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A Review of Federal Efforts to Demonstrate Carbon Capture and Storage with Commercial-Scale Coal-Based Power Plants (2003–2016)

By Eric Redman | June 2020

The AEIC Scaling Innovation Project

This paper is one in a series of case studies examining the role of demonstration projects in the commercialization of new clean energy technologies.

In the first AEIC report, *A Business Plan for America's Energy Future (2010)*, a New Energy Challenge Program was proposed as a way for the U.S. government to support the demonstration and eventual commercialization of new energy technologies. For the United States to meet aggressive mid-century decarbonization commitments, a technology-inclusive portfolio of clean and innovative technologies, including advanced nuclear and renewable energy systems, zero-carbon fuels, long-duration electricity storage, and carbon capture and storage, must be deployed commercially at scale. The initial demonstration of complex technologies is a well-recognized challenge in the energy sector where first-of-kind risks are difficult to manage and projects must operate in highly regulated commodity markets, many of which may not yet appropriately value their advanced attributes. Because of this, the AEIC and many other experts have concluded the federal government has a role to play in overcoming this so-called demonstration "valley of death."

The AEIC believes there is an opportunity – and a need – to strengthen federal policy frameworks in support of scaling innovation to more effectively accelerate the commercialization of new energy technologies. The case studies in this series look back to notable policy efforts in the past to help inform a new policy agenda for the future.

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Key Lessons Learned

Between 2003 and 2016, the U.S. Department of Energy (DOE) oversaw the FutureGen project and four Clean Coal Power Initiative (CCPI-3) projects, four of which were gasification projects (not coal-burning projects) and all of which were designed to demonstrate carbon capture and sequestration (CCS) at large coal-based power plants. Only one of the projects – the least ambitious one – was successful. The vast majority of the money Congress provided for these projects was never spent, the billions in tax credits were mostly never used, and – with the exception of one project – the many millions of dollars of private investment were all lost. Individuals, not just companies, were financially hard hit.

There has been almost no interest in building large coal-based CCS power plants or retrofitting them for carbon capture in the years since, either in the United States or abroad. Yet much of the developing world remains dependent on coal for power and (via gasification) for chemicals, at the same time that the urgency of CCS deployment for climate purposes has emerged as a clear consensus among the Intergovernmental Panel on Climate Change, the International Energy Agency, and leading climate scientists.

What went wrong? What went right? What lessons should we learn? Are there glimmers of hope for CCS and climate mitigation – perhaps brightened by these very lessons?

1 **Large, first-of-a-kind (FOAK) demonstration plants struggle with cost and schedule.**
Cost and schedule challenges may be inherent in very large projects of all types, not just power plants. This certainly proved true for the necessarily very large, FOAK coal gasification projects. A key reason is that for FOAK plants, the design and construction priority is to make sure the plant actually works – and works reliably. Implementing CCS at power plants requires the non-traditional integration of rotating equipment with chemical plant equipment, which in turn means marrying the culture of power engineers with that of chemical engineers. Minimizing cost and speeding construction are desiderata, but not the main goal. Equally important, perhaps, with a FOAK project, the project contractors and equipment vendors are proceeding somewhat in the dark, with little particularized experience to guide them. They have no incentive to take financial risks when they contractually guarantee cost, performance and schedule for the FOAK plant, especially if they begin to foresee – as they did with DOE's CCS projects – that there will be no follow-on plants and no resulting line of new business.

2 **Government policy for these projects was ill-suited to overcome cost and schedule struggles.**
The funding and schedule limitations imposed on FutureGen and the CCPI projects by Congress and DOE appeared initially to be generous. In practice, however, neither Congress nor DOE (nor, it must be said, the project developers themselves) fully appreciated the cost and schedule challenges the FOAK plants would present. Had additional funding and better-designed financial incentives been available and had more time been allowed in recognition of these challenges, it is quite possible that at least two of the gasification projects

might, in the end, have been completed and successfully operated. Even the one successful CCPI-3 project, a CCS retrofit to capture carbon dioxide (CO_2) from a portion of the flue gas of an existing coal-burning power plant, required – and was fortunate to receive – many schedule extensions from DOE.

3 **Government policy needs to be constant, patient, and reliable.**

The governments of not only the United States, but also the United Kingdom and the European Union embarked on CCS programs for coal-based (and a few natural gas-fired) power plants at roughly the same time. They then wavered, had second thoughts, and withdrew financial and policy support, after private parties had already invested large amounts of their own time and money to develop the CCS power projects the governments had selected. This inconstancy reflected partly a loss of nerve in the face of the FOAK cost and schedule struggles already mentioned and partly a greater concern for the public fisc than for the losses the government reversals imposed on the developers. However, other factors were also at work (see below).

The comparative success of wind and solar projects reflects fewer cost and schedule struggles, to be sure. Fundamentally, though, the U.S. (federal and state), U.K., and E.U. governments have provided ample financial incentives, subsidies, and policy support for wind and solar – and stayed the course for decades with only minor ups and downs. That sort of constancy would have allowed CCS power plants to be built and – like wind and solar – come down the cost curve, too. For CCS power plants, though, government patience and interest ran out first.

4 **Crisis response is a poor basis for innovation policy.**

Apart from climate concerns, there is no fundamental public policy reason to capture CO_2, an inert, nontoxic, naturally occurring gas. Climate concerns, however, did not directly drive FutureGen – which was intended to help save the coal industry – or the CCPI-3 projects – which were intended to be "shovel-ready" and quickly boost employment during and after the Great Recession of 2008. For these projects, carbon capture was a constraint, but not the primary policy objective. As already noted, the development schedules for the CCS projects proved to be long, while government interest proved to be shorter and not tied to climate.

By 2016, saving the coal industry was no longer a high priority for U.S., U.K., or E.U. policymakers. Also, by 2016, the Great Recession had been overcome, employment had been restored, and the economy had recovered. The fracking revolution had flipped market expectations and made natural gas cheap, not expensive, making new coal-based plants economically irrelevant in the United States and a target of growing environmental opposition.

The need for the Western world to demonstrate CCS on coal with FOAK plants "for export" was simply forgotten for policy purposes, but it had initially been very important, because without CCS being proven and becoming economical, the developing world would keep burning coal in amounts that would put international climate goals out of reach.

5 **"E pur si muove" – And yet, it moves.**
Fortunately, several crucial points have not been entirely lost in the experience of the last decade. (1) Carbon capture itself is well-proven technically, chemically, and commercially. (2) Carbon sequestration is also proven geologically, especially in depleted oil fields, but increasingly in other formations as well. (3) Hence, when capture and sequestration technologies are integrated, CCS is entirely feasible. (4) For power plants, carbon capture needs to be applied at a scale smaller than FOAK mega-projects, while also being applied to natural gas, which in the West has displaced more coal-based power generation than have wind or solar. (5) Without implementing CCS at coal-based power and chemical plants, and at natural gas plants, in the developing world – and in industrial plant "clusters" in the developed and developing world alike – it seems highly likely, if not indeed certain, that no desirable limits on carbon emissions or atmospheric concentrations of CO_2 can or will ever be attained.

Having learned some or all of these lessons, companies throughout the world are continuing to pioneer carbon capture and geological sequestration technologies at scale, with a focus on climate and, it may be hoped, greater constancy of suitable climate-driven policy support from governments. As the symbol of Icarus stands in relation to humankind's achievement of flight, perhaps with respect to tomorrow's successful global CCS sector, we may one day say of FutureGen and the CCPI-3 projects: "Greatly did they fail, but greatly did they dare," and take inspiration and comfort from that.

