The Urgent Need to Move From CCS Research to Commercial Development

Andrew Minchener
General Manager,
IEA Clean Coal Centre
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Benjamin Sporton
Chief Executive,
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Carbon Capture, Utilization, and Storage

In November 2012, *Cornerstone* was launched as the official journal of the World Coal Association. *Cornerstone* has since become an internationally recognized credible, independent, high-quality publication, featuring some of the most insightful and informative articles on industry developments. We have looked closely at the technological innovations being pioneered across the coal industry and offered some remarkable thought leadership pieces—from academia, research institutes, investors, and mining companies—that have engendered discussion in the industry.

The mission of *Cornerstone* was to communicate coal’s involvement in energy communities, the industry’s scientific and technological advancement, and coal’s vital function in propelling the world toward a sustainable future. It also addressed the key challenges that coal faces and brought a wide variety of stakeholders into the discussion to advance the sustainable use of coal. In 2016, *Cornerstone* has reached more than 70,000 views worldwide and is circulated in print in English and Mandarin. All the articles are accessible at: www.cornerstonemag.net

After four years, however, it is time to say farewell to *Cornerstone*. This is our last edition of this journal. In 2017, we will be bringing readers a new journal, named *Clean Energy*, that will cover not only coal but also other energy technologies, such as solar, wind, unconventional oil and gas, hydrogen energy and fuel cell, energy storage, and smart grid technology developments.

*Cornerstone* has been instrumental in providing a platform for discussing low-emissions coal technologies, carbon capture and storage (CCS), and the sustainable mining practices being applied across the sector. The journal has also championed the need for policy parity for CCS and for financial investment in low-emissions coal.

So, it is fitting that the final issue focuses on carbon capture, utilization, and storage (CCUS) as we examine the current and future role that CCUS needs to play in the global energy mix. Our cover story, written by the General Manager of the IEA Clean Coal Centre, looks at the urgency of moving CCS from research to commercial development. Other articles examine CCUS developments in Norway and the development of CCUS over the last 20 years. We also explore the challenges and the exciting developments that are happening with CCUS in China.

This issue also examines clean coal technology developments in Japan and the United Arab Emirates. CCUS remains a key technology for the coal and industrial sector. Experts agree that CCUS needs to be better supported politically and economically in order to continue to play an important role in reducing CO₂ emissions in the industrial and energy sector.

With this issue, *Cornerstone* has come full circle. We hope it informs and encourages readers to understand the developments happening with CCUS today.

We would like to extend our gratitude to the Shenhua Group for bringing together stories, knowledge, and insight from various sections of the industry.

On behalf of our team, I hope you enjoy this final issue and we look forward to bringing you the new journal in 2017.
Climate change is a serious issue that requires a global response. However, that response will not be a “one size fits all global solution”. In this article, the General Manager of the IEA Clean Coal Centre discusses the urgency of moving CCS research to large-scale demonstration and deployment.
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Climate change is a serious issue that requires a global response. However, that response will not be a "one size fits all global solution". Despite strident calls from some activists for a switch to renewables, with an immediate rejection of fossil fuels, the reality is that each nation will need to decide how it might move toward a lower carbon economy while deciding how best to balance the strategic energy trilemma. Compared to OECD countries, developing and industrializing nations will have different priorities, with a focus on ensuring that their populations have access to electricity, which can be the most effective means to improve both their education and standard of living through industrialization. In such cases, the fuel of choice is coal, being readily available, relatively low cost, and a proven choice for grid-based power generation.

"...without CCS, the transformation of the power sector will be US$3.5 trillion, or 138% more expensive."
From CCS Research to Commercial Deployment

That said, recognition grows that lowering carbon emissions, especially from coal, is both achievable and a valid near-term contribution to global greenhouse gas emissions reduction. In recent years, various critical advances have occurred in coal-based power generation technology, which can now achieve cycle efficiencies of some 45% (net, LHV basis), consistent with a 20% reduction in CO₂ emissions compared to those from conventional coal-fired plants. Equally importantly, in China and Japan especially, various developments are being tested that are designed to achieve cycle efficiencies of some 50% within the next decade.¹,²

Ultimately, to achieve “near-zero” CO₂ emissions from coal-fired plants, it will be necessary to introduce carbon capture and storage (CCS), which comprises various options to capture CO₂, then pressurize and transport it to a geological location for injection and permanent storage. This can include a depleted oil field where the injected CO₂ will result in an increase in oil extraction with the majority of the CO₂ remaining underground. This option, known as carbon capture, utilization, and storage (CCUS) will provide a revenue stream to offset some of the CO₂ capture costs.

The Stern Review in the UK concluded that the cost to decarbonize the global economy would be significantly higher if CCS is not included for coal-fired power plants.³ Equally importantly, subsequent analysis has shown that the use of fossil fuels, particularly coal, for industrial applications such as iron/steel, cement, and chemicals cannot be replaced by renewable energy. However, these processes can be decarbonized through the introduction of CCS, which needs to be seen as a core part of the global climate response.

PROGRESS TOWARD COMMERCIAL-SCALE DEMONSTRATION AND DEPLOYMENT

Research and development have delivered technology advances across capture, transport, and storage technologies. Such efforts will continue to be important to refine and improve CCS technologies, but the critical step must come through large-scale demonstration and deployment. In that regard, the limited number of operational plants and the relatively small scale of operation compared to commercial-scale units means that CCS is not yet having the impact required to significantly contribute to meeting global decarbonization targets (Table 1).

TABLE 1. List of operating and near-operational large-scale CCS projects⁴

<table>
<thead>
<tr>
<th>Project Name (Location)</th>
<th>Project Life-Cycle stage</th>
<th>Nominal Operation Start Date</th>
<th>Industry Sector</th>
<th>Capture Type &amp; Annual Capacity (Mt)</th>
<th>Transport &amp; Storage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Val Verde Natural Gas Plants (U.S.)</td>
<td>Operate</td>
<td>1972</td>
<td>Natural gas processing</td>
<td>Pre-combustion (1.3)</td>
<td>Pipeline EOR</td>
</tr>
<tr>
<td>Enid Fertilizer CO₂-EOR Project (U.S.)</td>
<td>Operate</td>
<td>1982</td>
<td>Fertilizer production</td>
<td>Industrial separation (0.7)</td>
<td>Pipeline EOR</td>
</tr>
<tr>
<td>Shute Creek Gas Processing (U.S.)</td>
<td>Operate</td>
<td>1986</td>
<td>Natural gas processing</td>
<td>Pre-combustion (7.0)</td>
<td>Pipeline EOR</td>
</tr>
<tr>
<td>Sleipner CO₂ Storage (Norway)</td>
<td>Operate</td>
<td>1996</td>
<td>Natural gas processing</td>
<td>Pre-combustion (0.9)</td>
<td>Direct injection for dedicated geological storage</td>
</tr>
<tr>
<td>Great Plains Synfuel Plant &amp; Weyburn-Midale Project (U.S.)</td>
<td>Operate</td>
<td>2000</td>
<td>Synthetic natural gas</td>
<td>Pre-combustion (3.0)</td>
<td>Pipeline EOR</td>
</tr>
<tr>
<td>In Salah CO₂ Storage (Algeria)</td>
<td>Operate</td>
<td>2004</td>
<td>Natural gas processing</td>
<td>Pre-combustion (injection suspended)</td>
<td>Pipeline</td>
</tr>
<tr>
<td>Snøhvit CO₂ Storage Project (Norway)</td>
<td>Operate</td>
<td>2008</td>
<td>Natural gas processing</td>
<td>Pre-combustion (0.7)</td>
<td>Pipeline for dedicated geological storage</td>
</tr>
</tbody>
</table>
Globally, 15 large-scale CCS projects are currently in operation, with a further five under construction and expected to start operations by 2017. These 20 projects represent a doubling since the start of this decade, while their total annual CO₂ capture capacity will be close to 40 Mt once all are fully operational. Half of these are based on stripping CO₂ through natural gas processing and, in all but two, using the CO₂ for EOR. This approach is cost effective since removing CO₂ from the natural gas, to ensure product quality specifications, will result in a revenue. In addition, there are six projects based on hydrogen, fertilizer, and synthetic natural gas production plants with CCS and EOR. More recently, this global portfolio includes a 115-MWₑ coal-fired power plant with CCS and EOR at Boundary Dam in Canada, and a 582-MWₑ unit with IGCC-based CO₂ capture and EOR is just beginning operations at the Kemper County, Mississippi, facility. Shortly, these will be complemented with a 240-MWₑ unit at Petra Nova, Texas (Figure 1). Projects currently under construction will further diversify this portfolio, including the world’s first iron and steel CCS project in Abu Dhabi and a bioethanol plant in the U.S. This diversity indicates that CCS is a technology to limit carbon emissions from a wide range of power and industrial processes.

### TABLE 1. Continued

<table>
<thead>
<tr>
<th>Project Name (Location)</th>
<th>Project Life-Cycle Stage</th>
<th>Nominal Operation Start Date</th>
<th>Industry Sector</th>
<th>Capture Type &amp; Annual Capacity (Mt)</th>
<th>Transport &amp; Storage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Century Plant (U.S.)</td>
<td>Operate</td>
<td>2010</td>
<td>Natural gas processing</td>
<td>Pre-combustion (8.4)</td>
<td>Pipeline EOR</td>
</tr>
<tr>
<td>Coffeyville Gasification Plant (U.S.)</td>
<td>Operate</td>
<td>2013</td>
<td>Fertilizer production</td>
<td>Industrial separation (1.0)</td>
<td>Pipeline EOR</td>
</tr>
<tr>
<td>Air Products Steam Methane Reformer EOR Project (U.S.)</td>
<td>Operate</td>
<td>2013</td>
<td>Hydrogen production</td>
<td>Industrial separation (1.0)</td>
<td>Pipeline EOR</td>
</tr>
<tr>
<td>Lost Cabin Gas Plant (U.S.)</td>
<td>Operate</td>
<td>2013</td>
<td>Natural gas Processing</td>
<td>Pre-combustion (0.9)</td>
<td>Pipeline EOR</td>
</tr>
<tr>
<td>Petrobras Lula Oil Field CCS Project (Brazil)</td>
<td>Operate</td>
<td>2013</td>
<td>Natural gas processing</td>
<td>Pre-combustion (0.7)</td>
<td>No transport required (direct injection)</td>
</tr>
<tr>
<td>Boundary Dam Carbon Capture and Storage Project (Canada)</td>
<td>Operate</td>
<td>2014</td>
<td>Power generation</td>
<td>Post-combustion (1.0)</td>
<td>Pipeline EOR</td>
</tr>
<tr>
<td>Quest (Canada)</td>
<td>Operate</td>
<td>2015</td>
<td>Hydrogen production</td>
<td>Industrial separation (1.0)</td>
<td>Pipeline for dedicated geological storage</td>
</tr>
<tr>
<td>Uthmaniyah CO₂-EOR Demonstration Project (Saudi Arabia)</td>
<td>Operate</td>
<td>2015</td>
<td>Natural gas processing</td>
<td>Compression/dehydration from natural gas liquids recovery plan (0.8)</td>
<td>Pipeline EOR</td>
</tr>
<tr>
<td>Illinois CCS (U.S.)</td>
<td>Execute</td>
<td>2016</td>
<td>Chemical production</td>
<td>Industrial separation (1.0)</td>
<td>Pipeline for dedicated geological storage</td>
</tr>
<tr>
<td>Kemper County (U.S.)</td>
<td>Execute</td>
<td>2016</td>
<td>Power generation</td>
<td>Pre-combustion (3.0)</td>
<td>Pipeline EOR</td>
</tr>
<tr>
<td>Petra Nova Carbon Capture (U.S.)</td>
<td>Execute</td>
<td>2016</td>
<td>Power generation</td>
<td>Post-combustion (1.0)</td>
<td>Pipeline EOR</td>
</tr>
<tr>
<td>Abu Dhabi CCS Project (Abu Dhabi)</td>
<td>Execute</td>
<td>2017</td>
<td>Iron and steel production</td>
<td>Industrial separation (0.8)</td>
<td>Pipeline EOR</td>
</tr>
<tr>
<td>Gorgon CO₂-EOR Storage Project (Australia)</td>
<td>Execute</td>
<td>2017</td>
<td>Natural gas processing</td>
<td>Pre-combustion (3.4–4.0)</td>
<td>Pipeline for dedicated geological storage</td>
</tr>
</tbody>
</table>
COP21 and the Need to Move Forward

The IEA produced a CCS roadmap suggesting the input required from CCS deployment as part of an initiative to limit the average global temperature rise to no more than 2°C (Figure 2).

This projection emphasized three goals that would need to be met, if the necessary CCS contribution toward carbon reduction through to 2050 is to be achieved:

- **Goal 1:** By 2020, the capture of CO₂ is successfully demonstrated in at least 30 projects across many sectors, including coal- and gas-fired power generation. This leads to over 50 MtCO₂ stored each year.
- **Goal 2:** By 2030, CCS is routinely used to reduce emissions in power generation and industry, having been successfully demonstrated in industrial applications. This level of activity will lead to the annual storage of over 2000 Mt CO₂.
- **Goal 3:** By 2050, CCS is used routinely to reduce emissions from all applicable processes in power generation and industrial applications at sites around the world, with over 7000 Mt CO₂ annually stored in the process.

With hindsight, it is evident that the suggested timescale for large-scale deployment of the initial CCS techniques for use with coal-fired power generation and other industrial processes was overly optimistic, at least in making a significant start with CCS deployment. This is not because the techniques were technically unsuitable, but because there was insufficient attention given to establishing an enabling environment, taking into account the need for supporting policies, robust regulations, and an adequate financing model. The IEA projections suggested that there would need to be some 20 large-scale CCS projects in operation by 2020, capturing some 40 Mt of CO₂ each year. In practice, while there is likely to be close to 20 projects, few will be coal based and the CO₂ capture rate will be below 40 Mt/hr. More importantly, when the ramp-up of further projects is considered, the GCCSI database shows only a few additional projects close to operational status, which suggests a loss of momentum for several years.

Most of the projects that are not based on natural gas processing have included some level of capital grants from the host government. Although this is a reasonable expectation, given such demonstration projects are both strategic in nature and carry a level of risk, such funding sources can be politically fragile. To establish a large-scale commercial CCS plant will require a high capital investment because of the scale of operation. However, this issue should not prevent funding being obtained, provided an appropriate and stable incentive framework is in place. In many countries the lack of a coherent energy policy, wherein environmental issues are considered almost in isolation from security of energy supply and economic competitiveness, has discouraged funding and created
reluctance for developers to take up opportunities because of uncertainties regarding long-term return on investment. This is linked to an ill-conceived opposition to fossil fuels; many institutions are refusing to finance coal-fired power generation and other fossil fuel projects, which represent the most cost-effective means to reduce carbon emissions in the near-to-medium term. Not only does this make it more difficult for coal-based HELE (high-efficiency, low-emissions) technologies to be supported but it has the potential to impact on future CCS investment, as some institutions do not allow support for projects even with CCS.

“China has established significant capacity across the CCS chain through research and development, including the construction of nine pilot projects…”

In a “no CCS” scenario variant of the IEA Two Degree Scenario (2DS), assuming that the limitations of replacing coal or gas by expanding renewables use within a grid-based generation system can be overcome, without CCS, the transformation of the power sector will be US$3.5 trillion, or 138% more expensive.7 When the so-called ambition of achieving a decarbonization target consistent with an average global temperature rise of well below 2°C is considered, even more attention to CCS would be needed—and, at this stage in the technology development and deployment, it is hard to envisage how its input could possibly be ramped up.

The Possible Role of China to Drive CCS Forward

China has established significant capacity across the CCS chain through research and development, including the construction of nine pilot projects, and has benefited from extensive international cooperation. Consequently, it has reached an adequate level of readiness to take forward large-scale CCUS demonstration projects.

The National Development and Reform Commission (NDRC) of China and the Asian Development Bank (ADB) have worked closely together on several CCS/CCUS institutional capacity-building projects, which led to the creation of a coal-based CCUS development and deployment roadmap for China.8 This included the identification of a number of early opportunity demonstration projects based around large coal-to-chemicals plants in which CO2 capture is a low-cost (less than US$20/tonne) possibility. Many of its coal-to-chemicals plants are also in the vicinity of oil fields amenable to CO2-enhanced oil recovery (CO2-EOR). Thus, China has the unique opportunity to demonstrate CCUS at low cost, which would allow Chinese industry to gain familiarity in establishing major, multi-stakeholder projects, thereby building expertise on all aspects of the CCS/CCUS chain. These activities led to a declaration of intent by the Ministry of Finance of China at COP21 that the Chinese government will work with the ADB to establish several CCUS demonstration projects using this approach. This should also kick-start China’s intended overall CCUS demonstration and deployment program, which should position the nation as a global leader for ensuring that HELE clean coal technology will form a key part of a global low-carbon future.

The current low oil prices may have temporarily reduced incentives for CO2-EOR projects in China, but the fundamental drivers remain strong. Nonetheless, China imports more than half of its oil consumption while about 70% of its domestic oil production comes from nine large oil fields, which are all mature and are facing or will soon face a decline in production. In some of these oil fields, water flooding is no longer effective in maintaining oil production levels.8 Introducing CO2-EOR is thus inevitable to maintain the economic viability of such oil fields. To deploy CO2-EOR in these oil fields, it is essential to undertake early-stage pilot testing and demonstration. To overcome the lack of interest under the current oil prices, the government will need to incentivize industries to capture and transport CO2 and to conduct CO2-EOR.

