Carbon Capture Journal

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The Clean Power Plan: what it means for CCS

New approaches to implementing CCS and a Roadmap for coal

Sept / Oct 2015 Issue 47

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Front cover: Dresser-Rand's supersonic compression technology represents a significant advancement for many compressor applications, and specifically for CO2 compression

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Obama administration releases final Clean Power Plan

On 3 August, US President Barack Obama and Environmental Protection Agency (EPA) Administrator Gina McCarthy released the final Clean Power Plan, which establishes the first national standards to limit carbon pollution from power plants.

The final Clean Power Plan sets standards to reduce carbon dioxide emissions by 32 percent from 2005 levels by 2030, nine percent more ambitious than the proposal. It establishes the first-ever national standards to limit carbon pollution from power plants.

The final plan takes into account the input EPA received through extensive outreach, including the 4 million comments that were submitted to the agency during the public comment period.

"The result is a fair, flexible program that will strengthen the fast-growing trend toward cleaner and lower-polluting American energy," says a statement from the President. "The Clean Power Plan significantly reduces carbon pollution from the electric power sector while advancing clean energy innovation, development, and deployment."

"It ensures the U.S. will stay on a path of long-term clean energy investments that will maintain the reliability of our electric grid, promote affordable and clean energy for all Americans, and continue United States leadership on climate action."

Key features

- Flexibility for states to choose how to meet carbon standards
- More time for states to prepare for compliance paired with strong incentives for early deployment of clean energy
- Rewards states for early investment in clean energy, focusing on low-income communities
- Ensures grid reliability by giving states a "safety valve" to address, on a case-by-case basis, any reliability challenges that arise
- Continues US leadership on climate change by continuing momentum towards COP-21 in Paris
- Sets state targets by using updated information about the cost and availability of clean generation technologies and establishing separate emission performance rates for all coal plants and all gas plants
- Maintains energy efficiency as a key compliance tool
- Requires states to engage with vulnerable populations, including low-income, minority and tribal communities and workers in the utility and related sectors
- Includes a proposed Federal Implementation Plan to provide a model states can use and help ensure the standards are met in every state

EPA's Clean Power Plan establishes carbon pollution standards for power plants, called carbon dioxide (CO2) emission performance rates. In the U.S., there are 1,000 fossil fuel fired power plants with about 3,100 units covered by the rule. Utility planners are already making plans to address an aging fleet. The average age of coal units is 43 years. The average age of oil units is 46 years. The average age of natural gas combined cycle units is 15 years.

States develop and implement tailored plans to ensure that the power plants in their state meet these standards– either individually, together, or in combination with other measures like improvements in renewable energy and energy efficiency.

The final rule provides more flexibility in how state plans can be designed and implemented, including: streamlined opportunities for states to include proven strategies like trading and demand-side energy efficiency in their plans, and allows states to develop "trading ready" plans to participate in "opt in" to an emission credit trading market with other states taking parallel approaches without the need for interstate agreements.

All low-carbon electricity generation technologies, including renewables, energy efficiency, natural gas, nuclear and carbon capture and storage, can play a role in state plans.

State plans are due in September of 2016, but states that need more time can make an initial submission and request extensions of up to two years for final plan submission. The compliance averaging period begins in 2022 instead of 2020, and emission reductions are phased in on a gradual "glide path" to 2030.

EPA also released a proposed federal plan today. This proposed plan will provide a model states can use in designing their plans, and when finalized, will be a backstop to ensure that the Clean Power Plan standards are met.

What the rules mean for CCS

In a blog on the Center for Climate and Energy Solutions website, Patrick Falwell concludes that the EPA's power plant rules provide regulatory context for CCS, but CCS remains a relatively expensive option in the power sector.

"In its final rules for limiting carbon dioxide emissions from new and existing power plants, EPA recognized the importance of carbon capture and storage technologies to achieving U.S. carbon reduction goals," he says.

"New coal-fired power plants will likely need to capture some portion of potential emissions to meet final federal standards for emissions. While not required, existing coal and natural gas power plants may pursue carbon capture and storage (CCS) to meet state emissions targets under the final Clean Power Plan."

"However, a regulatory requirement for CCS does not guarantee the development of commercial-scale projects, and additional work will be needed to address the economic barriers to CCS."

"In the rule covering new power plants, EPA confirmed its original finding that CCS is technically available and feasible to implement. EPA's final rule set an emissions standard of 1,400 pounds of carbon dioxide (CO2) per megawatt-hour (MWh) of electricity generated. This is less stringent than the 1,100 lbs CO2/MWh limit originally proposed. But given that the most efficient coal plant without CCS is still likely to emit around 1,700 lbs CO2/MWh, adopting CCS is likely required."

"EPA justified its conclusion by citing the experience to date in deploying CCS technology. This includes the successful launch of the world's first commercial-scale CCS power plant by SaskPower in Saskatchewan in 2014, two commercial-scale projects under construction in the United States in Mississippi and Texas, a variety of CCS projects at industrial facilities, and numerous demonstration-scale CCS projects. In addition, EPA noted that Linde and BASF offer a performance guarantee for their joint carbon capture technology and that other well-established companies actively market CCS technology and express confidence in the technology's ability to perform well."

"Despite EPA's confidence in CCS's availability, it does not foresee new coal plants, with or without CCS, going forward between now and 2020. The ability of low-cost natural gas and renewables to meet new demand for electricity or replace retiring power plant capacity has and will likely continue to eliminate the need for new coal capacity. In the event that new coal capacity becomes necessary, the rule makes sure that CCS is used to reduce potential CO2 emissions."

"Overall, EPA's power plant rules provide regulatory context for CCS, but CCS remains a relatively expensive option in the power sector. Like with any other emerging technology, the cost of carbon capture will come down over time through the repeated deployment of commercial-scale projects that can provide insights into how costs can be reduced. SaskPower estimates it could build its next CCS power project at 30 percent less expense, with even greater cost reductions for the project after that. In addition, the ability to sell captured CO2 for utilization in opportunities like enhanced oil recovery (EOR) creates revenue to offset the cost and risk of investing in CCS. Most of the existing or under-construction CCS projects take or intend to take advantage of EOR."

"Given that coal and natural gas are expected to continue to be a major source of energy in the United States and globally for years to come, investing in CCS and getting more commercial-scale projects under development should be a priority."

What the US can learn from Europe

Gerard Reid on the Energy and Carbon blog concludes that the Clean Power Plan is, "likely to transform the US power industry just as the 2007 '20-20-20' targets have radically changed the European energy landscape."

He makes several points:

• **There will be a massive move away from fossil fuel generating technologies to renewables.** This will not be a smooth transition and we may see asset writeoffs and massive restructuring by slow to move energy companies and their service providers. Given the fact that technologies such as solar are highly competitive these changes may happen faster than it did in Europe.

• **Energy prices are likely to fall.** In Europe the push towards zero marginal cost renewables as well as weak demand due to energy efficiency has pushed wholesale power prices to the lowest levels in a decade. The same is likely to happen in the US noting that technologies such as solar and LEDs are now much cheaper than what they were.

• **Nuclear may be clean but it will not be a winner.** Fukushima may have made all the headlines and pushed Germany to move out of nuclear but the economic reality is that nuclear technology is too expensive to build and decommission, especially in comparison to increasing cost competitive renewable technologies.

• **Resistance buys time but will not help companies and regions in developing sustainable strategies.** Most European utilities have spent the last decade campaigning against change rather than embracing new technologies and business models and as a result their very existence are under threat.

• **Different states will move at different paces.** Some will move very fast (think Germany and California) while some will stall and resist (think Poland and Virginia).

• **It will be a bumpy road ahead.** We will see a concerted media, PR, legal and political campaign against the Clean Power Plan. It will range from "coal is good" to "wind is bad for the birds" and it will include legal challenges and political and regulatory backlashes all of which will make investing in the energy area a more tricky place to operate.

• **Exciting new businesses will come our way.** Out of the European renewable boom has come a whole range of new and exciting global leaders such as Vestas in wind, SMA in solar, PSI in grid, and EDPR and Enel Green Power in the utility area. We are already seeing the starting of this in the US with businesses such as SolarCity and SunEdison but more will come as momentum begins to build.

• **Other new technologies will come quicker to market.** The coming clean energy boom in the US will enable storage technologies such as batteries to significantly reduce costs and it may help other nascent technologies such as fuel cells to come quicker to market. These technologies will have a significant impact not only on the US but the global energy market.

More information

Detailed information on the rule can be found at:

www2.epa.gov/cleanpowerplan

www.whitehouse.gov

Comments are from:

www.c2es.org

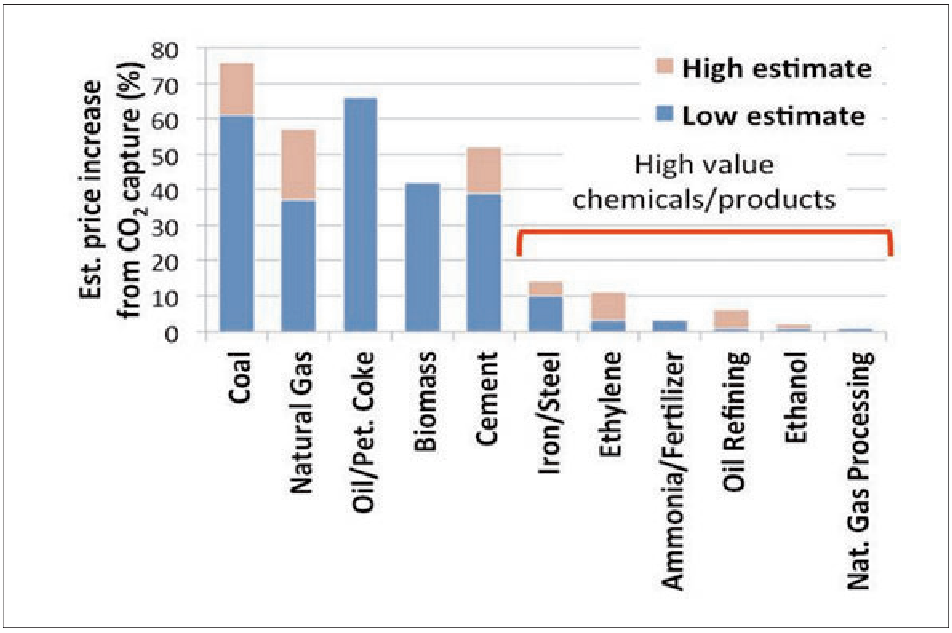
energyandcarbon.com

Evaluating a new approach to CO_2 capture and storage

In a perspective paper published in Greenhouse Gases: Science and Technology, researchers examined a new approach that could potentially overcome many barriers to deployment and jumpstart this process on a commercial scale.

At present, 68 percent of the electricity generated in the United States results from burning fossil fuels, more than half of which uses coal , the most CO2-intensive source, as the primary energy source. Implementing CO2 capture, utilization, and storage (CCUS) might enable a gradual transition to energy sources that emit less CO2 per unit of energy while continuing to leverage the useful lifetime of the existing energy infrastructure.

The strategy could also be employed developing countries that are expanding their fleet of coal-fired power plants. However, the cost of CO2 capture has hindered commercial-scale application of this climate mitigation approach. Implementing CO2 capture in coal-fired power plants could result in almost a doubling of electricity prices for consumers.



Estimated produce price increase due to the captured CO2 process

The researchers examined near-term market-viable opportunities to demonstrate integrated CCUS while other pathways for technology development are pursued. As a result of their comparison of approaches, they concluded that a financially viable demonstration of a large-scale process requires offsetting the costs of CO2 capture by using the CO2 as an input to the production of marketable products.

The scientists propose that a near-term demonstration of this technology could focus on implementing CO2 capture on facilities that produce high-value chemicals/products such as such as ethanol, iron/steel production, and oil refining. High-value chemicals/products industries collectively emit 360 million tons of CO2 per year, which is roughly the same amount of CO2 that natural gas power plants emit.

Calculations suggest that the high-value chemicals/products facilities could better absorb the expected impact of the marginal increase than could coal-fired power plants. In addition, the captured CO2 could be sold for market-viable products. This alternative method of capturing CO2 and storing from stationary sources could enable a viable commercial-scale demonstration of the technology.

The researchers calculated and compared the estimated increase in the cost of the production price of product due to the addition of CO2 capture and storage for fossil fuel-fired power plants and for a series of high-value chemicals/products. Many of the high-value chemicals/products facilities are large in size and clustered in location, which provides logistical advantages for this approach.

The estimated proportional increases in price for high-value chemicals/products facilities range between 1 and 15 percent, which is substantially less than the estimated relative increases in the price of fossil-based electricity. The team performed a case study of a successful integrated CO2 capture, utilization, and storage system where CO2 is captured from ethylene producers and used for enhanced oil recovery in the US Gulf Coast region.

The researchers include Richard Middleton, Philip Stauffer and Hari Viswanathan of LANL's Computational Earth Science group; William Carey of LANL's Earth System Observations group; Jonathan Levine of the DOE National Energy Technology Laboratory; and Jeffrey Bielicki of The Ohio State University.

The US-China Clean Energy Research Center, Advanced Coal Technologies Consortium (ACTC), the DOE Big Sky Carbon Sequestration Partnership CO2-EOR, and the Los Alamos Laboratory Directed Research and Development (LDRD) program funded different aspects of the work. The research supports the Lab’s Energy Security mission area and the Materials for the Future science pillar via the evaluation of technologies to capture and sequester anthropogenic CO2 emissions.

More information

www.us-china-cerc.org

lanl.gov

Let's Get Serious About CCS

Third Way, a Washington, DC-based centrist think tank, has released a report calling for increased support for the commercial development and deployment of CCS technologies.

By Ryan Fitzpatrick and Melissa Carey

What if there were a way to substantially cut carbon emissions worldwide by improving an existing technology that can be used on coal- and gas-fired power plants, as well as oil refineries, steel mills, and other major industrial facilities? What if this technology helped ensure the diverse, cleaner energy mix analysts argue the world needs to maintain economic growth and address climate change?

This technology actually exists. It's called CCS.

The perception in Washington, however, is that CCS has collapsed under its own weight of cost over-runs and project cancellations. But a yearlong study by Third Way has found that while CCS is desperately needed, its development has been undermined by a combination of market and policy failures.

Main conclusions

Washington has failed to give carbon capture and storage (CCS) the attention it deserves, especially since this technology has the capacity to resolve some of the nation's greatest environmental and economic challenges. Commercial development of CCS offers a chance to:

• Decarbonize fossil fuels that will remain in global use for decades.

• Ensure a reliable electric grid in the face of tightening environmental standards.

• Lead fossil-reliant communities to a thriving future amidst rapidly changing energy markets.

Instead of letting CCS technology languish and fall short of its potential, the federal government must do more to help the private sector develop and commercialize this potentially game-changing technology.

Targeted policy reforms and re-focused funding can build on current CCS project successes and help jumpstart private sector CCS development in the United States. This would preserve a role for American innovation and American fossil fuels in a global market that is facing simultaneous pressure to grow and decarbonize.

Another "Inconvenient Truth" about Climate Change

Virtually every day, it seems, we read another headline about the rapid rise of renewables at home and abroad: double-digit growth, enhanced projections about the role of solar and wind in our energy future, and advances in battery technology seem to indicate that the fossil fuel era is drawing to a close.

Stanford Professor Mark Jacobson, wind advocate Steve Sawyer, the Sierra Club and many more have described a world powered entirely by renewables in the next few decades. We'd love that to be true. We are vocal supporters of renewable energy and are thrilled to see record growth in the United States and globally over the past decade.

But the reality is much more complicated than headlines suggest. As the charts below make clear, fossil fuels are still keeping the lights on, both at home and abroad—and they are projected to continue to do so for a long time to come.

So here's the unfortunate truth that policymakers must address: we're very unlikely to see a renewables-only world in our lifetime. Dave Roberts, the columnist who coined the term "climate hawk" and is an outspoken climate advocate, describes mitigation plans that rely too heavily on renewables as little more than "thought exercises."

DotEarth columnist Andrew Revkin says that reports suggesting a 100% renewable future have a lot of "that darned fine print." Of a recent Intergovernmental Panel on Climate Change (IPCC) report, Revkin takes issue with language suggesting that existing renewable technology can largely resolve climate concerns, saying, "you'd have to dig deep and long in the background chapters to learn that 'many of these technologies exist today' hides huge gaps, particularly at the scale that would be needed to blunt emissions of greenhouse gases."

These more realistic assessments echo the findings of some of the most respected authorities on climate and energy. Even after the Clean Power Plan is fully implemented in 2030, the U.S. Environmental Protection Agency (EPA) believes that coal and natural gas will still rule the grid, respectively accounting for 28% and 32% of America's electricity generation.

The U.S. Energy Information Administration (EIA) also expects coal and gas to continue providing over half of U.S. electricity, and projects an increasingly troubling reliance on fossil fuels worldwide. EIA forecasts suggest that by 2040, global energy demand will grow by 56%, and fossil fuels will supply 80% of that demand.

As Maria van der Hoeven, Executive Director of the International Energy Agency (IEA) concluded, "With coal and other fossil fuels remaining dominant in the fuel mix, there is no climate friendly scenario in the long run without CCS."

U.S. Energy Secretary Ernest Moniz has made similar statements and specifically highlighted the need for CCS on cleaner-burning natural gas, saying "Eventually, if we're going to get really low carbon emissions, natural gas, just like coal, would need to have carbon capture to be part of that."

Of course, energy projections can (and often do) turn out to be incorrect. Predicting the speed of innovation and deployment for technologies like wind and solar is tricky, and none of the aforementioned organizations is infallible. If the EIA, EPA, and IEA are wrong and renewables displace the overwhelming majority of the world's coal and natural gas within the next few decades, we'll be well on our way to meeting our carbon reduction goals. Excellent news.

But, what if the EIA, EPA, and IEA projections are right?

By the time we find out, it'll be far too late to ask for a do-over. On this basis alone, it makes sense to ensure that CCS is ready to assist in cutting emissions from fossil fuel consumption around the world—because it's the only technology that can do the job.