Introduction

Carbon capture and sequestration (CCS) – and particularly carbon capture with geological sequestration – is increasingly recognized as one of the many tools that will be needed to combat climate change. For any operator of a power plant, however, incorporating CCS technology is a constraint or requirement rather than a primary objective. From the early 2000s to 2016, the federal government in the United States provided funding to help develop and demonstrate carbon capture with geological sequestration at coal-based power plants through the FutureGen project and the Clean Coal Power Initiative (CCPI). The rationales for these programs included saving the domestic coal industry, stimulating the economy and providing jobs during the Great Recession, and supporting particular states or localities. From the perspective of power plant owners, though, the commercialization of CCS technology *per se* was never the main objective.[a]

With a few key exceptions, these efforts were not successful. Neither FutureGen nor the majority of the CCPI projects were completed (although at least one CCS project, which involved an ethanol plant rather than a power plant, did get completed under a sister program). One CCPI project that did get built, at a coal plant in Kemper County, Mississippi, failed

a In the U.S. context, the "S" in CCS is generally understood to stand for "sequestration." Elsewhere, the preferred term is "storage." However, "storage" has connotations of impermanence and suggests the potential for withdrawing something later. Carbon dioxide placed in geological formations for purposes of climate-change mitigation cannot later be withdrawn.

to operate successfully. The plant was later converted to run on natural gas with no CCS. The most successful of the CCPI projects, NRG Energy's Petra Nova project at an existing NRG coal plant, was arguably the least ambitious and, although its CCS system continues to operate exceptionally well, it captures carbon dioxide (CO_2) from only a fraction of the plant's flue gases.

Unfortunately, the failure of FutureGen and the poor success rate of the CCPI projects have created or reinforced the impression, among members of the public and in government, industry, and NGO circles, that CCS is too expensive, or impractical, or infeasible – hence of little value in the fight against climate change. CCS also remains stubbornly associated in the public mind with coal, even though CCS is equally important (and entirely feasible) for natural gas-fired electricity production, which has expanded rapidly and accounts for two-thirds of the reduction in U.S. coal use in recent years. Additionally, the development and demonstration of CCS is critical for controlling emissions from industrial sources, such as steel and cement production, which together account for almost 10% of global CO_2 emissions.[b]

While efforts to implement CCS at new-build power plants have struggled, attention has shifted to CCS for industry and to options for capturing CO_2 from the ambient air. Known as carbon dioxide removal (CDR), the latter options rely on biological processes, such as planting trees, or on mechanical and chemical systems, in the case of direct air capture (DAC) technologies. Several companies are actively developing DAC systems at present; Carbon Engineering is one of the best known. Meanwhile, coal use – for electricity production and other industrial purposes – continues to grow outside the wealthy economies of North America and Europe, particularly in China, in countries that are part of China's Belt & Road Initiative, and elsewhere in Asia and Africa. With increased reliance on coal and natural gas (and fossil fuels in the transportation sector), but without CCS, global CO_2 emissions have continued to rise.

Given these developments, it is not only useful but arguably essential to understand what went right and what went wrong with FutureGen and with the CCPI projects. Analyzing this history and its lessons, it is possible to begin sorting out to what extent the decidedly mixed results from past government efforts to support CCS (particularly in coal-based power plant applications) reflect inherent limitations and shortcomings of the technology itself and to what extent these failures reflect limitations and shortcomings of the support efforts themselves (including conditions imposed on projects by government programs). More broadly, how did political and policy considerations affect the government's efforts and how might we learn from that to improve future programs and more effectively advance CCS technology – not so much for coal plant applications in the United States, where the construction of new coal plants of any type seems unlikely, but for the coal plants still being built elsewhere in the world and for natural gas-fired facilities, both in this country and globally?

General Factors Affecting CCS Applications in Power Plants

A common feature of FutureGen and all the CCPI projects is that they were very large. Unlike modular technologies, such as solar panels or wind turbines, the minimum scale for a commercial unit of CCS is the plant itself (in the case

b The scope of this paper does not allow for a discussion of hydrogen, gas-to-power (GtP), ammonia, and other approaches to decarbonizing electricity generation and other industrial sources, but it is worth noting that efforts to develop these and other potential alternatives are ongoing.

of gasification and pre-combustion capture of CO_2) or a very large chemical plant added to the power plant (in the case of post-combustion capture). FutureGen and all the CCPI projects, with the exception of Petra Nova (which, as noted, handled a slipstream of flue gases from an existing power plant), were multi-billion-dollar projects. Moreover, no two projects were alike, and it quickly became apparent that, unlike wind farms and solar projects, these large CCS plants would always remain large and could never be completely standardized. The size and uniqueness of each project had several important implications.

First, the projects, besides being large-scale, were also necessarily somewhat experimental, since they were "first of a kind." No one had previously built, from scratch, a power plant that integrated carbon capture. Moreover, the power industry and power plant engineers have long focused on power generation and rotating equipment, whereas CO_2 capture requires expertise that is more commonly found in the chemical industry. In fact, to capture CO_2 at a power plant, an actual chemical plant has to be integrated with the rotating equipment of the power plant. So, these projects were also first of a kind (FOAK) in the sense they involved marrying not just two fundamentally distinct types of technology, but two fundamentally distinct industry sectors and professional cultures. As FOAK plants, FutureGen and all the CPPI projects were not only very large, but very experimental indeed.

A key determinant of the ultimate cost of these large projects turned out to be the total tonnage of steel required, particularly the quantity of specialty steel needed to deal with the acidic and corrosive properties of CO_2, oxygen, and other gases and liquids in the carbon capture process. One construction company executive observed that "you don't know how to minimize the required amount of steel until you've designed an offshore platform." The design engineers for these early CCS projects, however, were not focused – at least initially – on minimizing steel requirements. Instead, they were focused on a FOAK design that would work – and work reliably. This is just one example of many of the kinds of challenges that could be better addressed with more experience, thereby helping to drive down the cost curve for future generations of CCS technology. Although, more experience can be gained only if more plants are built.[c] Because FutureGen and the CCPI projects were not followed by a second generation of CCS plants, there was little application of this type of learning by doing.

A related issue, from a cost perspective, is the behavior of contractors and equipment suppliers. Their key goal in a FOAK project is to avoid making mistakes and incurring losses. On a large project, contractors or vendors who must bid for the job or who must guarantee price, performance, and schedule (as most must) can lose huge sums if they mis-estimate. Each company involved with a FOAK project – and each individual who performs tasks for the company – is thus incentivized to understate actual expected performance; provide ample padding and contingencies when estimating expected cost; and build as much extra time as possible into the project schedule – while also insisting on large contingency allowances. All these factors directly affect profit and loss and all of them must be guaranteed in the company's contracts with the project developer. There is a school of thought that very large projects of all types – other examples would be nuclear plants, high speed rail systems, or huge oil refineries – are inherently prone to cost overruns

c With the benefit of learning by doing, including a better understanding of required man-hours and other project inputs, the plant owner, lead contractor, and CCS technology provider for the post-combustion capture addition to the Boundary Dam coal plant in Saskatchewan have all stated publicly that they could build and install a second such capture system at a cost savings of 30% to 35%.

and schedule delays for these reasons.[d]

The factors and incentives that tend to drive up project cost were particularly strong in the case of FutureGen and CCPI, particularly as the larger context for these programs changed over time. Initially, during the 2000s, all participants expected power plants with CCS to become a major business line in the future. It was widely anticipated a tax or price of some type would be levied on carbon emissions, coal was expected to remain cheap compared with natural gas, and wind and solar had barely begun to be considered as important carbon-free generation alternatives. However, as time went on, these things changed. Both FutureGen and the CCPI projects began to look more like one-off technology experiments and potential museum pieces, not precursor technologies for an entire new industry sector. As a result, no contractor or vendor had any real incentive to take financial risks in hopes of getting in on the ground floor of a burgeoning business opportunity.[e]

Besides cost, another consequence of the incentive structure for contractors was that schedules for project completion tended to stretch well beyond original expectations – so far, in fact, that projects were still underway in a period when Congress and the administration, including the U.S. Department of Energy (DOE), no longer felt the same need for CCS technology at all. No one understood, initially, that these FOAK plants would all take more time to complete than had been anticipated and built into project schedules.