The other factor that drives China’s intended CCS demonstration program is that “learning by doing” will subsequently drive down capital and operational costs. For example, engineers at the Boundary Dam coal-fired CCS project have announced that should they be required to design another CO2 capture unit, they could reduce the capital investment requirements by 30%. Equally importantly, in the future, rather than focusing on individual CO2 emitters, the costs of CO2 transport and storage, between 10 and 30% of the total CCS costs, could be significantly reduced by clustering power emitters together with industrial processes and using existing gas infrastructure. These industrial clusters could be linked to CO2 storage hubs via trunk pipeline networks and shipping routes. Again, China is well placed to adopt this approach in its industrial bases.

CONCLUSIONS

CCS can achieve significant decarbonization when applied to fossil fuel power generation technology, a wide range of industrial applications, and natural gas production. In particular,
when applied to coal power technology, it can ensure developing countries and industrializing nations the low-carbon opportunity to maintain security of energy supply and economic competitiveness with low environmental impact of using coal. This will allow such nations to take the steps necessary to lift their people out of energy poverty and improve education prospects through access to electricity.

“CCS can achieve significant decarbonization when applied to fossil fuel power generation technology…”

It seems inevitable that targeted support will be essential for CCS in the near term, and this will require innovative approaches that can achieve adequate financial support within a consistent policy and regulatory framework.

EOR can provide the foundation for future CO₂ storage, by combining oil extraction with monitored CO₂ storage to produce verifiable emissions reductions. EOR is expected to continue to act as a major driver for CCS since practices to promote increased CO₂ utilization together with verified, permanent storage could deliver significant climate benefits.

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We’d appreciate hearing from you regarding what topics you would like us to cover.

Clean Energy will be launched in 2017. The new journal aims to cover not only coal but also other energy technologies, such as solar, wind, bioenergy, hydrogen energy and fuel cells, energy storage and smart grid developments.

Our goal is to include diverse material, such as technical articles, reviews, global news, conference listings, etc. If you are interested in contributing or have suggestions about what we should cover, please don’t hesitate to contact the editorial team.

If you have a suggestion, email the editorial team at john.kessels@nicenergy.com (English) or hanmeiling@nicenergy.com (Chinese)
Beyond HELE: Why CCS Is Imperative Now

By Brad Page
CEO, Global CCS Institute

It is now clear that the outcome of the Paris climate talks was a game changer, delivering a renewed global commitment to addressing climate change. No longer are we aiming to limit global warming to 2°C. We are now aspiring for well below that—perhaps as low as 1.5°C. Significantly, the agreement also sets out global ambition for carbon neutrality by mid-century. In the post-COP21 discussions, thinking has shifted from “how much do we do?” to “how do we do so much?”

But the numbers are confronting.

The targets set by the countries signing up to the Paris Agreement only put the world on a track toward about 3°C. For many countries, the targets they volunteered are more ambitious than they have previously been; for many others, they remain more easily achieved. For some, and especially among developing countries, the outlook is not as simple: Energy poverty must be addressed alongside economic growth and environmental stewardship. Although these are not mutually exclusive, addressing all three imperatives concurrently can be expensive in the immediate term.

But the atmosphere is not forgiving. We are already at 400 ppm of CO₂ and on track to exceed 450 ppm. To achieve the Paris ambition, emissions most likely have to peak in the next decade and there is a growing likelihood that negative emissions technologies will be necessary.

Assuming that current and announced climate policies are implemented, the International Energy Agency (IEA) forecasts that, despite the extensive, worldwide government support for renewables and increasing energy efficiency, fossil fuels are expected to meet approximately 75% of primary energy demand in 2040, down marginally from the historic share of around 80%.

“Contrary to the views of some, CCS is not experimental.”

Against this backdrop, energy access in developing countries is the path to improved living standards. The majority of increased fossil fuel usage will come from here, alongside an associated escalation in emissions, unless there are fundamental changes in approach.

Without doubt, visionary, bold, and innovative policy solutions are necessary. It will not be enough to single out popular technologies for support, and hope they will do the job. That is the path the world has been on for at least the past two decades and today we are farther away from our emission objectives, in absolute terms, than we were 20 years ago.

It is clear that renewables and energy efficiency will—must—play a significant and increasing role. Support for these will continue and their penetration will continue to increase from today’s base. But in the time available, this will not be enough.

Industrial processes account for approximately 25% of greenhouse gas emissions. Energy efficiency is relevant but the main, perhaps only, technology to address this problem is carbon capture and storage (CCS). Renewables offer very limited potential in this area.

In power generation, the installed stock of fossil fuel plants is so great that much of it will not be retired in the next 30 years. Additionally, Carbon Tracker reports that more than 2000 new coal-fired generators are planned for construction by 2030. This level of additional coal-fired generation capacity is completely inconsistent with the Paris Agreement unless it is accompanied by CCS.

To the extent that new coal-fired generators are constructed and operated, it is imperative they are of the highest efficiency.
available and operated to contribute positively to energy security while minimizing their emissions. HELE (high-efficiency, low-emissions) coal-fired generators need to be the minimum specification acceptable for new-build and replacement coal plants.

But will this be enough against the Paris Agreement backdrop? The short answer is no.

Coal-fired generation technology is mature, relatively low cost, and widely available. Continual research and development over many decades has lifted efficiency from 20% in old subcritical plants to as high as 40+% in the latest ultra-supercritical plants. These improvements in efficiency have also seen greenhouse gas emissions fall per unit of output by upward of 25%.

It is entirely sensible that all new coal-fired generators should be ultra-supercritical. The additional electrical output per unit of fuel as well as valuable efficiencies in water consumption and emissions should make the latest technology (when viewed over the life of the plant) highly attractive. Nonetheless, although this technology represents a huge improvement in all aspects of performance over the average of the global-installed fleet, these plants remain relatively emissions intensive.

Even at 650–800 kg CO₂/MWh, ultra-supercritical plants are about twice as emissions intensive per MWh as the latest combined-cycle gas turbines. Yet with the need to peak emissions within 10 years, gas turbines will be unacceptably high in emissions in the short run, unless CCS is part of their utilization.

While this picture leads to a conclusion that CCS is vital, the path to its widespread uptake is far from clear.

Over the decade to 2014, global investment in renewables was just short of US$2 trillion. Over the same period, investment in CCS was US$20 billion. How can such a disparity in investment exist if the world is trying to achieve what amounts to a complete energy system redesign—indeed, redevelopment—in the next 35 years?

In short, it comes down to the business case. When there is not a clear and enduring value for carbon dioxide, and policies instead are deliberately constructed to favour specific technologies, then capital will go to where the best reliable return can be achieved. For more than 20 years this has essentially flowed to renewable technologies: first on-shore wind, then solar, and, close on their heels, off-shore wind.

Doubtless this has led to a fast and continuing lowering of the unit price of all of these technologies. When all of the available clean energy technologies are needed to address emissions, this is clearly positive. However, when fossil fuels represent the overwhelming majority of primary energy demand and are projected to do so for another 15–25 years at least, then ignoring the key technology that can make fossil fuels “low emission” directly threatens the ability to arrest the climate challenge. As emissions need to peak in the next 10 years, this looks increasingly unlikely.

Those opposing CCS are vocal but their arguments warrant critical analysis.

Contrary to the views of some, CCS is not experimental. Currently 15 large-scale integrated facilities are operating in various countries around the world, capturing and storing 28 million tonnes of CO₂ every year. Another seven are under construction (including two very large power plants) and, when operating in the next 2–3 years, these will increase capture and storage to 40 million tonnes per annum.

Others say it is too expensive. “Compared to what?” should be the rejoinder. If the comparison is to unabated fossil fuel technology, then of course it is. In comparison to renewable or nuclear generation options, however, it is rarely more expensive. Successive studies have shown that CCS is generally more expensive than old hydro and on-shore wind but...
generally competitive with utility-scale solar PV, geothermal, and new hydro while being lower in cost than small-scale PV, off-shore wind, nuclear, and the many other nascent technologies—especially when the real cost of filling-in for intermittency is included. Yes, it is a high capital cost addition. But it also delivers dependable, secure, dispatchable baseload, and load-following power. From a system security perspective, few low-emissions alternatives compare favorably.

"CCS is consistently reported as having a key role in solving the decarbonization challenge at least cost."

Another claim is that it simply perpetuates the use of fossil fuels. The alternative, and more realistic, approach is that the continued use of fossil fuels over the period of concern is going to happen anyway. And it will be in large volumes. This is reality. It is simply not possible in the space of one or two decades to switch off fossil fuels. Even if the world’s electricity system could be run exclusively on zero-emissions generation in the time period (highly unlikely, of course), the industrial sector—chemicals, fertilizer, steel, and cement production, for example—will continue to require carbon-based fuels. The industrial processing sector alone is 25% of global emissions and cannot be ignored if climate objectives are to be achieved. Only CCS can deal with these unavoidable emissions. Perhaps more significantly, much of the developing world will exploit its carbon-based fuels, coal key among them, to lift national and personal incomes and give their citizens a better way of life. Plans for new coal-fired power stations confirm this. CCS must be part of the plan for these power stations.

Increasingly it appears inevitable that negative emissions technologies—those that actively take CO₂ out of the atmosphere—will be necessary to achieve 2°C, let alone 1.5°C. Few options exist in this area; forestry is obvious, but the time taken to embed carbon in trees is long compared to the rate at which emissions occur. Bio-energy production with CCS is the main alternative and is already a reality; the Illinois Industrial Project at Decatur in the U.S. represents precisely this. But the infrastructure, pipes and storage facilities, doesn’t simply turn up at will. It requires planning, permitting, and proper evaluation and construction, as well as a sound business case and preferably many users to minimize the cost per tonne transported and stored. The likely most efficient approach to this is to start early and decarbonize whole industrial clusters by providing common user infrastructure and rewarding those that choose to move to a low-carbon production model. This is again a question of policy, policy that needs to be long term in its thinking with cost minimizing as a key objective.

After Paris, one thing is clear: There’s no place to hide when it comes to decarbonizing the world. Countries have signed up to an agreement that includes provisions to prevent so-called “backsliding”. Future targets and commitments can only be more ambitious, and if the temperature objectives are to be achieved, then this is necessary and inevitable. Every sector of the global economy will be under close examination, including many (especially in the industrial processing arena) that, to date, have been largely left alone.

Time is short. The challenge is huge.

The overriding guiding principle for decarbonizing should be to do it at minimum cost. That isn’t the track the world has been on for over 20 years as many policies have led to abatement cost multiples above what was necessary.

CCS is consistently reported as having a key role in solving the decarbonization challenge at least cost. Combined with HELE in coal-fired power generation, increased efficiency in many industrial processes, and applied to bioenergy production, CCS can make the difference in whether or not the Paris Agreement objectives can be achieved.

But to do this we need worldwide policies that focus on delivering clean energy, not just those that, for whatever reason, are popular or preferred in any given period.

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The ratification of the Paris Agreement marked an historic milestone for the energy sector and confirmed a global target of limiting future temperature increases to “well below 2°C”. Achieving this will require a much faster and more extensive transformation of the energy sector than previously contemplated. All technologies and all options for reducing emissions will need to be embraced—with carbon capture and storage (CCS) being core among these. The Paris Agreement therefore presents enormous opportunities for the deployment of CCS technologies.

CCS provides a unique and important solution to emissions from current and future use of fossil fuels in industry and in power generation. It is the only technology able to significantly reduce emissions from coal- and gas-fired power plants. Crucially, CCS is also one of few technologies that can address emissions from industrial processes, including the production of steel, cement, and chemicals, all of which will remain building blocks of modern society. The Intergovernmental Panel on Climate Change (IPCC) has further emphasized the importance of CCS with bioenergy in delivering future “negative emissions” if more ambitious climate targets are to be achieved.1

Fortunately, CCS technologies are now well understood and global experience in delivering large-scale projects continues to grow. The Sleipner CCS project in Norway has now been operating for 20 years, safely and permanently storing almost 17 million tonnes of CO2 deep under the North Sea. The International Energy Agency (IEA) has recently acknowledged this milestone and reviewed the progress achieved in developing and deploying CCS technologies in its report “20 Years of Carbon Capture and Storage – Accelerating Future Deployment”. The report also highlights the importance of CCS in achieving future climate goals.

**THE SHIFT TO WELL BELOW 2°C WILL REQUIRE CCS**

CCS plays a key role in moving the energy sector onto a pathway consistent with limiting future temperature increases to 2°C. Analysis by the IEA suggests that CCS could account for around 12% of the cumulative emissions reductions needed to transition from a “business as usual” (6DS) approach to a 2°C (2DS) target by 2050 (Figure 1).2 This amounts to 94 gigatonnes (Gt) of carbon dioxide (CO2) captured in the period to 2050, with around 55% of this (52 Gt) in the power sector and 42 Gt in industrial applications and fuel transformation.3 Coal-fired power generation is the single largest source of CO2 captured in the IEA 2°C scenario, with 40 GtCO2 captured in the period to 2050 and around 570 GW of global coal-fired generation equipped with CCS in 2050.
CCS UNDERPINS THE FUTURE OF COAL POST-PARIS

More than any other fuel, coal use will be substantially impacted as the energy sector transitions to a 2°C or well-below 2°C target. The successful and widespread deployment of CCS technologies will be a key determinant of the future role of coal as climate policies are strengthened globally.

In the IEA’s 2DS, around 75% of global coal-fired power generation capacity is equipped with CCS and provides around 3300 TWh of generation in 2050. The remaining unabated plants run at very low capacity factors. In a 2DS, the average emissions intensity of the global power sector must fall from more than 500 g/CO₂ per kWh to around 40 g/CO₂ per kWh in 2050. In a well-below 2°C case, this may need to be reduced even further.

This leaves virtually no room for unabated coal-fired power plants in the power mix, and even challenges the role for CCS-equipped coal plants in the long term. An ultra-supercritical coal-fired power plant with a CO₂ capture rate of 90% would produce emissions of around 100 g/CO₂ per kWh — substantially higher than the average global fleet in 2050, notwithstanding a major reduction from the more than 760 g/CO₂ per kWh of an unabated plant. Opportunities to further reduce this include technological improvements related to plant efficiency, higher CO₂ capture rates, and co-firing coal with biomass in CCS-equipped plants. The latter option, in particular, has the potential to yield zero-emissions coal plants which could be the key to a future role for coal in a well-below 2°C world.

Putting scenario analysis aside, today’s reality is that more than 1950 GW of coal-fired generation capacity currently operates globally, with a further 250 GW under construction and 1000 GW in various stages of planning. Around 500 GW of existing capacity has been added since 2010, and the average plant age for developing countries is around 15 years. Much of this fleet has a technical operating life that extends to 2050 and beyond, meaning that early retirements would be unavoidable to achieve a 2°C target. In practice, this would present significant social, economic, and political challenges, particularly with more than 40% of fossil fuel power generation publicly owned. CCS, including retrofitting, can provide an important and strategic alternative to early retirements, preserving the economic value of these investments while bridging the gap between today’s reality and the achievement of future climate ambitions.

STABLE POLICY FRAMEWORKS ARE NEEDED FOR CCS INVESTMENT

CCS is far from being a new technology. Individual CCS technologies have been used in industry for decades, including the
injection of CO₂ for enhanced oil recovery purposes, which commenced in the U.S. in the early 1970s. Globally, 15 large-scale CCS projects are currently operating across a range of applications, with six more projects expected within the next 12 months. With all of this experience, it is evident that there are no insurmountable technological barriers to CCS deployment. The part of the equation that has been missing has been the financial incentives and climate policies necessary to support investment.

Over the past 20 years, policy and political support for CCS has fluctuated considerably and provided an uncertain foundation for investment (Figure 3).

Following the release of the IPCC Special Report on CCS in 2005 and the G8 leaders’ pledge to deploy 20 large-scale CCS projects before 2020, there was a considerable upswing in momentum. New international initiatives such as the Global CCS Institute were launched and around US$30 billion in public funding commitments were made globally, with the aim of supporting as many as 35 projects. However, by 2014 less than US$3 billion of this had been spent, and only seven projects have ultimately received support from these programs.

A number of factors have influenced this, including the failure of the Copenhagen climate negotiations in 2009 which saw climate change temporarily fall down the list of political priorities. Budget pressures following the global financial crisis also impacted public funding availability. Remarkable cost reductions in renewable technologies and advances in energy efficiency have arguably also captured the policy focus.

However, a major contributor was the fact that deploying first-of-a-kind, large-scale CCS projects also proved to be more complex, time consuming, and expensive than many governments and project proponents had anticipated. For every project that has successfully reached a final investment decision, two have been cancelled. This is not necessarily unexpected given the stage of the technology, the need for confidence in storage, and the size of the investment required. Yet it underscores the critical importance of increasing the number of projects under development and pulling through more investment with targeted support and stable policy frameworks.

**WILL PARIS BE A TURNING POINT FOR CCS?**

The analysis by the IEA confirms that the successful implementation of the Paris Agreement will almost certainly require deployment of CCS across industry and power applications, as well as investment in bioenergy with CCS for “negative emissions”. This investment in CCS is not just for the long term, with substantial deployment of CCS needed in the period to 2030 under our lowest-cost scenarios. Enormous opportunities for CCS could therefore emerge as global governments act to implement their Nationally Determined Contributions (NDCs) in parallel with planning for their long-term (2050) climate strategies.

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**FIGURE 3. Fluctuating policy and political support for CCS**

Source: IEA (2016), 20 years of Carbon Capture and Storage: Accelerating Future Deployment. Figure adapted from SBC Energy Institute (2016), Low Carbon Energy Technologies Fact Book Update: Carbon Capture and Storage at a Crossroads.
Yet we must also recognize that the ratification of the Paris Agreement is just the beginning. A considerable gap exists between the level of effort represented in the NDCs pledged prior to Paris, and what is required to achieve the ambitions of the Paris Agreement. IEA analysis finds that the NDCs would put us on a pathway for temperature increases of almost 3°C and would not lead to an emission peak in the near future. The difference between this and a well-below 2°C target is immense, and could represent more than 40 years’ worth of current emissions.