Cutting carbon...and costs

According to the International Panel on Climate Change (IPCC) and International Energy Agency (IEA), CCS offers the most effective means of drastically reducing emissions from fossil fuel-fired power plants—and the only means of making deep cuts in some of the world's most carbon-intensive industries such as cement and steel production.

Access to CCS technology will also be critical in keeping mitigation costs from skyrocketing. The IPCC has found that without CCS, reaching the aggressive mitigation goals suggested by the scientific community will be 138% more expensive than if CCS were used. To put this into perspective, having limited penetration of renewables on the grid would also increase mitigation costs, though by just 6%.

Ensuring reliability while decarbonizing the grid

President Obama's Clean Power Plan has sparked a heated debate about the challenges of maintaining grid reliability while simultaneously cutting emissions from the power sector. Recent analysis suggests that utilities and grid operators have options for complying with the Clean Power Plan that won't affect their ability to provide dependable service to customers.

But even if this turns out to be accurate, what about future requirements to further decarbonize the grid? The Clean Power Plan is just one piece of President Obama's strategy to cut U.S. emissions roughly 27% below 2005 levels by 2025. But the IPCC finds that, by 2050, developed countries like the U.S. will need to have made much more aggressive cuts (at least 80% below 1990 levels) in order to avoid the worst impacts of climate change.

Even after the Clean Power Plan is implemented, the power sector will still be one of the greatest contributors to U.S. emissions.16 Because of this, it stands to reason that electricity production will be a top target for subsequent cuts. So what will happen if utilities and grid operators already have exhausted the low-hanging fruit of decarbonization options?

At issue is the fuel shift that utilities are anticipated to make—away from coal and toward lower-carbon power sources like renewables and natural gas—in order to meet emissions requirements. Utilities are largely unable to predict or control how much electricity will be generated by wind or solar installations at any given point, like they can with a coal plant. Retiring coal plants and replacing them with renewables therefore adds variability. Significantly expanding renewable use without degrading reliability creates significant technical and financial challenges for grid operators.

There are also limitations to the amount of coal generation that can be shifted to natural gas without creating reliability concerns. In many cases, a utility can cheaply store enough coal onsite to fuel a power plant for weeks or even months, allowing it to adapt to unexpected surges in demand or emergency fuel supply interruptions like what occurred during the polar vortex of 2014.

Increasing reliance on natural gas, however, may require utilities and regional grid operators to invest heavily in transmission and storage infrastructure in order to maintain a similar level of reliability—a challenge that the nation's largest grid operator, PJM, is already anticipating in its Mid-Atlantic and Midwest service territory.

If CCS technology were more readily available today for power plants, utilities and grid operators would have the option to keep coal in their portfolios while still meeting regulations on greenhouse gas emissions—no matter how aggressive they become in the future. That's because CCS can enable the power sector to produce reliable, long-term base load power with near zero emissions and enhance overall grid performance while renewables ramp up.

A path forward for fossil industries and the communities depending on them

Fighting climate change might not be a top priority for fossil fuels industries. But these companies are certainly paying close attention to climate policy efforts in the U.S., E.U., China, and elsewhere. These attempts to decarbonize could have a massive impact on the size of fossil fuel markets—and profits.

As Wyoming State House Speaker Tom Lubnau (R) put it upon returning from a recent trip to China, "It doesn't matter what you think, if there's anthropogenic—fill in the blank: climate change, global warming … Our markets change, and if we want to continue utilizing coal we have to respond to the market."

Access to CCS technology could enable these industries to compete in markets with increasingly stringent emissions requirements and reduce the risk of losses from "stranded assets." Given their relatively high CO2 emissions, coal-fired power plants are the first electricity sources impacted as emissions limits are ratcheted downward. Such is the case with the Clean Power Plan, which is expected to exacerbate challenges the coal industry already faces in competing with natural gas.

Some voices from America's coal country see CCS and related technologies as a way to stabilize the industry and the local economies that rely on it. Wyoming Governor Matt Mead, for instance, has worked with the state's conservative legislature to fund a facility that will test ways of utilizing captured CO2 and turning it into marketable products—helping to offset some of the costs of carbon capture. Though a climate skeptic himself, Governor Mead has explained that global markets for coal are beginning to change in response to climate concerns and that Wyoming, which relies on coal for 6% of its jobs and 14% of its GDP, must adapt to keep up.

Coal isn't the only fossil fuel industry that will need access to CCS technology—especially if energy markets in certain parts of the world continue their trend toward decarbonization. Natural gas power plants and processing facilities will be likely targets of emissions reductions plans too. For example, California has found that in order to meet its 2050 emissions goals, electricity production from natural gas power plants will have to be significantly curtailed if they are not equipped with CCS.

Today, California's power plants consume 10% of the natural gas used for electric generation in the U.S., purchasing roughly \$4.5 billion worth of gas each year. Losing a large piece of the market in just this one state would have a sizeable impact on the natural gas industry. But the pain might not stop there. Since California's emissions reduction targets are in line with the cuts that scientists are recommending on a global scale, it is possible that natural gas plants in other states and countries seeking to achieve this same level of reduction will need CCS too.

California's decarbonization efforts could also create demand for CCS from petroleum refineries—the state's second largest stationary source of emissions, after power plants.24 And there is always the chance that EPA will expand federal regulations on greenhouse gas emissions to include refineries, as it agreed to in the same legal settlement that precipitated the Clean Power Plan.

In any of these cases, commercial availability of CCS technology could mean the difference between profit and loss for companies in several fossil industries—as well as the employees, investors, and communities that depend on them. As some forward-looking members of these industries have acknowledged, it's in their best interest to have CCS technology as accessible and affordable as possible for when they eventually need to use it.

Picking Up the Pace of CCS Development

Even with all of the reasons to move ahead on CCS, it is important to be clear about where things stand today: carbon capture and storage is a first-generation, nascent technology that hasn't received serious attention or investment in nearly a decade. Today's CCS systems—the few that exist at commercial scale—are large, complicated, heavily engineered, and at a learning-by-doing stage of development. CCS is technically feasible and in operation but it isn't elegant, and it certainly isn't cheap.

Most new and complex technologies require a certain degree of public investment, in partnership with the private sector, in order to get off the ground. CCS is no exception to this rule. And in light of the public benefits it can provide, this technology is certainly worthy of more public backing than it currently receives.

To be effective, federal investment in CCS must be sizeable and consistent, and it must address the distinct needs of CCS projects at all stages of development—from R&D to construction and through operation.

Shift Research and Development Into High Gear

Even after the Clean Power Plan is fully implemented, fossil fuels will still account for at least 60% of U.S. electricity generation. Yet we are spending only 4% of our energy research budget on the technology most badly needed to address this massive source of emissions in the long-term.

The Department of Energy has done a commendable job of stretching its limited fossil energy technology budget to reduce the environmental impacts of using coal, natural gas, and other carbon-heavy fuels—including research and development for CCS. But these resources do not come close to meeting the needs of such a significant source of carbon emissions in the U.S. and global economies.

The federal government should support more research and development in reducing or eliminating emissions from the very fossil fuels that are expected to generate more than half of the electricity in the U.S. for at least the next several decades. Though basic technologies for capturing, transporting, and sequestering carbon dioxide were developed decades ago, expanding federal research and development would help to improve integrated CCS system performance and lower costs.

Support Construction of the Next Wave of Demonstration Plants

Once the various pieces of a CCS system are proven in the lab and at the pilot-scale, the next step is to integrate them together in a large-scale demonstration plant. These "first of a kind" projects are a critical step in improving CCS technologies and driving down the cost of future plants. But in a competitive market, the expense of these initial projects is still too great for the private sector to take on alone.

A brief surge of direct federal investment nearly a decade ago is responsible for the handful of large-scale CCS projects underway in the U.S. today. Unless policymakers follow-up with additional rounds of this type of funding, future projects are unlikely and the momentum we have built toward CCS commercialization will be lost.

Help CCS plants reach long-term profitability

Even if R&D and large-scale demonstration efforts succeed in drastically lowering the cost of building a CCS plant, most facilities will still need some form of public support in order to operate profitably. This isn't so much a flaw in CCS technology as much as a failure of the electricity market itself. Running a CCS system on a power plant requires a significant amount of energy and increases operating costs. But because U.S. policy does not make polluters pay for the CO2 they emit, utilities that take on the added cost of sequestering their CO2 put themselves at a competitive disadvantage to those who simply release their pollution into the atmosphere for free. To make up for this market flaw, a federal tax credit was created to reward CCS operators for each ton of CO2 that they sequester. The value of this credit, however, has not been adequate to offset the costs of CCS.

Conclusion

Like it or not, the odds are that the world will remain heavily reliant on fossil fuels for electricity and industrial processes for many decades to come. This is awful for the climate. That is why so many countries around the world are beginning to put policies in place to restrain carbon emissions. There is the slim possibility that such policies, and improvements in technology, might be enough to lead us to an almost entirely renewable energy-powered planet.

But what if that doesn't happen? Or what if your job, your company, or your state relies on fossil fuels for economic growth?

That is why we must invest in developing and commercially advancing carbon capture and storage, the only technology that can address fossil fuel and industrial emissions at large-scale. This is a technology that already exists but has been starved of critical funding that can improve performance, lower cost, and get it more broadly to market. If CCS is further developed and deployed more widely at commercial scale, it can clean up the fossil fuels that the world will continue to burn, help ensure a reliably functioning electric grid, and provide an economic lifeline for fossil fuel-dependent communities.

At worst, this is an insurance policy that turns out not to be needed. But, we believe much more likely, it will turn out to be the critical technology that keeps the lights on, keeps our factories running, and keeps us on track to win the fight against climate change—but only if the right federal investments are made today.

More information

The full report with references can be viewed or downloaded at:

www.thirdway.org

The CURC-EPRI 2015 Advanced Coal Technology Roadmap update

A joint report between the Coal Utilization Research Council (CURC) and the Electric Power Research Institute (EPRI) presents a RD&D plan for developing technologies that convert coal to electricity and other useful forms of energy and manufacturing feedstocks.

Earlier Roadmaps were published by CURC and EPRI in 2003, 2008, and 2012. This update includes new data on recent advances in technology; addresses the increased stress on the U.S. economy which has diminished support for technology development; accounts for low-cost, increased domestic supplies of natural gas; and recognizes regulations to control both hazardous and criteria air pollutants from coal use as well as new, proposed policies for controlling emissions of CO2.

Reflecting on these changed conditions, the 2015 Roadmap update includes pathways for pilot-scale demonstration activities; reflects the need to replace existing capacity with smaller scale, more modular commercial systems that may be needed in the 2025-2030 timeframe to account for slower load growth and to serve as replacement options for aging coal units; takes into account market constraints likely to result in slower penetration of emerging integrated gasification combined cycle (IGCC) technologies; and provides a more detailed analysis of transformational technologies that can introduce new methods of converting coal to useful energy.

The Roadmap Update also includes an examination of the technology needs to ensure the economic and energy security benefits provided by the existing coal fleet can be maintained well into the future.

The Roadmap identifies coal technology advancements that can achieve specific cost, performance and environmental goals, and identifies pathways for developing the technologies needed to achieve those goals through collaborative efforts between the public and private sectors.

Specific benefits which can be achieved through successful implementation of the Roadmap are discussed below, and can generally be categorized as:

1. Aggressive reduction of water use and air pollutants, including NOx, SO2, Hg and PM;

2. Reduction of CO2 emissions;

3. Production and preservation of affordable electricity essential for U.S. competitiveness through a diverse generation technology portfolio;

4. Improved energy security by –

a. Using captured CO2 as a commodity to recover crude oil, thereby increasing domestic oil production;

b. Deploying technologies for the production of liquid fuels and other marketable products;

c. Generating affordable power for electricity consumers including increased industrial and

Summary - the 2015 update

The 2015 Roadmap Update was undertaken amid several new market conditions that required a re-examination of the technology development needs for the new and existing fleet of coal plants. This re-examination took into account several factors, including fluctuations in the market for coal use in the United States today; the impact of recently proposed regulations to limit emissions of greenhouse gas (GHG) emissions from fossil-fueled power plants; the availability and growth of low-cost, domestic supplies of natural gas being used in both new and existing power generation, increasing levels of renewable electricity generation; and an electric power market that is experiencing and projecting low or no load growth over the next decade.

Additionally, since 2012, two carbon capture utilization and storage (CCUS) projects have been completed or nearly completed their construction phase, which has provided a better understanding of the costs of carbon capture and storage (CCS)/CCUS. Lastly, amid growing concerns associated with an aging, existing coal fleet and anticipated coal fleet retirements, the 2015 Roadmap Update also examines the ability to accelerate the development of transformational technologies so that viable new coal-based technology options will exist in the 2025-2030 timeframe to replace retiring coal capacity. However, the availability of these transformational options will be strongly dependent on the level of federal funding available to implement the technology development recommendations included in this report.

The 2015 Roadmap Update examines three new technology development pathways:

(1) A new program that considers the value of the existing coal fleet, and describes a technology program necessary to support the existing coal fleet as it takes on new challenges in responding to new regulatory and dispatch requirements;

(2) A new "transformational" technology program that defines development needs for new technologies that will deliver significantly higher value in terms of cost, efficiency, flexibility and environmental performance relative to current coal-based electricity generation; and

(3) A new large-scale pilot program that anticipates federal support of evaluating new technologies under real operating conditions at a scale beyond laboratory and bench- scale and before testing technologies in a commercial-scale demonstration.

advanced manufacturing customers and to fuel electric vehicles; and

d. Improving the operational flexibility of the existing and future coal plants to ensure continued electricity grid reliability and stability.

5. Ensuring significantly improved technologies are tested at large pilot-scale to assure availability of coal generation options by the 2025-2030 timeframe when a significant portion of the existing fleet of coal plants may be candidates for retirement.

Funding ($M/year)		2016-2020	2021-2025	2026-2035
RD&D	Total (Industry and Federal)	346	241	97
	Federal (80%)	277	192	77
Pilots	Total (Industry and Federal)	279	322	89
	Federal	279	322	89
Demos	Total (Industry and Federal)	28	854	654
	Federal (50%)	14	427	327
Total (Public/Private) Annual Funding		653	1,416	850
Annual Federal Budget		570	941	493

Public-Private Sector Cost Share to Implement the Roadmap

Funding

CURC recommends continuation of the current RD&D policy of 80% federal and 20% private or other funding for research and development activities. For commercial-scale demonstrations, existing authorities require industry to contribute up to one half of the demonstration funds required by the project. Despite this, nearly all of the clean coal power initiative projects identified have not received a full 50% federal cost-share contribution to the project.

The Roadmap contemplates full 50% federal cost-share towards the stated demonstration projects which will be necessary to achieve the projected cost and performance goals of the Roadmap. With respect to large pilots, CURC views the financing difficulties for any amount of industry cost share in today's market for large-scale pilots as an impediment to advancing these technologies and recommends 100% federal financial support for such a program, with industry taking the lead in providing the intellectual and human capital necessary to advance the technologies.

Environmental Benefits

New coal-fueled power plants being built show even more dramatic reductions in emissions. Compared to power plants built in 1970, today's new plants emit 95% less SO2 and NOx, and 90% less Hg. The addition of CO2 emissions control technologies can reduce these criteria air emissions to near zero emission levels. Significant advances also have been achieved in managing solid wastes from coal combustion.

Today's modern coal-fueled power plants can achieve conversion efficiencies of 39% higher heating value and more compared to efficiencies of 33% or less in coal plants constructed in the 1970's. These increases in efficiency alone result in more than a 15% reduction in potential CO2 emissions. Further reductions in CO2 emissions will require RD&D as described in this Roadmap. The public/private collaborative research, development and demonstration efforts now underway in the United States to address CO2 emissions from coal-fired power plants are significant, and with continued support, can achieve targets for cost and performance that are highly competitive with other forms of clean energy generation.

Looking to the future, many of the environmental benefits expected from implementation of the proposed technology Roadmap derive from the reduction in CO2 emissions. Just as today's new coal plants achieve much lower levels of emissions than those of two decades ago, tomorrow's new coal plants are projected to achieve near zero levels of emissions. By combining successful implementation of technology advances identified in the Roadmap with opportunities for beneficial use of captured CO2, coal-based power plants could achieve lower CO2 emissions at a cost of electricity competitive with other low-carbon generation alternatives.

The central goal of the Roadmap is to reduce the cost and improve the environmental performance of both existing and new coal conversion systems, including reducing the costs to install CO2 capture systems and reducing the consumption of energy from the power plant needed to operate those systems. Even though first-generationtechnologies capable of capturing CO2 from power plants exist today, they are not commercially viable, are very expensive to implement, and have not yet been demonstrated in electric power generation systems at scale.

Additionally, there is very limited experience with storing large volumes of CO2 in saline geologic formations. One important strategy to overcome the cost challenges is to use captured CO2 for beneficial purposes. Consequently, this research area is sometimes referred to as "Carbon Capture, Utilization and Storage," or CCUS. For example, there appears to be a significant domestic market for CO2 use in EOR today. With increased volumes of CO2 supplies, the completion of major CO2 pipelines, and new EOR projects announced by industry, NETL estimates that EOR production using anthropogenic sources of CO2 will grow significantly.

Another economic benefit of coal research can come from the sale of captured CO2 to enhanced oil and gas recovery. The United States currently produces about 4% of its oil by use of CO2 for EOR. In addition to conventional oil plays where EOR is occurring, the United States has a wealth of oil and gas reserves in the unconventional (shale) oil reservoirs in the United States. Thanks to recovery technologies such as horizontal drilling developed by the DOE's Fossil Energy program, the United States has begun to access those reserves. However, those fields are experiencing low recovery levels with these extraction techniques.

Additionally, there are pilot projects underway targeting the Residual Oil Zone to access those fields. Using CO2 to access the large amount of oil trapped in those reservoirs is another source of domestic oil production. Most of this oil production uses relatively inexpensive "natural" CO2 extracted from the ground in a manner similar to natural gas extraction. But future supplies of this inexpensive CO2 are projected to be limited.

In addition to the economic value of the oil, the associated economic activity related to its production could have a measurable impact on jobs and the U.S. economy. Moreover, increased domestic production of oil using CO2 for EOR could directly displace oil imports, reducing the U.S. trade deficit, and enhance energy security.