When FutureGen was launched, the federal government wanted to find more diverse and environmentally friendly uses for coal – a major domestic resource – than simply burning it to produce heat to make steam. After all, we don't burn crude oil; we refine it. Similarly, we don't just burn wood; we mill it to make lumber, plywood, paper, and other products. FutureGen was presented as a "refinery" for coal: the coal would first be gasified, making it possible to separate pure hydrogen from the carbon, sulfur, and mercury in the process stream; then the hydrogen could be burned (with just the "right amount" of carbon needed for high-hydrogen combustion turbines to handle the hydrogen) to produce clean power. Most of the CCPI projects were likewise conceived as demonstrations of better and more acceptable uses for coal than just burning it.

The big boost to CCPI – $800 million in grant funds – was authorized as part of the American Recovery & Reinvestment Act of 2009 (ARRA) when, in the midst of the Great Recession, the president and Congress sought a Keynesian stimulus for the national economy. The projects selected for these grants (the so-called CCPI-3 projects) appeared to be doable with relatively little technology risk and on a fast timetable. They were also geographically dispersed. Immediately after project selection in December 2009, DOE accelerated its contracting process and eventually provided a (temporary) 80% government contribution to project costs – considerably more generous than the 50/50 public–private cost share originally contemplated. The purpose was to get more money out into the economy fast. When the projects later took longer than expected to complete, the government eventually lost interest in the uncompleted ones. By then

d The author is indebted to Professor Ahmed Abdulla of Carnegie Mellon University for this insight.

e The well-publicized stream of continuing cost overruns and schedule delays on the Kemper County project (discussed later in this paper) severely impacted the other CCPI projects by alarming contractors and vendors, who were about to sign fixed-price contracts with schedule guarantees for those projects. Most eventually insisted on boosting their prices and lengthening their guaranteed schedule in reaction to what was happening at Kemper.

the economy had recovered and coal had largely fallen into disfavor for new power plant investments.[f]

Besides project costs, all of which escalated over time, FutureGen and the CCPI projects had to contend with a number of additional difficulties:

- What do to with captured CO_2. There was no market for CO_2 in the volumes that would be generated by these projects other than from oil producers, who could use CO_2 for enhanced oil recovery (EOR). Other uses of CO_2, for example in algae production[g] or for carbonated beverages,[h] required much smaller volumes – at most a very small percentage of the output from CCS projects.

- How to arrange sales of CO_2 to oil producers for use in EOR operations, while also providing the connections to CO_2 pipelines needed to facilitate such sales. Unlike a wind or solar project, which require only a connection to the power grid, CCS power plants also required infrastructure to deliver captured CO_2 for geological sequestration, including EOR. Many rules related to geological sequestration or CO_2 sales were also unwritten or unclear, including rules for sales to oil producers.[i]

- The lack of a carbon tax, carbon price, or suitable production tax credit for captured and sequestered CO_2. The Section 45Q tax credit for CCS that existed at the time – and that is much improved today – could not be relied on for project financing purposes. It was worth only \$10 or \$20 dollars per ton of CO_2 (\$10 if used for EOR) and was limited to 75 million tons CO_2 in total. Also, there was no way to allocate the 75-million-ton cap to individual projects. Moreover, the understanding at the time was that the 75-million-ton amount was quickly being used up by natural gas producers who separate naturally occurring, geological-origin CO_2 from natural gas and use or sell it for EOR.

- The lack of any portfolio standard for electric utilities that would create market demand for power from fossil fuel plants that captured their carbon emissions. The renewable portfolio standards (RPSs) adopted in many states, along with tax credits, provided a key boost to the commercial deployment of wind and solar projects, but nothing similar existed for CCS projects. Nor were any policies in place to favor CCS procurement by the federal government as part of power purchase

f Notably, there was very little support for CCS in either the coal industry or the utility industry – and little acceptance of the need for this technology for climate-change mitigation purposes. Both industries preferred to support "clean coal" – a term that was understood to mean more efficient coal-burning power plants with modern emission controls for other types of pollutants (such as sulfur dioxide), but no carbon capture capability. Environmental advocates pounced on the term "clean coal" as disingenuous, given that carbon emissions and climate-change impacts were, in their view, the primary concern with continued coal use at this point in time. The fact that coal-based power plants, particularly coal gasification plants, could be designed and built with carbon capture tended to be either ignored or viewed as part of industry efforts to mislead the public about "clean coal."

g Algae can be used to produce biofuels and other products. Adding CO_2 to an algae pond boosts algae growth, creating a small market for CO_2 among algae producers. To provide a sense of scale, though, an algae pond that could use all the captured CO_2 from one of the large CCPI projects would have to be the size of Lake Champlain.

h The Chinese power producer Huaneng captures 125,000 tons of CO_2 per year from a very small slipstream (1%) of the flue gases of a coal-fired power plant in Shanghai. The CO_2 is processed and sold as food-grade CO_2. According to Huaneng officials, they could capture more CO_2 but 125,000 tons per year is the total size of the market for food-grade CO_2 in Shanghai, one of the world's largest cities.

i For example, there was uncertainty about whether the U.S. Environmental Protection Agency (EPA) would require Class II or Class VI wells for EOR operations that used CO_2 captured from "anthropogenic" sources, such as power plants. To many oil producers, the difference in operating costs would rule out the use of captured CO_2, and the risk of allowing EPA to become involved in oil field operations at all, despite the "oil and gas exception" in EPA's authority, seemed to argue against buying CO_2 from CCS power plants.

agreements (e.g., for military bases or other government complexes) or by state governments.

The Political and Policy Environment

Recognizing these and other obstacles to CCS investment, Congress provided three main forms of financial assistance to FutureGen and the CCPI projects: cash grants, investment tax credits (ITCs), and loan guarantees (although it is worth noting that loan guarantees and cash grants were treated until the very end as being mutually exclusive, which was not the case for other technologies, such as solar projects, for example). The large scale and attendant large cost of FutureGen and CCPI projects meant that financing would be complicated even with these forms of assistance, for several reasons:

- Government grants typically covered only a portion of pre-construction project development costs – nearly 100% in the case of FutureGen, but otherwise a relatively small fraction – and an even smaller portion of actual construction costs (except for FutureGen).[j] The CCPI program required cost-sharing by private parties, all of which was at risk and would not be reimbursed if the project was never completed.
- ITCs, though they generated cash yields for tax equity investors once a project achieved commercial operation, provided no cash to project developers up front – and, ironically, the magnitude of ITCs available for individual CCS projects created difficulties for tax equity investors, who were accustomed to more bite-sized and standardized tax equity investment opportunities for wind and solar projects.
- For large CCS projects with grants, a lack of access to federal loan guarantees meant that billions of dollars of project debt would have to be found elsewhere. However, private-sector lenders had no assurance of being repaid for their loans to these novel projects, since the federal government was not offering loan guarantees.