Given the gap between the NDC pathway and a well-below 2°C target, the fact that CCS was mentioned in only 10 out of 162 NDCs could be seen as both a symptom and a cause. CCS is a technology essential for achieving more ambitious temperature targets, but the lower the ambition the less of a role for CCS, particularly in the near term. A refocusing of efforts to deploy CCS will be essential as we work to bridge the gap between action and ambition globally.

CONCLUSION

More than 20 years of experience with CCS technologies and a growing number of large-scale projects confirms that there are no insurmountable technological barriers to deployment. The ratification of the Paris Agreement now provides the foundation for significantly strengthened climate action that could unlock enormous opportunities for CCS. Given the climate challenge ahead, CCS is a solution that’s simply too big to be ignored, particularly for emissions from industrial processes and today’s large coal-fired power fleet. The coal industry has a particularly strong interest in the widespread deployment of CCS, with the future role of coal in the energy mix inexorably linked to CCS in low-emissions development pathways.

NOTES

A. The decision adopting the Paris Agreement (1/CP.21 paragraph 35) invites Parties to communicate, by 2020, “mid-century, long-term low greenhouse gas emission development strategies”.

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Any hard-nosed assessment of the energy sector should conclude that there is no future for coal without carbon capture and storage (CCS). Yet for the last decade, governments, their agencies, and the coal industry have failed to support CCS development in a way that would be consistent with this existential threat. The result is that CCS has little credibility as a material contributor to reducing emissions with governments and those outside the fossil fuel industry. This is despite projections by reputable bodies such as the International Energy Agency (IEA) that show CCS does make a material contribution to delivering a low-emissions future at lowest cost. The prospects for bridging that gap rests with several demonstration projects or a major mobilization by a country such as China.

**CCS: WHY IS IT SO HARD?**

Reducing greenhouse gases and particularly carbon dioxide (CO₂) is at the heart of the global commitment to addressing climate change. That means we either stop burning fossil fuels or prevent the CO₂ from entering the atmosphere, or both. Neither is simple or cheap.

Hydropower, wind, and solar energy are making a significant and growing contribution to the former approach, although hydro is constrained by available sites, while wind and solar need major progress on storage technologies to get to the majority side of the supply ledger. Nuclear energy remains either too expensive or politically unacceptable in many parts of the world.

Attempts to turn CO₂ into a solid material through mineralization have generally proven to be expensive or not scalable. Capturing and permanently storing the CO₂ underground remains a tantalizing prospect that could significantly contribute to reductions in greenhouse gas emissions, while allowing the ongoing use of fossil fuels, coal and natural gas, for decades into the future. At the least, this prospect would allow us more time to develop cost-effective alternatives.

For most of the current century, the cost of wind and solar power has fallen as their deployment has grown. Government support through policies such as renewable portfolio standards and mandated targets or attractive feed-in tariffs have driven this growth in many countries. Actual deployment has consistently exceeded the projections of the most well regarded bodies such as the IEA, and this story has yet to reach an end. Yet the same agencies have consistently projected deployment of CCS that has turned out to be highly optimistic.

The IEA’s most recent *World Energy Outlook* includes a 450 Scenario that depicts a pathway to the 2°C climate goal committed to by the international community and reaffirmed as a minimum target in the Paris Agreement of December 2015. Under this scenario, the IEA’s analysis indicates that coal consumption will begin to decline from before 2020 and that, by 2040, coal accounts for only 16% of the world’s energy mix. Further, even the 12% of electricity output that is based on coal in this scenario depends on CCS for three-quarters of its produced power. With only one such operational plant in the world to date, and a couple close to commissioning, that projection seems a distant prospect.

Few governments have adopted policies over the last decade or so that would drive CCS development and deployment, and few show any appetite to do so today. The most common reaction from political leaders and energy industry executives is that CCS does not work, is untested, or is just too expensive.
to be taken seriously. The fossil fuel industry has consistently failed to mobilize financial or political support to counter this perception. Only a handful of demonstration projects have progressed beyond the drawing board, at the same time as supporters of renewable energy have successfully lobbied for large and ongoing government subsidies.

There is a little progress with the development of CCS, despite international organizations such as the IEA publishing forecasts about the key role CCS could play in reducing CO\textsubscript{2} emissions and calls for governments to fund demonstration projects. CCS faces significant hurdles: the high costs that were associated with wind and solar a decade ago; capital intensity, shared by nuclear power, that creates high financial risk; and widespread opposition by environmentalists as a smokescreen to extend the life of fossil fuels when they should be confined to history. Its friends are few. So, where or what might give rise to change?

**CHINA: A GREAT HOPE?**

Growth in energy demand has been the central impetus behind increasing global greenhouse gas emissions for many decades. Decoupling of energy consumption from economic growth, together with low economic growth across the developed world, has constrained the need for large-scale energy production. Things have been different in developing economies. The People’s Republic of China (PRC) has been a major driver of increasing emissions this century, and its actions will be critical if climate change is to be effectively addressed. The PRC has ratified the Paris Agreement and is making progress toward a national emissions trading scheme as a central policy response. Even with lower economic growth in very recent years, the PRC continues to need more energy. Further, CO\textsubscript{2} emissions from industrial production outside the power generation sector are major source of emissions for the PRC, and for which wind and solar do not provide a solution.

It the COP21 meeting in Paris, the PRC’s National Development and Reform Commission (NDRC) and the Asian Development Bank launched a CCS Roadmap\textsuperscript{2} that incorporates policy, legal, technology, financial, and public engagement as an integrated approach to CCS for the PRC. It demonstrates that CCS can contribute to meeting the country’s emissions reduction targets from 2025 onward. The key messages in the Roadmap are:

- CCS demonstration and deployment is essential for cost-effective climate change mitigation, not only in the power sector, but also for reducing emissions in carbon-intensive coal-chemical, steel, cement, and refinery plants.
- The PRC can benefit from international experiences.
- Unique low-cost CCS demonstration opportunities exist in the PRC, most notably in regions that offer prospects for CO\textsubscript{2} capture from coal-chemical plants and enhanced oil recovery.
- CCS demonstration faces formidable challenges in the absence of targeted support that should include financial support, enabling policies, and an appropriate regulatory framework.
- Current low oil prices have reduced the incentive for enhanced oil recovery but the fundamental drivers in the PRC remain strong.
- A phased approach to CCS demonstration and deployment is needed. Early-stage demonstration projects based on low-cost capture in parallel with intensive research and development and limited application in the power sector can bring down costs and deliver new knowledge. Success in the 10 years to 2025 can pave the way for wider deployment of cost competitive CCS from 2030 onward.

There is both strong interest and healthy debate around committing to a CCS Roadmap in the PRC, with several projects showing signs of tangible progress and the NDRC continuing to be actively engaged.

**DEVELOPED ECONOMIES: WISHFUL THINKING?**

Reducing CO\textsubscript{2} emissions from fossil fuel combustion requires pricing the environmental impact of the emissions (carbon pricing), valuing low-emissions technologies, or regulation. Carbon pricing has generally lacked ambition consistent with the global 2°C target, so the prices have fallen far short of levels necessary to drive major technology changes. Regulation to shut down older, more polluting plants has been applied but only in a few countries and then only gently. The driver in deployment of these technologies has been policies to support renewable energy via various forms of subsidy.

In developed economies, government support has existed for CCS technologies, primarily through funding for research and development or for demonstration projects. Yet failure has been more visible than success. European attempts to allocate a substantial block of funds by reserving permits for CCS projects never
materialized; the UK process to fund demonstration projects has failed to progress at least twice; U.S. projects, notably FutureGen, suffered several false starts; and the Australia’s CCS Flagship Program failed to make substantial progress on any of its mooted projects. Governments can be criticized for failing to deliver and maintain serious support for CCS and industry for failing to step up with real commitment. And CCS projects do not come cheap.

Beyond the Boundary Dam project in Canada, a sole lighthouse on a barren coastline, the hope in developed economies may lie with a couple of U.S. power projects that may still be commissioned soon. So, most governments are no longer actively interested in CCS, if they ever were, and the power generation and coal and gas industries have failed to develop the compelling narrative that would convince a policy maker to risk significant political capital on the alternative.

WHAT NEEDS TO CHANGE?

Current policies and positions by governments and industry will repeat the history of the last decade. For CCS to be deployed at the scale for which proponents have argued and neutral bodies such as the IEA have projected, two things must change. First, governments must adopt credible, long-term climate change policies consistent with the commitments they have made under the Paris Agreement. Second, both governments and industry must themselves be sufficiently convinced of the case for CCS to deliver the major and consistent financial support for early-stage pre-commercial deployment to drive down the cost.

Not many years ago, governments were prepared to see CCS as one of a basket of technologies that would contribute to emissions reduction. On this basis, funding for demonstration projects as described above was established in several developed economies. These projects generally failed to proceed either because the funding was inadequate, the costs blew out beyond the proponents’ expectations, or the proponents themselves abandoned the projects.

Few, if any, political leaders or energy/resources ministers are advocates for CCS today. The political risks are high and CCS proponents have failed to convince politicians with arguments compelling enough to invest scarce political capital. This is despite the logic that suggests if CCS had received the same level of support as wind and solar technologies, the cost of CCS would have fallen as it did for those technologies. And, despite the threat to coal and gas that will follow if governments meet their commitments under the Paris Agreement, those industries have failed to put sufficient financial effort into CCS projects to change the game by demonstrating technical credibility and cost reduction potential.

Credible, stable climate change policies are rare around the world. Even when, as in Europe, emissions trading schemes have been implemented, design flaws or economic conditions have meant that carbon prices have failed to reach levels that would support the widespread adoption of low-emissions technologies. It has fallen to specific subsidy schemes to drive the adoption of renewable energy such as wind and solar power. The possibility that CCS could have delivered similar levels of emissions reduction at similar cost levels remains untested. The result is that politicians shy away from climate change policies that would lead to carbon prices high enough to deploy CCS technologies alongside wind and solar in a lowest cost mix, yet are prepared, often with community endorsement, to subsidize wind and solar power such that the overall cost is almost certainly higher.

The lack of substantial progress with CCS in developed economies leads many to look to the PRC as a possible savior. The PRC government has shown a preparedness to support low-emissions technologies across the spectrum of wind, solar, hydro, and nuclear; and several CCS projects, including enhanced oil recovery and some focused on the coal-chemical sector, are making progress. The current levels of air pollution in their major cities, much associated with fossil fuel combustion, also provide a strong driver to address non-CO2 pollution and greenhouse gas emissions within the same policy response.

The CCS Roadmap described above provides a possible way forward and one that might lead the PRC to a global leadership position on CCS technologies as was achieved with solar. Yet, it is far from clear that the PRC government is any more wedded to this prospect than were western governments over the last decade. Government representatives often share the western view that CCS is just too expensive and means less productivity from the fossil fuels that are burned. Cooperation across governments and with strong support from the coal and gas sector to finance real projects could provide a catalyst.

A compelling case for CCS may yet emerge from a combination of demonstration projects and the emergence of high-cost scenarios for alternative approaches in developed economies. The PRC may support CCS and achieve the major cost reductions envisaged in its Roadmap.

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Solving Energy Poverty, Unemployment, and Growth Challenges in South Africa

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INTRODUCTION

The three fundamental objectives of South Africa, and most emerging nations, are to address inequality, unemployment, and poverty. These objectives cannot be achieved by redistribution of wealth alone. They can only be achieved by raising the economic growth rate. A higher growth rate is dependent on having the correct public policies in place and having an adequate and growing supply of affordable electricity. In order to ensure economic growth, South Africa must develop its industrial base and therefore it is essential to supply electricity at the lowest possible cost.

RENEWABLES

In South Africa the major electricity supply company is Eskom. The major issue raised by Eskom executives in this debate concerns renewables. They have accurately described the fallacy and weakness of the primary renewables, wind and solar. These are highly variable, often supplying power when they are not needed and not supplying power when they are needed. As a result, these are expensive forms of energy production, yet the supply must be bought in terms of the purchase agreements at set prices. This has been the experience of Germany (under the “Energiewende” program) where the country sells unwanted electricity at a loss to other countries and purchases the required supply at a premium. These prices are in effect financial subsidies for wind and solar.

In Germany, they are fortunate that they have other major electricity-generating countries nearby; they can tap into electricity provided by nuclear power plants in France, coal-generated electricity in Poland, or hydro-electricity from Scandinavia. South Africa does not have that option. Due to these financial subsidies, Germany, aside from Denmark, has the most expensive industrial and household electricity in Europe. Consequently, Germany has now placed a cap on the supply of renewables and is in the process of removing all financial subsidies to renewable companies. What “Energiewende” has clearly established is that wind energy and solar CSP are not technologies suitable for mass baseload electricity supply. This theme has been repeated in other countries such as Australia where their wind energy drive is a case in point and echoes what has happened in Germany.

The drive for “green energy” is slowing growth and enforcing poverty in emerging economies. In developed economies, it is causing unemployment, reducing living standards, and increasing energy poverty. This can be seen in the political backlash in Britain, the U.S., and even Germany. In these nations, affluent environmentalists argue that the cost is merited. They have the ear of financial institutions and governments. The institutions see secure profits because of guaranteed prices and subsidies, and governments can afford the subsidies because there are limited objections to “green” taxes. Green taxes can become a regressive tax with people on lower incomes having to pay relatively more than people on higher incomes. Consequently, renewables are in effect a tax on the poor.

In South Africa, concerns exist over plans to introduce massive windfarms totalling 60 GW spread across South Africa. It is deemed that geographically separated windfarms will ensure a more continuous supply of electricity. A wind profile study has been conducted across the country. This theoretical study held the view that somewhere in the country, the wind is blowing. This is not the experience of Europe and the UK where the average load factor from all onshore windfarms remains 30% or less. Electricity generation would still need to
have back up for baseload power when delivery fails. As set out by the Council for Scientific and Industrial Research (CSIR), a full delivery plan for 16 GW of baseload electricity requires a total of 60 GW energy capacity consisting of onshore facilities (offshore windfarms have not yet been considered, as they are far too expensive) of 32 GW wind, 12 GW solar PV, and 16 GW of gas for consistent secure delivery of electricity. This full delivery plan for 16 GW baseload power would require more than 6000 km² of unsightly windfarms generally built on high ground to ensure maximum efficiency. More than 12,000 km of roads will be needed to service all the units and the landscape of the countryside would be criss-crossed by at least 10,000 km of additional transmission lines. They would also damage the local habitat, with extensive evidence from other windfarms of mortality to insect, bird, bat, and other flying life that are particularly vulnerable to windfarms. Windfarm developers in the planning stages must take adequate preventative provisions and actions to avoid habitat, ecological, and environmental problems.

“By 2030, it is estimated that there will be 16 million new workers entering the work force.”

NUCLEAR

The second major issue raised by Eskom concerned nuclear. The CEO of Eskom stated that baseload electricity should be provided by coal (presumably including other fossil fuels, primarily gas) and nuclear. The question remains, how much nuclear? Nuclear power stations can take up to 10 years and longer to build, and the upfront costs make a large build program unaffordable for a country such as South Africa. As an example, Britain recently approved the construction of the Hinkley Point nuclear power station project. The total cost for the 3200-MW Hinkley Point nuclear power station could be US$30 billion. In comparison, the new 4800-MW Medupi coal-fired power station costs an estimated US$14 billion and the initial, now installed, renewables 2310-MW program cost approximately US$12 billion.

Renewables in South Africa only have a load factor or deliver power 31% of the time, their total cost exceeds nuclear with load factors of 92% while clean coal-fired plants such as Medupi with load factors of 85% are far less expensive. Renewable capital costs have dropped substantially since 2011 and are currently far below the initial costs as set out above. The guaranteed delivered costs for wind-generated electricity are approximately 62 cents/kWh. A first assessment would indicate that wind is cheaper than its coal and nuclear competitors. However, based on this guaranteed delivered price and a load factor of only 31%, this guaranteed price effectively becomes a subsidized price as it is paid for whether the electricity is required or not. There are also increased costs due to a low load factor on transmission costs, and furthermore, greater distances are involved. As a result, the true total cost of wind power as a deliverable baseload dispatchable power source is significantly more expensive than coal-generated electricity. The cost is also greater than nuclear which, in turn, is also approximately 30% more than equivalent coal-fired electricity.

These significantly higher final delivered electricity prices would have a major detrimental impact on the economy. Increased electricity costs would slow economic growth and devastate the goods-producing industries—in particular, the key mining, manufacturing, agricultural, and agro-processing industries. These industries are important to South Africa's export performance and employment growth, particularly among the relatively unskilled work force. By 2030, it is estimated that there will be 16 million new workers entering the work force. With low baseload electricity growth of only 2.5% per annum, due to the planned heavy reliance on renewables unsuitable for baseload power, GDP growth is unlikely to increase at more than approximately 2.8% per annum. At this growth rate, fewer than 6 million jobs will be created by 2030, resulting in unemployment growing by at least 10 million job seekers.

INDEPENDENT POWER PRODUCERS

The third major issue raised concerned the role of Independent Power Producers (IPPs). The point made was that Eskom would no longer sign new agreements with IPPs. According to Eskom, the issue concerned the guaranteed prices and
offtakes of renewables, not the IPPs themselves. It would be uneconomic for Eskom to pay guaranteed prices without assurance that electricity would be delivered. This is economically, and from a business perspective, absolutely correct and there is now concern about the future role of IPPs. However, IPPs are essential for the future of energy provision and economic development of the economy.

Eskom is already a giant monopoly controlling generation, transmission, and distribution of the entire market, which cannot be allowed to continue in a market-orientated economy. Eskom generates, distributes, and controls through the grid close to 40,000 MW. By 2035, in less than 20 years, South African electricity demand is expected to increase to over 70,000 MW. The bulk of this electricity growth should be provided by IPPs to ensure a more competitive power market.