Estimating Costs in 2015 Roadmap Update

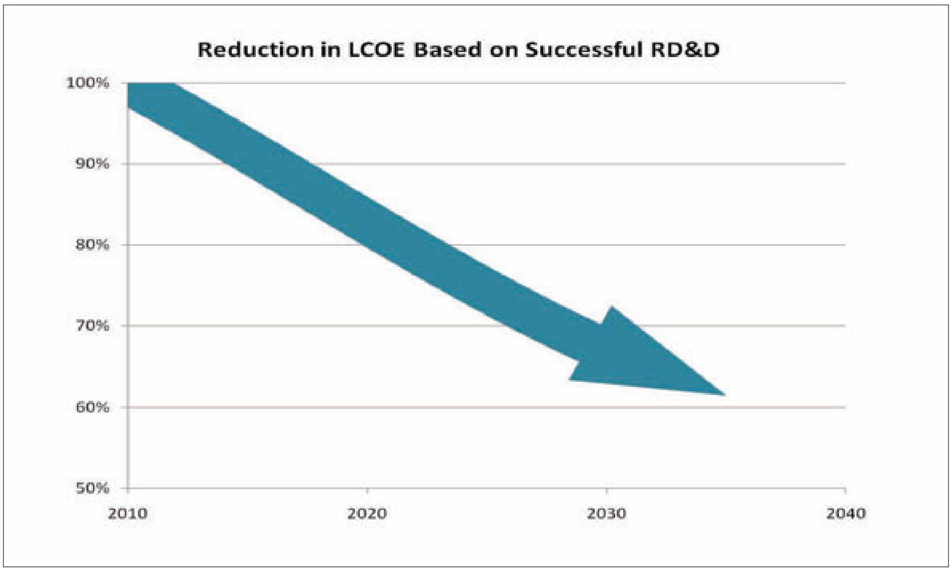
Part of the progress in CCS technology development since publication of the 2012 CURC-EPRI Roadmap has been the construction of two commercial-scale CCS systems: the Boundary Dam Pulverized Coal CCS repowering project (BD-PC) in Saskatchewan, Canada; and the Kemper County IGCC project (KC-IGCC) in Kemper County, Mississippi.

The BD-PC project officially started up in September 2014 and the KC-IGCC project is very near completion of construction, so their capital costs are well established. Hence, the accuracy of estimating the cost of currently available CCS technologies can be improved over 2012 estimates by beginning with data from these "real world" projects (although these are FOAK projects that have experienced some unique costs), and making adjustments for any differing design criteria and cost conventions used in the Roadmap.

Capital cost data for these projects available in October 2014 were adjusted to reflect a 90% capture rate rather than the actual design rate of 65% at KC-IGCC. This adjusted average cost represents "as spent" capital costs for a FOAK demonstration project. The Roadmap cost conventions call for a "total plant cost" characterization of capital cost, which excludes certain components of "as spent" costs, such as financing costs during construction.

Additionally, the Roadmap is based on costs for SOAK projects, which do not include features unique to demonstration projects, and which tend to benefit from a small, additional "learning curve" cost reduction. Each of these factors are estimated to reduce the capital cost from reported demonstration project capital costs by about 20%, for a theoretically constructed SOAK CCS project.

Combining this reduced capital cost with published National Energy Technology Laboratory (NETL) estimates for O&M and heat rate for more generic CCS designs yields an approximate estimate of the current cost for electricity generated by coal-fueled units equipped with CCS that is consistent with



the conventions used in the Roadmap to project future CCS technology costs.

CURC compared this current cost with projected costs from more advanced designs that are expected to evolve, if the research program advocated by the report is implemented and is successful.

The projected reduction in power cost from a new unit is portrayed by the broad arrow in the Figure above. The width of this arrow is intended to convey the fact that these projected cost reductions have a significant amount of uncertainty. Nevertheless, projected cost improvements are believed sufficient to meet both the 20% cost reduction goal set by DOE/NETL in that organization's program planning report for CCS ready to be deployed by 2025, as well as longer-term goals previously published by NETL.

These results are robust over a range of CCS technologies, including relatively traditional approaches to capture systems for both pulverized coal and gasification-based power systems. Moreover, if RD&D is successful on emerging "transformational" power concepts such as pressurized oxycombustion, chemical looping systems, and power plants that use CO2 as a working fluid instead of water, then CURC estimates that slightly larger cost reductions are possible by 2035.

In short, with an appropriate level of RD&D, coal-based power generation with CCS technology could overcome technical and cost barriers that challenge today's industry, and could thereby allow coal to continue to make a major contribution to the U.S. economy and energy security for the foreseeable future.

Results - New Electric Generators

With the implementation of the recommended Roadmap technology development program, coal-based power generation equipped with CCS could advance significantly in terms of environmental performance, while reducing the cost of electricity by approximately 40%, compared to a new coal-fired power plant built with current CCS technology.

The Figure above shows the relative improvement in technology and cost over time. The bandwidth in the arrow represents the range of estimates in the Roadmap cost analysis, and reflects both combustion-based and gasification-based technology cost improvements.

The cost of electricity results presented in the Figure include the estimated cost for permanent storage of captured CO2 in a geological saline reservoir. If, on the other hand, the power facility was reasonably close to an EOR opportunity, the CO2 could become a valued commodity. In this instance, the LCOE from such an advanced power plant equipped with CO2 capture and selling the CO2 for EOR could decrease significantly.

More information

The full Roadmap is available from:

Coal Utilization Research Council
www.coal.org

and the Electric Power Research Institute
www.epri.com

US-China deal on CCUS collaboration but no projects yet to materialise

On 26 August 2015 during the US-China Clean Coal Industry Forum (CCIF) which took place in Billings, Montana, the world's two largest contributors to climate change signed a memorandum of understanding (MoU) committing themselves to joint efforts in advancing carbon capture, utilisation and storage (CCUS) among other low-carbon technologies.

By Bellona Europa

"While pleased to see the world's largest emitters committing themselves to further R&D collaboration on CCUS, what we really need to be seeing is a concrete commitment to large scale CCS deployment" – notes Jonas Helseth, Director at Bellona Europa, in reaction to the two-country-agreement.

Helseth further commented that "for CCS to play its crucial role in the decarbonisation of Chinese industry and energy, efforts will need to rapidly focus on the delivery of CO2 storage and not only on CO2 utilisation."

This agreement formalises existing collaboration between the US and China in the field of low-carbon technologies. Moreover, last week's MoU will commit the two countries to work on six advanced CCUS pilot projects in China, research and development under the US-China Clean Energy Research Center, and the joint Fossil Energy Protocol signed in 2000.

During last year's Asia-Pacific Economic Cooperation meeting China and the US made a joint announcement, committing themselves to ambitious greenhouse gas emission reductions: while the US committed to emission reductions of 26% to 28% below 2005 levels by 2025, China announced a goal of peaking their CO2 emissions by 2030 and increasing their non-fossil fuel sources to about 20% of the total energy mix by the same year.

In addition to sending a strong signal towards the upcoming UN climate negotiations at COP 21, their declaration featured an agreement to boost cooperation in the field of CCUS and to undertake a major project with enhanced water recovery in China.

Unfortunately, we have not seen any concrete actions in the direction of a CCUS project in China.

Key points from the Forum

The forum brought together U.S. and Chinese industry and government executives to foster cooperation and expand opportunities between the two countries and their energy companies. The two days of meetings and discussions focused on clean coal technologies, including carbon capture, utilization and storage (CCUS).

During keynote remarks opening the CCIF, ASFE Smith pointed out that coal is a key part of both the U.S. and Chinese energy mix. But because coal is a major source of CO2 emissions driving climate change, China and the U.S. have taken steps to reduce CO2 emissions from power plants. These efforts include collaboration on clean coal technology development and initiatives to promote deployment of large scale CCUS projects in both countries.

The importance of CCUS to both countries was highlighted during the forum when ASFE Smith and Vice Administrator Shi Yubo finalized a Memorandum of Understanding between the Department of Energy and the NEA, agreeing to continue their ongoing collaboration on fossil energy technologies, including CCUS. The agreement is expected to be signed in September.

Today, U.S. and Chinese partners are advancing six CCUS pilot projects in China. At the same time, Chinese companies have invested in CCUS projects here in the U.S. And both countries continue to collaborate through the U.S.-China Clean Energy Research Center and the joint Fossil Energy Protocol, under which the U.S. and China are working together on clean coal science and technology. The CCIF is an outgrowth of that Protocol.

Two initiatives are being pursued: a large scale CCUS demonstration project in China that would ultimately store 1 million tons of CO2 per year and a project using CO2 in enhanced water recovery, in which CO2 can be used to bring salty water known as brines from deep underground to the surface where it can be turned into fresh water.

As revealed by China's pledge (also known as an INDC) towards COP 21, the country intends to "to strengthen R&D and commercialisation demonstration for low-carbon technologies, such as energy conservation, renewable energy, advanced nuclear power technologies and carbon capture, utilisation and storage (CCUS) and to promote the technologies of utilising carbon dioxide to enhance oil recovery and coal-bed methane recovery".

While pleased at the explicit mention of CCS in the pledge, it is disappointing to see a concrete plan for a CCS project in China being omitted. Given that coal still accounts for around 66% of China's energy consumption, this makes CCS an indispensable tool for enabling the country to cut its emissions and sustain economic growth.

More information

www.bellona.org

Compression solutions for large-scale Carbon Capture, Utilization and Storage

Dresser-Rand's supersonic compression technology can achieve high compression efficiency at high single-stage compression ratios, resulting in product simplicity and small size.

By Mark Kuzdzal, Director, Business Development, Dresser-Rand

Dresser-Rand has extensive carbon dioxide (CO2) compression experience and has been supplying CO2 compression solutions for more than 87 years. The first unit, a reciprocating compressor, went into service in 1928, and the company shipped its first centrifugal compressor for CO2 service in 1948. In total, Dresser-Rand has shipped more than 400 reciprocating and centrifugal CO2 compressors representing more than 900,000 bhp (671 MW) and believes it has the largest installed base of CO2 compression equipment in the world. More than 250 of these units are on CO2 injection service, totaling more than 500,000 bhp (372 MW).

It's no secret that the company remains highly motivated to remain at the forefront of compression technology and has taken many steps to sustain this position. One such step included Dresser-Rand's acquisition of key assets from Ramgen Power Systems LLC in August 2014. The focus of this article is on Dresser-Rand's progress with its new supersonic CO2 compression product, the DATUM® S compressor. But first, let's examine Dresser-Rand's history in CO2 compression.

History of CO2 compression

The highest pressure achieved using a Dresser-Rand® CO2 centrifugal compressor is more than 8,250 psia (550 bara), while the maximum inlet flow is greater than 48,000 acfm (82,000 m3/hr). With a Dresser-Rand CO2 reciprocating compressor, the maximum discharge pressure achieved is more than 6,015 psia (425 bara) and the maximum inlet flow exceeds 4,000 acfm (7,000 m3/hr).

The re-injection process is an enhanced oil recovery (EOR) technique that helps bring oil to the surface by both pressurizing the well and reducing the oil's viscosity. The first CO2 re-injection project developed specifically to mitigate greenhouse gas emissions (not for EOR purposes) began operating in the North Sea in August 1996. As of January 2015, more than 15.2 million metric tonnes of CO2 have been injected at this site (approximately 0.75 million metric tonnes of CO2 per year). The source of the CO2 is from an amine plant that captures the CO2, which is then compressed and stored in a saline aquifer. The objective is to reduce the CO2 content in methane from nine to 2.5 percent, such that the methane can be exported as "sales gas". Compressor availability has been reported at 98 to 99 percent.

On May 4, 2012, a successful hydrocarbon test (CO2 and methane blend) was performed on a DATUM® Frame 6 centrifugal compressor at Dresser-Rand's facility in Olean, New York, USA. This was the highest discharge pressure CO2 compressor ever tested in Olean at more than 8,250 psig (581.4 bar) with a suction pressure of approximately 3,500 psig (241 bar). Also, this compressor is believed to be the highest density compressor ever manufactured and tested in the world, 34.7 lbm/ft3 (556.2 kg/m3), compressing gas that has a molecular weight of approximately 36 and consists mainly of carbon dioxide.

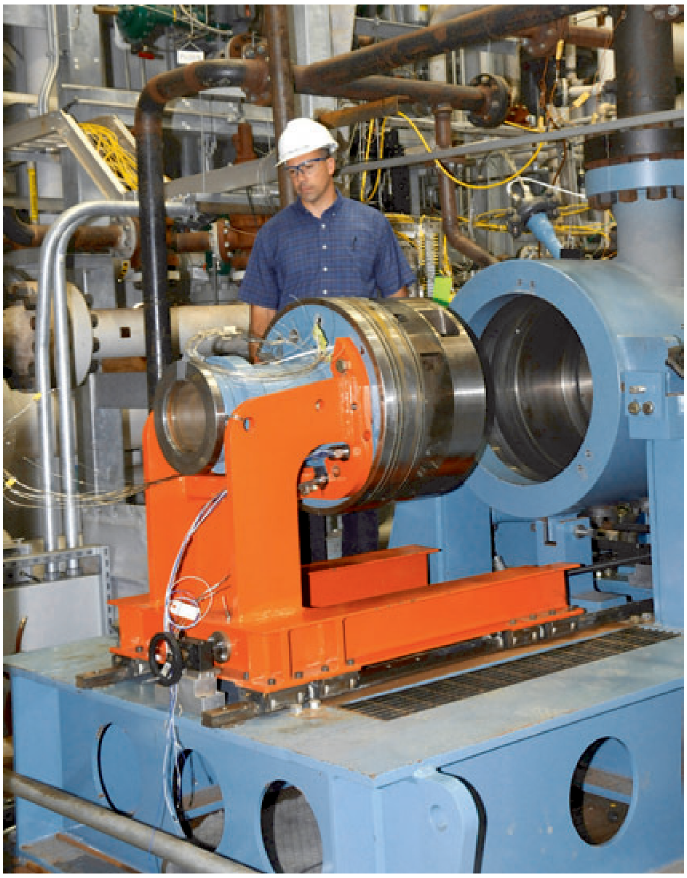


Fig. 1 - the DATUM S supersonic compressor for use on high molecular weight gases like CO2

The supercritical gas mixture exits the compressor at 55 percent the density of water. This unit was purchased for a floating production, storage, and off-loading (FPSO) vessel gas reinjection project for offshore Brazil. Full-load, full-pressure testing results were such that, as tested, head and power aerodynamic performance curves matched the predicted curve and head and power guarantees were achieved.

Typically, as the power, gas density and discharge pressure of a centrifugal compressor increase, there is concern that rotor vibrations will increase; particularly sub-synchronous vibrations. However, through its R&D activities, Dresser-Rand developed advanced bearing and sealing technologies that actually improve rotordynamic stability as power, gas density and discharge pressure increase. This was demonstrated during a rotordynamic stability test at full load and full pressure using a magnetic bearing exciter to impart asynchronous forcing functions into the rotor while operating at full speed and load.

The purpose of the testing is to evaluate the robustness of the design by "exciting" the compressor to extract a stability parameter known as logarithmic decrement. During testing of the 8,250 PSIA (581.4 bara) compressor, the logarithmic decrement was measured as the compressor discharge pressure was increased.

Again, the testing results matched the predictions, confirming that the rotor became more stable as power, gas density and pressure increased. The testing validated both the mechanical and aerodynamic robustness and successfully mitigated risk prior to field operation.

Looking toward the future

The next chapter in CO2 compression is being written with the DATUM® S compressor. In August 2014, Dresser-Rand acquired key assets from Ramgen Power Systems LLC and opened a technology center in Seattle, Washington. This center is staffed with engineers whom have been working on supersonic CO2 compression technology for almost a decade.

This team, together with the Olean-based R&D team, is developing the DATUM S supersonic compressor for use on high molecular weight gases like CO2. The primary goal is to build a low-cost, high-efficiency CO2 compressor that will reduce the overall capital and operating costs of carbon capture, utilization and storage (CCUS).

The CO2 compressor power required for a pulverized coal (PC) power plant is eight to 12 percent of the plant rating, depending on compressor suction and delivery pressure. Many proposed applications require a pressure ratio of 100:1 or more. A 550 MWe PC plant would require 73,750 hp (55 MW) of CO2 compression.

The most significant impact on capital expense, however, is an aerodynamic design practice that limits the stage pressure ratio on heavier gases such as CO2. Conventional centrifugal compressors typically require eight to 12 stages of compression to meet the requirements of these applications; an integrally geared machine may require seven or eight stages of compression to achieve a 100:1 pressure ratio.

Competitive advantage

The DATUM S compression technology represents a significant advancement for many high mole weight applications, and specifically for CO2 compression. The principal advantage is that it can achieve high compression efficiency at very high single-stage compression ratios. The result is a product that lowers both capital and operating costs in a smaller footprint, thereby reducing installation costs.

Cost effective heat integration, enabled by the mid-grade heat of compression associated with the very high compression ratio, substantially improves the economics of CCUS. System level analysis indicates if the control volume is drawn around the compression, cooling and heat generation systems, integration of the waste heat CO2 stream developed by the high-ratio compressors improves operating expense.

For a compression solution with a 100:1 pressure ratio, (66 MMSCFD system), upwards of 250 BTU/Lbm can be harnessed from the CO2. Typical uses of the waste heat include: boiler water pre-heat which reduces boiler fuel gas consumption, amine re-generation, CO2 dehydration, or electricity generation.

The cooler log mean temperature difference (LMTD), a key determinant of the cooler surface area required, will be three times that of the integral gear designs. The result is coolers that require one-third of the surface area to achieve the same cooling duty.

Test validation of aerodynamic and mechanical performance

The Olean / Seattle team is concluding a testing program of a 10:1 pressure ratio, 10,700 HP (8 MW) CO2 unit with a 2,215 PSIA (152 bar) discharge pressure. A "generation three" design was tested in March 2015 on a dedicated closed loop CO2 test facility at Dresser-Rand's Olean Operation.

The goal is to validate aerodynamic performance, as well as operating characteristics and mechanical integrity. The high-pressure stage is shown in Figure 1.

