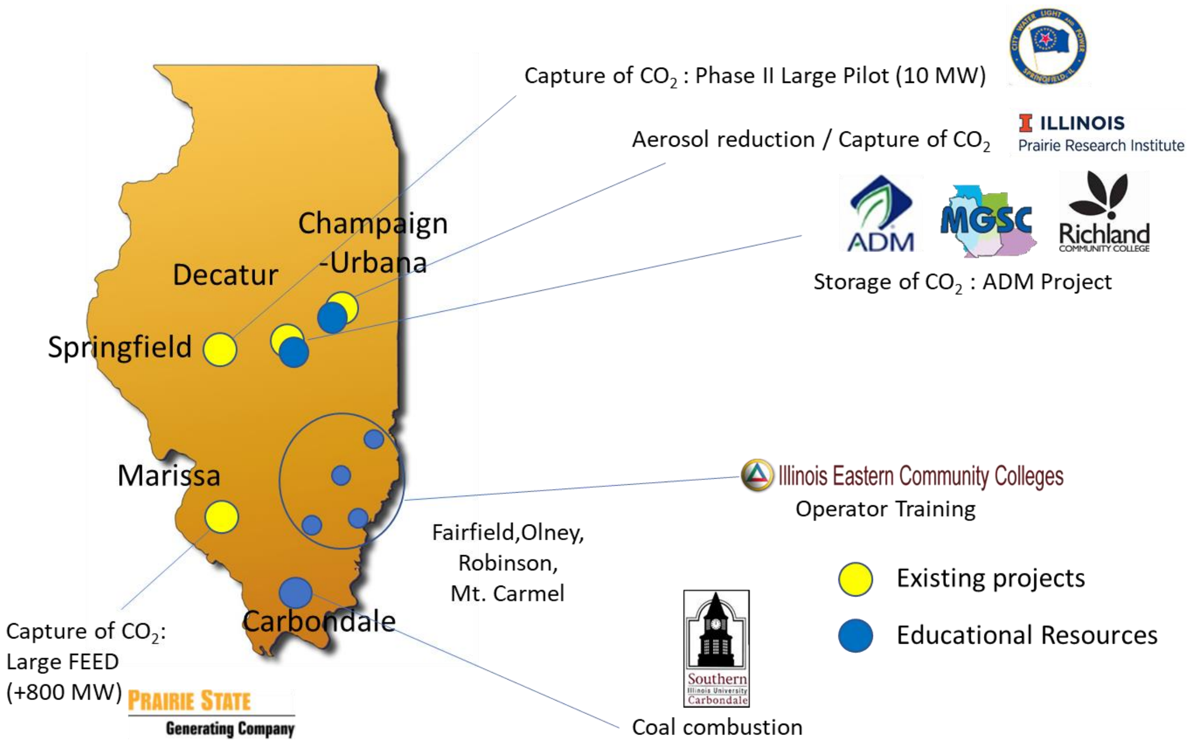


Fig. 7. Illinois CCUS Economic Cluster: projects and research organizations.

Fig. 8. Three host sites within Illinois CCUS economic cluster.

3.3. Abbott Power Plant Host Site

Abbott Power Plant (Abbott) is a cogeneration facility that supplies 70-75% of the energy demand for the UIUC campus [11]. The plant, located on the UIUC campus, 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 ~800,000 lb/hr (~80 MWe). Of these facilities, three are coal-fired boilers and are of the 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. 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 176,000 lb/hr of steam. Electrostatic precipitators (ESPs) and a wet jet bubbling flue gas desulfurization (FGD) scrubber are used in conjunction with the coal boilers to remove particulate and sulfur dioxide (SO_2) from the flue gas. The three coal boilers combined are permitted to produce up to 350,000 lb/hr of steam (~35 MWe) as limited by the capacity of the FGD scrubber. All three coal boilers burn an Illinois high sulfur coal. This combination of natural gas and coal-fired boilers enables technologies to be readily evaluated for their performance on both natural gas-fired and coal-fired systems all at the same host site location. This flexibility is important as the interest in capture from natural gas fired systems increases. Because Abbott is located on the UIUC campus, it is very convenient for training undergraduate and graduate students on the capture process.