The existence of a mega-monopoly, whether state-controlled or privately owned, prevents competition and will affect negatively on the economy. The structure of Eskom in this process must be addressed. Eskom, one of the largest electricity utilities in the world, should be split into at least two, and preferably three, stand-alone independent operating companies: a generation company (Genco), a company responsible for the grid transmission and market operations (Gridco), and a distribution company (Disco).

Internationally, countries are increasingly privatizing and deregulating their electricity sectors to ensure more efficient management. The three companies, Genco, Gridco, and Disco, should be set up as three independent public-private partnerships with management firmly in the hands of the private sector. Genco would focus on baseload generation, replacing its aging fleet using clean coal technologies supported by major gas operations. This structure would allow the IPPs to flourish and bring in genuine competition free of all subsidies. This must include all generating, grid, and distribution subsidies. If subsidies are required, for example to encourage distribution and poverty alleviation, these must be government funded not company funded. Some difficult political decisions would need to be made in a transparent way.

**ENVIRONMENTAL**

The fourth major issue in the background of every decision regarding energy is climate change and the commitment to COP21. The outcome of COP21 was the Paris Agreement. What was important was not only what was agreed but more importantly what was not agreed.

Governments were able to negotiate a set of sound long-term global objectives. The Paris Agreement reflects a “hybrid” approach, blending bottom-up flexibility (to achieve broad participation) with top-down rules, to promote accountability and ambition. Importantly, the agreement asked for no firm commitments by any country. Many provisions establish common goals while allowing flexibility to accommodate different national capacities and circumstances. The reason for an objective or goal without binding obligations was simply that various countries were unable to reach national political agreement internally (e.g., the U.S.). Emerging countries were also not going to make firm commitments as they had other priorities such as high levels of poverty and/or had rich fossil fuel reserves. In summary, countries were expected to do what was in their best economic and financial interests. This is and needs to be exploited by all emerging economies with high levels of poverty and with extensive, relatively cheap fossil fuel resources.

**ENERGY POLICIES IN EMERGING ECONOMIES**

The emerging countries include the ASEAN countries, China, Russia, India, Vietnam, Korea, and Poland. Many of these countries are embarking on major expansions of coal and fossil fuels. They have determined that clean coal and gas are the cheapest, most efficient, and reliable sources of electricity to achieve their economic growth objectives and, in turn, poverty reduction, with replacement of aging inefficient power stations a major objective. Clean coal is globally recognized to be a cost-effective and efficient method of reducing emissions and reducing other pollution.

The 10 ASEAN countries are prime examples of countries using clean coal technologies. In these countries, electricity generation increased by an average of 7.5% per year, from 155.3 TWh in 1990 to 821.1 TWh in 2013. Fossil fuels generated 79.4% of ASEAN electricity in 2013. Coal-based electricity capacity is projected to increase from about 47 GW in 2013 to 261 GW in 2035, an average growth rate of 8.1%. In Vietnam, GDP growth is expected to average 6% per annum between 2015 and 2030. Coal generation will increase from 36% of electricity generation to 56%, increasing at 7.2% per annum. All these countries are expecting annual growth of over 5% for the next...
15 years. South Korea expects growth in its power sector of 3.6%, the major proportion of which will be coal and gas. In Poland, electricity growth is also expected to be primarily coal-based generation.

Piyush Goyal, Minister of State with Independent Charge for Power, Coal, New and Renewable Energy in the Government of India, has stated, “We will be expanding our coal-based thermal power. That is our baseload power. All renewables are intermittent. Renewables have not provided baseload power for anyone in the world.” It is not surprising, therefore, that in India annual average electricity demand between 2000–2013 grew from 376 TWh to 897 TWh, most of it coal based. Coal-fired electricity is forecast to grow at over 4% per annum from approximately 166 GW to 500 GW by 2040.

In comparison, the average growth in “Electricity available for distribution in South Africa” as measured by StatsSA grew an average of only 1.7% during 1990 and 2015. Average GDP growth was 2.5% during the same period. Even worse, average electricity demand growth from 2000 to 2015 has averaged only 1.3% per annum. Over this period, the average GDP was 3.1% per annum. This higher economic growth was due to excessive growth in the services sector, primarily in the public and government sectors, not from the mining and manufacturing sector where growth was poor. The equivalent figures for the period 2008 to 2015 were electricity supply growth of only approximately 1.1% per annum and GDP growth of only 1.9% per annum. It is little wonder that South African GDP growth does not parallel other high-growth emerging economies. In terms of the IRP, electricity growth between 2015 and 2030 appears to be approximately 3.9%. However, because of the low load factors of renewables, real deliverable baseload electricity growth could be only 2.5% per annum. As a result, future average growth to 2030 is unlikely to average more than 2.8% per annum.

THE WAY FORWARD

South Africa is facing slow growth and lack of both domestic and foreign investment primarily in the mining and manufacturing industries. From a policy point of view, public policies need to change radically to make South Africa (a treasure chest of coal and minerals) attractive to such investment again. Planning for low baseload electricity growth is a self-fulfilling prophecy. Industrialized countries and their leaders need to recognize that the needs and requirements for emerging and developing economies are independent from their own with different priorities such as poverty alleviation.

Emerging markets need secure baseload electricity power at the lowest possible cost to give them a comparative economic advantage, whether that natural resource is oil, hydropower, or a fossil fuel such as coal or gas. The developed world needs to recognize that, at this stage of technological development, fossil fuels in the form of gas and coal will continue to play a substantial role in providing the country’s major energy source. In a speech earlier this year, President Obama acknowledged that emerging economies such as India, China, and the ASEAN countries would be building coal-fired power stations out of necessity, but advised they should use clean coal technology.

It is time for South Africa to break away from the vested idealistic or financial interest driving the large renewable expansion schemes. They are not the panacea for the country’s future energy problems and growth. Nuclear and coal are the only sources of energy that can provide security of baseload electricity supply at internationally competitive prices. The fact that nuclear is capital-intensive upfront means that South Africa cannot afford a major investment in nuclear as the way forward. Nevertheless, if procurement goes ahead, it should be no more than a maximum of 3200 MW. The way ahead for South Africa lies in limited nuclear build, major new build, and replacement of relatively older coal-fired power plants with new clean coal power generation supported by major expansion of gas plants. It should be made mandatory to install solar

“Nuclear and coal are the only sources of energy that can provide security of baseload electricity supply at internationally competitive prices.”

Cape Town settlement
PV on all new domestic houses and all business buildings. Tax incentives should be available to install solar PV on new and existing structures.

**CONCLUSION**

The South African economy cannot afford to restructure its economy and industry towards renewable energy nor can it afford the other structural changes this implies, including any form of carbon tax, either now or in the foreseeable future. Such a move will only increase uncertainty and further reduce long-term domestic and foreign investment. Carbon tax and massive renewable policies are poised to take South Africa in the wrong economic direction resulting in slow economic growth and increased unemployment. This will have major detrimental economic, political, and social consequences affecting the country for a generation.

The cost and burden of such plans always fall on the poor in terms of high unemployment, regressive taxation, and increasing poverty. South Africa already has these problems and needs to follow the lead of other emerging nations that are increasingly using coal and gas to pursue higher growth. Energy, electricity, and employment growth are the keys to South Africa’s future economic, social, and political prosperity, sustainability, and stability. It is time to put South Africa first.

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Coal-Fired Power Generation in Japan and the World

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The Japanese government set its 2030 power generation target shares for coal at 26%, nuclear at 22%, and gas at 27%. Due to concerns over the slow restart of nuclear power generation, the power sector’s interest in building more efficient coal-fired power generation facilities with low CO2 emissions is increasing. This article examines the reasons behind Japan’s energy policy and the choice of coal. In addition, it looks at the importance of coal for the future of Asian countries and the ways in which Japan is contributing to clean coal technologies both domestically and internationally.

COAL-FIRED GENERATION IN JAPAN

Historically, Japan’s use of energy resources for power demand and supply has experienced two major changes, as depicted in Figure 1. One is the gradual reduction of oil dependence in 1970–2010 and the other is the dramatic disappearance of nuclear after 2011. The heavy dependence on oil (around 70%) in the 1970s risked Japan’s energy security with the oil crisis. Consequently, a new and stronger energy policy was implemented to reduce dependence on oil by promoting coal, liquefied natural gas (LNG), and nuclear power. The result of this diversification reduced oil dependence from around 70% to 8% by 2010 (red bar in Figure 1). However, the major earthquake coupled with the disaster at the Fukushima Daiichi nuclear power plant in 2011 cast a huge shadow over Japan’s energy scene and resulted in major changes. All 54 nuclear reactors in Japan were shut down. In 2012, Japan established a new safety institute, the Nuclear Regulation Authority (NRA), following the introduction of the most stringent new safety standards in the world, which must be implemented before a nuclear reactor can restart.

“Japan is a world leader in USC technology for clean coal technology…”

In 2015, the Japanese government set a new energy policy that includes a 2030 energy supply-and-demand target. The policy was developed to balance energy security, economy,
The modern, efficient, and low-emission Isogo Power Station.

environment, and safety. The power generation national targets set for 2030 are nuclear 22%, coal 26%, LNG 27%, oil 3%, and renewables 22%. Coal-fired power will contribute 56% to the baseload, as the government aims to ensure around 60% baseload for stable supply, together with nuclear, hydropower, geothermal, and biomass.

To date, restarting the existing nuclear reactors has taken longer than anticipated. With the permanent shutdown of six reactors at Fukushima Daiichi and five other older reactors, there are now 43 potential reactors that could become operational again. An assessment to meet the new nuclear standard requirements can take up to two years. The NRA has assessed 26 reactor submissions. To date, only five reactors have passed assessment. Due to the extended time it was taking to restart the reactors, several regional power utilities were encouraged to find alternatives to increase baseload power generation. In addition, ongoing deregulation of the power market has encouraged new power generators to utilize more cost-effective power sources. As a result, several new coal-fired power generation projects are being planned, with some already under construction. Figure 2 depicts the breakdown of Japan’s installed power generation capacity by energy source. Coal-fired power generation capacity is 40 GW, accounting for 16% of the total.

The main owners of Japan’s coal-fired power plants are 10 regional power utilities and J-POWER. Figure 3 depicts the total coal-fired power generation capacity in Japan and the share held by different companies.

J-POWER was established in the 1980s as a state-owned power wholesaler and has promoted imported coal-fired power generation in accordance with government policy. It is the largest coal-fired power plant operator in Japan.

Coal and nuclear are considered the best options for baseload power generation in Japan because it is less expensive than gas. Gas imported as LNG has a high price due to the liquefaction cost and the additional freight cost. According to the International Energy Agency, the relative price of coal to gas differs in the U.S., Europe, and Japan. In the U.S., coal is almost equivalent in price to gas for electricity generation, whereas the price of coal in Japan is substantially lower than gas.

Before the Fukushima disaster, no new coal-fired power projects had been built in Japan in the 21st century. All the environmental impact assessments (EIAs) for coal-fired power projects were rejected by the Ministry of Environment (MoE) because they would increase CO₂ emissions in Japan. However, after the shutdown of all nuclear power reactors, serious concern developed about a power shortage in the Greater Tokyo area, which resulted in a call for tenders from the Tokyo Electric Power Company (TEPCO) for 2.6-GW baseload power

FIGURE 2. Power generation capacity by energy source in Japan, 2014

FIGURE 3. Owners of coal-fired power plants in Japan, 2014
generation. But bidders were reluctant to make detailed bids for coal-fired projects because the MoE would block any coal project in the EIA process even if it won the tender. This obstacle concerned the Ministry of Energy, Trade and Industry (METI), which is responsible for management of energy demand and supply in Japan.

“Our current 17 GW of new coal-fired power projects are at various stages of development in Japan…”

To eliminate concern among potential bidders about the MoE’s hostility to coal-fired power generation, METI and the MoE made an agreement. If new fossil-fired power projects met two conditions, MoE would not block the project in the EIA process, so that companies could submit a tender to TEPCO without fear of being rejected. The first condition is to use the best available technologies (BAT); thus only ultra-supercritical (USC) technologies were eligible. The other condition is that the power sector established a coalition with a targeted emissions cap which is consistent with the government’s 2030 energy mix and CO2 emissions targets—and the CO2 emissions from the approved project must be within the cap. The MoE published the energy efficiency standard required to be met by potential bidders in a table by fuel type (coal and gas) and by plant size. For example, a 1000-MW coal-fired power plant must achieve 45% (LHV, gross) energy efficiency.

Currently, 17 GW of new coal-fired power projects are at various stages of development in Japan, ranging from the early stage of the EIA process to being constructed. All the large-scale projects plan to use USC technology to meet government conditions. The proposed coal-fired power projects include small power projects without USC as USC is not suitable for smaller size coal-fired power plants. As an alternative for smaller projects, co-firing of biomass fuel is used to reduce CO2 emissions.

In February 2016, due to the MoE’s concerns about the increasing number of new projects, METI announced amendments to two existing laws. One amendment regulates power generators to achieve energy efficiency standards consistent with the 2030 national target; the other regulates power retailers in procuring a share of non-fossil power consistent with the 2030 national target.

Both regulations allow “collective action” to achieve the goal. The 35 main players in the power sector have formed a framework to achieve the goal collectively.

In May 2016, the Oxford Smith School of Enterprise and Environment published a report, “Stranded Assets and Thermal Coal in Japan: An Analysis of Environment-Related Risk Exposure”. The report concluded that the new coal fleet investment of US$6-8 billion would result in a stranded asset in 5–15 years. However, several of the assumptions in the report were incorrect. First, the number of coal-fired power projects was exaggerated; the Oxford paper assumes 28 GW while the Japanese government says a maximum of 17 GW of coal-fired power will be built. The Oxford paper also names eight new J-POWER projects: Takehara, Takasago, Nishiokinoyama, Osaki Coolgen, Kashima Power, Yokohama, Shin Yokosuka, and Yokosuka. However, three of them—Yokohama, Shin Yokosuka, and Yokosuka—are not J-POWER’s projects.

The biggest problem with the Oxford paper, as noted by Professor Arima, is its failure to consider Japan’s energy policy and 2030 national targets. It also fails to consider Japan’s energy security or economy, focusing only on the environment. The study assumes that coal-fired power generation is hazardous for human beings and does not recognize that Japan requires stable and cost-effective power generation. Moreover, the new coal-fired power plants will use the most advanced clean coal technology, which will remove SOx, NOx, and particulate matter (PM) at a nearly 100% rate (depending on the coal’s characteristics). CO2 emissions will also be reduced through high-efficiency plants and through use of CCS in the future.

Japan is a world leader in USC technology for clean coal technology and continues to make further improvements through R&D. As a result, Japan has built coal-fired power plants achieving low emissions. J-POWER’s Isogo Power Station demonstrates Japan’s best clean coal technology, with an efficiency of 45% (LHV, gross), reduced flue gas, single-digit ppm SOx, less than 10 ppm NOx, with PM less than 5 ppm at the stack.
Located in Yokohama, the second largest city in Japan by population, Isogo Power Station is only 6 km from Yokohama’s city center and 30 km from central Tokyo. It is a unique, urban coal-fired power station that employs some of the most advanced clean coal technologies in the world.

“Oh, Japan intends to remain a world leader in clean coal technologies.”

Originally, Isogo Power Station had two 265-MW subcritical boilers. The old station started commercial operation in the 1960s, and had been supplying base load power for more than 35 years. In 1996, the government approved a replacement plan. As a result of discussion with the buyers and Yokohama City, the new station was designed to have 2 units of 600 MW with the world’s highest energy efficiency and lowest emissions for a coal-fired power station. The boilers and turbines use USC technology with a main steam temperature/pressure of 600°C/25 MPa and a reheating steam temperature of 610°C. The plant uses a dry-type DeSOx system to reduce emissions.

Figure 4 shows that SOx and NOx emissions from Isogo are less than those from fossil-fired power plants in other developed countries, due to this advanced DeSOx and DeNOx system.

Currently, J-POWER and Chugoku Electric Power are conducting R&D on oxygen-blown integrated coal gasification combined cycle (IGCC). The aim is to improve energy efficiency and develop economic CO2 capture from syngas, and A-USC to further increase efficiency and reduce CO2 emissions. The goal for commercialization of IGCC is the early 2020s; then triple combined-cycle technology also employing fuel cells and integrated coal gasification fuel cell combined cycle (IGFC) is the next R&D step to improve energy efficiency further. Japan intends to remain a world leader in clean coal technologies. It is important to allocate sufficient budget and invest in innovative technologies wisely.

GLOBAL PERSPECTIVE ON COAL FOR POWER

According to the IEA, in 2014, coal provided 40% of the world’s power generation—the largest share. Historically, in the 1990s the OECD’s share in coal-fired power generation was 70%, as depicted in Figure 5. The volume of coal-fired power generation has more than doubled since then and is expected to grow 24% by 2040. The share of non-OECD’s coal-fired power generation began to accelerate in 2000 and, at current levels, is expected to be more than 60% today and will be more than 80% in 2040. Coal demand in the Asian power sector will increase by 67% from today to 2040.

Figure 6 shows the cumulative capacity of retired and added coal-fired power plants by region between 1990 and 2040. In OECD countries, the total retirement of coal-fired plants is more than 300 GW, whereas total additions are 100 GW. In China and Southeast Asia, a large number of additional coal-fired plants is expected to be built. According to the IEA,
between 2015 and 2040 the total additional capacity of coal-fired power plants in non-OECD countries will be more than 1000 GW, or more than half of the existing capacity of coal-fired plants in the world.

Countries are building coal-fired power generation primarily because coal is an inexpensive power source in comparison to other energy sources. Many of those countries, such as China and Indonesia, also have large reserves of coal. Many of the economic growth plans of non-OECD countries are built around an energy policy based on inexpensive coal-fired power. Therefore it is important to encourage use of coal in the most efficient way—that is, through high-efficiency power generation technology in order to reduce CO₂ emissions—particularly in non-OECD Asia.