This unit achieved a 9.7:1 pressure ratio on pure CO2. This unit is sized to compress in excess of 3,500 tonnes of CO2 per day or the equivalent of 90 percent capture of a 200 MWe coal-fired power plant. Additional testing with a higher inducer flow coefficient is planned for fall 2015. Furthermore, we believe the technology can be scaled too much larger sizes with future R&D efforts.

Dresser-Rand is in the process of developing a family of supersonic compressors to serve the market. The high-pressure ratio-per-stage capability of the DATUM S technology is the key enabler needed to achieve this goal.

The technology concept addresses the two key objectives identified by the U.S. DOE for the capture and storage of CO2: lower cost and improved efficiency.

The suite of frame sizes will support both existing capture technologies, as well as emerging capture technologies. The planned frame sizes would be able to support a full capacity 800 MWe power plant. CO2 capture units that run below one bara, such as a membrane system, may require a booster gas compressor.

The DATUM S has both capital and operating cost advantages. The configuration will require approximately the same shaft input power as the eight- or 10-stage equivalent when inter-stage temperatures and pressure drops associated with intercooler are included. Heat recovery from the high-ratio supersonic solution is of significant value when fully integrated at scale.

Dresser-Rand's supersonic compression technology represents a significant advancement in the state-of-the-art for many compressor applications, and specifically for CO2 compression.

The principal competitive advantage is that it can achieve high compression efficiency at high single-stage compression ratios, resulting in product simplicity and small size.

This, combined with improved availability and integration of waste heat, underscore the merits of employing the DATUM S compressor to achieve lowest total cost of ownership.

More information

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Integrally-geared compressors as state-of-the-art technology

After presenting a short market overview, this article gives examples of recent projects in this sector along with a number of improvements by MAN Diesel & Turbo on such compressors.

By Rene Dittmer and Dr. Robert Strube, MAN Diesel & Turbo

Integrally-geared compressors were introduced as a solution for CO2 high-pressure business decades ago. Back then, this design was seen as a high risk option, while a number of plant owners and EPCs saw the inherent advantages. Nowadays, the integrally-geared design is the first choice for CO2 HP compression. This design has been optimized over the years for more efficiency and reliability. This option is now available with proven references to fulfil an increasing demand from the market.

Fig. 1 - Integrally-geared compressor (RG type) for CO2 compression by MAN Diesel & Turbo

Introduction

CO2 has a long tradition in modern industrial processes and plays an increasing role in the present discussion of the worldwide climate change. Especially in refinery and food industry applications, CO2 is widely used and has been a commodity for years. The negative effects of CO2 as a greenhouse gas lead to an increased research activity, which aims at carbon capture and storage solutions (CCS) and at CO2 supercritical power cycle technologies.

While CCS stores CO2 safely underground after a capture process, the supercritical power cycle is a long developed idea to improve power plant efficiencies. Nowadays, numerous industrial processes require CO2 not in a gaseous but in a supercritical compressed state at a specific pressure and temperature. [1]

The use of high-speed reciprocating compressors for Urea production (in fertilizer plants), for Sequestration (CCS), or for Enhanced Oil Recovery (EOR) is the historical and traditional use of compressed CO2. Nevertheless, there are several limits of this technology – e.g. the maximum flow rates are restricted due to the mechanical design limitations.

For this reason, centrifugal type compressor systems are now state of the art and very useful for future CO2 projects. Centrifugal compressors generally can be split into two major types, namely single-shaft (in-line, between bearings) centrifugal and multi-shaft integral-gear centrifugal compressors.

Especially for very high-pressure ratios above 100 the integrally-geared compressor is far superior to the single shaft design. Therefore, the article focusses on this compressor type.

A number of CO2 compression projects are already in operation worldwide. Despite low oil prices and slowing down of market activi-

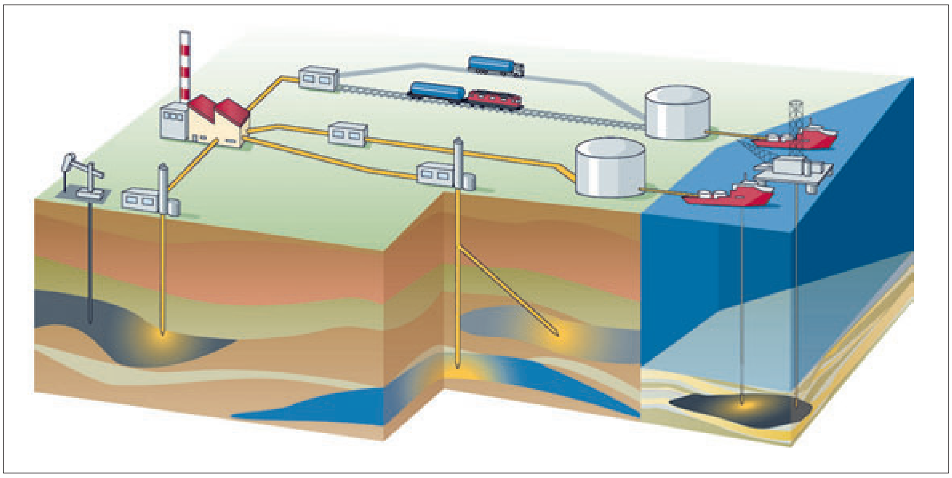


Fig. 2 - CO2 applications at a glance

ties, even more projects are in a start-up phase or at least are heading towards realization.

CO2 applications on the rise

The market for CO2 compressors in CCS and EOR (enhanced oil recovery) applications is diverse. Private investors are trying to quickly bring projects into operation. For example, in Louisiana, North Dakota, and Texas (USA) an existing and growing CO2 infrastructure is results in an increasing demand for high-pressure CO2 compressors. Here, privately owned companies are selling CO2 to EOR pipelines and the fertilizer industry.

Also the publicly funded sector has gained importance. In order to sequester CO2 for environmental reasons, governments are providing funds for CO2 Capture and Storage projects (CCS). It has been found that developing EOR in the North Sea can help decarbonizing the power industry [2]. EOR could provide the missing funds required to install capture plants and infrastructure for CO2 transport. In other words, EOR with CO2 is a valuable driver for improved production rates whereas CCS of CO2 is driven by political incentives, since this method leads to lower CO2 emissions but also to a reduced power plant efficiency.

Worldwide there are several plants of demonstration size currently put into operation. These projects are for example Boundary Dam3 (Regina, Canada), Kemper County (USA, Louisiana), Geismar (USA, Louisiana), Parish Thompsons (USA, Texas), Shell Quest (Canada, Fort Saskatchewan) and Hawiya (Saudi Arabia). Additional studies for CO2 projects (CCS or EOR) can be seen mainly in USA, Canada, Middle East, China, South Korea and Great Britain.

Compression technology needs in-depth process expertise

As a leading provider of compression technology, MAN Diesel and Turbo (in the following referred to as MDT) can look back at a running fleet of high-pressure CO2 compressors in integrally-geared design with more than 600.000 operating hours. MDT has also successfully designed and manufactured the first and only 10-stage machine in the market, which has been in operation for 20 years now.

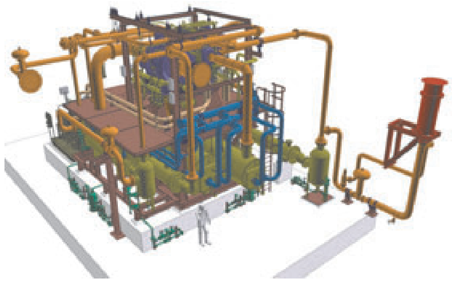


Fig. 3: CAD drawings of a complete compressor rig

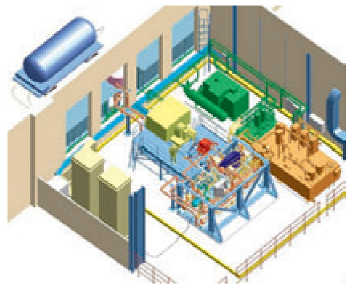


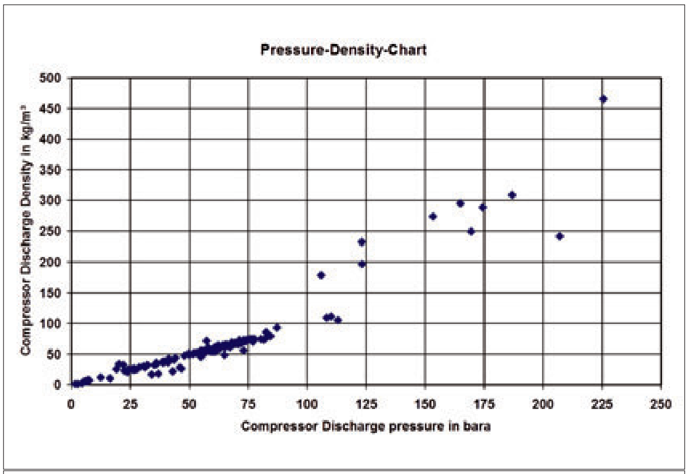
Fig. 4: CORA test rig for CO2 compressors

A typical HP CO2 compressor train can be seen below. Discharge pressures above 100 bara and pressures up to 250 bara are typical for such compressors. Every single component involved has the potential to improve overall performance. This is why MAN developed CORA [Fig. 4], an own CO2 compression research test rig for comprehensive R&D activities. It offers the possibility of testing original designs, components and equipment in a full scale machine environment. This test rig has been in operation for some years now and a number of innovations have already been implemented as standard design features.

MAN has developed an extensive expertise about gas properties of CO2 mixtures and about the mechanical requirements for complete compressor trains including coolers, separators, piping, driver, control philosophy and maintenance [Figure 3]. Figures 5 & 6 give an idea of densities and compressibility factors in current HP CO2 compressors and in the CORA test rig.

In the early stages of CO2 compression, the integration of dehydration units, oxygen removal units and multiple pressure stages of CO2 side streams into the compressor were not required. These special process requirements are now already incorporated as advancements into the MAN compressor design.

Why dehydration units? Amine-based washing of power plant exhaust gas is one of the most popular processes for CO2 capturing. This process is well proven and has been applied in oil and gas business for decades. This method is producing wet CO2. However, long pipelines cannot accept water in the gas as they are based on carbon steel, which would suffer from massive corrosion due to carbonic acid.



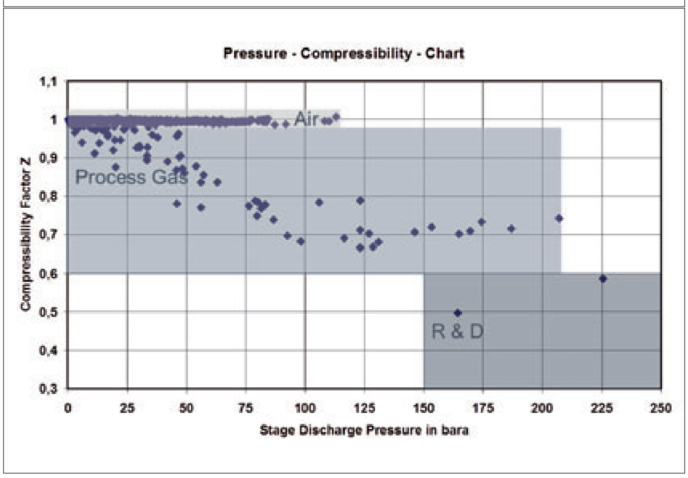


Fig. 5 (top) Discharge conditions of existing integrally-geared compressors

Fig. 6 (bottom) Discharge conditions of existing integrally-geared compressor stages at standard operation condition

Fig. 7 - Old (left) and new (right) impeller designs for high pressure CO2 applications

There are mainly three types of dehydration technologies available. The most widely used type is TEG (TriEthylene Glycol) washing. The second technology, resulting in the driest CO2 stream, is a molecular sieve. A third option is to expand a partial CO2 stream using the Joule-Thomson-Effect for cooling the process stream in order to flash out water (Dexpro®). All three technologies have their place in the industry.

TEG units are preferred due their robustness against pressure ramps which can be seen at start-up and shutdown procedures. It produces a fairly dry CO2 stream with relatively low heat requirements for regeneration purposes. On the other hand, TEG emissions with the gas stream require attention.Molecular sieves serve the need for extremely dry CO2 streams. For shutdown and start-up it needs to be completely isolated from the compressor, as pressure ramps are not acceptable to the drier bed. In comparison to TEG it takes a considerably higher amount of heat for regeneration purposes and requires higher investments in general.

Dexpro® units are a relatively new and robust technology to bring down humidity levels. It requires a part of the high-pressure CO2 stream for flashing out water in the main gas stream by using the Joule-Thompson-Effect. This depressurization leads to a considerable recycle flow in the high-pressure section of the compressor and increases the power requirements of the compressor. For all three dehydration technologies, pressure losses in the range of 1bar need to be considered. In order to reduce this additional loss, it takes the close cooperation of both process owner and compressor OEM. Each of these three technologies has been successfully integrated by MAN into different high-pressure CO2 compressors.

Additional potential lies in the heat integration in the regeneration process of such dehydration units. Heat integration is a way to further reduce overall energy consumption. A considerable amount of heat is required for the regeneration of TEG units and molecular sieves. The high interstage temperatures in CO2 compression need to be lowered by intercooling. These high temperature streams could therefore be a suitable heat source for the regeneration process. Most plants are on pilot or demonstration level for Carbon Capture process itself. Therefore, heat integration has not been used in capture plants due the increased plant complexity. Only in most recent projects the regeneration gas stream is not produced separately, but taken from the main CO2 flow, making an additional small compressor unit obsolete. External heat is still required to get up to temperatures required for the regeneration process.

A high-pressure CO2 compressor requires a robust flow control mechanism. For integrally-geared compressors variable Inlet Guide Vanes (IGV) are the first choice. CO2 capture processes are getting more complex in order to get more efficient. Therefore, some projects allow CO2 entering the compressor not only through one single low-pressure inlet, but at various pressure levels.

Even gas extractions, leading to an even more variable flow, have been considered.In order to control inlet conditions and performance it is required to have additional variable IGV in front of each compression section. Such guide vanes are subject to high mechanical forces when being operated at high pressures. This high-load range already starts at around 10bara. In order to take these requirements into account, a high-pressure design was successfully developed by MAN Diesel & Turbo, which has been tested and operated, even for suction pressures far above 100bara.

In order to find the optimum between sometimes diverging demands of the capture plant, requirements of the compressor and the dehydration unit, all options need to be discussed on an economic basis.

A new optimized impeller design [impeller on right side of Fig.7] for supercritical CO2 was tested by MAN Diesel & Turbo in its test rig in 2013. This impeller is also designed for easy and reliable manufacturing, especially for small diameters and for a wide range of

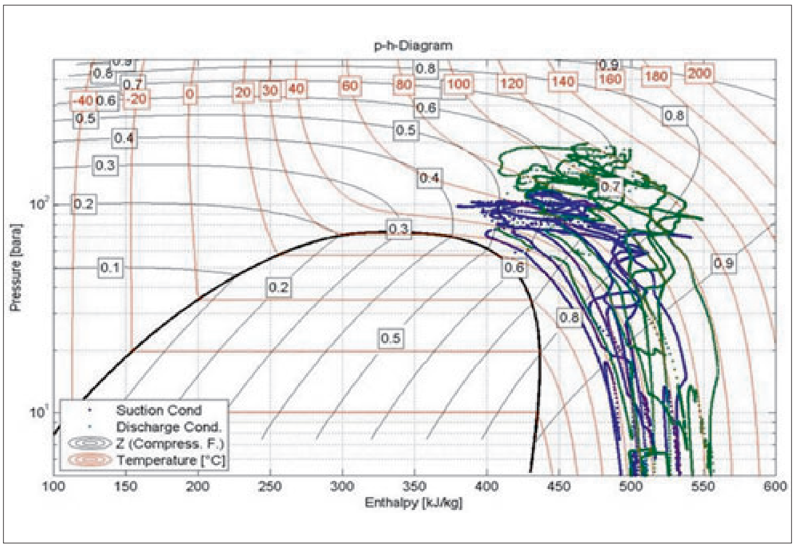


Fig. 8 - Pressure at suction and discharge side during a test campaign

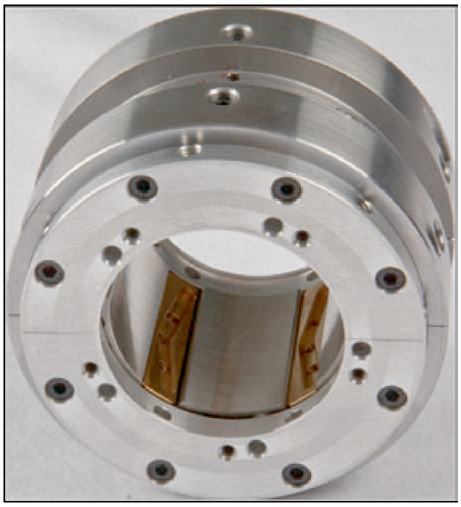


Fig. 9 - MAN TurboTOP™ journal bearings (Thermal Optimized Pad for turbomachinery)[3]

materials. The former design can be seen in Figure 7 [impeller on left side of Fig. 7]. Operation near the critical point of CO2 has been carried out multiple times during the different test campaigns with a compressibility factor down to 0.4 and suction temperature down to 40°C in the supercritical phase region [Fig.8]

Another decisive factor for CO2 compression is power density, which has continuously increased due to the latest process and technology advancements. In order to overcome current limitations in bearing loads, new bearings have been designed, patented and successfully tested by MDT [Fig. 9 & 10]. A number of those bearings are already in commercial long-term operation with excellent results, as both temperatures and dampening have been strongly improved.

Testing a complete CO2 compressor train is a challenging task, either performed at site with original equipment and gas or in a workshop test bed.

Shop tests are generally preferred due to better measurability and a better risk estimation. These tests, however, require high efforts with regards to installation and interconnection of the compressor with coolers, separators, VFD starter and other auxiliaries. These components are usually not part of site test, as they are not part of the standard scope of compressor suppliers. While costs of shop tests are nearly equivalent to site tests, they sometimes represent almost a quarter of the whole production schedule due to the required installation and interconnection of the equipment.