The United States was not alone in wrestling with these problems as it began pursuing the development of FOAK coal power plants with carbon capture. In the second round of a government-sponsored CCS power plant competition, the British government ultimately selected three coal-based projects and one natural-gas-based project as semi-finalists for cash grants to cover front-end engineering and design (FEED) costs. The European Union provided two billion euros for CCS power projects, including in the United Kingdom, under its NER-300 program. China began construction of an integrated gasification and combined cycle (IGCC) power plant in Tianjin, with carbon capture slated for the second phase. All of these non-U.S. efforts ultimately faltered, for a variety of reasons: disillusionment with high FOAK costs, a more general movement away from coal, a lack of resolution on the part of national governments, the failure to adopt a carbon tax or price to encourage CCS, etc. Thus, the loss of government support for, and patience with, most power plant CCS projects was not isolated to the United States. On the contrary, it occurred worldwide.

Fundamentally, this loss of support in the U.S. context relates back to the varied objectives that motivated support for these projects in the first place. None was initiated solely or primarily for climate reasons. FutureGen, as mentioned, aimed to save the coal industry by promoting gasification

j Jim Wood, a Deputy Assistant Secretary of DOE, observed that every time DOE increased the amount of the cash grant to a project, project costs would go up by a corresponding amount. The size of cash grants was public information; thus, there was no way to “hide” the government’s contribution from the contractors and equipment vendors working on any given project.

technologies that would yield useful commercial products, in addition to electric power, and do so while capturing excess carbon. The CCPI-3 projects were funded through the ARRA, which aimed to stimulate the economy and generate jobs. Over time, FutureGen came to be viewed as primarily a public works project for two states: Texas and Illinois. As performance expectations for the program were continually scaled back, the program itself became largely redundant with CCPI-3 gasification projects, including, specifically, the Texas Clean Energy Project (TCEP), the Hydrogen Energy of California (HECA) project, and the Kemper County project in Mississippi. In the end, of course, only Kemper County was actually built, and it didn't work.

As noted above, time and the changing tides of political and public opinion also played a role. Midway through the George W. Bush administration, it really did seem as if FutureGen might help save the coal industry. By the final days of the Obama administration, ten years later, the fracking revolution was in full force. At that point, saving the U.S. coal industry was a priority for only one portion of one political party. It was largely a matter of indifference to the other party and it was anathema to the increasingly vocal and effective environment and climate change advocacy community, which was not particularly interested in the fact that carbon could be captured from coal.

Ironically, and perhaps fatefully, most of the coal industry and most electric utilities never expressed support for CCS. Only a few national environmental groups – the Natural Resources Defense Council, Environmental Defense Fund and Clean Air Task Force – openly supported CCS or individual CCPI-3 projects. Meanwhile, the projects themselves were taking even longer to complete than expected and the use of coal for power generation in the United States seemed in permanent decline. "White elephant" was a term increasingly heard in connection with FutureGen and CCPI-3 projects.

In funding the CCPI-3 projects, DOE intended to support the demonstration and eventual application of CCS technology elsewhere in the world, recognizing that other countries were unlikely to stop building new coal-based capacity even if the United States did. The initial objective of FutureGen, likewise, was to demonstrate the viability of carbon capture with multiple coal types, together with the viability of sequestering captured CO_2 by injecting it into a saline formation – both important ways to show that the technology was applicable in international contexts. TCEP, for example, was positioned as a "counter-facing" project to China's IGCC plant at Tianjin under the two countries' bi-lateral Strategic & Economic Dialogue (S&ED). In a further expression of this cooperative approach, reliance on Chinese contractors, equity investors, and lenders was encouraged as part of TCEP. Similarly, the Petra Nova project became, in effect, a joint U.S.–Japan effort once NRG Energy selected Mitsubishi to provide the CCS technology. At that point DOE devoted considerable time and effort to encouraging the Japanese government and relevant Japanese agencies, lenders, and companies to support the project.

DOE recognized that if the CCPI-3 projects could succeed and could be proven at commercial scale in the United States, CCS might be deployed in coal-dependent Asia, where systems to limit carbon emissions were otherwise unlikely to be included in new power plant projects. As Professor David Victor of the University of California San Diego has observed, "Anything that doesn't move the needle in China doesn't move the needle on climate."[1]

One more U.S. wind or solar project would not attract attention in China. CCS systems that could capture and sequester two million or more tons of CO_2 annually from a commercial-scale power plant, by contrast, very well might. During the Obama administration, which viewed climate change as a concern from the outset, this rationale was initially accepted and articulated by DOE secretaries Stephen Chu and Ernest Moniz as among the important objectives of CCPI-3. However, as noted, the policy environment changed, as did market conditions and stakeholder interest. Over time, the impacts of these changes came to be reflected in the tortuous history of the FutureGen project.

The FutureGen Project

FutureGen was first proposed and funded in 2003. At the time, the plan was to build a brand-new, full-scale, coal-based IGCC plant that would capture carbon and produce hydrogen. By 2015, as FutureGen 2.0, the project had turned into a proposed demonstration of an oxygen-fired ("oxy-fired") CCS retrofit to an aging coal-burning power plant. In retrospect, FutureGen appears to have been, from the start, a project in search of a mission. The FutureGen experience also exemplifies the maxim that, if the aim is to hit a moving target, one cannot wait years and years to pull the trigger.

Conceived from the beginning as a public–private partnership, the FutureGen Industrial Alliance originally included many U.S. and international coal producers, electric utilities, and large power producers. The original plan, to inject captured CO_2 in a deep saline formation rather than an oilfield, was viewed as a key feature of FutureGen, since saline formations are widespread globally and demonstrating this form of carbon sequestration would increase the worldwide applicability of the project.

The federal government provided almost all initial project funding: $1 billion, sufficient to cover an estimated 95% of project costs. Nevertheless, key project decisions were left to the FutureGen Industrial Alliance, including decisions about what the project was expected to accomplish – initially, an ability to handle a wide variety of coal types, so as to further the technology's international applicability – and where the project would be located.

The much-hyped location decision – which came to involve an effectively national competition among eager U.S. localities – transformed public and political perceptions of FutureGen. The competition seemed necessitated by the need for state as well as federal support for the project. As a large industrial demonstration project, FutureGen was widely seen as a major public works prize. Thus, it became the object of a perceived political tug-of-war between Texas and Illinois and between the Bush and Obama administrations. This in turn lessened private-sector and congressional confidence in a project that was always going to face significant technological and cost-control challenges, even without added political baggage.

The site selection process formally began in May 2006. Seven states submitted twelve site proposals. The Alliance selected four finalists, two in Illinois and two in Texas. DOE promptly kicked off the National Environmental Policy Act (NEPA) review process by developing an environmental impact statement (EIS), which concluded that all four sites were suitable. Final site selection was scheduled for December 2007 – less than a year before the 2008 presidential election. DOE delayed issuing its record of decision (ROD) for continued federal funding of the project and urged the Alliance to delay final site selection. The Alliance declined DOE's advice on grounds that delay would increase project costs. The general expectation was that Odessa, Texas would be selected, but instead the Alliance chose Mattoon, Illinois on December 18, 2007. Little over a month later, on January 29, 2008, DOE pulled federal funding for the project.