“\textit{To achieve CO₂ emissions reduction targets, countries will need to implement a wide array of mitigation technologies...}”

In the wake of increased awareness about the risks of climate change, criticism of coal is increasing in OECD countries. In addition, public financing for new coal-fired power projects is being restricted. An agreement was reached after several months of intense argument over a proposal by the U.S. and the UK to ban all public financing of coal-fired power projects and a counter-proposal by Japan and Australia to allow efficient coal-fired power projects, with high-efficiency technology to be eligible. In September 2015, the OECD’s Export Credits Arrangement review process was changed to allow investment in coal-fired power projects that employ USC technology. OECD member countries accepted that efficient use of coal helps non-OECD countries reduce CO₂ emissions effectively, instead of banning officially supported export credits to all coal-fired power projects.

Given the need for efficient use of coal in Asia, Japan intends to encourage and deploy its clean coal technologies in countries to effectively mitigate global CO₂ emissions. J-POWER is engaged in several projects in Indonesia, including construction of two IPP 1000-MW USC coal-fired units in Central Java. The project will use local subbituminous coal and be Indonesia’s first coal-fired power plant to use USC technology. The plant is expected to become operational in 2020. The project will also contribute to the sustainable development of Indonesia and CO₂ mitigation.

CONCLUSION

The Paris Agreement went into force in November 2016 under the United Nations Framework Convention on Climate Change (UNFCCC). To achieve CO₂ emissions reduction targets, countries will need to implement a wide array of mitigation technologies, including clean coal technologies. In the short term, efficient use of coal is the key to CO₂ emissions reductions in Asian countries. Japan’s clean coal technology will contribute to using coal most efficiently in power generation and support sustainable development in Asia. J-POWER is engaged to demonstrate and implement clean coal technologies commercially both in Japan and internationally and to continue with further research and development.

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The Emirate of Dubai is one of the fastest growing cities in the world and a regional hub for tourism, logistics, and finance. The Dubai government is implementing an innovative strategy to manage demand, diversify fuel sources, secure its energy supply, and foster green growth. One strategic aim is to continue to fuel Dubai’s economic growth and maintain its regional and global prominent position.

Dubai’s installed generation capacity is about 10 GW. The main source of this power is from imported natural gas, which makes Dubai a net energy importer. Therefore, energy security is a high priority with forecasted electricity demand for the next decade projected to increase annually by 5–6%. In addition, the Emirate is pursuing a sustainable development path and plans to use clean energy technologies.

“...the Emirate is pursuing a sustainable development path and plans to use clean energy technologies.”

The economic success story of Dubai demonstrates how it managed to design and implement an energy strategy that captures the key levers driving its economy: energy security, demand-side management, and sustainable growth. Dubai is a living model of a coherent and cohesive energy strategy that meets future energy needs through an optimal energy mix that delivers affordable, sustainable, and clean energy to its citizens and residents.
The strategy builds on a world-class regulatory framework to accelerate the diversification of the energy mix, ensure security of supply, and facilitate effective demand-side management, as shown in Figure 2 with Dubai’s Integrated Energy Strategy up to 2030.

The DIES includes the following elements:

- **Governance and Policies:** To achieve the DIES targets, the policy and regulatory regime in Dubai’s energy sector has been overhauled. New principles such as public–private partnerships have been put in place to increase market participation in key projects, including clean coal and solar power generation. The regulatory framework for district cooling and energy service companies (ESCOs) is also supporting the implementation of DIES 2030.

- **Energy Efficiency and Demand Reduction:** Demand reduction through energy efficiency is a focus of Dubai’s policy interventions to rationalize the use of power and water. The demand-side management (DSM) strategy has led to nine different programs and technical levers for energy efficiency and demand reduction. This has resulted in savings in capital, operational, and opportunity costs (as discussed in the next sections).

- **Energy Security and Sustainable Cost of Gas:** Diversification of Dubai’s energy sources is a key focus of DIES 2030. This has led to several projects to increase future energy security including the proposed building of a clean coal power plant, solar, and encouragement of Independent Power Producer (IPP) projects. The Mohamed bin Rashid Al Maktoum Solar Park is an example of Dubai’s commitment to renewable energy. Other important elements in development include the use of imported nuclear energy, clean coal, waste-to-energy, hybrid and electric vehicles, and the distributed solar program (Shams Dubai).

- **Financial Mechanism and Capacity Building:** DIES 2030 has launched measures and projects targeting DSM, renewable power, energy service contractors, Green Building Codes, and energy efficiency technologies. Financial mechanisms, such as the announced Dubai Green Fund currently under development, will encourage deployment of clean energy technologies in Dubai.

### MARKET TRANSFORMATION

A market-based approach using public–private partnerships (PPPs) has been developed to meet the fast-growing demand for infrastructure in Dubai. The PPP approach leverages funding sources and helps balance the risk between the government and private investors. By fostering partnerships with leading international firms in clean energy, Dubai also aims to expand its local capacities through transfer of knowledge and skills.

Since the DSCE’s inception, it has rolled out a series of step-by-step regulatory reforms and policies to open the electricity market for independent power producers. This involved establishing the Regulatory and Supervisory Bureau (RSB) for the electricity and water sector in 2010. The RSB’s responsibilities include licensing of new entrants in the power sector.

One of the pillars of the DSEM, and a crucial factor in transforming Dubai’s energy market, was the review of the electricity and water tariff structure. In 2011, the Dubai Electricity and Water Authority (DEWA) introduced cost-reflective tariffs to incentivize lower consumption and more efficiency in the use of electricity and water. This sent positive signals to clean energy investors as the market became economically attractive for clean technologies, allowing for successful PPPs. Dubai’s robust regulatory framework provided investors with three key elements for long-term investment: transparency, longevity, and certainty.

### SECURITY AND DIVERSIFICATION OF DUBAI’S ENERGY SUPPLY WHILE MAINTAINING SUSTAINABILITY

After evaluating the options to provide supply security of supply for Dubai, the government decided to shift from dependency on fossil fuel and to increase the renewable energy share. This culminated in a target of 25% of clean installed capacity by 2030 and 75% by 2050 using CO₂-free generation sources. To achieve these targets, Dubai is taking progressive strides to integrate solar power into an energy mix portfolio that is currently dependent mainly on imported natural gas.
The robust regulatory framework and commercial terms have attracted international and regional investors resulting in the lowest levelized cost of electricity (LCOE) for 200 MW at 5.64 US cent/kWh and recently DEWA announced an 800-MW solar photovoltaic (PV) power plant at 3.0 US cent/kWh. This development marked a turning point in the journey to diversify Dubai’s energy mix and demonstrated the value proposition of strategic PPPs for procuring energy at a record low price.

The transformation of the energy sector in Dubai is also occurring on the customer side. Residents can generate their own electricity using solar panels that can also feed extra energy to the Dubai power grid. This step will gradually transform the consumers to “prosumers”, a term used to describe consumers that also generate part of their own energy consumption. Dubai currently deploys a simple net-metering system wherein customers achieve savings by generating their own electricity.

**CLEAN COAL IN THE DUBAI CLEAN ENERGY STRATEGY 2050**

For Dubai to diversify its energy mix, a decision was made to integrate clean coal to reduce dependency on imported natural gas and meet rising energy demand. Several reasons led to the decision to develop coal as an energy source. Coal is highly competitive with its low prices, dispatchability, and baseload compatibility. In addition, the combination of technological advances that allows both for higher efficiencies and reduced pollutants and emissions make it an ideal option to meet Dubai’s future energy needs.

In fact, Dubai’s commitment to a clean future stipulates the clean energy targets of the DIES 2050 strategy do not include clean coal without carbon capture and storage (CCS). Dubai has some of the most stringent emission standards and limits in the world for flue gas emissions. The deployment of clean coal technology will require meeting aggressive emissions and international environmental standards set for flue gas emissions. The limits are stricter than those in the Industrial Emissions Directive (IED) of the European Union and in the International Finance Corporation (IFC) guidelines. Dubai’s clean energy targets also include achieving CO₂-free generation sources of 25% of its installed capacity in 2030 and 75% in 2050.

In 2016, Dubai awarded the first phase of the Hassyan Clean Coal Power Project comprising four 600-MW units. The ultra-supercritical technology to be deployed will aim for 50% high heating value (HHV) efficiency compared to only 35% efficiency in the current pulverized coal-fired plants. The first 600-MW unit will be commissioned in 2020. The full project size is 2400 MW; it will be the first clean coal power plant in the Gulf Cooperation Council (GCC) region. The electricity from the coal-fired power plant will be utilized during the high peak demand periods of the summer season to ensure security of supply at a reasonable cost.

Dubai has developed attractive commercial terms to secure the lowest levelized cost of electricity (LCOE) of about 4.5 US cent/kWh for the Hassyan project based on an IPP procurement model on a build-own-operate (BOO) basis. The project is 78% debt and 22% equity financed. This IPP model also fosters partnerships with leading international firms in clean energy, leverages funding sources, and helps balance the risk between the government and private investors.

“Dubai’s clean energy targets also include achieving CO₂-free generation sources of 25% of its installed capacity in 2030 and 75% in 2050.”

**DEMAND-SIDE MANAGEMENT**

DIES 2030 also has an objective to reduce 30% of Dubai’s energy demand from the current business-as-usual scenario. To achieve this reduction by 2030, a detailed DSM strategy for electricity and water has been implemented, which is the first of its kind in the region. The DSM strategy has opened up new business opportunities for sustainable and efficient businesses by outlining policies, regulations, awareness schemes, technologies, and finance schemes.

The strategy is based on nine programs with a specific database, reduction targets, and enablers to influence behavior and encourage well-thought-out measures. To ensure that the measures are effective, the government has engaged key stakeholders for consultation on the proposed programs, reduction measures, and timeline with a clear roadmap targeting 30% consumption reduction of water and electricity by 2030. The stakeholders’ engagement and global benchmarking will provide information and knowledge in the following areas: building regulations, building retrofits, district cooling, standards and labels for appliances and equipment, water reuse and irrigation, outdoor lighting, change of tariffs, demand response, and distributed solar.

**GREEN MOBILITY IN DUBAI**

To accelerate the uptake of hybrid and electric vehicles (EVs), the Emirate established the Green Mobility Initiative to lead the world in becoming more sustainable using smart technologies. The initiative complements the spirit of Dubai Plan1
2021 by providing alternative modes of transportation that reduce fuel usage and CO₂ emissions. Road transportation is the third largest source of Dubai’s greenhouse gas (GHG) emissions. This initiative is an important contributor to Dubai Carbon Abatement Strategy 2021, which aims to reduce carbon emissions by 16% in 2021 compared to the business-as-usual scenario in 2021.

The Dubai Supreme Council of Energy and its entities have developed a comprehensive approach founded on the principle of “leading by example”. A detailed analysis was undertaken by the government of the market potential of hybrids and EVs. Based on this analysis a decision was made that the government vehicle fleet would be 10% hybrid or EVs by 2021.2

In addition to creating a market for hybrids and EVs, leading by example will enable the government to build the learning curve necessary to expand the deployment of such vehicles in the arid climate of Dubai. The Road and Transportation Authority (RTA) has already demonstrated the successful use of hybrid vehicles. The RTA3 employed over 140 hybrid taxis in 2015 and reported that around 30% fuel savings were achieved and found no performance challenges with the vehicles. The RTA is currently planning to convert 50% of its fleet to hybrid taxis by 2021 and is monitoring feasibility of hydrogen cell vehicles based on recent advancement in this technology.

DUBAI CARBON ABATEMENT STRATEGY 2021: LOCAL ACTION...GLOBAL CHANGE

In a short time, the Emirate has created a platform to find solutions for energy challenges by development of specific programs and projects. The first-in-the-region Dubai Carbon Abatement Strategy 2021 details programs that integrate alternative and renewable energy to diversify Dubai’s generation mix. This strategy will allow the Emirate to manage its energy demand, to increase efficiency, and to develop sector-based GHG reduction targets.

To design a performance-based program for carbon abatement, the strategy defined major sectors contributing to carbon emissions, referred to as “high-impact sectors”. Based on the carbon emissions profile for 2011, these sectors are power and water, manufacturing, road transportation, and waste. An unpublished technical evaluation of the emissions reduction potential for these high-impact sectors was carried out with the support of the Dubai Carbon Centre of Excellence, resulting in a target of 16% reduction of GHG by 2021 in comparison with the business-as-usual estimations for the same year.

In 2015, members of the Dubai Carbon Abatement Strategy saved 5.7 million tons of CO₂e, which is equivalent to 10.6% reduction from business as usual in 2015.

BECOMING A ROLE MODEL IN ENERGY MANAGEMENT AND SUSTAINABILITY

The efforts of the UAE and Dubai to spearhead clean energy development in the region contribute greatly beyond the borders of the UAE. In a rapidly changing world, Dubai has seized the opportunity to follow a sustainable development pathway as it continues to grow. The clear and supportive vision of its leadership paved the way to develop a long-term strategy and deliver phased, but steadily implemented progress to achieve the goals of its DIES 2030. The strategy has resulted in investment certainty for the private sector and in several successful PPPs that resulted in low-cost solar energy, with positive ramifications for the future of solar not only in Dubai but the entire region.

The Emirate’s model as illustrated in Figure 3 is becoming a benchmark for the transition to a clean energy future in a region historically perceived as a synonym for “oil”. By 2030, Dubai expects to turn its sunny days into a sustainable fuel for generations to come and deliver strategic programs to support its Green Agenda to become a role model in energy management and sustainability in the region.

REFERENCES


FIGURE 3. Dubai’s Sustainable Energy Model
Consensus is growing among industry, the environmental community, and international governments that future carbon dioxide (CO₂) emission reduction goals cannot be met by renewable energy alone and that carbon capture, utilization, and storage (CCUS) technologies for all fossil fuels must be deployed to achieve climate objectives in the U.S. and globally. Fossil fuels—including coal, natural gas, and oil—will remain the dominant global energy source well into the future by virtue of their abundance, supply security, and affordability.

Achieving global climate objectives will require a portfolio of approaches that balance economic realities, energy security, and environmental aspirations. The most influential action the U.S. can employ to reduce CO₂ emissions is to incentivize the rapid deployment of CCUS technologies. CO₂ utilization can, in theory, help to reduce CCUS costs and incentivize deployment, but most CO₂ use technologies face numerous and significant challenges in moving toward commercialization.

Geological CO₂ utilization options have the greatest potential to advance CCUS by creating market demand for anthropogenic CO₂. The use of CO₂ for enhanced oil recovery (CO₂-EOR), including production and storage activities in residual oil zones (ROZ), remains the CO₂ use technology with the greatest potential to incentivize CCUS.

“*The most influential action the U.S. can employ to reduce CO₂ emissions is to incentivize the rapid deployment of CCUS technologies.*”

Non-geological CO₂ utilization options are unlikely to significantly incentivize CCUS in the near to intermediate term because of technical, greenhouse gas (GHG) life-cycle analysis (LCA) considerations, and challenges associated with scalability. Despite these barriers, further investments in non-geologic CO₂ utilization technologies may, on a case-by-case basis, hold promise for turning an uneconomic CCUS project into an economic one. A broadly deployed mix of CO₂ utilization technologies may help advance CCUS deployment incrementally, providing sufficient incentive to keep CCUS technologies moving forward.

**NATIONAL COAL COUNCIL MISSION**

The National Coal Council (NCC) is a federally chartered advisory group to the U.S. Secretary of Energy, providing advice and recommendations on general policy matters relating to coal and the coal industry. In August 2016, the NCC completed a white paper for Energy Secretary Ernest Moniz that assessed opportunities to advance commercial markets for carbon dioxide (CO₂) from coal-based power generation. This article highlights key findings and recommendations from the report, “CO₂ Building Blocks: Assessing CO₂ Utilization Options”.

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**CO₂ Utilization as a Building Block for Achieving Global Climate Goals**

**By Janet Gellici**
Chief Executive Officer, National Coal Council

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A way forward for CCUS in the U.S.
DRIVING THE NEED FOR CCUS

CCUS technologies provide the most impactful opportunity to capture, use, and store a significant volume of CO₂ from stationary point sources. These technologies can be used to reduce CO₂ emissions from electric generation as well as from key industrial sectors, such as cement production, iron and steel making, oil refining, and chemicals manufacturing. Additionally, CCUS technologies significantly reduce the costs of decarbonization. Not including CCUS as a key mitigation technology is projected to increase the overall costs of meeting CO₂ emissions goals by 70% to 138%. Finally, the commercial deployment of CCUS preserves the economic value of fossil fuel reserves (coal and natural gas) and associated infrastructure.

Commercial markets for CO₂ from fossil fuel-based power generation and CO₂-emitting industrial facilities have the potential to provide a business incentive for CCUS. The extent of that economic opportunity will depend on many factors, including but not limited to expediting the development of and reducing the cost associated with CO₂ capture technologies. And while commercial markets may provide significant opportunities for CO₂ utilization, the global scale of CO₂ emissions suggests a continued need to pursue geologic storage options with significant CO₂ storage potential and initiatives such as those being undertaken by U.S. Department of Energy (DOE) through its Regional Carbon Sequestration Partnerships Program and related programs.

Fossil fuels generally, and coal specifically, are dependent upon CCUS technologies to comply with U.S. GHG emissions reduction policies. A number of U.S. regulatory policies have been adopted to reduce GHG, with geologic storage options (specifically including CO₂-EOR) as preferred mitigation technologies. Included among existing and pending U.S. regulations that encourage compliance via the use of CCUS technologies are the Clean Air Act’s Prevention of Significant Deterioration (PSD) and Title V Operating Permit programs; the Environmental Protection Agency’s (EPA) Standards of Performance for GHG Emissions from New, Modified and Reconstructed Electric Utility Generating Units (111b); and the Clean Power Plan (CPP). These U.S. policies are reinforced by the 2015 Paris Agreement, which largely envisions the decarbonization of major energy systems through the use of CCUS and other technologies by the 2050 timeframe.