3.4. City Water, Light, and Power (CWLP) Host Site

The CWLP power plant supplies both electricity as well as water to Springfield, Illinois – state capitol of Illinois. Springfield is located approximately 90 miles west of the UIUC campus. CWLP has four coal-fired steam turbine-generators with a total nameplate capacity of 578 MW. The newest unit, Dallman #4, is a nominal 200 MW pulverized coal (PC)-fired unit that became operational in 2009 [12]. This is unit used for the slipstream 10 MW large pilot testing. Dallman #4 employs a Foster Wheeler front and rear wall-fired PC boiler equipped with low oxides of nitrogen (NO_x) burners; a selective catalytic reduction (SCR) unit for NO_x removal; a hydrated lime injection (HLI) system for sulfur trioxide (SO_3) removal; a fabric baghouse to capture particles; FGD system to mitigate SO_2 emissions; and a wet electrostatic precipitator (WESP) to remove liquid droplets such as sulfuric acid mist. The slipstream will be removed just before the flue gas enters the stack.

3.5. Prairie State Generating Company (PSGC) Host Site

The PSGC power plant is a +1,600 MW facility outside of Marissa, Illinois (194 miles SW of UIUC), and is the newest coal-fired power plant in Illinois. The facility is owned by nine (9) non-profit municipal utilities and rural electric cooperatives with a mission to create a sustainable, secure energy future for the communities it serves. PSGC is a PC plant equipped with the latest supercritical power generation technology to burn high sulfur Illinois coal from the Lively Grove mine located adjacent to the plant. The mine-mouth power plant has two units, each with a nominal capacity of 816 MW net output. Unit #1 was commissioned in June 2012, followed by Unit #2 in November 2012. The plant's youth makes it attractive for retrofitting for CCUS.

Each PSGC unit uses a supercritical, spiral wound coal-fired boiler manufactured by Babcock & Wilcox (B&W). The boilers deliver main steam at 3,780 psig and 1,055 °F at the super-heater outlet. The steam turbine-generators were supplied by Toshiba, nominally rated at 877 MW at an exhaust pressure of 3.0 inches of mercury. Each steam turbine is a 3,600-rpm, extraction condensing, reheat type unit. The air pollution control devices include low-NO_x burners equipped in the boiler, followed in sequence by a selective catalytic reduction (SCR) system for NO_x control, an activated carbon injection (ACI) system for mercury control, a dry ESP for particulate control, wet FGD for SO_2

control, and WESP for aerosol control. The SCR supplied by B&W and other air pollution control devices supplied by Siemens represent the most advanced air pollution control technologies to remove greater than 98% of SO_2, 90% NO_x, and 99.9% of particulate matters. Bottom ash and fly ash from the boilers and air quality control systems are collected and combined with FGD wastes and conveyed to an ash storage area. Wastewater produced by the power plant, such as boiler and cooling tower blowdown, is reused in the ash handling and FGD systems to achieve zero wastewater discharge.

3.6. Project Portfolio

The CCUS project portfolio for the Illinois CCUS economic cluster is shown in Fig. 9. Selected projects are shown and their TRL range is shown based on the TRL scale outlined in Fig. 6. The cornerstone storage project, CarbonSAFE, is shown in the first column. Subsequent projects are either capture or utilization related. For capture projects, the size in MW is called out. The location for the project is shown in parenthesis. For example, the second column calls out the 816 MW front-end engineering and design (FEED) project being conducted at Prairie State Generating Company, while the 10 MW large pilot being conducted at CWLP is shown in the third column. A brief description of each of the project is listed below. All projects are funded by DOE/NETL.

	TRL	CarbonSAFE	816 MW capture (PSGC)	10 MW capture (CWLP)	Algae-Utilization (CWLP)	0.5 MW capture (Abbott)	Aerosol Reduction (Abbott)	40 kW capture (Abbott)	Water Reuse (CWLP)	Chemical-Utilization (UIUC)
	1									
Concept	2									
	3							■	■	■
Small Prototype	4						■	■	■	■
	5					■	■	■		
Large Prototype	6				■	■	■			
	7			■	■					
Demonstration	8	■	■	■	■					
	9	■	■	■						
Early Adoption	10	■	■							
Mature	11									

Fig. 9. Portfolio of projects within Illinois CCUS economic cluster.

One of the strengths of the portfolio is that it encompasses a wide range of TRLs, hence great portfolio diversity. The projects also address carbon capture, utilization (non-EOR), and other aspects such as reducing aerosol formation during carbon capture with solvents and water reuse in power plants. Some of the projects are in support of small businesses (e.g., chemical utilization), while others interact with multi-national technology developers (e.g., 816 MW and 10 MW). EPC firms play a critical role in the projects, which are 10 MW or greater in size.