DOE justified this decision on the basis of rising project costs (construction costs were, in fact, rising worldwide during this period). Suspicions immediately arose, however, that the decision was political and reflected President Bush's ire, as a Texan, with the choice of a site in Illinois. Suspicions were further fueled when the final decision was made and announced (and defended before Congress) by another Texan, Clay Sell, the Deputy Secretary of Energy and a former close White House aide to the president. Deputy Secretary Sell consistently maintained that the same decision would have been made had the Alliance selected the Odessa site. Judging by the facts, it is easy to believe that this was true,[k] but nothing DOE said dispelled the suspicions.

Campaigning for the 2008 presidential election was already underway at that time and candidate Barack Obama not only expressed support for FutureGen, now slated for his home state of Illinois, but also promised to build four more coal-based CCS projects if elected. Indeed, promptly after Obama's inauguration, his administration proposed and Congress funded, as part of the ARRA, $800 million for additional CCS projects. Less than a year later, DOE had selected four CCPI-3 projects to receive this funding, none of which was in Illinois – indeed, one of the projects, TCEP, was actually sited at the Odessa location that had been considered for FutureGen. These developments did not, however, diminish the politics around FutureGen, which remained a project of intense interest to the state of Illinois. The Illinois legislature enacted laws to accommodate FutureGen[l] and, in Washington, D.C., the state's powerful senator, Dick Durbin, worked to ensure that DOE under the Obama administration would not only revive the project but see it through to completion.

By this point, however, some six years into the project, new questions had arisen about what FutureGen would be. There was no longer a need to demonstrate IGCC technology with carbon capture since three of the four CCPI-3 projects (HECA, TCEP, and Kemper County) entailed precisely that. Moreover, it had become clear that selling captured CO_2 for EOR was the only way to make these FOAK projects economical. By contrast, the original plan for FutureGen, to demonstrate CO_2 injection into saline formations, would produce no income apart from not-necessarily-available Section 45Q tax credits. Unfortunately, Illinois, though it does offer some potential EOR opportunities, was not prime territory for EOR applications.

Eventually the project was reborn as FutureGen 2.0, still with $1 billion of federal funding but for a considerably different purpose: to demonstrate an oxy-fired retrofit of an existing coal plant. At the time, oxy-combustion was considered a potentially promising technology for enabling CO_2 capture from coal. Instead of combusting coal with air and then having to extract CO_2 from the much larger volumes of nitrogen in the flue gas stream – air is 78% nitrogen – a large air-separation unit (ASU, also known as an "oxygen plant") would allow the coal to be burned in a pure oxygen environment, yielding a flue gas stream of almost pure CO_2 for capture. In this way, oxy-combustion was considered a new approach to post-combustion CO_2 capture.[m]

As an experiment in technology development, this was probably a good idea; no oxy-fired coal plant with CCS had

k Estimated project construction costs had indeed risen dramatically, although the same was true everywhere. As a result, the federal cost share was headed to a number that far exceeded what DOE had expected or Congress had appropriated. The Alliance proposed capping the federal share at $800 million, but that raised doubts that the Alliance – which by this time was losing members – would be able to finance the remaining share. In addition, the Alliance had dropped the idea of making the project suitable for a wide variety of coal types, having encountered the reality (which was common knowledge in the chemical industry) that, just as oil refineries must be designed for particular types of crude, gasifiers must be designed for a narrow range of coal types. Hence the value of the project as an international demonstration had somewhat diminished in DOE's eyes.

l For example, in 2007 Illinois enacted a statute under which the state assumed ownership of the captured CO_2 and all liabilities associated with it.

m The White Rose Project in Yorkshire was also intended as an oxy-fired CCS power plant and was selected as a finalist in the United Kingdom's CCS power plant competition – a program the United Kingdom then canceled in 2015.

ever been (and still has never been) built. Time and change had worked against the project, however. FutureGen's industry participants promptly dropped out. A power plant retrofit for CCS is completely different from a greenfield IGCC plant; it is not something that power companies or utilities have ever expressed much interest in for political, financial, and technical reasons. The new leader of the project, the FutureGen Corporation, had never developed a power plant before. The coal plant slated for retrofit was not in Mattoon and, although the captured CO_2 would still have been injected at Mattoon, the community withdrew its support for the project. By the middle of Obama's second term, DOE, which was focused on the CCPI-3 projects and on other priorities, had more or less lost interest and faith in FutureGen 2.0. DOE finally pulled the plug in 2015.[n]

The tale of FutureGen is, of course, far more complex than can be captured in this summary, and the project was always unique among government-supported efforts to promote CCS. However, even this short account points to some lessons learned that may be useful in designing future programs. These lessons are the subject of the final section of this case study.

The Kemper County Project

The Kemper County project (Kemper) involved a proposed IGCC power plant with carbon capture. The plant was owned by Mississippi Power, a subsidiary of Southern Company, and used a proprietary form of circulating fluidized bed gasification technology that engineering firm KBR, Inc., formerly known as Kellogg Brown & Root, and Southern Company named Transport Integrated Gasification, or TRIG™. Kemper was the largest and most expensive of the three CCPI-3 gasification projects and the only project that was actually built. Unfortunately, after many billions of dollars of cost overruns (total project cost increased from $2.4 billion to $7.5 billion) and a three-year delay, when it was finally started up in 2017, Kemper operated only briefly before it was shut down for technical reasons.[o] The facility was later converted to a natural gas-fired power plant.

Even if Kemper had operated perfectly from a technology standpoint, its long development schedule, like that of the other CCPI-3 projects, left it vulnerable to unanticipated market developments. Kemper was designed to operate on lignite, which accounts for half of all coal reserves globally. A global market for TRIG™ was indeed intended. The expectation at the time was that coal, especially lignite, would be cheap and natural gas would be expensive – possibly even scarce. The head of Southern Company expected gas prices (in dollars per MMBtu) "in the double digits."[2]

Over the course of all the CCPI-3 projects (the other projects were designed for sub-bituminous coal) and FutureGen, however, the fracking revolution began to hit full stride and natural gas prices in the United States plummeted into the low single digits.

Like the other CCPI-3 projects, Kemper was born out of stimulus efforts and relied on grant funding and investment tax credits authorized by the ARRA. Construction began when only about 10% of final design engineering was complete. As noted above, an IGCC plant – unlike a conventional plant that burns coal – is also a chemical plant (a "refinery" for coal). Also, the

n Worth noting is that FutureGen, unlike the CCPI-3 projects, was never intended to be a long-term commercial project, despite its planned commercial scale. The initial intention was to operate it for approximately four years. The saline sink for captured CO_2 at Mattoon was sufficient for that, but not necessarily for more.

o "Problems included: chronic coal dust suppression issues; tube leaks in the synthetic gas cooler; insufficient process water capacity; and a too-small nitrogen plant, which required trucks to haul gas to the plant."
David Wagman, "The Three Factors That Doomed Kemper County IGCC," *IEEE Spectrum*, June 30, 2017. Available at: https://spectrum.ieee.org/energywise/energy/fossil-fuels/the-three-factors-that-doomed-kemper-county-igcc.

culture and experiences of power engineers and chemical engineers proved difficult to integrate. The project team faced the challenge of scaling up multiple systems at the same time. For example, the feed system for the coal and the ash handling (waste management) system both had to be modified during construction. Not surprisingly, this led to project delays and cost overruns – a pattern that was not unique to CCS projects.[p]

The project also encountered some bad luck. Six months were lost to construction delays because of rain that made concrete pouring impossible. The result was a $500 million increase in project cost.[q]