“Fossil fuels generally, and coal specifically, are dependent upon CCUS technologies to comply with U.S. GHG emissions reduction policies.”

U.S. law currently favors geologic storage/utilization technologies; non-geologic CO₂ uses must demonstrate that they are as effective as geologic storage. Additionally, the emissions reduction targets and deadlines associated with U.S. and international climate goals point toward the use of CO₂ utilization technologies that are either already commercialized or near commercialization.

CO₂-EOR represents the most immediate, most mature, and highest value opportunity to utilize the greatest volumes of anthropogenic CO₂ to meet U.S. and global climate objectives (see Table 1).
GEOLOGIC CO₂ UTILIZATION MARKET POTENTIAL

A 2011 report from the Global CCS Institute estimated current global demand for CO₂ at about 80 million tons per year (MTPY) and suggested potential future demand could grow by an order of magnitude, reaching nearly 300 MTPY for each of a handful of technologies—most notably CO₂-EOR—and more modest growth for an additional group of technologies. The potential global demand for CO₂ for EOR was confirmed in 2015 in an International Energy Agency (IEA) study indicating that, by 2050, conventional CO₂-EOR could lead to storage of 60,000 MTPY of CO₂ and, through the application of advanced technologies, so-called EOR+ could increase to 240,000–360,000 MTPY of CO₂.

In the U.S., CO₂-EOR offers major potential for utilizing and storing CO₂ in a diversity of geological settings.

- CO₂ floods in the main pay zone (MPZ) of discovered oil fields (onshore lower-48 states, Alaska, and offshore Gulf of Mexico) offer a technical potential for utilizing and storing 38,320–52,240 MMmt of CO₂.
- Although the economically viable potential from the MPZ (at an oil price of $85 per barrel and with CO₂ costs linked to oil prices) is more limited, the CO₂ utilization and storage volumes are still significant at 10,740–23,580 MMmt plus 28–81 billion barrels of economically viable oil recovery.
- CO₂ floods in the residual oil zone (ROZ) resources assessed to date could provide an additional 25,300 MMmt of technically viable CO₂ utilization and storage, and significant volumes of associated oil recovery.

Other geologic utilization markets—including tight oil/shale gas formations, enhanced coal bed methane (ECBM), and enhanced water recovery (EWR)—also hold current and future promise as incentives for CCUS deployment. Key knowledge gaps and technical barriers remain in the pursuit of commercial deployment of these technologies. Progress has been and is being made with these emerging technologies but additional research is required to advance to the next stages of technological maturity.

NON-GEOLOGIC CO₂ UTILIZATION MARKET POTENTIAL

Outside of CO₂-EOR and other geologic CO₂ use markets, research is underway on two general paths for non-geologic

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**TABLE 1. U.S. regional CO₂ utilization/storage and oil recovery potential**

<table>
<thead>
<tr>
<th>Region</th>
<th>Oil Reservoirs Favorable For CO₂-EOR</th>
<th>CO₂ Demand (MMmt) Technical</th>
<th>Oil Recovery (Billion Bbls) Technical</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>SOA</td>
<td>&quot;Next Generation&quot;</td>
</tr>
<tr>
<td>Appalachia</td>
<td>103</td>
<td>520</td>
<td>1160</td>
</tr>
<tr>
<td>California</td>
<td>89</td>
<td>1340</td>
<td>2320</td>
</tr>
<tr>
<td>East/Central TX</td>
<td>193</td>
<td>4120</td>
<td>6040</td>
</tr>
<tr>
<td>Michigan/Illinois</td>
<td>148</td>
<td>660</td>
<td>1050</td>
</tr>
<tr>
<td>Mid-Continent</td>
<td>183</td>
<td>4220</td>
<td>6530</td>
</tr>
<tr>
<td>Permian Basin</td>
<td>217</td>
<td>6070</td>
<td>8620</td>
</tr>
<tr>
<td>Rockies</td>
<td>146</td>
<td>1930</td>
<td>2790</td>
</tr>
<tr>
<td>Gulf Coast</td>
<td>209</td>
<td>2590</td>
<td>3390</td>
</tr>
<tr>
<td>Williston</td>
<td>86</td>
<td>820</td>
<td>1150</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1374</strong></td>
<td><strong>22,270</strong></td>
<td><strong>33,050</strong></td>
</tr>
</tbody>
</table>

*Includes 0.1 billion barrels already produced or proved with CO₂-EOR.
*Includes 2.2 billion barrels already produced or proved with CO₂-EOR.
*Includes 0.3 billion barrels already produced or proved with CO₂-EOR.
*Evaluated using an oil price of $85/B, a CO₂ cost of $40/mt and a 20% ROR, before tax.

Source: Advanced Resources International
CO₂ utilization: breaking down the CO₂ molecule by cleaving C=O bond(s) and incorporating the entire CO₂ molecule into other chemical structures. The latter path holds relatively more promise as it requires less energy and tends to “fix” the CO₂ in a manner akin to geologic storage. Utilizing CO₂ in non-geologic applications faces hurdles, including yet-to-be resolved issues associated with thermodynamics and kinetics involved in the successful reduction of CO₂ to carbon products and inadequate support for demonstration projects leading to commercialization. Still, these technologies are worthy of continuing evaluation, and many hold long-term potential in specific applications.

**Market forces alone are unlikely to incentivize CCUS as CO₂ utilization faces numerous hurdles.**

Non-geologic utilization opportunities that tend to “fix” CO₂ include (1) inorganic carbonates and bicarbonates; (2) plastics and polymers; (3) organic and specialty chemicals; and (4) agricultural fertilizers. Various technical and economic challenges face these commercially immature technologies, suggesting they are unlikely to incentivize CCUS deployment in the immediate future. They may, however, have an advantage over other non-geologic markets, such as fuels, which require cleaving of the CO₂ bond through chemical and biological processes.

Transportation fuels do represent a significant market opportunity. They are, however, unlikely to incentivize CCUS in the immediate future for a variety of technical and economic reasons, including: (1) transportation fuels are ultimately combusted and thus release CO₂ to the atmosphere and (2) current U.S. policy favors geologic-based utilization pathways for Clean Air Act (CAA) compliance. Although the case could be made that some CO₂-derived transportation fuels have lower GHG emissions than fossil-based fuels on a GHG LCA basis, non-fossil-based transportation fuels still face significant market competition and displacement hurdles.

**CO₂ UTILIZATION CHALLENGES**

Market forces alone are unlikely to incentivize CCUS as CO₂ utilization faces numerous hurdles.

- **Cost of capture.** The current major user of CO₂, the EOR industry, typically cannot offer a “price” for CO₂ that overcomes the cost of capture for a coal-based utility. This conclusion applies even in the face of existing economic incentives, such as the current Section 45Q CCUS tax incentive.
- **Insufficient scope of the market/supply considerations.** Only CO₂-EOR holds promise for incentivizing CCUS at any reasonable scale for compliance purposes for coal-based utilities.
- **Nearly all non-geologic CO₂ utilization technologies are not yet commercialized.** Even if some of the nascent utilization technologies being explored worldwide hold potential for use at scale, they face a decades-long slog along the technology development path and typical technology deployment “valley of death” investment hurdles. These time frames suggest that, on their current trajectory, many utilization technologies will not be commercially available in time to influence CCUS deployment in the context of 2050 climate goals.
- **Geographic/infrastructure considerations.** Unless the utilization technology is deployed beside every coal-based facility, the captured CO₂ must be transported to industrial facilities making use of CO₂. This issue remains a challenge even for EOR, let alone nascent technologies that are not yet commercial.

- **Legal & regulatory considerations.** Under current law, CO₂-EOR owners and operators must (1) conduct their

**Thermodynamics & Kinetics of CO₂**

The CO₂ molecule is particularly stable and has a Gibbs energy of formation of -394.4 kJ/mol, which must be overcome.

Thus, breaking the C=O bond(s) and forming C-H or C-C bond(s), or producing elemental carbon, is possible. However, such molecules are at a much higher energy state, meaning that a tremendous amount of energy must be used. Converting CO₂ to fuels or other high energy state molecules requires more energy input than could ever be derived from the end products.

CO₂ can also be incorporated into various chemicals as a C₂ building block. This is not thermodynamically challenged because the entirety of the CO₂ molecule is used and thus the C=O bonds are not broken. For this application, the principal challenge is the scale of available reactants and market for products, both of which are dwarfed by global CO₂ emissions.
In its “CO2 Building Blocks” report for Energy Secretary Moniz, the National Coal Council recommended that research investments in CO2 utilization technologies should be prioritized first according to the ability of the CO2 utilization technology to:

- Be deployed onsite at fossil fuel-based power plants and CO2-emitting industrial facilities.
- Have realistic market potential, taking into account displacement considerations.
- Be as effective as geologic technologies.
- Provide non-trivial economic returns.
- Favorably score under existing and forthcoming GHG LCA.

"Achieving stabilization of GHG concentrations in the atmosphere requires the deployment of CCUS technologies worldwide."

The Council further noted that monetary, regulatory, and policy investments in the following CO2 utilization and storage technologies, in descending order, are most likely to incentivize the deployment of CCUS technologies:

1. **Current CO2-EOR technology.** It is imperative that the government clarify the existing regulatory structure, provide support for infrastructure, such as pipeline networks, and offer financial incentives for carbon capture deployment so that the promise of this existing commercial technology is fully realized.

2. **“Next generation” CO2-EOR technologies.** Advances to existing CO2-EOR technologies would enable ROZ resources to be efficiently recovered.

3. **Other geologic storage technologies that provide economic return.** ECBM and CO2 injections into ROZs provide market demand for CO2 under certain general oil and gas market conditions. They also fit within the current U.S. legal framework that gives preference to geologic storage over non-geologic uses of CO2. Not all geologic formations (ECBM, for example) have access to protocols and/or methodologies to document storage.

4. **Saline storage.** Saline storage remains EPA’s gold standard for CO2 storage and may be required to provide a backstop for CO2 utilization projects. The hurdles facing saline storage are primarily economic and regulatory, which current DOE policy recognizes, i.e., the new CarbonSAFE program. The fact remains, however, that the federal government needs to put more resources into these projects and reduce the regulatory impediments currently facing them.

5. **Non-geologic storage technologies that provide economic return and that are effective as geologic storage.** The current U.S. legal framework prefers geologic storage over other CO2 uses. However, non-geologic technologies that
keep the CO2 out of the atmosphere may be credited for the purposes of federal programs with appropriate evidence of atmospheric benefit.

6. **Non-geologic storage technologies that provide economic return yet are not as effective as geologic storage if appropriate EPA research waivers may be obtained.** On a case-by-case basis, a CO2 utilization technology may exist or emerge that provides an economic return to a fossil fuel-based power plant or a CO2-emitting industrial facility. The technology nonetheless could be helpful in lowering the cost of capture. Appropriate legal recognition would be needed, however, for purposes of compliance with emission reduction obligations.

**“CO2 utilization technologies can serve as building blocks in advancing a foundation on which to achieve global climate goals.”**

**CONCLUSION**

Achieving stabilization of GHG concentrations in the atmosphere requires the deployment of CCUS technologies worldwide. Consensus grows among industry, the environmental community, and international governments that future CO2 emission reduction goals cannot be met by renewables alone and that advancing CCUS is not just about coal.

CO2 utilization technologies can serve as building blocks in advancing a foundation on which to achieve global climate goals. A broadly deployed mix of CO2 utilization technologies, including geologic and non-geologic, may help to advance CCUS incrementally and may, even if they do not offer full-scale carbon management solutions, provide sufficient incentive to keep CCUS technologies moving forward. CO2-EOR offers the most immediate, most commercially mature, and highest value opportunity to utilize the greatest volumes of anthropogenic CO2. Monetary, regulatory, and policy investments that prioritize geologic CO2 use technologies first while continuing to support non-geologic applications on a longer-term basis provide the greatest promise of achieving global climate goals.

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PHASING OUT COAL-FIRED POWER PLANTS IN ALBERTA BY 2030: RECENT DEVELOPMENTS

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ALBERTA: THE CANADIAN POWERHOUSE

The province of Alberta, located in Western Canada (see Figure 1), is regarded as the pillar of Canada’s energy economy. It is home to the third largest oil reserves in the world, produces 68% of Canada’s natural gas, holds significant renewable energy resources, and is the site of Canada’s first commercial windfarm. Yet the most abundant fossil fuel energy resource in Alberta is coal. The energy content of coal in Alberta is greater than the energy content of natural gas and oil combined, including the oil sands. Coal-bearing formations underlie 304,000 km² or 46% of Alberta’s total area, making the formations larger than the United Kingdom. Alberta’s coal resource is estimated to be greater than 2 trillion tonnes.

Since the deregulation of the Alberta electricity market in 1996, electricity supply has been dominated by coal. It accounted for 51% of electricity generation in 2015 and 39% of the current generation capacity in the province. Alberta’s electricity sector accounted for 17% of its greenhouse gas (GHG) emissions in 2013. Coal-fired plants are the primary source of these emissions. Against this backdrop, a newly elected provincial government in May 2015 brought a change to the political leadership and also to the provincial climate change policy. In June 2015, the provincial government introduced bold new changes to the Specified Gas Emitters Regulation (SGER). The emissions levy was increased from the original CDN15/tonne (US$11.19) to CDN30/tonne (US$22.13) by 2017. Additionally, a higher performance criterion was put in place: By 2017, emissions intensity must be reduced by 20% from an established baseline, as opposed to the original target of 12%. In November 2015, the government articulated the following points relevant to the electricity sector, as part of its Climate Leadership Plan:

- Mandated phaseout of pollutant emissions from coal-fired plants by 2030.
- Coal-fired plants will pay CDN30/tonne for emissions, based on an emissions performance standard, by 2018.
- Replacement of existing coal-fired plant capacity (6299 MW), with about 4200 MW of renewables (two-thirds of existing coal capacity) and 2100 MW of natural gas (one-third of existing coal capacity), will be achieved by 2030.
- Thirty percent of Alberta’s electricity generation (MWh) will be from renewables by 2030.
In November 2016, plans for a capacity market (by 2021) to complement Alberta’s current energy-only market system were announced.9 In the energy-only market system, generators are only compensated for the actual amount of energy (MWh) supplied to the grid. The introduction of a capacity market is intended to strengthen the reliability of supply and stabilize electricity prices, while providing an opportunity for generators to earn revenue by making generating capacity (MW) available to be dispatched when required.

In light of this new era in Alberta’s electricity market, this article aims to address the following questions: (1) What do these changes mean for coal-fired power plants in the context of Alberta’s electricity market? (2) What are the key determining factors for the successful phaseout of coal and what are the implications? (3) Are we living in a post-coal era or is a future coal resurgence possible?

To address these questions, we first need to understand the current basic Alberta economics of electricity generation as it pertains to coal-fired plants.

THE WHOLESALE PRICE OF ELECTRICITY AND ITS DRIVING FORCES

In Alberta’s wholesale electricity market, the price is determined by supply and demand forces; a price floor of $0/MWh and a price ceiling of $999/MWh are set in place. The mechanism to determine the price of electricity involves the Alberta Electric System Operator (AESO) using a merit-order system where generators offer bids to supply electricity at various prices (often related to their marginal cost of electricity generation). The AESO dispatches supply bids in ascending order of costs—i.e., the least-cost bid is dispatched first, and so on—to service demand. The last bid dispatched within a one-minute time frame sets the system marginal price (SMP). Finally, the average of the SMP for each minute in a given hour sets the hourly pool price. The hourly pool price is used to compensate all generators that supply electricity in a particular hour.10 An exception occurs when a supply bid was dispatched for only part of an hour, at a price greater than the average price in that hour. In such a case, the AESO pays the supply bid price for that portion of that hour.10

The economics of operating coal-fired plants in Alberta are quite challenging for several reasons. First, to coincide with the oil price shock in the last quarter of 2014, electricity demand weakened (about two-thirds of Alberta’s electricity demand is industrial) as new supply capacity was about to be commissioned.8 As a result, the pool price began a steep descent and reached levels (< $CDN20/MWh) not seen in two decades.11 Second, sustained low natural gas prices make gas plants a competitive option relative to coal, particularly for baseload operations. Third, the April 2015 introduction of wind power plants into the merit-order system10,12 added downward pressure on the pool price. Wind plants have near-zero marginal costs and can afford to bid into the market at low energy prices that are uneconomic for coal. With significantly increased renewable penetration anticipated (plants with generally low marginal costs), the downward pressure exerted on prices will likely increase in magnitude. Last, the changes to the SGER resulted in a material increase in the cost of compliance for coal power plants; it is expected to rise from $CDN2/MWh in 2015 to $CDN6/MWh in 2017.13

COAL PHASEOUT IN ALBERTA: KEY DETERMINANTS OF SUCCESS

The difficult economic circumstance of coal-fired plants is not unique to Alberta; it is indicative of a broader trend in electricity markets across North America. For example, both the Electric Reliability Council of Texas (ERCOT) and wholesaler PJM® have low natural gas prices. Additionally, the increased penetration and cost-efficiency of renewables such as wind and solar are reducing the market share and competitiveness of coal significantly.14 A successful phaseout of coal by 2030 must be done in a planned, orderly fashion to ensure the reliability of the grid, affordability of energy prices, and the continued downward trend of GHG emissions in the future. This is dependent on several factors that serve as key determinants of success in the impending phaseout.

Striking a Delicate Balance

The rate at which coal is phased out vis-à-vis the rate at which gas and renewable generators are phased in is a delicate balance that needs to be carefully struck.