A site test can be integrated into the normal installation and commissioning activities. Even instrumentation can be planned for such an event without much additional cost. The savings are comprised of nearly a full period of installation (shop test duration) and the cost of the otherwise required shop installation including disassembly for transport.Experience for both shop and site tests is available with MDT. Site tests are more or less the standard in Air separation business whereas shop tests are the standard for refinery and oil and gas industry.

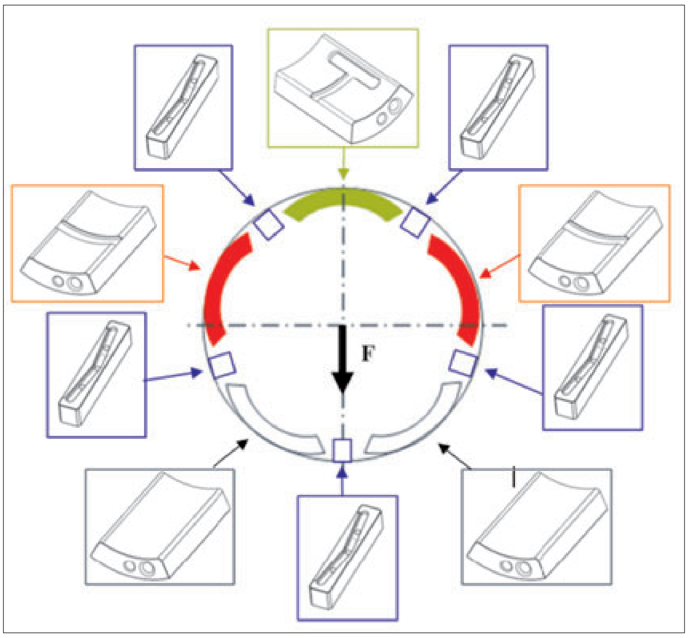


Fig. 10 - combination of design features: (1) V-shaped spraybar-blockers, (2) T-groove on the surface of the unloaded tilting-pad and (3) circumferential grooves on the surface of the outer tilting pads [3]

Conclusion and summary

Nowadays, the integrally-geared compressor design is widely accepted throughout various industries and especially in CO2 compression. Improvements as shown above lead to a wider competitive range not limited to flow and pressure. Therefore, the integrally-geared RG design by MDT is being used even outside its traditional applications like the compression of Air and Nitrogen. Carbon dioxide, propylene, propane, carbon monoxide and others have become typical process gases for this compressor type.

On a global scale, the number of carbon capture plants is growing continuously. This is not only due to the political awareness of CO2 as a greenhouse gas but also due to CO2 becoming a useful commodity for enhanced oil recovery.

These growing market requirements result in the need for research and development. As a leading provider of compression technology, MAN Diesel & Turbo has conducted extensive R&D with regard to CO2 compression. This results in a high expertise in engineering, production and servicing of CO2 compressors, allowing the company to support plant owners and EPCs in demanding projects.

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More information

Rene Dittmer and Dr. Robert Strube are bid managers for MAN Diesel & Turbo in Berlin. While Dr. Strube has taken care of numerous compression projects in the oil and gas industry, Dittmer focusses especially on CO2 compression. Both are bringing the RG technology of MAN Diesel & Turbo into the market.

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Integrated design and operational analysis of CO2 compression systems

Ensuring an efficient and flexible operation of CO2 compression trains for carbon capture and storage (CCS) applications is a key consideration for those designing and operating this machinery within whole-chain CCS systems.

By Mario Calado, Consultant – CCS & Power, Process Systems Enterprise Limited

Although CCS is seen as an essential technology to meet CO2 emission targets from power plants and industrial plants, the main factors preventing its commercial deployment are still the perceived high capital costs and energy penalty. These factors are not only associated with capturing and purifying the CO2, but also with drying and compressing it. However, compressor manufacturers, like Siemens or Man Diesel & Turbo, still see CCS as an important future market.

Over the last few decades, compressor manufacturers have been focusing their development efforts on producing compression systems capable of delivering higher flows at higher discharge pressures. This is a step towards the right direction regarding CCS applications, given the typically high CO2 volume flowrates (up to around 150,000 m3/h) and discharge pressures (up to around 200 bar) involved. However, CO2 compression trains within a CCS chain face very specific challenges when compared with more standard applications in the chemicals and petro-chemicals industry.

While the design of gas compression trains is usually optimised for full load conditions and is not expected to operate off that point for extended periods of time, a CO2 compression train is expected to handle the flexible operation requirements of the different sub-systems in the CCS chain. Fossil fuel power plants provide the flexibility required to cater for dynamic changes in electricity demand and compensate for the intermittency of renewable energy.

In order to reduce their respective emissions, all downstream sub-systems, i.e. capture and compression plants, need to follow the load changes both on a daily basis but also through the different horizons and predictions of renewable energy growth. The compression system is seen as what ties the CCS chain together, in the sense that it needs to couple the fast load transients of the power/capture plants with the slow changing pressure requirements of all downstream systems throughout the pipeline network and reservoir pressure build up.

gCCS: advanced compression train systems modelling

The Energy Technology Institute (ETI) funded the £3m CCS Systems Modelling Tool-kit project with the objective of producing a software package that would support the future design, operation and roll-out of cost-effective CCS systems in the UK.

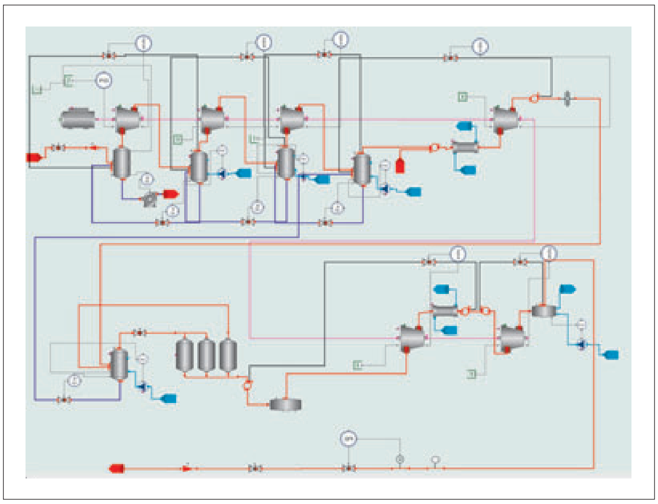

Fig. 1 – example compression train flowsheet from the gCCS modelling environment

The project involved the consortium partners E.ON, EDF, E4tech, Rolls-Royce, CO2DeepStore, Process Systems Enterprise (PSE) and the resulting product was gCCS, launched in July last year, being the world's first process modelling environment specifically designed for supporting design and operating decision across the full CCS chain. The tool is implemented in PSE's gPROMS advanced modelling platform and covers all process units from power generation to capture, compression, transport and injection.

As part of this project, detailed compressor models where developed by PSE along with Rolls-Royce, who provided expertise on the machinery performance and guidelines on control strategies and operating procedures for the entire compression train system. To predict off-design performance, the compressor model requires the user to introduce the machine's performance map. This is a semi-empirical curve that relates the suction volumetric flow with the compressor's pressure increment and efficiency, which is determined by the manufacturer through extensive performance tests under a controlled environment, and then provided to the compressor operators. In order to provide full flexibility in the machinery of choice, it is possible to model both single-shaft compressors and integrally geared compressors by providing the performance map for different rotational speeds and/or Inlet Guide Vane (IGV) angles for each compression stage.

To accurately predict the fast transient behaviour of the entire compression system, the shaft inertia is taken into account, which affects how fast the driver can accelerate and decelerate, as well as the holdup in the knock-out drums and coolers. The same applies to valve dynamics, both opening and closing times and control parameters. These are extremely important parameters and have to be customised in order to avoid each compression stage to go into surge.

Surge occurs when the compressor operating flow reaches the minimum value specified as safe by the vendor. Once this line is surpassed, the gas flow inside the machine becomes un-stable and can ultimately cause failure if it remains there during extended periods. Given the fast transient behaviour of the system, in the order of seconds, it becomes essential to accurately predict the fine balance between possible perturbations, anti-surge valve opening time and controller response time.

Supercritical behaviour of near-pure CO2 mixtures

Another specific challenge of CO2 compression when compared to other gases is the conditions to which it is compressed. CO2 has a critical point of around 74 bar and 31 degree Celsius. For transportation in CCS applications, CO2 is usually compressed to the dense or supercritical phases. These are the best choices for CO2 transmission, because CO2 presents a liquid-like density but a gas-like viscosity. The CO2 supercritical properties, together with its high molecular weight and strong non-ideal gas behaviour, have crucial consequences for the design of compression trains: until the required phase is reached, the fluid density increases significantly in each compression stage, with the associated decrease in volume flow.

This translates in a large disparity of impeller sizes throughout the train. For example, a multi-stage compression train compressing CO2 from near atmospheric pressure to around 200 bar can have impeller diameters of about 1.2 m in the first stages, going up to around 200 mm for the last stages (Siemens compressors are gearing up for CCS, Carbon Capture Journal, Sep-Oct 2014).

One of the many challenges involved in the development of a CO2 compression modelling tool is the provision of accurate physical properties. In addition to the peculiarities regarding the behaviour of pure CO2 in the supercritical and dense phases, there are three main issues that need to be addressed for a physical properties engine for CCS compression to be suitable:

(1) The presence of impurities - physical properties of the CO2 streams being transported will be greatly affected by composition. Different combinations of sources and capture technologies will produce CO2 streams with a varying number and concentration of impurities, such as H2O, N2, O2, H2, Ar, H2S, CO and SO2.

(2) The engine needs to cover a wide range of conditions, in terms of pressures and temperatures.

(3) There is a lack of experimental data: the range of conditions is limited, there exists gaps for several relevant binary mixtures, and data is very scarce for ternary mixtures and beyond. This exacerbates the difficulty of fitting and validating thermodynamic models.

For the abovementioned reasons, a predictive physical properties package is paramount. To this end, molecular-based equations of state (EOS) are a very appealing alternative to more classical approaches, such as cubic EOS. In particular, the Statistical Association Fluid Theory (SAFT) is especially suited for its ability to deal with complex fluids. SAFT-based EOS are rooted on statistical mechanics, so they involve a limited number of parameters, with a clear physical meaning. Hence, they can be fitted to a limited amount of experimental data, and used to predict phase behaviour and physical properties for a wide range of conditions, including those far from the ones employed for parameter estimation.

Process Systems Enterprise's gSAFT is a commercial implementation of one of the most advanced SAFT-based EOS: SAFT- Mie EOS, developed by Imperial College (Dufal et al., 2014 and Papaioannou et al., 2014). A gSAFT-based physical property package has been developed for the compression components of the gCCS tool. Pure component and binary interaction parameters are regressed to publicly available vapour-liquid equilibrium data. The models are then validated by comparing the predicted behaviour of relevant mixtures with experimental data.

Figure 2 illustrates the capabilities of the approach. The experimental and calculated bubble point of a mixture of CO2 and H2 (molar fraction of H2 is 0.02) are presented. For comparison purposes, the vapour pressure of pure CO2 is shown as well. The first thing to note is that a very small concentration of H2 can greatly shift the VLE. Furthermore, predictions for the GERG equation of state (as available in Infochem's MultiflashTM 4.1) are also presented. GERG is widely regarded as an apt choice for CCS compression and transmission systems.

The physical properties and phase equilibrium are therefore accurately described for a set of components ¬ and their mixtures ¬ that cover the sort of systems that are likely to occur in CCS CO2 transportation. This means that two-phase behaviour in the water knock-out drums, density of the fluid and compressibility across the different compression stages is correctly captured.

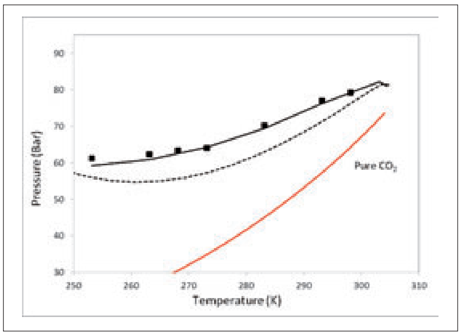

Fig. 2 - bubble point of mixtures of CO2 (98%mol) and H2 (2%mol)

While the first impacts the final water content of the CO2 mixture, the last two have a direct impact on the capital investment and energy requirement respectively. Assuming an incorrect estimate of fluid density or compressibility can lead to an inappropriate compression train design. Hence, benefiting from advanced thermodynamics and a robust and rigorous library of process unit models, the gCCS user is able to easily model complex compression and transmission networks with a high degree of accuracy.

Flexible design of compression train systems

In addition to the supercritical behaviour of near-pure CO2 streams, the decision criteria of the optimum compression solution should account for possible fluctuations of CO2 production, particularly when capturing from a flue gas generated by a power plant.

Nevertheless, the daily cycle of CO2 production is not the only dynamic factor that affects the compression train performance throughout its life time. In a pure CCS chain facility, after the start of the CO2 injection operation, CO2 starts accumulating in the reservoir. The accumulation of CO2 trapped in the reservoir results in an increase of its internal pressure, hence there is a higher discharge pressure requirement for the compression train. Although it is a much slower, but gradual, operating constraint than the power plant daily cycle, it does significantly impact the decision making process of selecting the best compressor train size at the time of investment, prior to operation. For example, the size of the electric motor should match the increase in horse power requirement over the years of operation.

Using gCCS's compression library models, state-of-the-art optimisation techniques can be applied to determine the number of compression sections and stage configurations for maximum overall efficiency, accounting for an expected diurnal and/or seasonal fluctuation in compression loads. In addition to determining the best train configuration, the same optimisation model can be used to calculate the optimal inter-stage pressures on a daily operation basis. Where applicable, it can be used to determine the number of trains operating in parallel, so that all units operate as close as possible from their design points.

When looking into the long term operating spectrum, the discharge pressure requirement can significantly increase over the years as CO2 accumulates in the reservoir. Therefore, one might need to install additional compressor sections/stages to increase the pressure to the expected value. In this aspect, gCCS can be used to perform the scheduling of purchasing and installing additional stages, taking into account several economic decision variables like the depreciation of the equipment's value and the (clean) electricity price expected in future horizons.

The optimal train configuration for the initial expected discharge pressure is not necessarily the best train after a couple of years of operation. When this is the case, additional capital expenditure linked to oversizing all the machinery can lead to significant cuts in the operating cost. This is a trade-off that can be optimised using a rigorous advanced modelling formulation approach like gCCS to accommodate all decision variables and respective constraints, either operational or sizing limits, to get the best train sizing, configuration and operating procedures over the years of operation.

Another case of long term planning is when the CO2 captured and compressed is used for Enhanced Oil Recovery (EOR). Given the potential of gCCS to accurately predict and support long-term decisions, the ETI continued to support the development of gCCS to accommodate and develop models for EOR processes. PSE has been working with a major oil company in the development of the tool to improve its capabilities and maximise the value for future users.

Some oil exploration fields utilise the Water-alternating-gas (WAG) technique to maximise the additional produced oil. This reservoir development technique utilises alternating slugs of CO2 and water to recover additional oil. The cyclic requirement of CO2 for EOR typically repeats itself on the order of years. Again, the decision-making process for the best compression train should account for this variation and the same optimisation technique can be applied with gCCS's model environment.

Finally, even for CO2 injection-only EOR operations, there is an intrinsic dynamic decision to make when it comes to select the compression train used to recycle the produced CO2 back to the injection wells. At the beginning of CO2 injection, it first accumulates and starts mixing with the oil in place in the reservoir, and it can take a year or more for the CO2 to "break through" to the production wells. The amount of recycled CO2 starts as near zero but after it breaks through, the flow can increase up to almost the same value as the injected amount. The flexibility of choosing when to install another compression train in parallel (if applicable) and how the transition is made becomes an important decision to make in large scale projects, for example, in the Rocky Mountain or Gulf Coast regions in the US.

Optimal compressor scheduling for gas-fired CCS plant

The Peterhead project is the world's first commercial-scale full-chain CCS demonstration project for gas-fired power generation. The Front-End Engineering Design (FEED) scope includes the design from scratch of both the carbon capture plant and compression train, including modifications to the existing combined cycle gas turbine power plant. The project aims to capture, compress and transport one million tonnes per year of CO2 by pipeline to the Goldeneye off-shore gas reservoir beneath the North Sea for long-term storage.

The CO2 capture technology that will be used at Peterhead has been tested at the Technology Centre Mongstad (TCM), in Norway since 2014, which accelerates its preparation for CCS commercialisation. However, the compression station technology is outsourced and selected amongst several CO2 compression suppliers, which reduces the freedom of adapting the compression technology to the specific requirements of this first-of-a-kind plant. Different suppliers offer different solutions: from integrally geared centrifugal compressors supplied by MAN Turbo or Siemens, which can have up to 12 stages within the same casing to allow better impeller flow coefficient and inter-stage speed, to the state-of-the-art Ramgen's super-sonic shock wave CO2 compressor, having only 2 stages but allowing higher heat integration potential with the hot inter-stage CO2 compressed stream.

In addition, the CO2 is then transported a long distance to suitable storage, which introduces operations with larger timescales and further potential for downstream faults, failures and disturbances that can also affect the compression train system. The implementation of the CCS chain, particularly the CO2 compression system, is not only about a power station that solely needs to respond to the grid demand but it is also connected to a much more complex system that can disrupt or affect operations in many different ways. Consequently, several interlinked questions related to the different sub-systems need to be addressed.

In order to understand the dynamic behaviour of the system, Shell and the UK Department of Energy and Climate Change (DECC) have commissioned a simulation project of the entire CCS chain (from flue gas to storage) covering a wide range of scenarios, from start-up and shut-down procedures to several trip/failure events. Presented at the 14th Annual CCUS Conference (Pittsburgh), the project was the first commercial application of gCCS whole-chain systems modelling software and was used during the FEED study phase to provide insight into the behaviour of the different sub-systems when subject to major transient operations, such as the sequential start-up, shut-down and trips of the compression system, whilst analysing the behaviour of the rest of the chain.