Opinions differ on how significantly the FOAK gasification technology, TRIG™, contributed to the Kemper project's unhappy outcome. The gasifier did in fact work and was still working during the few weeks before the IGCC operation was shut down; the technical problems that halted operation cropped up elsewhere in the plant. On the other hand, the TRIG™ reactor design demanded a granular flow of coal particles. Achieving this kind of flow proved to be particularly challenging because of problems with wear, agglomeration, settling, blockages, etc. These problems affected, and were affected by, the performance of other plant components. It is very difficult to simulate granular flow mechanics in advance of actual experience. Conventional computational fluid dynamics (CFD) software and systems are not necessarily satisfactory for modeling actual flows of granular materials.[r]

Like FutureGen and the other CCPI-3 projects, Kemper was unique in many ways and so are the details of its development. Yet uniqueness was an inherent characteristic of the necessarily large CCS projects attempted in the post-ARRA period. To some significant degree, that will always be the case even if variants of such projects are ultimately built, for example in Asia. Though CCS technology can certainly benefit from some standardization, each site location presents different characteristics in terms of coal type, coal transportation, process water availability, and proximity to CO_2 transportation and sequestration infrastructure. In addition, almost none of that CO_2 infrastructure is yet developed anywhere in the world except in the Permian Basin of Texas and in other oil-producing regions in the United States. Nonetheless, as with FutureGen, the experience with Kemper does point to some generalized lessons, which are the subject of the final section of this case study.

The Petra Nova Project

Petra Nova is the one CCPI-3 project that succeeded. It captures more than 1.4 million tons of CO_2 per year from a slipstream of post-combustion flue gases from Boiler No. 8 at the W.A. Parish coal-fired power plant near Thompson, Texas (the plant is owned by NRG Energy). The captured CO_2 is delivered by pipeline to the West Ranch oilfield about 80 miles away. The pipeline was built as part of the project and a commercial arrangement allows the Petra Nova owners to share in the benefits from EOR operations, which have increased oil production at the West Ranch oilfield from the

p In the 1970s and early 1980s the Washington Public Power Supply System (WPPSS) attempted to build five nuclear power plants on overlapping schedules with construction commencing before final design engineering was complete – as with Kemper. At the time, WPPSS felt itself to be in a race against time because of inflation, interest during construction, and the various factors that make it seem imperative to go fast – including, in Kemper's case, deadlines established by grant funding and ITCs. Ultimately, however, only one of the five WPPSS plants was completed; the other four were abandoned mid-construction, with enormous resulting costs.

q For this and other key observations about FutureGen, I am indebted to Dr. Julio Friedmann, who at the time was the principal deputy assistant secretary for Fossil Energy at DOE.

r A great deal has been published about Kemper, but, at the time of this writing, the federal government was conducting investigations of the project. As a result, individuals who had the most direct experience with the technical difficulties the plant encountered were unavailable to be interviewed.

previous 300 barrels per day (bbl/day) to 4,000 bbl/day – with the potential to further boost output to 15,000 bbl/day).[s]

The project as a whole, which includes a separate gas-fired plant to provide power to the post-combustion CO_2 capture facility, cost somewhat over $1 billion. It was financed with extensive U.S.–Japan collaboration. The amine-based CO_2 capture facility employs Mitsubishi technology. DOE provided a $190 million grant (when the plant was already under construction[t]), NRG Energy and JX Nippon invested $300 million each (and each received 25% of revenues from increased oil production), and Japanese banks provided a $350 million loan. Petra Nova also benefits from state tax incentives, Hurricane Katrina recovery tax benefits, and other financial concessions that were originally enacted by the Texas legislature in 2009 primarily to benefit TCEP and another CCS project (Tenaska Trailblazer), neither of which was built.[u]

Petra Nova's success seems to reflect the happy convergence of a number of excellent design features and good decisions, the oversight of an exceptionally able and highly motivated project management team, and comprehensive government (federal and state) financial support. In an interview, David Greeson, the former NRG Energy executive who was in charge of project development, construction, startup, commissioning, and initial operations (the plant has now operated for more than three years) offered several reasons for the project's success:

- A committed board and senior management team at NRG Energy. Greeson reported that NRG Energy had spent $150 million on the project before the board's final vote to build it, at a time when NRG Energy's market capitalization was only $600–$700 million. "They were committed to finding a way to decarbonize coal," he said.
- A dedicated team that quit secure jobs to come work on the project. "We burned the ships," Greeson said, "and that drove our thinking out of sheer terror and survival."
- "The right project in the right location and state, with good permitting and a prime location for EOR." The oilfield owner, Greeson said, had no way other than EOR to boost production. Owning interests in the oilfield was "a good thing to get it over the line," although current oil prices "would not have worked" and something like the new Section 45Q tax credits would have been needed to fill the revenue hole.
- The project's Japanese finance partners joined during construction, not earlier; they were likeminded and as committed to the project's success as NRG Energy during the most difficult development moments.
- The key U.S. construction contractor, Kiewit, "put their A-team on it," and pairing Kiewit with Mitsubishi "was what made the technology work." The Kiewit team spent four months in Japan working with Mitsubishi on "constructability" issues. NRG Energy and Kiewit both viewed the Mitsubishi CO_2 capture technology as ready to be commercial, but not yet commercial when the collaboration started. DOE grant support was a "game changer" because it provided immediate credibility for the project with the NRG Energy board, the oil and gas industry, and others. "People started returning phone

s The project was conceived in an era of $100-per-barrel oil prices. At the current, much lower oil prices, the EOR operation by itself may or may not continue to be profitable.

t Petra Nova was selected as a CCPI-3 project when Southern Company withdrew Plant Berry, the previous DOE choice.

u The Texas incentives include exemption from the state franchise tax (a form of corporate income tax), a 75% total reduction in the oil severance tax, a sales tax exemption for all plant and equipment, and a variety of property tax exemptions.

calls," Greeson said. Schedule pressure from the DOE grant – DOE granted six extensions – was actually helpful. According to Greeson, "It helped move things along." Since the project took longer than expected, DOE flexibility was also important. "We had the right DOE team."

Dr. Julio Friedmann, the principal deputy assistant secretary of DOE's Office of Fossil Energy at the time, praises key project decisions as well as Petra Nova's management. In his view, building the gas-fired plant to provide power to the carbon capture facility (rather than de-rating the coal plant to do so) was "brilliant" and overturned prior DOE assumptions about retrofits for post-combustion capture.[v] In addition, Dr. Friedman says, NRG Energy made the "bold choice" to use modular construction for the tall units, particularly the stripper column, in order to save time and money. The project helped demonstrate the commercial potential of EOR, Friedmann adds, and took advantage of other helpful factors in project financing; in addition, "DOE undertook a major charm offensive with the Japanese government and Japanese banks."[3]

Although it's commonplace that failure offers more lessons than success, the experience with Petra Nova usefully reinforces some observations from other contemporaneous coal-based CCS projects and provides additional insights based on what the project achieved.