There are many implications to this careful balancing act. The phaseout of coal will result in gas becoming the dominant baseload energy generation option. Moreover, due to the intermittency of renewable generators, natural gas peaking plants will increasingly be relied upon to firm up supply; these peaking plants will have attendant GHG emissions during their operation. With this in mind, there is an opportunity for technological innovation that will facilitate the penetration of utility-scale low-carbon energy storage technologies (e.g., pumped hydro, redox flow batteries, sodium sulfur batteries, etc.) in Alberta’s electricity market. Energy storage has the potential to mitigate the intermittency of renewables, without the attendant operational GHG emissions aforementioned. Gas being the anchor baseload generator will also lead to the increased exposure of the grid to the dynamics of natural gas prices which, historically, have been quite volatile. Furthermore, the concentration of electricity supply from one
fuel type, i.e., gas, is likely to create the same challenges of phasing out a dominant generation option such as coal. From a GHG perspective, gas-fired plants of today are likely to be the coal-fired plants of tomorrow, as our energy economies become increasingly GHG averse. A portfolio approach that ensures sufficient diversification of the energy supply mix will provide stability for the grid in the future.

The Incentive to Build

In light of the coal phaseout, the need for additional renewable capacity in Alberta’s electricity market cannot be overstated, if the climate leadership objectives are to be realized. However, in a low-price electricity market, the incentive to build additional capacity is practically nonexistent. Addressing this issue is quite complex and presents several challenges. The Alberta government has introduced a renewable electricity incentive program (to be carried out by AESO) that will provide support for the addition of 5000 MW of renewable capacity by 2030. The details of the first auction (400 MW of renewable capacity) have been released by AESO. Some key features of the auction include: a competitive bidding process; use of existing transmission or distribution infrastructure; renewable credits provided will be indexed to the pool price, i.e., a contract for difference; and plants must be operational by 2019. As reported by AESO, the indexed renewable credits create three possible scenarios that are a function of the (winning) bid price in the auction and the pool price of the market.

In the first scenario, if the pool price is lower than the bid price—the government pays the difference to support the project. Second, if the pool price is equal to the bid price—there are no payments made by the government. Last, if the pool price is higher than the bid price—the plant owner pays the government the difference. Going forward, the competitive nature of this entire 5000-MW program and the effective apportioning of the risks involved will be crucial in creating a favorable investment environment, while also making electricity prices affordable.

Accessing the Opportunity of Change

Alberta’s electricity market is in a state of transition. This fluid state of the market has included competitive auctions for renewable energy generation, along with the planned addition of a capacity market by 2021. The capacity market, depending on the way it is designed, holds significant promise not just in enhancing the reliability of supply, but in incenting innovation. Apart from “traditional” generators (gas, hydro, wind, solar, biomass), nontraditional generators, which have baseload and load following functionalities, with low to zero GHG emissions during operation, are likely to benefit significantly from the revenue certainty a capacity market provides in a carbon-constrained electricity sector. Nontraditional technologies that hold some potential in this regard include commercial technologies such as geothermal power, as well as emerging technologies including next generation small modular nuclear reactors. These technologies create opportunities for innovation and the mitigation of greenhouse gas emissions from the electricity sector.

That said, whether Alberta’s future electricity market will encompass the nontraditional technologies as legitimate participants will become clearer as time progresses.

WILL COAL BE BACK?

Some would argue that coal in Alberta has no future and is slowly becoming a relic of the past. This argument is founded on a number of factors, but often, it does not consider that coal is a resource, not just a fuel for electricity. Coal as a resource will remain the same; recovery and production technologies will evolve. The evolution of technology in response to the economic, environmental, and social constraints will be a crucial determinant of the question: Will coal be back? In this light, several technological trends and opportunities are worth highlighting.

In the near term, before the 2030 phaseout, the co-firing of coal with other carbon-neutral feedstock such as biomass, economics permitting, provides an opportunity to lower the cost of compliance of coal-fired plants (due to the reduced GHG emissions) and utilizes potentially stranded coal assets.

The technological development and maturity of carbon capture and sequestration as well as underground coal gasification, considering their cost effectiveness, environmental performance, and social acceptability, has the potential to introduce new life into coal for the production of fuels; for example, hydrogen, synthesis gas, dimethyl ether, and others. Carbon conversion technologies that transform CO₂ into a value-added product such as fuel or cement introduce additional potential for the environmentally sustainable use of
coal. Finally, coal can be used in non-combustion applications. Current efforts are being made to extract rare earth metals from coal, which enable crucial functionalities in renewable technologies and other technology platforms such as consumer electronics and aerospace. New materials produced from coal, such as carbon foam, are alternative uses of coal that could be sustained in a low-carbon era.

CONCLUSION

For the phaseout of coal to be conducted successfully without adverse impacts on Alberta’s grid, it must be undertaken in a careful, deliberate, and orderly manner. Despite the need for new capacity to come online to replace coal-fired plants, the effective apportioning of the risks involved should be carefully considered. The future concentration of supply on one fuel type (i.e., gas), with limited diversification of the supply mix, is likely to create the same challenges currently being experienced in phasing out coal-fired plants, as energy economies become increasingly GHG adverse. Finally, we must remember that technology rose to the occasion to find ways to access and utilize coal during the Industrial Revolution. Technological innovation will be vital if coal is to have a place in an energy future with heightened environmental consciousness.6

NOTES

A. The SGer was originally introduced in 2007. It required large emitters (≥100,000 tonnes CO2/yr) to reduce their emission intensity against an established baseline, earn emission offsets or performance credits, or pay a levy of $CDN15/tonne into a Climate Change and Emissions Management Fund. The 2007 SGer is available at: www.qp.alberta.ca/1266.cfm?page=2007_139.cfm&leg_type=Regs&isbncln=9780779738151

B. Alberta’s largest gas-fired plant (800 MW of capacity) began commercial operation in March 2015.

C. PJM is the wholesale electricity market for all or parts of several northeastern states in the U.S. More information is available at: www.pjm.com/about-pjm/who-we-are.aspx

D. More information on the Renewable Electricity Program is available at: www.alberta.ca/release.cfm?xId=434069BDC1E17-D70A-8BEE-63FDAE67F6CC37EA

E. The bid price is, ideally, the lowest possible price the project developer can accept to advance the project.

F. CFOAM® carbon foam and CSTONE™ are enabling technologies for a host of next-generation material systems and components. More information is available at: www.cfoam.com/whatis/

G. The views expressed are that of the authors and do not represent the opinions of Alberta Innovates or the University of Calgary.

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New British Deep Mine to Deliver 50-Year Coking Coal Project

By Tony Lodge
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The British government’s plan to ban all coal-fired power stations by 2025 has made headlines around the world.1 Many will now close early and, with that closure, the mining, coal handling, and import facilities that once dominated British ports will become redundant. Though now in decline, this formerly large thermal coal dependency supported many deep and surface mines across Britain and supplied thermal coal internationally. Britain’s electricity supply industry is now looking to combined-cycle gas turbine (CCGT) plants, renewable energy, and new nuclear power plants in its quest to meet ambitious CO₂ reduction targets.

But the end of thermal coal mining and coal-fired electricity generation in Britain risks overshadowing significant new coal mining ambitions to supply Europe’s growing coking coal demand. The British metallurgical coal (also known as hard coking coal) resource is significant and of high quality. It is this prospect, as well as the growing markets in the recovering European steel-making sector, that has prompted a pioneering British project to propose and seek to develop Britain’s first new deep coal mine for 30 years.

West Cumbria Mining (WCM) is at the forefront of plans to produce some of the finest hard coking coal in the Western Hemisphere with production planned to start in 2020. Importantly, this coal production will not face the UK government’s high carbon taxes that have penalized thermal coal burning power plants as it will be used in the steel-making sector. This distinction is important; this is not an energy-related project, but rather a 50-year mining operation to supply the steel- and iron-making industries with high-quality metallurgical coal.

The timing of this project is important. Morgan Stanley has declared coal to be “the spectacular turnaround story of 2016”.2 On the back of Chinese coal production caps, coal prices have soared with coal vastly outperforming other commodity markets. The value of coking coal shipped from Australia, the world’s top exporter of the industrial commodity, had tripled by December 2016 to more than US$300 a metric ton for the first time since 2011. Macquarie forecasts coking coal to stabilize at around US$200 a ton, with global output of metallurgical coal remaining in high demand as steel mills source more supply.

“...a pioneering British project to propose and seek to develop Britain’s first new deep coal mine for 40 years.”

WCM has secured the rights to extract metallurgical coal from the rich offshore coal seams of the Cumbrian coast in the North West of England. The company, led by CEO Mark Kirkbride, plans to use two abandoned drift tunnels constructed to access a former anhydrite mine. These will connect the offshore coal resource with an abandoned industrial site onshore where modern, low-profile coal treatment and handling buildings will be sited. An underground conveyor will move coal to a rapid rail loader situated on the existing coastal railway less than a mile from the site.

The proposal is ambitious both in its design and output targets. It will utilize state-of-the-art technology and mining methods to achieve production of around 3 million tonnes per annum, aiming to deliver up to 2.5 million tonnes of saleable metallurgical coal product a year.3 The target seams are High Volatile Hard Coking Coals (HV HCC). They are sought by European steelmakers due to their excellent furnace performance characteristics (very high fluidity) and extremely low ash and phosphorous content.

Planning consent is being sought in spring 2017 from local government bodies to take the initial development of the project to the next phase of what will be one of the major metallurgical coal mining operations in Europe. Local political

A visual image of the proposed new mine’s surface buildings
figures strongly support the project, which will create more than 510 skilled mining, engineering, and supporting jobs.\(^8\)

Bad headlines dominated the European steel sector in 2015 with prices at record lows, but there are now signs of growing stability and rising prices.\(^3\) WCM’s product would be a core component for incorporation within a blend of other types of metallurgical coals to produce suitable coke for use in iron and steel production. Indeed, it is extremely similar in character to the premium hard coking coals mined in the eastern U.S. and currently imported and consumed by the UK and European steel industry. The WCM coal is the equivalent of US HV-A material, a key market benchmark coal for pricing purposes.\(^5\)

Consequently, the future global market outlook for HCC demand is key. World and European steel demand is set to grow significantly by 2030, particularly in the construction sector. The forecast global HCC demand to meet such growth is unlikely to be met by operating and proposed new metallurgical coal mining projects. There is a real risk of a future global shortage in HCC supply with so few new mining projects being proposed.\(^9\)

Forward planning by WCM has already identified a sea freight export facility in North East England, where its metallurgical coal can be exported easily and quickly from the deep-sea wharf Redcar bulk terminal facility into Europe. This was until recently part of the vast SSI steelworks that became an early victim of the collapse in world steel prices. This coal loading berth at Redcar is a direct 100-mile rail journey from the proposed mine. WCM will also seek to supply metallurgical coal to British steelworks which are showing signs of recovery following the recent slump in output and prices.

The mine’s development and operation will be undertaken by bolter-miners and remote operated continuous miners, working a partial extraction run-out and pocket retreat mining method. WCM argues that this method offers the greatest flexibility and can respond quickly to prevailing ground conditions to maintain consistent production levels, especially where multiple mining sections are operated.

Importantly, given local environmental considerations, the mine will have state-of-the-art low-profile surface buildings to ensure minimum visual impact. This will be in stark contrast to the large headstock and winding gear of traditional mine buildings, which can still be seen in the area where they have been preserved as a monument to the area’s industrial legacy. There will be no tips of mine discard, as this will be transported from the site by rail to a quarry where it will be crushed and screened prior to use as fill material on construction and other such projects.

Although the UK is turning away from thermal coal to generate electricity, this new project is attracting considerable interest as curious observers learn that not all coal is the same. As readers of this journal know only too well, there are various types, qualities, and consequently different markets.

As coal’s thermal markets come under greater policy strain, projects like this allow the fuel a valuable platform to demonstrate its alternative and varied uses. Consequently, it deserves the attention, focus, and support it is receiving.

\section*{NOTES}

A. Author interview with WCM CEO Mark Kirkbride, December 2016.
B. WCM has met and is working closely with Jamie Reed, local Member of Parliament, local councillors, and policy leaders.
C. Key parameters and qualities of WCM coal are equivalent to US High Volatile ‘A’ Hard Coking Coal type.
D. Analysis and forecasts provided to WCM by Wood Mackenzie.

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\url{www.cornerstonemag.net}
The Future of CCS in Norway

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The Norwegian government seeks to realize at least one full-scale carbon capture and storage (CCS) demonstration project by 2020, and three industrial carbon capture projects are about to enter the concept phase. Twenty years of experience with full-scale CCS combined with the world’s largest CCS test facility and more than 20 years of CCS research underlie the country’s ambition to contribute to further development of CCS. This article examines Norway’s efforts to mitigate CO₂ emissions by applying CCS and the importance of industrial emissions being mitigated as well as power generation CO₂ emissions.

THE ONLY TWO CCS PROJECTS IN EUROPE

In 1990, Norway implemented a CO₂ tax. This led to two CO₂ storage projects on the Norwegian continental shelf: Sleipner and Snøhvit,¹ both operated by the Norwegian oil company Statoil. Since 1996, CO₂ from natural gas production on the Norwegian shelf has been captured and reinjected into sub-seabed formations. The CCS projects on the Sleipner and Snøhvit petroleum fields are the only CCS projects currently in operation in Europe and the only projects offshore. Since 1996, up to one million tonnes of CO₂ annually has been separated during processing of natural gas from the Sleipner Vest field, and stored in the Utsira formation. Since 2014, CO₂ from natural gas production at the Gudrun field has also been separated out at the Sleipner Vest platform and stored in the Utsira formation. Since 2008, the Snøhvit facility on Melkøya has been separating the 5–6% content of CO₂ from the well stream before the gas is chilled to produce liquefied natural gas (LNG). This CO₂ is transported back to the Snøhvit field by pipeline and injected into a sub-seabed formation.

“"The Norwegian government seeks to realize at least one full-scale CCS demonstration project by 2020...”

Gassnova, owned by the Norwegian Ministry of Petroleum and Energy, was established in 2007. Its purpose is to manage Norway’s interests regarding technology development, and capture, transport, injection, and storage of CO₂, as well...
as to implement the projects determined by the enterprise. Gassnova’s work is aimed at reducing the costs of CCS, as well as advising the Ministry on CCS matters.

**World’s Largest Technology Center for CO₂ Capture**

In addition to administering the government’s full-scale projects and the CCS research and demonstration program CLIMIT, Gassnova oversees the state’s interest in the CO₂ Technology Centre Mongstad DA (TCM). TCM was inaugurated in 2012, and is still the world’s largest and most advanced test center for CO₂ capture technologies. It is a joint venture between the Norwegian state, Statoil, Shell, and Sasol.

TCM’s focus is on testing and improving CO₂ capture technology in the final stage before full-scale operation. It aims to help reduce the cost and risks of CO₂ capture technology deployment by providing an arena where vendors can test, verify, and demonstrate proprietary CO₂ capture technologies.

TCM provides access to two intrinsically different, real-life flue gases for testing: flue gas from a gas turbine power plant and flue gas from a refinery catalytic cracker, which resembles flue gas from a coal-fired power plant. The CO₂ concentration is about 3.5% and 13%, respectively, with flexibility to dilute/enrich the flue gas sources. Uniquely, this enables vendors to flexibly test their capture technologies for both coal- and gas-fired power plants, as well as on other industrial applications, using the same facility. The TCM test site is equipped with two distinct units for post-combustion capture technology verification with space available to add others.

Four companies have successfully validated their technology at TCM: Aker Solutions, Alstom (now GE), Shell Cansolv, and Carbon Clean Solutions Limited (CCSL). ION Engineering has just started its testing program.

**Industrial CCS**

Without CCS, the global climate objectives set in Paris in 2015 will be difficult to achieve. The importance of using CCS has been stated by the UN’s Climate Panel (IPCC) and the International Energy Agency (IEA). The Norwegian parliament agreed to the government’s CCS strategy when it was proposed in 2014. The strategy encompasses a broad range of activities.

Feasibility studies were completed in July 2016.³ Three companies studied the feasibility of CO₂ capture at their industrial facilities and Gassco and Statoil studied transport and storage feasibility:
• Norcem AS assessed the possibility for capturing CO₂ from the flue gas at its cement factory.
• Yara Norge AS assessed CO₂ capture from three different emission points at its ammonia plant.
• The Waste-to-Energy Agency for the Oslo municipality (EGE) assessed CO₂ capture from its energy recovery plant.
• Gassco completed a ship transport study (CO₂ fullskala transport, mulighetsstudierapport [Gassco DG2], June 2016).
• Statoil ASA completed feasibility studies of CO₂ storage at three different sites on the Norwegian continental shelf.

The purpose of the studies was to identify at least one technically feasible CCS chain (capture, transport, and storage) with corresponding cost estimates. The results from the feasibility studies showed that it is technically feasible to realize a CCS chain in Norway.

The studies demonstrate a flexible CCS chain. Instead of transporting CO₂ by pipeline to a storage site, the plan is to transport CO₂ by ship to a hub tied to the storage site. A flexible transport solution and ample storage capacity could contribute to realizing capture from additional CO₂ sources. That would mean that the initial investment in CO₂ infrastructure could be utilized by several projects.

CO₂ capture is technically feasible at all three emission locations. An onshore facility and a pipeline to the Smeaheia marine aquifer is considered the best storage solution; the CO₂ captured will be transported by ship. The cost is lower than for projects considered in Norway earlier: Planning and investment is estimated at US$0.86–1.5 billion (excluding VAT). These costs will depend on the quantity of CO₂ captured, where it is captured, and the number of transport ships needed. Operational costs vary between approximately US$42 and US$106 million per year for the different alternatives. The cost estimates are based on the reports from the industrial players and have an uncertainty of ±40% or lower.

The government’s budget proposal for 2017 includes funding for the continued planning of full-scale CO₂ capture plants on all three industrial sites. The government proposes allocating US$44 million to concept studies. The timeline is for a full-scale CCS plant to be operational by 2022 with a basis for investment decision presented in autumn 2018. The Norwegian parliament will then make a final investment decision in spring 2019.