A summary of the projects are as follows:

- **CarbonSAFE**: Storage project discussed previously. Encompasses large portions of the state. Links CO_2 sources with sinks.
- **816 MW Capture**: Front-end Engineering and Design (FEED) to retrofit Prairie State Generating Company (PSGC) with a carbon capture one of the two units at the plant.
- **10 MW Capture**: FEED and subsequent build/operate for a large pilot (10 MW) capture system at City Water, Light, and Power (CWLP).
- **Algae Utilization**: Design of algae system to utilize CO_2 at CWLP. Algae to be harvested and used for animal feed, biochar, and/or biofuels.

- **0.5 MW Capture**: Design, build, and operate a 0.5 MW novel capture system at Abbott Power Plant (Abbott) on the UIUC campus.
- **Aerosol Reduction**: Design, build, and test a 0.45 MW system at Abbott to reduce aerosol formation when capturing CO_2 using solvents.
- **40 kW Capture**: Design, build, and operate a 40 kW novel capture system at Abbott.
- **Water Reuse**: Design and testing of a forward osmosis membrane system to reuse highly degraded water sources from the CWLP power plant.
- **Chemical Utilization**: Fabrication of packed bed reactor for the direct conversion of CO_2 to dimethyl carbonate (DMC) for use in battery applications. Teaming with small business to develop technology in UIUC laboratories.

4. Summary

CCUS activities have advanced significantly in the state of Illinois due to federal funding for large projects and the increased commercial interest in CCUS as a result of the 45Q tax credits. This creates an opportunity to form a CCUS economic cluster. Storage and capture projects are being coordinated and linked through CarbonSAFE. A broad portfolio of projects that encompasses capture and utilization (non-EOR) of CO_2 from major point sources within the state. RD&D is driven by the fact that three host sites exist that span a wide range of field-testing capabilities (i.e., kW level to MW level). Appropriate educational resources have been linked to provide the necessary human resources from an engineering to an operator level. The R&D portfolio for the cluster is diverse and covers a range of TRLs. This combination of resources provides an economic engine to drive development of CCUS within the region.

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References

[1] Porter ME. Clusters and Competition: New Agendas for Companies, Governments, and Institutions. On Competition (Harvard Business School Press: 1979)

[2] The Reut Institute. Economic Cluster. http://reut-institute.org/en/Publication.aspx?PublicationId=3753 [Accessed Oct. 26, 2020]

[3] Kearney. Next-Generation Economic Clusters. https://www.kearney.com/public-sector/article?/a/next-generation-economic-clusters [Accessed Oct. 26, 2020]

[4] Stork M, Schenkel M. ICCUS Readiness of UK Industrial Clusters: An Assessment. ECOFYS 2017. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/759424/iccus-readiness-of-uk-industrial-clusters.pdf [Accessed Oct. 26, 2020]

[5] Abouelnaga, M. Carbon Capture Offers Dual Economic and Climate Opportunities in Pennsylvania. Center for Climate and Energy Solutions 2020. https://www.c2es.org/2020/06/carbon-capture-offers-dual-economic-and-climate-opportunities-in-pennsylvania/ [Accessed Oct. 26, 2020]

[6] van Os P. ALIGN-CCUS. https://www.alignccus.eu/ [Accessed Oct. 26, 2020]

[7] National Energy Technology Laboratory. CarbonSAFE. https://www.netl.doe.gov/coal/carbon-storage/storage-infrastructure/carbonsafe [Accessed Oct. 26, 2020]

[8] CarbonSAFE Illinois. What is CarbonSAFE-Illinois. http://carbonsafe-illinois.org/ [Accessed Oct. 26, 2020]

[9] U.S. Energy Information Administration. Illinois: State Profile and Energy Estimates. "Profile Analysis". http://www.eia.gov/state/analysis.cfm?sid=IL [Accessed Oct. 26, 2020]

[10] International Energy Agency. Special Report on Carbon Capture Utilisation and Storage: CCUS in clean energy transitions. Energy Technology Perspectives 2020.

[11] University of Illinois Facilities & Services. Abbott Power Plant. https://fs.illinois.edu/services/utilities-energy/production/abbott-power-plant [Accessed Oct. 26, 2020]

[12] City Water, Light, and Power. Electric Generation. https://www.cwlp.com/Departments/ElectricDeptHome/ElectricInformation/Generation.aspx [Accessed Oct. 26, 2020]