Some expected scenarios can be tested on actual experimental facilities. Siemens' Mega Test Centre (MTC) Duisburg test facility is an example of this, in which the two CO2 compressors delivered to the Kemper County IGCC project were tested at full load, full pressure with various gases and different compressor drivers (electric motor, gas turbine and steam turbine). However, it is not possible to test the interactions with the other systems or try different approaches/procedures that could possibly put at risk the safety of the operation or damage the equipment. The use of predictive modelling can help the project team to either replicate these tests within the overall operation of the chain or work together with the compressor supplier to try new approaches and optimise trade-offs with the other sub-systems.

More information

The project team included Mario Calado, Dr Ade Lawal, Dr Penny Stanger, Gerardo Sanchis and Dr Javier Rodriguez

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The costs of CCS and other low carbon technologies - 2015 update

The Global CCS Institute paper examines costs of major low and zero emissions technologies currently available in power generation and compares them in terms of emissions reduction potential (CO2 avoided) and costs (levelised cost of electricity).

The paper, by Lawrence Irlam, Senior Adviser Policy & Economics, Global CCS Institute, examines the costs and emissions intensities of low emission technologies in power generation.

It uses cost data for the US from a variety of published sources and applies these in a common methodological framework, based on the levelised cost of electricity (LCOE) that allows comparisons between different technologies in terms of emission reductions. This follows the same approach used in the original 2011 study, "The costs of CCS and other low-carbon technologies". Comparisons of this type have implications for designing policies that lead to a least-cost emissions reduction pathway.

The paper is limited to providing a range of costs for various generation technologies at a particular point in time and in a particular location. These are important caveats given the complexities involved in comparing generation costs across different countries where costs of construction, fuel and utilisation rates can vary considerably.

The paper also does not consider revenue expectations or other investment viability considerations. It combines outputs of the LCOE framework with estimates of CO2 emissions from various plant to compare technologies in terms of the cost of CO2 abated.

"Overall our analysis demonstrates that CCS is a mid-range technology in terms of cost and value for money in emissions reduction potential," says report author Lawrence Irlam.

"The key cost advantage of CCS-equipped power generators, relative to some renewables like wind and solar, derives from the fact that they are typically used to provide baseload or controllable output, and thus have higher rates of capacity utilisation. For this reason, while CCS currently has a higher investment cost than other low emission technologies, this is spread over a larger amount of clean electricity output."

"Technologies like hydro, nuclear and geothermal generation also have high rates of capacity utilisation and therefore may also provide better value for money in terms of costs per megawatt-hours (MWh) generated and per tonne of CO2 avoided."

"These are general conclusions however, and reflect a range of plant types and costs that are specific to the United States, including natural gas prices. They also reflect the state of each technology at present and do not include assumptions of expected cost and performance improvements that are likely to arise for many of the technologies considered."

"These results also should not be interpreted

Key findings

• CCS is a cost competitive power sector emissions reduction tool when considered among the range of available low and zero emissions technologies. While CCS adds additional costs to traditional fossil fuel generation, the underlying coal and gas generation technology and fuel sources are relatively cheap. CCS has higher rates of utilisation than some renewables technologies.

• Nuclear generation plant as well as hydro and geothermal plant can also be cost competitive in some markets given their high utilisation rates (ie can be operated up to 80 to 90 per cent of the time). The relative costs of solar and wind generation technologies are affected by lower capacity factors (up to 40 per cent availability).

• Hydropower and onshore wind technologies are among the least-cost emissions reduction technologies identified.

• Offshore wind, solar PV and solar thermal are the highest cost technologies examined here in terms of displacing emissions from fossil fuel sources (ie CO2 avoided), highlighting the importance of expected cost reductions and improvements in technical efficiency for these technologies.

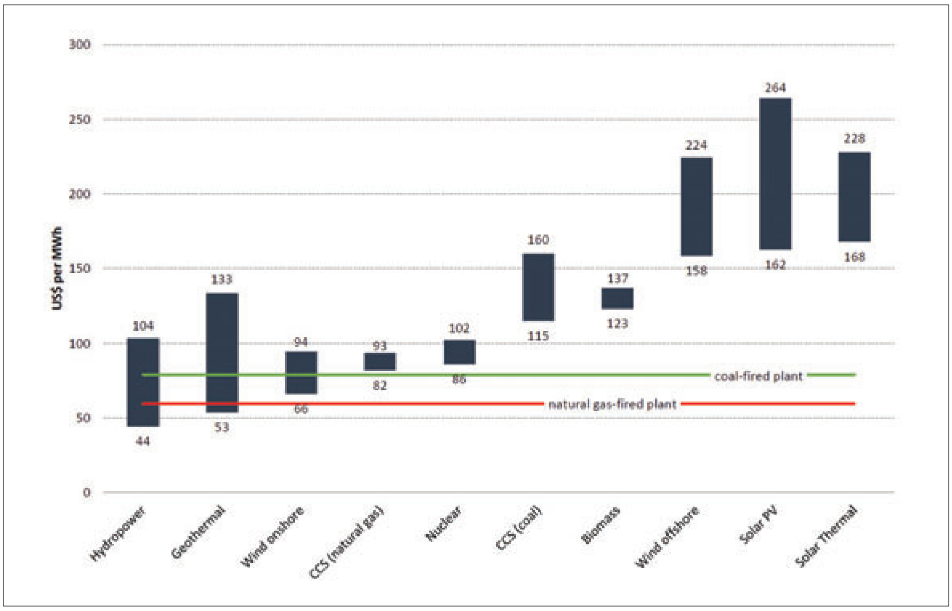
• Significant cost reductions are also expected for CCS technologies with increased deployment. While capture technology is already widely deployed at pilot and demonstration scale in the power sector, integrated CCS at commercial scale in the power sector is still in its earliest, highest cost stage of deployment, with the world's first-of-akind CCS power plant at Boundary Dam, Canada, commencing operations in late 2014.

• Using data from current studies, coal-fired generators with CCS capability would be on par with traditional (unabated) coal and gas generation if carbon were priced between US$48 and US$109 per tonne.

• The particular electricity generation mix consistent with a least cost, low carbon power sector will depend on the availability of resources that can be commercially exploited in the particular location. In the case of CCS, this depends on the presence of geological storage options as well as on the relative prices of coal and gas as fuel stock.

to mean that technologies with the lowest cost should be favoured, while those with relatively higher costs should be excluded. Decarbonising the world's energy supply is a significant task, with around two-thirds of all power generation currently coming from fossil fuel sources. All low emission technologies will have a role to play in addressing power sector emissions."

"The particular least-cost power generation mix consistent with achieving climate goals will depend on a variety of locational specific considerations, including local fuel costs and access to suitable wind, solar, hydro and CO2 storage resources. Policies designed to encourage a transformation of the power sector should allow for investment that reflects local commercial and technical conditions, rather than block or favour particular technologies."



Levelised cost of electricity (2014 US$). Coal with CCS is a mid-range technology in terms of cost when compared against a range of low-emissions technologies. Source: Global CCS Institute analysis

What is 'levelised' cost of electricity?

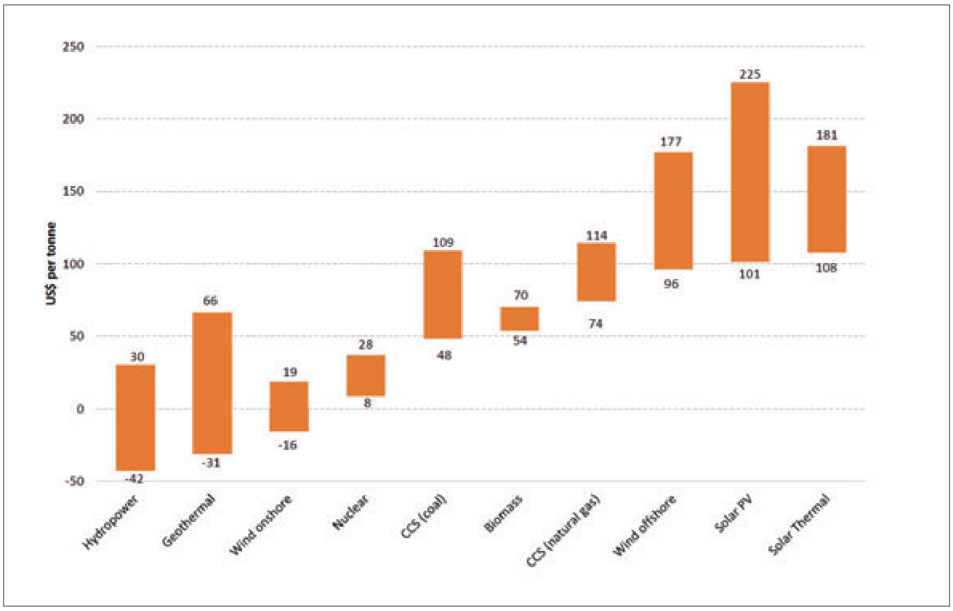
The LCOE is a measure frequently used to analyse the commercial viability of particular power generation technologies.

LCOE is the present value of costs per unit of electricity generated over the life of a particular plant. It may be interpreted as the price of output the plant must receive over its lifetime to break even, expressed in a way so as to be comparable to other plants that have different lifetimes and cost profiles.

Costs include fixed capital costs as well as ongoing fuel and maintenance, in addition to a commercial rate of return paid to owners and financiers of the plant. Other parameters in the calculation of the LCOE include:

- how many hours a year the generator can run
- fuel costs and fuel efficiency
- plant life and construction time.

Values used in most LCOE calculations are assumptions or generalisations around particular plant types. Actual cost and performance characteristics depend on a variety of real life factors, for example, locational specific costs, contractual arrangements around fuel contracts (including hedging instruments) and fi



Avoided cost of CO2, (2014 US$). Source: Global CCS Institute analysis

Cost per tonne of CO2 avoided

The LCOE of a particular plant can be converted into a cost per tonne of CO2 avoided when it is assumed that a new plant displaces the output, and associated emissions, from an existing fossil fuel generator. This is a useful metric in terms of examining changes in a generation portfolio associated with climate change policy and the incremental cost involved in such a change.

The Figure above illustrates the cost of CO2 avoided where one megawatt-hour (MWh) of output from each different generation plant is assumed to replace the same unit of output from a standard, unabated coal-fired generator (or gas generator in the case of CCS – natural gas). The difference in levelised cost that results from replacing this output is divided by the amount of emissions that are avoided in doing so.nancing arrangements.

More information

The complete paper, "The costs of CCS and other low carbon technologies - 2015 update" can be downloaded here:

www.globalccsinstitute.com

CCS policy indicator: 2015 update

The Global CCS Institute compares and reports on levels of national policy support to drive domestic action on CCS through its CCS Policy Indicator. Here are the results of the latest update.

Several developed countries with a heavy reliance on fossil fuels have improved their policy rankings since 2013 through the development or introduction of emissions performance standards on power generation plant and in progressing carbon pricing.

Achieving emission reduction targets at least cost requires that all emission reduction technologies are deployed in reflection of their relative cost effectiveness. Such an outcome is best achieved through policy that is technology neutral.

There are 51 large-scale integrated CCS projects in the world today in operation or in various stages of planning, with investment in CCS totaling around US$13B since 2007. While encouraging, this compares to investment in renewables power generation technologies (predominantly wind and solar PV) of around US$1,800B over the same timeframe3, which in part reflects that CCS has not been afforded comparable policy support and much more effort is required to encourage further deployment.

CCS policy indicator main findings

- The United Kingdom continues to provide the strongest policy leadership in encouraging CCS
- Canada and the USA also rank highly and have improved in standing since 2013
- China has a strong inherent interest in setting favourable policies towards CCS and has implemented a range of positive measures since 2013
- India, Russia, Malaysia and Indonesia also have a strong inherent interest in promoting CCS and would benefit from stronger policy support.

What is the CCS-PI?

The composite indicator (CCS-PI) includes two indexes (Inherent CCS Interest Index and Constituent Policy Index), which are made up of lead indicators (fossil fuel production, fossil fuel consumption, adoption, demonstration, and deployment), sub indicators (oil, gas, coal, comprehensiveness, appropriateness and adequacy), and variables (policy instruments).

The Constituent Policy Index draws from an extensive Institute database of policy measures for a wide range of countries, including direct support for CCS as well as broader implicit support through measures such as carbon pricing. These measures are weighted and aggregated to derive relative levels of support for CCS demonstrations and deployment.

Policies are captured in the Constituent Policy Index where they have been implemented but also under development (with the degree of development affects a policy's weighting).

Inherent CCS interest is a relative index based on global shares of fossil fuel production and consumption. It provides one indication only (among many possible methods) of the underlying potential interest countries may have in implementing policies that locally contribute to the global CCS development effort and hence in reducing emissions from fossil fuel sources.

Generally we should observe that countries with a higher inherent interest in CCS would logically be working towards developing a supportive policy environment. This is reflected in the results. Similarly, there is a correlation between inherent interest, policy support and the number of large-scale projects for particular countries.

The Figure shows the results of the latest update of the CCS-PI, reflecting data as at the middle of 2015.

The strongest ranking countries are the United Kingdom, the United States and Canada. All three countries have a strong inherent interest with respect to CCS in their particular circumstances and have implemented or are about to implement various key policies that support large scale deployment, including emissions performance standards on power generation and public funding to support first-of-a-kind projects.

The UK also has market-based mechanisms in the form of a carbon price floor and contracts for difference, as well as a relatively strong long-term commitment to CCS.

China also has a high degree of inherent interest and continues to demonstrate relatively strong policy support for CCS, including through research and development and partnerships with various countries around the world on CCS technology development. China has also been progressing plans to implement a national emissions trading scheme from 2016, which is an important technology neutral policy.

Countries in the European Union (EU) demonstrate varying degrees of inherent interest reflecting a diversity in their consumption and production of fossil fuels. EU policy on CCS covers a broad range of supporting categories including market pricing, legislative frameworks and direct funding. Reviews of the EU's carbon pricing arrangements and possible funding of CCS projects under the recent extension of the New Entrants Reserve are expected to result in improved rankings in the medium term for countries in this region.

More generally, the countries in quadrant 1 have CCS policy environments that reflect an early stage of technology demonstration, aligned with a relatively low level of inherent CCS interest.

In addition, some countries in this quadrant such as Algeria and Saudi Arabia with large-scale projects have identified the capacity to provide limited support for CCS in their particular circumstances without the need to implement prominent or broad policy instruments.

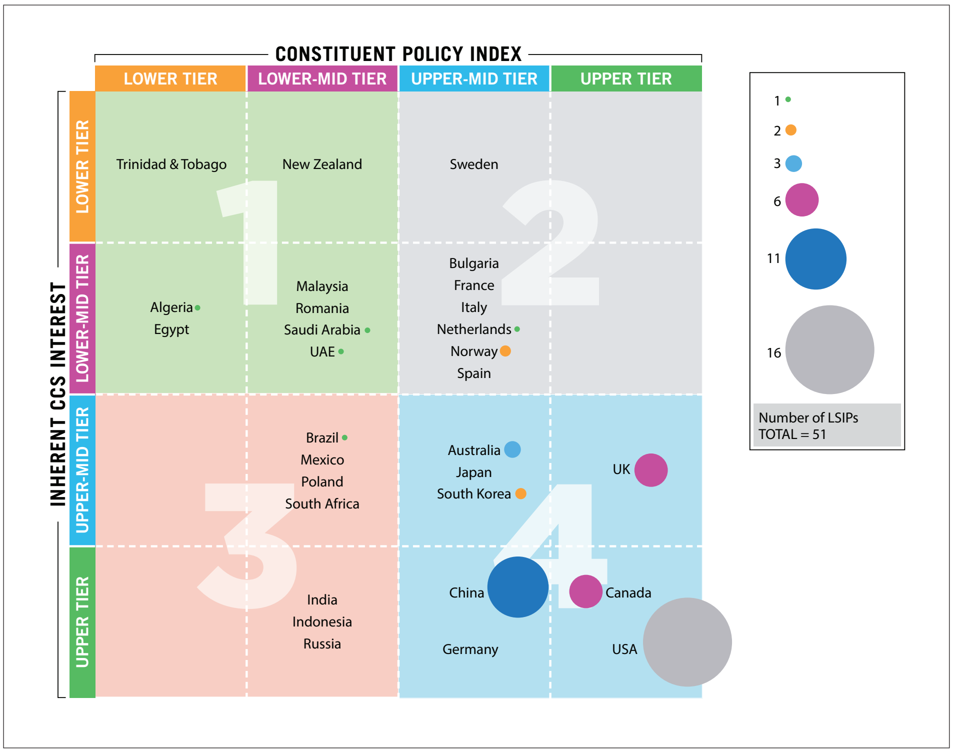
Countries located in quadrant 3 with a relatively high level of inherent interest include those with discrete but relatively limited policies that are supportive of CCS including Mexico and Indonesia, as well as Russia and India where the CCS is not high on the domestic political agenda in spite of a high dependence on fossil fuel consumption and export.

Some countries in quadrant 3, as well as in quadrant 1, may not have sufficient institutional or technical capacity to implement supportive policy for CCS (as well as climate change policy more broadly) and would therefore benefit from assistance.

The countries located in quadrants 2 and 4 have policy environments that demonstrate a higher-order potential to support CCS activities. Countries in these two quadrants include various EU member states as well as larger emitters in the Asia Pacific region.

These countries show a range of supportive measures in proportion to their capacity to responsibly manage current fossil fuel use and seek out lower cost pathways to lower overall emissions. In comparison to the 2013 CCS-PI results, the composition of countries located in quadrant 4 has not materially changed, reflecting their commitment to CCS deployment over the medium term.

The countries located in quadrant 2 do not necessarily have the same policy settings as those located in quadrant 4, and as such, they may well consider targeting the institutional and market barriers that tend to most inhibit domestic CCS demonstration projects from proceeding.



The results of the CCS-PI are presented as a matrix with the two leading indexes making up the X (Constituent Policy Index) and Y (Inherent CCS Interest) axes

More information

The complete issues brief, “Carbon Capture and storage policy indicator - 2015 update “ can be downloaded here:

www.globalccsinstitute.com

Projects and policy news

CAD$3Million available in CCEMC Grand Challenge Round 2

www.ccemcgrandchallenge.com

The Alberta-based Climate Change and Emissions Management Corporation (CCEMC) is inviting submissions for the second round of the $35 million international CCEMC Grand Challenge: Innovative Carbon Uses.