Lessons

Some of the lessons from FutureGen and the CCPI-3 projects relate to CCS technology itself, at least as applied to coal-based power plants. These plants had to be large, which in turn meant they were costly. This was especially true at the FOAK stage, when comparatively little effort was made to minimize steel, manhours, and other key inputs and when the primary focus was on completing and operating the project. Without a FOAK coal gasification demonstration plant and several more follow-on plants, it is possible that large projects like FutureGen and the CCPI-3 gasification plants simply won't be viable. In that case, the technology breakthroughs needed to cost-effectively capture CO_2 from coal – in the developing world, if not in North America – will need to come from smaller, more modular, more efficient, and less costly gasification technologies. Several companies are now trying to develop such technologies.[w]

The focus on CCS in power plant applications, at least in North America and in most OECD nations, will undoubtedly shift to natural gas-based plants, for which both post-combustion and pre-combustion technologies are already commercially available. These technologies are not being widely employed at present for lack of sufficient financial incentives, despite the new Section 45Q tax credits. Larger financial incentives, as well as a price or tax on carbon emissions, would prompt CCS implementation at natural

v Greeson says the natural gas plant solved two regulatory problems. First, a West Virginia regulator had stated, vis-à-vis a different post-combustion retrofit, he would never approve a power plant being de-rated to pay for CO_2 capture. Second, modifying the coal plant to integrate the CO_2 capture facility for power supply would have required New Source Review for the entire modified facility, and under EPA regulations the modification would have been too costly in relation to the coal plant's book value (the plant was nearly 40 years old at the time) to be approved.

w These include Wormser Energy Solutions, Inc. (WES) with its all-steam gasification (ASG) system, which is designed (because of the high efficiency of all-steam gasification) to achieve the same output as existing gasification systems with much smaller and shippable components; fewer inputs such as steel, concrete, and manhours; a smaller plant footprint; and no air-separation unit – for total project savings estimated at 40% compared to the existing gasification systems. The Gas Technology Institute (GTI) is in the process of demonstrating, in China, its Rocketdyne gasification system, which is also designed to be much smaller and less expensive than existing systems. Disclosure: The author is a consultant to WES.

gas plants without any new technology being required. New approaches for carbon capture from natural gas plants will also be attempted – such as the much-anticipated Allam-Fetvedt Cycle for power generation that NET Power is now developing with the aim of achieving 100% CO_2 capture – as natural gas increasingly displaces coal for power generation in the West.

If FutureGen or the CCPI-3 gasification projects had succeeded, however, the acceleration of carbon capture technology development might by now have begun to have a transformative and beneficial impact on coal use and climate impacts *globally*, at least in the many nations that remain largely dependent on coal for power generation and on coal gasification for the production of chemicals, fertilizers, plastics, synthetic fuels, and other commercial products.

Capturing carbon at a power plant, including at a natural gas-fired plant, forces a marriage of rotating equipment with a small chemical plant or refinery. This has proven difficult for cultural as well as technical reasons. It certainly accounted for difficulties at Kemper. At Petra Nova, notably, power for the CO_2 capture facility – the amine-based chemical plant – is provided by an entirely separate power plant. However, Petra Nova also benefited from an exceptional management team. This feature – rather than just a huge balance sheet, such as Southern Company's – proved essential to achieving success with a complex system that integrates power generation, a chemical plant, pipelines, and oilfields, not to mention saline formations, which will likely provide the world's largest geological sinks for captured CO_2.

The necessarily large scale of the FutureGen and CCPI-3 gasification projects also meant inherently long construction schedules, especially since these were FOAK plants. In addition to added cost (resulting from the accrual of inflation and interest during construction), these projects vividly demonstrate that times and markets – and hence public policy as well – can change, sometimes drastically, before a project is completed and perhaps even before construction starts.

FutureGen and the CCPI-3 projects were all premised on expensive natural gas, a national desire and global need to continue using coal for power generation, and a recognition that CCS must be developed to help mitigate climate change. The first of these premises remains true in many parts of the world, but not in North America, where the fracking revolution has made natural gas cheap. The second premise, that new coal plants would continue to be built for power generation, has not held up in the United States, though it continues to be borne out, in spades, in the developing world – and the developing world can't afford expensive FOAK CCS projects. *An important rationale for federal investment in these projects in the first place was to drive down CCS costs so as to make this critical technology available to the coal-dependent developing world*. That intention seems to have gotten lost, but in practice CCS remains necessary for effective climate change mitigation. In theory, the same rationale of Western nations pioneering climate-friendly technology for application in the developing world could be revived.

Given the FOAK challenges encountered in early CCS power plants, consistent, predictable, and sustained financial and policy support was essential. FutureGen and the CCPI-3 projects, as well as similar CCS power projects in Europe and the United Kingdom, all show the importance of consistent, sustained support – and suffered for lack of it. By contrast, financial and policy support continued and proved essential for other climate-friendly energy technologies, such as wind and solar. Those have benefited from longstanding government programs, including mandates that have often expanded over time (examples include renewable portfolio standards and clean-energy requirements), and tax incentives such as the production tax credit (PTC) for wind and the investment tax credit (ITC) for solar.

More broadly, advancing technology innovation policy through perceived crisis responses has often proved inimical to sustained government support. In the 2000s, high natural gas prices seemed to present a crisis for the power sector and helped propel interest in FutureGen and the CCPI-3 projects, with their reliance on low-cost coal. The need for economic stimulus and job creation in the depths of the Great Recession added urgency to the CCPI-3 projects – none of which could meet their original construction schedules, precisely because of their complexity. Urgency itself led to mistakes in project development, such as starting construction when not enough of the design engineering had been completed. When natural gas suddenly became cheap and abundant, the fact that these projects were also intended to stimulate innovation in CCS – a technology that responded to an urgent, global need for low-carbon power-sector options for coal, regardless of how inexpensive natural gas might become in the United States – tended to be forgotten. And when, in addition, the U.S. economy recovered from the recession, the Obama administration essentially lost interest and patience with FutureGen and the not-yet-completed CCPI-3 projects.

The third premise of all these projects – that CCS was among the essential tools that would be needed to address climate change – would seem to have been inarguable. Yet this premise came to be not so much forgotten as disputed. Most coal producers and utilities were at best suspicious of climate motivations for the technology. At the same time, a growing number of climate activists became deeply skeptical of CCS, not only on grounds that it might not work, but also because they considered it a deceptive means of allowing the hydrocarbon industry to continue increasing emissions. Concern about the "moral hazard" of allowing continued coal use based on the ability to capture future emissions (or rather, on the *promise* that future emissions would be captured) overshadowed concern about the moral hazard of failing to develop one of the tools that the United Nations Intergovernmental Panel on Climate Change (IPCC), the International Energy Agency (IEA), and numerous climate modelers and experts have concluded is essential to combat climate change.

In China, where CCS technology enjoyed widespread support in government, industry, and academic circles during the eight years of the Obama administration, CCS now appears to be regarded as a climate-mitigation option, not a necessity. Western support for CCS development in China, widely anticipated in the context of the Obama–Xi climate accord of November 2014, is no longer seen as likely, much less expected, on the part of the Chinese.

Nevertheless, there are positive signs as well as positive lessons for CCS. For a long period in the last decade, CCS – not just for coal, but for power plants and even industrial plants in general – became very largely a policy orphan. With the climate crisis deepening, however, support for CCS now appears to be growing rapidly within the climate community, including among members of the IPCC. Other energy interests and organizations, including energy companies and the IEA, have likewise become increasingly emphatic in their views on the need for CCS.

For example, there is growing recognition that the electricity sector accounts for only about one quarter of CO_2 emissions globally. For much of the global industrial sector, the ability to achieve major CO_2 reductions may well depend on CCS technology. The concept of industrial CCS "clusters," with CO_2 transport and sequestration infrastructure designed to serve multiple industrial emitters, has rapidly gained support in Europe, the United Kingdom, and Scandinavia. As a practical matter, most of the clusters currently being contemplated by policymakers already have a power plant suited for CCS retrofit or will require a new CCS power plant as a high-capacity-factor "anchor tenant" to make the economics of the cluster work.