The competition seeks out technologies from around the world that can turn captured carbon dioxide emissions into useful products while reducing greenhouse gas emissions.

"CCEMC is looking for projects that take carbon dioxide emissions and use them to economically produce useful products right here in Alberta," said CCEMC Managing Director,

Kirk Andries. "If captured carbon is repurposed and becomes an enabling starting material, instead of a waste stream, we are confident it will attract new businesses and create new markets."

In the second round of the international competition, new entrants will join 24 round one winners. The focus becomes narrower and the stakes higher. CCEMC is placing emphasis on projects that can be commercialized in Alberta by 2020, and reduce GHG emissions by one megatonne annually. Submissions are due January 18, 2016.

CCEMC will name five second round winners in 2017. Each will receive CDN $3 million and have two years to refine their technology. At the end of the competition in 2019, one project will receive CDN $10 million to help them commercialize their technology in Alberta.

Technical teams will review all submissions. Final decisions are made by the CCEMC Board with input from an advisory panel comprised of leaders from across Canada and around the world.

The CCEMC Grand Challenge launched in 2013 and the .rst round drew 344 submissions from 37 countries. CCEMC selected 24 projects that each received CDN $500,000 to advance their ideas.

Winners from the first round include:

Solidia Technologies uses carbon dioxide instead of water to cure cement. Their technology reduces GHG emissions up to 70 per cent. LafargeHolcim signed a partnership agreement with Solidia in April 2015 to commercialize the technology for pre-cast concrete manufacturing.

In July 2015, Liquid Light secured a deal with Coca-Cola Company to further develop their technology that makes chemicals from carbon dioxide, including mono-ethlyene glycol. Mono-ethlyene glycol is a component in Coca-Cola's recyclable PET plant bottles.

Skyonic Corporation opened the world's first commercial scale carbon capture and utilization facility in Austin Texas in 2014. Skyonic builds and retrofits plants that produce carbon negative chemical products while mineralizing industrial CO2 emissions.

Their technologies economically extract and mineralize carbon dioxide from industrial flue gas into products such as baking soda, hydrochloric acid and limestone at a commercial scale.

Toshiba report on applying CCS to China steel plant

www.globalccsinstitute.com

Toshiba was commissioned by the Global CCS Institute for a feasibility report on applying Carbon Capture and Storage to a major steel plant in China.

The report "Applying Carbon Capture and Storage to a Chinese Steel Plant" is now available from the Institute website.

Toshiba with its partner Tongfang Environment Co. Ltd. worked together to study the application of Toshiba's solvent based capture technology on Shougang Jingtang United Iron & Steel 's Caofeidian Steel Plant.

The study also included the concept of capturing CO2 from the steel plant, compressing it for transport and potential storage in a nearby oilfield for Enhanced Oil Recovery (EOR).

Steel and iron production is one of the major contributors in the carbon emission. As the result of the study suggests that, China being the largest producer of steel and iron can be benefited by the cost effective means of reducing carbon emissions as the application is technically feasible and the project is economically viable.

Australian Government invests in CCS research fund

www.business.gov.au

The Australian Government is investing in the advancement of carbon capture and storage technologies, through a research fund designed to facilitate industry investment and research.

Minister for Industry and Science Ian Macfarlane launched the $25 million Carbon Capture and Storage (CCS) Research Development and Demonstration Fund, which will focus on transport and storage projects.

"Australia has a diverse energy mix, made up of traditional energy sources such as coal, through to gas and renewables. The diversity of this mix will continue to underpin Australia's economic future," Mr Macfarlane said.

"Australia's energy resources are one of our most significant competitive advantages.

"Just as we are using science to boost our key economic sectors, investment in research for carbon capture and storage technologies will be important as the coal and gas industries continue to develop both for our domestic use and for export.

"As Australia and our major trading partners continue to use our valuable resources responsibly, further research and development in low emissions energy sources will further strengthen Australia's role as an energy superpower.

"Industry has a critical role to play in developing CCS technologies and investing in its own future, through the application of science and research in this field."

The programme will address research priorities in CCS including subsurface knowledge and mapping, transport infrastructure, whole of chain integration and development of international collaboration and partnerships.

Activities under the Fund will be principally based in Australia to ensure national expertise on transport and storage is expanded however, the Fund will also provide support to leverage international expertise where advantageous.

IEAGHG technical review on regional CCS implementation

www.ieaghg.org

A new study aims to characterise key countries and regions worldwide where CCS could play an important part of mitigation efforts, based on national circumstances and priorities.

Meeting the long-term goal of the United Nations Framework Convention on Climate Change (UNFCCC) to limit global temperature rises to 2°C will require radical changes to energy systems over the coming decades. In this context, carbon capture and storage (CCS) represents a key mitigation option to achieve the envisaged emission reduction pathways in a cost efficient manner.

Given the need to reach an international climate agreement at the 21st Conference of the Parties (COP21) in December this year in Paris, the study provides a basis for understanding the relevance of CCS within this process. The study also looks at how CCS deployment barriers can be addressed and needs met, and identifies how CCS can be supported through international frameworks.

The key messages from the report are:

CCS is an opportunity for many countries to reduce their greenhouse gas (GHG) emissions. A portfolio of CCS technologies is available, depending on CO2 sources and availability of suitable storage sites.

The relative importance of CCS within a country's portfolio of climate actions will vary according to national circumstances, e.g. reliance on fossil power generation, expected economic growth, presence of carbon intensive industries, storage availability, etc.

There are significant drivers for CCS deployment across all world regions. However, this deployment will take place over several decades and with different rates according to countries' different circumstances.

Uptake of CCS is far behind the levels necessary for the envisaged global emission reductions , as CCS deployment faces a broad spectrum of barriers in both developed and developing countries, e.g.:

Legal and regulatory: Lack of suitable frameworks, laws and regulations to ensure safe and effective CCS

Policy: CCS is often overlooked in national policy priorities, so policy makers need to implement and design them in a way to facilitate private and public sector investments

Economic and financial: Incentives are likely necessary to overcome investments risks and ensure economic viability of CCS projects

Technical: Integration of capture, transport and storage components is still in its infancy

Institutional and public acceptance: Successful project deployment and public acceptance of CCS require significantly more capacity building and knowledge transfer on a national and international level

Countries and regions are at different stages along the CCS deployment pathway. Key elements during this process are:

• Scoping and agenda setting

• Building-up institutional capacity and legal/regulatory frameworks

• Designing and implementing suitable policies

• Creating a market for CCS, e.g. through carbon pricing, will facilitate wider deployment. However, experiences from countries leading in CCS (such as Canada, Norway, EU and USA) shows that this process can be very time-consuming.

• For many countries costs present a major challenge. Those countries could benefit from taking specific action that entail little costs (e.g. developing regulations and policies) first. This could increasing their level of "CCS readiness" for the coming years.

• Mechanisms within the emerging UNFCCC framework can help support CCS in both developing and developed countries through the following:

• Providing an overall mitigation policy framework (e.g. modalities and procedures (M&Ps), IPCC GHG Reporting Guidelines)

• Mobilising finance for CCS projects (e.g. Green Climate Fund (GCF), New Market Mechanism (NMM), a reformed Clean Development Mechanism (CDM))

• Addressing technology needs, transferring knowledge and building capacity (e.g. through the Technology Mechanism)

• National climate plans do not always adequately recognise CCS. At the time of writing the report only four parties had made specific reference to CCS within their Intended Nationally Determined Contributions (INDCs): Norway, Mexico, the EU and Canada.

UK business school backs US-China CCS partnership

www.business-school.ed.ac.uk

The University of Edinburgh Business School is placing its academic expertise at the heart of a new agreement between industry and academic partners in the US and China, to support the development of new carbon capture, utilisation and storage (CCUS) technologies.

The new agreement is the latest in a series of the School's initiatives to address one of the most pressing issues for world leaders today, the low carbon and sustainability agenda.

The University of Texas at Austin, The Clean Air Task Force (CATF) and US energy generator, Southern Company Services (SCS) have committed to collaborate with China's Guangdong CCUS Centre. The partners will collaborate on joint research and development of new technologies aimed at reducing global greenhouse gas emissions through the capture and storage of CO2 emissions from industry.

The collaboration will assess CO2 capture technologies and evaluate the viability of novel and safe storage facilities, such as offshore geological formations.

The Guangdong CCUS centre was officially founded in 2013 as a joint project between UK and Chinese engineers and scientists, including researchers from the Scottish Carbon Capture and Storage (SCCS) research partnership, of which the University of Edinburgh is one partner.

Dr Xi Liang, Director of the Centre for Business at Climate Change at University of Edinburgh Business School, signed the agreement in his capacity as Secretary General of the Guangdong CCUS Centre. He said:

"Through the Guangdong CCUS Centre, we are making great progress in demonstrating the benefits of CCUS in China. This is the latest milestone on our journey to develop technologies with potential to significantly reduce carbon emissions from energy production and key industries worldwide.

IEAGHG oxy-turbines report

IEAGHG undertakes studies on the performance and costs of plants incorporating various CO2 capture technologies, including oxy-combustion turbine power cycles.

Oxy-combustion involves burning gaseous fuel in high purity oxygen to heat high pressure CO2 and/or H2O, which is then expanded in a turbine. Various oxy-combustion turbine cycles have been proposed, some of which are still academic concepts but others are the subject of industrial development activities.

IEAGHG engaged Amec Foster Wheeler, in collaboration with Politecnico di Milano, to carry out a study to assess the performance and costs of various oxy-combustion turbine power cycles, in particular the supercritical oxy-combustion combined cycle (SCOC-CC), S-Graz cycles and cycles being developed by NET Power and Clean Energy Systems (CES).

The study provides an independent evaluation of the performance and costs of a range of oxy-combustion turbine cycles, mainly for utility scale power generation.

What's in the study

The study includes the following:

• A literature review of the most relevant systems featuring oxy-combustion turbine cycles, discussing the state of development of each of the cycles and their components.

• Detailed modelling of the gas turbine for the most promising cycles, including efficiency, stage number and blade cooling requirements. This modelling was carried out using calculation codes developed by Politecnico di Milano for performance prediction of gas turbines.

• Technical and economic modelling of complete oxy-combustion turbine power plants, including sensitivity analyses for a range of technical design and financial parameters.

• Assessment of potential future improvement, including high temperature turbine materials.

• High level evaluation of the most promising niche market applications for oxy-combustion turbines, particularly in smaller power plants.

• An assessment of oxy-combustion turbines combined with coal gasification

The study was undertaken in consultation with technology developers but to avoid any possibility of restrictions on dissemination of the results no confidential information was used.

Findings

The main highlights of the study are:

• The predicted thermal efficiencies of the cycles assessed in this study range from 55% (LHV basis) for the NET Power cycle to around 49% for the other base case cycles. For comparison, a recent IEAGHG study predicted an efficiency of 52% for a natural gas combined cycle plant with post combustion capture using a proprietary solvent.

• There was shown to be scope for improving the thermal efficiencies in future, for example by making use of materials capable of withstanding higher temperatures. Proprietary improvements by process developers may also result in higher efficiencies.

• The levelised cost of electricity (LCOE) of base-load plants using natural gas at 8 €/GJ are estimated to be 84–95 €/MWh, including CO2 transport and storage costs. The lowest cost oxy-combustion plant (NET Power) has a slightly lower LCOE than a conventional gas turbine combined cycle with post combustion capture (PCC) using a proprietary solvent.

• The cost of CO2 emission avoidance of the various cycles compared to a reference conventional natural gas combined cycle plant is 68–106 €/t CO2 avoided.

• The base case percentage capture of CO2 in this study was set at 90% but it was determined that it could be increased to 98% without increasing the cost per tonne of CO2 avoided, or essentially 100% if lower purity CO2 was acceptable.

• The water formed by combustion is condensed in oxy-combustion turbine cycles which would mean that if air cooling was used, the power plants could be net producers of water, which could be an advantage in places where water is scarce, although air cooling would reduce the thermal efficiency.

• Oxy-combustion cycles could have advantages at compact sites. The total area of an oxy-combustion combined cycle plant is estimated to be slightly less than that of a conventional combined cycle with PCC. The ASU could be located off-site if required to further reduce the power plant area. In addition, regenerative oxy-combustion cycles are significantly more compact than combined cycles.

• Oxy-combustion turbines could be combined with coal gasification. The predicted thermal efficiency of a coal gasification plant with a SCOC-CC is 34% (LHV basis), which is similar to that of more conventional CCS technologies (IGCC with pre-combustion capture and supercritical pulverised coal with post combustion amine scrubbing) but the estimated capital cost and cost of electricity of the oxy-combustion turbine plant are significantly higher.

More information

The report is free to member countries/organisations, to receive a copy, please contact Becky Kemp:

Becky.kemp@ieaghg.org

www.ieaghg.org

Berkeley develops CO2 conversion catalyst

A molecular system that holds great promise for the capture and storage of carbon dioxide has been modified so that it now also holds great promise as a catalyst for converting captured carbon dioxide into valuable chemical products.

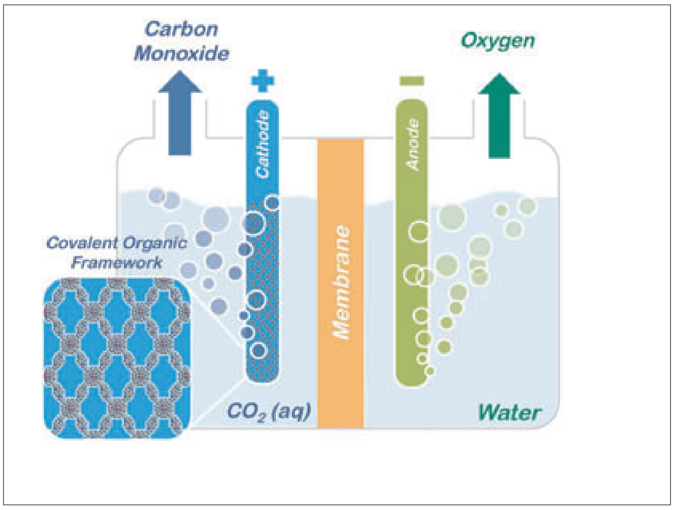
Researchers with the U.S. Department of Energy (DOE)'s Lawrence Berkeley National Laboratory (Berkeley Lab) have incorporated molecules of carbon dioxide reduction catalysts into the sponge-like crystals of covalent organic frameworks (COFs).

This creates a molecular system that not only absorbs carbon dioxide, but also selectively reduces it to carbon monoxide, which serves as a primary building block for a wide range of chemical products including fuels, pharmaceuticals and plastics.

"There have been many attempts to develop homogeneous or heterogeneous catalysts for carbon dioxide, but the beauty of using COFs is that we can mix-and-match the best of both worlds, meaning we have molecular control by choice of catalysts plus the robust crystalline nature of the COF," says Christopher Chang, a chemist with Berkeley Lab's Chemical Sciences Division, and a co-leader of this study. "To date, such porous materials have mainly been used for carbon capture and separation, but in showing they can also be used for carbon dioxide catalysis, our results open up a huge range of potential applications in catalysis and energy."

Chang and Omar Yaghi, a chemist with Berkeley Lab's Materials Sciences Division who invented COFs, are the corresponding authors of a paper in Science that describes this research in detail. The paper is titled "Covalent organic frameworks comprising cobalt porphyrins for catalytic CO2 reduction in water." Lead authors are Song Lin, Christian Diercks and Yue-Biao Zhang. Other co-authors are Nikolay Kornienko, Eva Nichols, Yingbo Zhao, Aubrey Paris, Dohyung Kim and Peidong Yang.

Yaghi and his research group at the University of Michigan in 2005 designed and developed the first COFs as a means of separating carbon dioxide from flue gases. A COF is a porous three-dimensional crystal consisting of a tightly folded, compact framework that features an extraordinarily large internal surface area – a COF the size of a sugar cube were it to be opened and unfolded would blanket a football field. The sponge-like quality of a COF's vast internal surface area enables the system to absorb and store enormous quantities of targeted molecules, such as carbon dioxide.



Conceptual model showing how porphyrin COFs could be used to split CO2 into CO and oxygen (courtesy of Omar Yaghi)

Now, through another technique developed by Yaghi, called "reticular chemistry," which enables molecular systems to be "stitched" into net-like structures that are held together by strong chemical bonds, the Berkeley Lab researchers were able to embed the molecular backbone of COFs with a porphyrin catalyst, a ring-shaped organic molecule with a cobalt atom at its core. Porphyrins are electrical conductors that are especially proficient at transporting electrons to carbon dioxide.

"A key feature of COFs is the ability to modify chemically active sites at will with molecular-level control by tuning the building blocks constituting a COF's framework," Yaghi says. "This affords a significant advantage over other solid-state catalysts where tuning the catalytic properties with that level of rational design remains a major challenge. Because the porphyrin COFs are stable in water, they can operate in aqueous electrolyte with high selectivity over competing water reduction reactions, an essential requirement for working with flue gas emissions."

In performance tests, the porphyrin COFs displayed exceptionally high catalytic activity – a turnover number up to 290,000, meaning one porphyrin COF can reduce 290,000 molecules of carbon dioxide to carbon monoxide every second. This represents a 26-fold increase over the catalytic activity of molecular cobalt porphyrin catalyst and places porphyrin COFs among the fastest and most efficient catalysts of all known carbon dioxide reduction agents. Furthermore, the research team believes there's plenty of room for further improving porphyrin COF performances.

"We're now seeking to increase the number of electroactive cobalt centers and achieve lower over-potentials while maintaining high activity and selectivity for carbon dioxide reduction over proton reduction," Chang says. "In addition we are working towards expanding the types of value-added carbon products that can be made using COFs and related frameworks."

This research was supported by the DOE Office of Science in part through its Energy Frontier Research Center (EFRC) program. The porphyrin COFs were characterized through X-ray absorption measurements performed at Berkeley Lab's Advanced Light Source, a DOE Office of Science User Facility.

www.lbl.gov

Capture and utilisation news

U.S. Department of Energy selects projects for funding

energy.gov/fe

The DOE's National Energy Technology Laboratory (NETL) has selected a range of projects for funding.

Sixteen projects being funded fall under five subtopic areas:

(1) Lab-scale, post-combustion capture

(2) Lab-scale, pre-combustion capture

(3) Bench-scale, post-combustion capture

(4) Bench-scale, pre-combustion capture

(5) Biological CO2 use/conversion.

A further nine projects concentrate on three research priorities:

(1) Carbon Capture and Storage (CCS)-specific intelligent systems for monitoring, controlling, and optimizing CO2 injection operations

2) diagnostic tools and methods capable of characterizing borehole leakage pathways or fluid flow in existing wells

(3) next-generation materials and methods for mitigating wellbore leakage

Another eight selected projects focus on advancing the development of a suite of post-combustion CO2 capture and supersonic compression systems for new and existing coal-based electric generating plants, specifically:

(1) supersonic compression systems

(2) small pilot-scale (from 0.5 to 5 MWe) post-combustion CO2 capture development and testing

(3) large pilot-scale (from 10 to more than 25 MWe) post-combustion CO2 capture development and testing.

TCM Mongstad starts new test campaign

www.tcmda.com

Technology Centre Mongstad has started new MEA tests aimed to reduce risks associated with scaling up the technology.

The main objectives of TCMs new MEA campaign are to increase learning and reduce technology risks with respect to scale-up and operation of a full scale generic capture plant.

MEA (Monoethanolamine) is a widely used solvent by companies for benchmarking and improving their technology. So by thoroughly testing the MEA solvent system in the amine plant, and openly sharing some of that information, TCM will help maximise the performance of various technologies and advance the CCS industry on a major scale, says TCMs technology manager Espen Steinseth Hamborg.

The new tests include measurement and evaluation of a number of important parameters, such as energy consumption, emissions, degradation, and plant operability. The test findings will be to a large extent published in several scientific papers. Ultimately, the testing will provide a valid MEA baseline for a variety of CCS applications, both in the process industry and in power production.

Based on experiences from the Aker Solutions' and TCM's previous MEA campaign carried out in the period from November 2013 to February 2014, some areas of the amine plant need improvement and a further understanding. Following a major upgrade of gas phase measurement instrumentation analyzers, the following areas will be further investigated in the campaign;

• The plant design capacity should be better explored and explained

• The CO2 mass balances, optimized capture rates and specific energy consumption were uncertain to some extent and improvements should be expected with better and more advanced instrumentation

• The plant performance and effect of higher CO2 concentrations in the flue gas should be better explored and explained, intended for preparation of amine plants treating flue gases from future gas turbine installation with exhaust gas recycling

• Emission monitoring with advanced mass spectroscopy and fourier transform infrared spectroscopy should be further investigated.

Heat buckyballs to help environment

barron.rice.edu/Barron.html

Rice University scientists have published a new study that shows how chemical changes affect the abilities of enhanced buckyballs to confine greenhouse gases.

The lab of Rice chemist Andrew Barron found last year that carbon-60 molecules (aka buckyballs, discovered at Rice in the 1980s) gain the ability to sequester carbon dioxide when combined with a polymer known as polyethyleneimine (PEI).

Two critical questions – how and how well – are addressed in a new paper in the American Chemical Society journal Energy and Fuels.

The amine-rich combination of C60 and PEI showed its potential in the previous study to capture emissions of carbon dioxide, a greenhouse gas, from such sources as industrial flue gases and natural-gas wells.

In the new study, the researchers found pyrolyzing the material – heating it in an oxygen-free environment – changes its chemical composition in ways that may someday be used to tune what the scientists call PEI-C60 for specific carbon-capture applications.

"One of the things we wanted to see is at what point, chemically, it converts from being something that absorbed best at high temperature to something that absorbed best at low temperature," Barron said. "In other words, at what point does the chemistry change from one to the other?"

Lead author Enrico Andreoli pyrolyzed PEI-C60 in argon at various temperatures from 100 to 1,000 degrees Celsius (212 to 1,832 degrees Fahrenheit) and then evaluated each batch for carbon uptake.

He discovered the existence of a transition point at 200 C, a boundary between the material's ability to soak in carbon dioxide through chemical means as opposed to physical absorption.

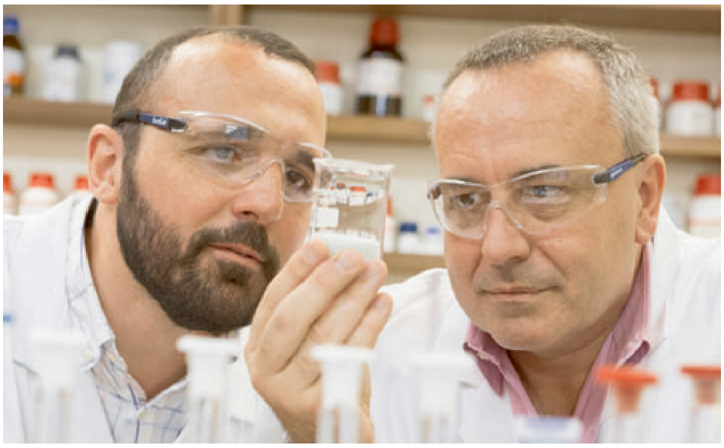
The material that was pyrolyzed at low temperatures became gooey and failed at pulling in carbon from high-temperature sources by chemical means. The opposite was true for PEI-C60 pyrolyzed at high heat. The now-porous, brittle material became better in low-temperature environments, physically soaking up carbon dioxide molecules.

At 200 C, they found the heat treatment breaks the polymer's carbon-nitrogen bonds, leading to a drastic decrease in carbon capture by any means.

"One of the goals was to see if can we make this a little less gooey and still have chemical uptake, and the answer is, not really," Barron said. "It flips from one process to the other. But this does give us a nice continuum of how to get from one to the other."

Andreoli found that at its peak, untreated PEI-C60 absorbed more than a 10th of its weight in carbon dioxide at high temperatures (0.13 grams per gram of material at 90 C). Pyrolyzed PEI-C60 did nearly as well at low temperatures (0.12 grams at 25 C).

The researchers, with an eye on potential environmental benefits, continue to refine their process. "This has definitely pointed us in the right direction," Barron said.



Enrico Andreoli, left, and Andrew Barron of Rice University are studying the use of enhanced carbon-60 molecules to capture carbon dioxide that would otherwise be released as a greenhouse gas. (Image: Welsh Government)

Transport and storage news

CO2 geological storage project enters final phase

www.co2ketzin.de

The final phase of a project on the geological storage of carbon dioxide at Ketzin/Havel has started with the abandonment of the first of five wellbores.

After successful completion of the active injection and the monitoring phase, the project, which is operated by the GFZ German Research Centre for Geosciences, will enter the final project phase termed COMPLETE and will abandon all wellbores of the pilot site.

The abandonment of the wellbore is done in a stepwise manner. The wellbore is completed with successive casings with decreasing diameters. The lower part of the innermost casing is cut at about 459 meter depth and pulled out. Subsequently, the wellbore is cemented up to a depth of 275 meter. After hardening of this first cement bridge, the next bigger casing is cut at about 265 meter depth, pulled out and the wellbore cemented up to the surface. The well abandonment is completed by deconstruction of the wellbore cellar and its foundation.

"The now started work will provide first-hand results on the safe abandonment and closure of a CO2 storage site that are also internationally unique", explained Axel Liebscher, Head of the Centre for Geological Storage at the GFZ.

"Together with its precursor projects CO2SINK and CO2MAN the ongoing project COMPLETE closes for the first time the complete life cycle of a CO2 storage site at pilot scale," Axel Liebscher continued. "Our research that already started in 2004 provided fundamental knowledge on construction, monitoring, operation and behaviour of a CO2 storage site from the exploration to the closure phase."

"We were able to prove that this technology is generally feasible. With fit-to-purpose designed scientific and technical monitoring, CO2 can be safely stored in the subsurface if the geological conditions are suitable."

After comprehensive pilot survey and the construction of the required infrastructure, a total of about 67,000 t CO2 have been injected at the Ketzin pilot site between June 2008 and August 2013 into porous sandstone at a depth of about 630 to 650 m. In autumn 2013 directly after termination of the injection the observation well Ktzi 202 was partly abandoned with CO2 resistant cement up to a depth of 521 m.

This cementation has been scientifically monitored over more than one and a half year before now the final abandonment of the well started. At the beginning of the final abandonment a three meter long core was drilled and recovered from the first cementation and surveyed on-site.

"Both, the scientific monitoring and survey of the recovered cement core showed, that the cementation performed in autumn 2013 has been successful. We therefore continued with the final abandonment of the well", Axel Liebscher explains. The remaining four wells at the site will be abandoned and deconstructed in 2016, so that the initial conditions of site will be re-established in 2017.

Abandonment works at the drillsite Ktzi 202 in Ketzin, core of the former cementation (photo T. Kollersberger, GFZ)

DOE funding for carbon storage projects

energy.gov/fe

The National Energy Technology Laboratory (NETL) has selected nine projects to receive funding to research intelligent monitoring systems and advanced well integrity and mitigation.

The selected projects concentrate on three research priorities:

(1) Carbon Capture and Storage (CCS)-specific intelligent systems for monitoring, controlling, and optimizing CO2 injection operations

2) diagnostic tools and methods capable of characterizing borehole leakage pathways or fluid flow in existing wells

(3) next-generation materials and methods for mitigating wellbore leakage

Free access to UK CO2Stored database

www.co2stored.co.uk

The Crown Estate and the British Geological Survey now offer free, licenced access to the CO2 Stored database for subscribers via a more user-friendly website.

The new web-enabled database, hosted and managed by The Crown Estate and the British Geological Survey (BGS) under licence from the Energy Technologies Institute (ETI), is now free to access to all subscribers, a saving on a typical licence of up to £4,000 per year on an individual basis.

In addition, the website has been enhanced to help users navigate the wealth of complex data and to set out more clearly information on how key attributes such as storage capacity of geological units have been calculated.

The website and database contain geological data, storage estimates and risk assessments of nearly 600 potential CO2 storage units of depleted oil and gas reservoirs, and saline aquifers around the UK. The Crown Estate manages the CO2 geological storage rights on the UK continental shelf. The database enables interested stakeholders to access information enabling more informed decisions related to the roll out of CCS infrastructure in the UK.

ETI seeks partners for under-sea CO2 storage study

www.eti.co.uk

The Energy Technologies Institute is seeking partners for a project to study the impact of removing brine from under-sea stores that could be used to store captured carbon.

The ETI will invest up to £200,000 in the nine-month project which will carry out a study on the effects brine production could have on costs, risk reduction and other benefits of under-sea CO2 stores. The request for proposals will close on 24 September 2015 – the deadline for notification of intention to submit a proposal is 10 September 2015.

A previous ETI project in its CCS technology programme led to the development of the UK's principal storage screening database, CO2Stored, which made a number of assumptions to estimate capacity and injectivity for each of the 550 stores off the UK's coast.

One of these was that brine was not produced from the reservoir before, during or after CO2 injection.

If a reservoir is pressurising as a result of CO2 injection, brine can potentially be removed through a purpose built well or wells from the store to depressurise it, and can still retain the operation and integrity of the store.

The brine could potentially be sent to another aquifer or disposed of in the sea. Brine production is a recognised way of controlling the reservoir pressure and potentially its flow, and its use is a contingency in several store designs.

Recent work published by Heriot Watt University showed that producing brine in the United Kingdom Continental Shelf (UKCS) may be beneficial to injection rates and storage.

This project will produce a cost-benefit analysis of brine production, using the CO2Stored database and models developed in the ETI's UK Storage Appraisal Project as a starting point. Analysis will cover both saline aquifers and oil gas reservoirs.

The first stage of the project will examine any changes in injectivity and storage capacity as a result of producing brine, the additional cost of the brine wells, and the savings, if any.

If the first stage shows there are potential benefits, these will then be refined and the operational implications examined.

Bristol seismologists join CCS research initiative

ukccsrc.ac.uk

Ways to improve monitoring of CO2 storage sites are being investigated by three University of Bristol seismologists as part of a new international collaborative research initiative.

The initiative, funded by the UK Carbon Capture and Storage Research Centre (UKCCSRC), recently got underway at CMC Research Institutes' field research station in Alberta, Canada.

The collaboration aims to investigate and improve monitoring for CCS sites where CO2 is captured as it is produced and then injected deep below the surface to be stored permanently in geological formations. Storage reservoirs are usually more than 1.5km deep and so sophisticated monitoring methods, such as geophysical and geochemical surveys, are required to ensure the CO2 remains at this depth.

Dr Anna Stork, Dr Anna Horleston and Professor Michael Kendall from the Bristol University Microseismicity Projects (BUMPS) group in the School of Earth Sciences have been at the site, located 20km southwest of Brooks, Alberta, Canada, installing three broadband seismometers to record seismic events over the next year. The project was one of four awarded funds by the UKCCSRC to support international collaborative research at the field research station (FRS), a site being developed for CCS research in affiliation with the University of Calgary.

Dr Stork's project will see a total of seven broadband seismometers installed at distances ranging from 200m to three kilometres from the site's two injection wells. The extremely sensitive seismometers will detect local microseismic events, some so small their energy is the equivalent of a pad of paper falling off a desk. They are also capable of recording large earthquakes occurring on the other side of the world.

Barring any power or equipment failures, the seismometers will run continuously for the next year with data used to map the underground structures in the area. The recordings will also provide baseline information on the background rate of seismic events in the area. This information will be compared to microseismic activity after injection starts in 2016 to determine which events are the result of injection operations and which are natural.

CO2MultiStore - unlocking the North Sea's CO2 storage potential

The secure and permanent storage of carbon dioxide within a single geological storage formation can be optimised by injecting CO2 at more than one point simultaneously, according to results from an innovative study of rocks beneath the UK North Sea.

The findings could help to unlock an immense CO2 storage resource underlying all sectors of the North Sea for the storage of Europe's carbon emissions, and will inform the work of those managing and operating this natural asset.

The process of storing CO2 captured from power plants and industrial facilities in deep geological formations is known as Carbon Capture and Storage (CCS) and is a key technological solution for meeting climate change targets over the coming decades.

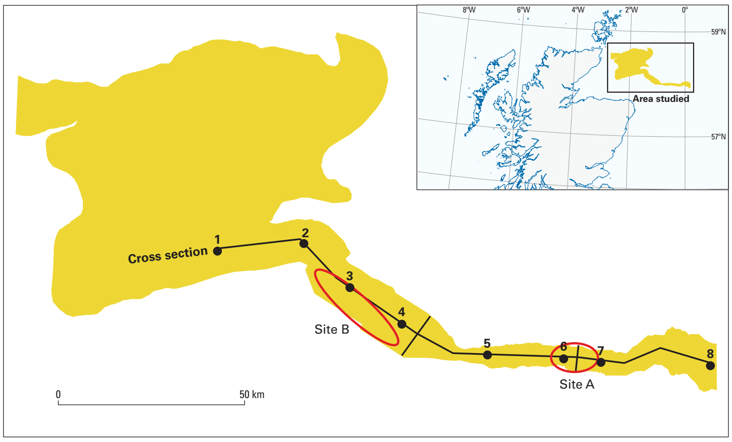
The research by scientists and prospective site operators has used a UK North Sea case study – the Captain Sandstone – to predict the performance of a potential CO2 storage formation when the greenhouse gas is injected at two points at the same time over three decades.

The study's conclusions will help to increase confidence among regulators and investors in the secure containment of CO2 within "multiple user" storage formations.

The work has informed how the UK can plan and manage subsurface geological CO2 storage, and design CO2 injection at more than one location by looking at regional-scale performance of an entire geological formation. It is an important step in the gradual process of developing the UK's vast CO2 storage potential, which has been estimated at 78 billion tonnes.

The findings also suggest that the Captain Sandstone, which lies more than a mile beneath the Moray Firth off north east Scotland, could securely store at least 360 Million tonnes (Mt) of CO2 in just one sixth of its area when CO2 is injected at a rate of between 6 and 12 Mt per year over three decades. As a comparison, 360Mt is the amount of CO2 emitted by Scotland's energy supply sector over 23 years.

Researchers on the CO2MultiStore joint industry project used cutting-edge methods, which will, in future, reduce the effort and resources needed to characterise other extensive storage sandstones that could be suitable for CO2 storage. As a result, generic learning from the project will be of considerable value to prospective site operators worldwide.



The extent of the CO2MultiStore Captain Sandstone case study area, offshore Scotland, UK North Sea(inset) and position of the injection sites and lines of cross section

Energy Minister Fergus Ewing said: "Carbon Capture and Storage (CCS) has the potential to be one of the most cost-effective technologies for decarbonisation of our power and industrial sectors, as well as those of economies worldwide. With £2.5 million of funding already committed this year to undertake substantial industrial research and feasibility studies in Grangemouth, the Scottish Government is already playing a pivotal role in the development and commercialisation of this innovative, exciting technology.

"This research confirms how the huge CO2 storage resource potential beneath the North Sea can be optimised, which, combined with the infrastructure already in place, again reinforces the huge opportunity for Scotland around CCS. CCS can contribute significantly to the diversity and security of electricity supply, and also has a unique role to play in providing a continuing supply of flexible clean fossil fuel capacity that is able to respond to demand in the way that other low-carbon technologies cannot.

Dr Maxine Akhurst, British Geological Survey, who led the project for SCCS, said: "Our study is one of the keys that will unlock the potential CO2 storage capacity underlying the North Sea and release this immense storage resource. Our results show that by using more than one injection site in a single sandstone operators can store greater volumes of CO2 compared to using a single injection site, so increasing Europe's capacity to reduce greenhouse gas emissions."

Paul Goodfellow, Upstream Director UK & Ireland, Shell, said: "This significant piece of work could help pave the way for the wider deployment of CCS in the UK. This project demonstrates the value of collaboration and knowledge sharing to build a new industry, and the results of this research will hopefully be of benefit to many different parties into the future."

More information

The SCCS CO2MultiStore Joint Industry Project was led by Scottish Carbon Capture & Storage (SCCS) with support from the Scottish Government, The Crown Estate, Shell, Scottish Enterprise and Vattenfall.

The report can be downloaded here:
www.sccs.org.uk