Growing recognition of the urgency of climate mitigation has led some observers to conclude that methods for sequestering carbon in the biosphere (e.g., by growing trees) can obviate the need for carbon sequestration in the geosphere (e.g., in deep rocks). Even so, there are important differences between the security and permanence of these two forms of sequestration and, given the scale of the mitigation challenge, many climate experts believe that both will be needed. At least CCS is back on the climate policy agenda, though at present technologies for removing CO_2 from the ambient air, rather than from large emissions sources such as power plants, are gaining interest and acceptance (the general terms for such technologies are "direct air capture" or "carbon direct removal"). In the United States, meanwhile, CCS for large fossil-fuel plants is increasingly seen as a lower priority.

Lessons from FutureGen and the four CCPI-3 projects may or may not prove helpful to a new generation of CCS efforts in countries where this technology could provide enormous climate benefits, such as China, India, Indonesia, the Belt & Road Initiative nations, and (arguably) Australia. If such efforts go forward, they would benefit from several key observations drawn from the U.S. experience:

1 The objective with a FOAK plant is to demonstrate the technology works as intended – not to minimize costs or rush the construction schedule. In any sector, the cost curve from the FOAK plant to the nth plant is "ski tip" shaped – for the FOAK plant, at the top of the ski-tip cost curve, the key goals are to get the plant built and operating as a way to reduce costs (particularly of contingency allowances) for the next plant, which will be further down the ski-tip cost curve, and to "learn by doing" for future plants. What should matter, and what matters in the long run, is the cost and performance of the nth plant, not the FOAK plant.

2 To have a global climate impact, future CCS systems will have to capture and sequester huge amounts of CO_2. This will require large sinks and large numbers of CCS projects, including, it seems likely, large individual projects as well. The experience of building large solar projects or wind farms will not be very helpful to these efforts. Nor will the industry's experience with building large numbers of conventional power plants extend to integrating conventional plants' rotating equipment with a chemical plant. CCS has a large, vital, and inherent chemical process component.

3 U.S. experience, including but not limited to Petra Nova, has demonstrated that vendors who can provide the equipment required for CCS power projects do exist. These vendors include major international industrial corporations that are willing to guarantee (currently with plenty of cushion) the cost, performance, delivery, and commercial operation schedule of their equipment. With policy and financial support, CCS plants could and would be built with technology that exists today, paving the way for even better technology tomorrow – just as wind turbines scaled up over time from 100-kilowatt projects to 6-megawatt projects and even larger. We would not have today's wind turbine technology had we not invested in yesterday's technology and the technology of the day before.

4 Sustained and patient government policy that is specifically focused on *decarbonization* – a need that will exist until the climate problem is brought under control – and that is not focused primarily on aiding a particular economic sector (such as coal) or on creating jobs, has to be the foundation of successful

strategy for commercializing and deploying CCS. As Professor David Victor of the University of California San Diego's School of Global Policy and Strategy has stated, "Achieving deep decarbonization requires government because the technologies needed for deep decarbonization technologies won't spring forward on their own."[4] A certain number of failures will occur along the way to a mature and successful CCS industry. Policymakers and, if possible, the public should be prepared for that. Solyndra was a failure, but solar power has since become a great success.

5 The new Section 45Q tax credit for CCS in the United States – if implemented reasonably and in good faith, and particularly if extended – exemplifies the kind of policy support, similar to the support that wind and solar have enjoyed, that can help jump-start CCS in this country and elsewhere. The credit is not sufficient by itself, but it is a good tool among the many that may be needed. Had this policy been available to the CCPI-3 projects, at least one more of them might well have been successfully completed. Today's Section 45Q credit would have contributed at least $700 million to TCEP, for example – a financial game-changer for that project.

6 FutureGen and the CCPI gasification projects led to a new generation of technologies, currently in development, that have benefited from the lessons of "too big" gasifiers and "too complex" total CCS power plant systems. Moreover, support for research and development to advance these technologies to the next stage of commercialization and make them available to the world has continued even in the current administration.

7 Post-combustion capture of CO_2 for natural gas plants can be achieved today, with existing technology. The systems required are simpler than for a coal gasification plant, and with U.S. reliance on natural gas growing rather than shrinking – not to mention all the installed natural gas power plant capacity that could be retrofitted – it is only the lack of a clear policy on carbon emissions that is holding up installations. Moreover, NET Power's promise to develop 100% CO_2 capture capability for natural gas as a power source is not only potentially revolutionary but could be particularly valuable as increasing reliance on intermittent wind and solar generators increases demand for low-carbon sources that can provide firm, dispatchable capacity.

8 Good management is especially important when executing a FOAK project, as the Petra Nova case shows, and is probably necessary for success. To the extent governments can assess the quality of the management team, not just the balance sheet, visibility, or political influence of the company for whom the team works, governments should be able to make their targeted support for individual projects more effective. This lesson has relevance in China, India, Indonesia, and elsewhere throughout the world. It is perhaps more easily stated than applied.

With renewed interest in tackling climate change, there is hope that the U.S. government might one day dust off the accumulated lessons from its early efforts to support large CCS demonstration projects and recognize the need to share these lessons – along with the specific design engineering and work products the projects generated – with other countries. Although most of the projects were not successful, they were not without value: millions of dollars' worth of detailed engineering solutions to particular design and constructability problems were developed, even for projects that weren't completed.

The (generally exaggerated) story of Thomas Edison and the many materials he tested before settling on the best filament for a light bulb is instructive on the larger point of what can be learned from failure as well as success. As Professor Henry Petroski of Duke University's Engineering School, and the author of *Success Through Failure: The Paradox of Design*, among many other books on this theme, has observed:

> Success stories don't teach us anything but that they are successes. They are things to emulate, but the word "emulate" means two things. One, it means effectively to copy. Nobody wants to copy. Everybody wants to be more creative. They want to do something better. So "emulate" also implies trying to go beyond – trying to make it better, somehow bigger, whatever the measure is.
>
> Successes are not very interesting other than in that regard. *When we do go beyond, then we move generally closer to failure. And what interests me about any failure is that it presents real lessons to be learned, because there's no ambiguity. When something fails, it failed.*[5]

About the Author

Eric (Ric) Redman is the former president & CEO of Summit Power Group, Inc., a developer of wind, solar, natural gas, and proposed CCS power projects, both for natural gas and coal. The latter included the Texas Clean Energy Project (TCEP), a DOE-funded project under the program described in this article. Redman headed TCEP from 2009 through 2014. He is a board member of the Global CCS Institute (GCCSI) and an advisory board member of Scottish Carbon Capture & Storage (SCCS). He is a senior policy fellow working on the Deep Decarbonization Initiative (D2I) at the University of California San Diego School of Global Policy & Strategy (GPS), where he co-teaches a course on real-world projects in energy and environment. Currently, he works as the head of Thunderbolt Clean Energy, LLC, a climate technology consulting group, and as senior policy advisor for Energy & Climate at Cascadia Policy Solutions, LLP, and the Cascadia Law Group, PLLP, of Seattle and Olympia, Washington.

Endnotes

1 Private communication.

2 David Wagman, "The Three Factors That Doomed Kemper County IGCC," *IEEE Spectrum*, June 30, 2017. Available at: https://spectrum.ieee.org/energywise/energy/fossil-fuels/the-three-factors-that-doomed-kemper-county-igcc.

3 Private communication.

4 Private communication.

5 Henry Petroski, *Success Through Failure: The Paradox of Design*, (New Jersey: Princeton University Press, 2018).

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