**Industrial Emissions Sources**

In its feasibility study, Norcem (owned by Heidelberg Cement) assessed solutions for capturing 400,000 tonnes of CO₂ per year from its cement plant in Brevik. Norcem seeks to achieve zero CO₂ emissions from its concrete products in a life-cycle perspective by 2030. In this context, the company investigated the possibilities of CO₂ capture from the flue gases in cement production. In 2010, Norcem started CLIMIT-supported projects to assess alternative capture technologies. Results from these projects were used as a basis for the feasibility study.

Before the feasibility study, Norcem determined that, from the perspective of what is achievable by 2020, amine technology is the most suitable capture technology and chose Aker Solutions as its technology supplier through a broad-based technology and supplier evaluation process. Aker Solutions conducted more than 8000 hours of testing on Norcem’s flue gas, and the technology was thus considered sufficiently qualified by Norcem to remove CO₂ from its flue gas. Norcem placed particular focus on how residual heat from cement production can be used for CO₂ capture. Available heat makes it possible to capture about 400,000 tonnes of CO₂, which corresponds to approximately half of the plant’s total CO₂ emissions. This was key when designing the CO₂ capture plant. Suitable solutions have also been found for interim storage and shipping of CO₂ on the quay in Norcem’s area. When Norcem is able to capture 400,000 tonnes of CO₂ per year, in combination with the use of CO₂-neutral energy (biofuel) in production, it will be able to achieve its goal for zero CO₂ emissions from its products in a life-cycle perspective.

Yara Norge has total CO₂ emissions annually of 895,000 tonnes from its ammonia plant in Porsgrunn. The company estimates it could capture 805,000 tonnes of CO₂ from the plant per year or 90% of the plant’s CO₂ emissions. This would come on top of the annual 200,000 tonnes that Yara already captures annually and sells for use within food production.

Yara has prioritized reducing greenhouse gas emissions from its production for many years. Its primary focus has been reducing nitrous oxide (NOₓ) emissions, with major reductions...
achieved. NOx is a greenhouse gas with a high CO2 equivalent, and a worldwide agreement on NOx reductions is included in the Gothenburg Protocol, signed in 1999. Yara first examined the establishment of a CO2 capture plant from ammonia production while working on the feasibility study. The production chain for compound fertilizer starts with making ammonia. This is the most CO2-intensive step in the process.

Ammonia can also be purchased in a global market. The ammonia plant in Porsgrunn is thus in a competitive situation where the cost of producing ammonia for compound fertilizer production must be cheaper than purchasing ammonia (including transport costs). There are three primary sources of CO2 emissions from the ammonia plant. The first two come from the process of cleaning CO2 from the production stream (through absorption of CO2 in water, so-called water wash). The third source is flue gas from a gas-fired reformer. This will require a CO2 capture plant with secondary combustion technology. Yara chose not to commit to one technology supplier in the feasibility study, but rather used an independent study supplier who designed and calculated the costs for an amine-based plant using freely accessible information about the commercially available amine, monoethanolamine (MEA).

Oslo municipality, represented by the Waste-to-Energy Agency (EGE), has assessed the possibility of capturing 315,000 tonnes of CO2 per year from the energy recovery plant at Klemetsrud. This constitutes about 90% of the total CO2 emissions from the plant. Klemetsrud is planning to ramp up production, thereby also increasing CO2 emissions from the plant. EGE has assessed two different capture technologies, and chose Aker Solutions and GE as sub-suppliers in an open competitive tender process. Both GE’s and Aker Solutions’ capture technologies are based on absorption technology, but they use different types of solvents. Aker Solutions’ technical solution is based on use of their proprietary amine, whereas GE’s technology is based on chilled ammonia. Both technologies use heat pumps and steam turbines to recover and return sufficient thermal energy to allow the energy recovery plant to maintain the same thermal energy balance, thus allowing it to maintain its deliveries to the district heating grid in Oslo. Both technologies will use electricity produced at the energy recovery plant. Efficient energy integration and the use of air coolers have removed the need for establishing a cooling water system or reinforcing the electricity supply for the plant.

The Norwegian government’s strategy for CCS aims at identifying measures to promote technology development and to reduce the costs of CCS. The government’s CCS policies span a broad range of measures including funding for research, development, and demonstration; realizing a full-scale CCS facility; transport, storage, and alternative use of CO2; and international cooperation for promoting CCS.

An important purpose of the CCS strategy is to increase knowledge sharing and contribute to global deployment of CCS.

The different business sectors in Norway have in 2016 worked on their roadmaps toward 2030/2050 as support for the government in following up on its commitments made in the Paris Agreement. The industry sector in Norway is highly engaged in CCS. The Federation of Norwegian Industries’ new roadmap for the process industry contains a vision of combining growth and zero emissions by 2050. This is impossible without CCS due to emissions being unavoidable in many industrial processes. Both Norcem and Yara have contributed to the work on this roadmap.

The municipality of Oslo has adopted its own climate and energy strategy. The CCS project at its fully owned waste-to-energy plant at Klemetsrud is an important project for this strategy.

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R&D and Demonstration of CO₂ Capture Technology Before and After Combustion in Thermal Power Plants in China

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Carbon capture, use, and sequestration (CCUS) technology can potentially reduce greenhouse gas emissions on a large scale, and represents an important technological option for slowing carbon dioxide (CO₂) emissions in the future. According to studies by the International Energy Agency, application of CCUS technology is a crucial emissions-reducing measure together with improving energy efficiency and employing nuclear energy and renewable energies. By 2050, emissions reductions realized through CCUS are anticipated to account for 17% of total emissions reductions.¹-³ China’s energy structure is dominated by coal; development of CCUS technology will be an important measure to effectively control greenhouse emissions. Meanwhile, it will help promote the transformation and upgrade of the power industry.

China’s power system features centralized emissions sources and produces large quantities of CO₂ emissions. The most challenging aspect of CCUS technology is capturing CO₂ at power plants (see Figure 1). However, CCUS is also one of the most efficient ways to reduce carbon emissions. CO₂ capture technologies are divided into three categories: post-combustion capture, pre-combustion capture, and oxygen-enriched combustion.⁴ Significant R&D progress has been made on CO₂ capture technologies worldwide. However, the high cost and high energy consumption of CO₂ capture remain obstacles. This is currently where major breakthroughs are being made in...fossil fuel power generation technologies are facing a bottleneck. CO₂ capture technology provides a new approach for power enterprises’ carbon emissions.”

FIGURE 1. Technical approaches for CO₂ capture
R&D technology. Demonstration tests solve various problems in the development of this technology through practice, but also create a path for its scaled and commercial application, so as to realize its full potential for reducing carbon emissions.

China's largest power generation enterprise, China Huaneng Group, is interested in developing CO₂ capture technologies suitable for power plant conditions, including post-combustion and pre-combustion capture. The company has built and put into operation several CO₂ capture test and demonstration facilities, and is using the knowledge and information from these tests to undertake long-term operational experiments as well as the verification and evaluation of new technologies. Meanwhile, by combining fundamental application studies in experiments and engineering design reviews, mature technologies will be further expanded to adapt to future requirements on emissions reduction technologies in terms of energy consumption, scale, and reliability.

**POST-COMBUSTION CAPTURE**

Post-combustion capture refers to capturing or separating CO₂ from flue gas behind the combustion equipment. Technical approaches to post-combustion capture include chemical absorption, adsorption, and membrane separation methods. Chemical absorption, the method used most extensively, takes advantage of the acidic properties of CO₂; it normally uses alkaline solutions to absorb CO₂. Regeneration of the absorbent then takes place by means of a reverse reaction. Figure 2 shows a typical post-combustion CO₂ capture process. Through the absorbent’s absorbing process in the absorbing tower and the absorbent’s regeneration process in the regeneration tower, the CO₂ becomes concentrated.

**Development and Verification of a New Compound Amine Absorbent**

In terms of large-scale CO₂ emission reductions in coal-fired power plants, high energy consumption, easy degradation, and large loss of traditional absorbents are factors in the high application costs of CO₂ capture technology. Huaneng Group
is targeting these problems by conducting independent R&D of new absorbents, such as organic amine molecules to which Huaneng researchers are applying design evaluations on molecular structure and functional groups. The evaluations explore the impact of such factors as carbon chain length, hydroxy group location, types and positions of substituents, as well as the steric hindrance effect on the performance of absorbents. By using theoretical simulation and high-flux selection evaluation on compound formulas and pilot optimization, and by combining the evaluation and selection of the performance of absorbents, Huaneng has managed to develop a new type of energy-conserving, highly efficient absorbent with properties that feature high circulating efficiency, high absorbing load, and low energy consumption for regeneration and low steam pressure, oxidation resistance, and low corrosion.

Progressing from the experimental stage to the pilot stage, Huaneng has developed the HNC-1–HNC-5 series of absorbents, suited for use in power plants with different flue gas conditions. The HNC-2 absorbent had a three-month trial run in Beijing Thermal Power Plant’s capture device, starting in September 2011. During the pilot stage, only a slight adjustment to the operating conditions of the capture system was required. The CO₂ absorption speed increased 30% and the usage life of the absorbents improved 50% compared with the original absorbents, thus greatly reducing the cost of CO₂ capture.

In 2015, the HNC-5 absorbent was run continuously for over 4000 hours at a capture facility in Shidongkou Second Power Plant with a 120,000-t/yr capacity, and compared with MEA absorbent under the same conditions. The results showed that, under the same operating conditions, the solvent consumption can be reduced to 1kg/t CO₂ and the energy consumption for CO₂ capture was below 3.0GJ/t, 20% lower than MEA’s energy consumption for CO₂ capture. In addition, degraded products were produced at a speed of 50% compared to MEA. This absorbent can reduce approximately 20% of the overall operational costs of capture, and this system can operate consistently in the long term.

**Development of Slurry CO₂ Absorbent**

With traditional chemical-absorbing methods, a high percentage of water in the absorbent is one of the main reasons for high energy consumption for CO₂ capture. Thus, increases in temperature and volatilization of water in the high-temperature desorption process will consume a large amount of energy. To reduce water involvement in the regeneration process, Huaneng has developed a slurry CO₂ absorbent based on potassium carbonate solution (see Figure 3). Taking advantage of the difference between K₂CO₃ and KHCO₃ in solubility, by precipitating KHCO₃ through the crystallization process and by regenerating high-concentration KHCO₃ slurry, water involvement in the regeneration process can be reduced and full use can be made of steam heat to reduce energy consumption in CO₂ capture. Scaled technical tests in the laboratory have shown that the potassium carbonate-based slurry CO₂ capture technology’s energy consumption reaches 2.6GJ/t CO₂, 20% lower than MEA. In addition, the cost of loss also decreases by 22–50% compared to MEA.

![FIGURE 3. CO₂ capture process (left) and pilot plant using slurry absorbent (right)](In the schematic: 1–4, absorber; 7, crystallizer; 10, concentrator; 12, mixing tank; 17, regenerator; 21, reboiler; 5, 9, 18, 19. pump; 6, 8, 11, 13, 15, 16, valve; 14, 20, heat exchanger)
Development of Extraction and Phase-Change CO₂ Absorbent

To decrease water usage in the regeneration process, extraction concentration technology and CO₂ capture research have been combined to develop a CO₂ absorbent that can achieve self-concentration extraction phase separation. Without the need for additional energy consumption, this type of absorbent, upon loading CO₂, can automatically be divided into liquid-liquid phases, and achieve redistribution of CO₂ in these two phases (see Figure 4). CO₂ is concentrated in the phase-rich layer with a redistribution degree of more than 95%. The phase-poor layer has virtually no CO₂ load, effectively concentrating CO₂ in the rich phase with a concentration rate of 60%. Moreover, the extraction agent has limited influence on the organic amine’s speed of and capacity for CO₂ absorption. The real thermal flow heat measuring method shows that, compared to direct desorption, phase-rich desorption after layer separation can significantly reduce regeneration energy consumption by 20–30%.

Beijing Thermal Power Plant Factory’s CO₂ Capture Device (3000 t/yr)

In July 2008, Huaneng Beijing Thermal Power Plant established China’s first CO₂ capture test demonstration device with a capacity of 3000 t/yr. Since becoming operational, this CO₂ capture plant has achieved continuous and stable performance. A series of studies has targeted problems such as solution consumption, steam consumption, and system corrosion in the operation process. The system and equipment are optimized through such measures as anti-corrosion treatment, capacity expansion of the circulation cooling water system, and restructuring and recycling discharged steam water from the reboiler for reuse. In this process, the specific solution consumption and loss at each consumption point is analyzed. Corrosion types can be analyzed by taking samples and performing long-term clip-on tests. Using new types of absorbent, the capture performance has been significantly improved and the capture cost has been greatly reduced.

“Using new types of absorbent, the capture performance has been significantly improved...”

Huaneng Shanghai Shidongkou Second Power Plant’s CO₂ Capture Device (120,000 t/yr)

To verify the operational stability and the technical and economic parameters of a larger scale CO₂ capture system, Huaneng built and put into operation China’s largest coal-fired power plant CO₂ capture demonstration project, Huaneng Shanghai Shidongkou Second Power Plant’s CO₂ capture device with 120,000-ton/yr capacity, at the end of 2009.

Since it began production, a series of experiments and studies have been carried out during different seasons to test and
perfect the operation optimization over a full year. Studies on device corrosion, safe treatment of waste liquid of the absorbent, and system reconstruction also have been conducted to ensure stable operation of the device. Meanwhile, to address the problem of large absorbent consumption by every unit of CO$_2$, the integration of decarbonized flue gas pre-treatment technologies with the main unit desulfurization system is being discussed and developed, and flue gas pre-treatment devices have been installed. After using the new type of absorbing solvent, the device’s heat consumption for capture has been reduced to less than 3.0GJ/t CO$_2$ and power consumption to less than 60kWh/t CO$_2$.

“**This project is part of a first-stage technical verification at a CO$_2$ capture project in Mongstad, Norway...**”

**Changchun Thermal Power Plant’s CO$_2$ Capture Device (1000 t/yr)**

To test the adaptability of the technology of post-combustion power plant flue gas capture to the extreme cold in Changchun (northeast China), Huaneng Changchun Thermal Power Plant built and tested a CO$_2$ capture device. Completed in early 2014, this pilot device has undergone a 1000-hour continuous test on multiple types of solutions, including MEA, over the past two years, verifying the operational status of the carbon capture system in extremely cold weather, and analyzing the CO$_2$ absorption-desorption features and stability of various new solutions.

This capture device’s absorption tower uses medium-cooling technology that effectively increases the CO$_2$ absorption rate of the solution and reduces the amount of solution in circulation. The regeneration tower uses mechanic vaporization recompression (MVR) technology to effectively recycle and reuse the residual heat at the bottom of the regeneration tower, thus increasing the system’s heat regeneration efficiency while reducing its energy consumption. The impact of important operational parameters (such as the liquid-gas ratio, volume fraction of CO$_2$, and regeneration pressure) on the capture system’s regeneration power consumption was systematically studied. In addition to studying each solution’s corrosion on the system, corrosion-measuring tags were hung at the bottom of the absorption tower (rich solution), inside the disk of the middle cooler (half-rich solution), and at the bottom of the regeneration tower (hot lean liquid) to provide reliable evidence for choosing construction materials for a full-size design.

**Gas Turbine Flue Gas CO$_2$ Capture Test Demonstration Device**

Currently, in addition to the demonstration projects mentioned above, many post-combustion capture projects have been put into use in coal-fired power plants across China, with a level of technical research in line with international standards. However, R&D on CO$_2$ capture technologies for the gas turbine are still in the initial stages.

In recent years, with increasingly strict environmental standards, more and more power generation units globally have been using natural gas combined-cycle (NGCC) power generation. The promotion of R&D and the industrialization of CO$_2$ capture technologies has also become a new topic of interest. Compared to flue gases in coal-fired power plants, the concentration of CO$_2$ in gases during the NGCC power generation process is lower (approximately 3% compared to a coal gas CO$_2$ concentration of 12–15%) and the oxygen concentration is higher (13–18% vs. 5% in coal gas).

Based on the characteristics of flue gas in gas turbines, and having learned from experience with carbon capture in coal-fired
power plants, Huaneng independently developed China’s first pilot device for the capture of CO₂ from gas turbine flue gas (see Figure 5). There are plans to use the device for further R&D testing. This device is designed to capture CO₂ in NGCC flue gas, with a processing capacity of 1000 tons of CO₂/year. The main part of the system is similar to a coal-fired power plant’s capture system and adds new types of energy-conserving units such as medium cooling and mechanical compressing units. To study the problem of secondary pollution from emissions, an online system and a test device with comprehensive functions were added and continuous follow-up and sampling inspection are being conducted on the flue gas discharge.

This project is part of a first-stage technical verification at a CO₂ capture project in Mongstad, Norway, with a capacity of 1.2 million t/yr. The project is being operated in strict accordance with EU standards and management models. Under the precondition of guaranteeing a 84–91% capture rate, this device has continuously operated for over 3000 hours, with highly stable system functions and each parameter meeting the designated targets. It features low emissions of pollutants in tail gases of the absorption tower and low consumption of solvents; emission of solvents in tail gases was <0.17 ppmv and discharge of nitrite amine was <3μg/m³. No amine was identified. The discharge performance meets the environmental requirements of northern Europe.

**PRE-COMBUSTION CAPTURE TECHNOLOGY**

Pre-combustion capture technology refers to transferring the chemical energy from carbon before the combustion of carbon-based fuel and separating the carbon from other substances carrying energy, thus achieving carbon capture prior to fuel combustion. Integrated gasification combined-cycle (IGCC) technology is commonly used for pre-combustion carbon capture. IGCC combines gasification and a gas-steam combined cycle, wherein fossil fuels will gasify and transform to synthetic gas (with the main contents being CO and H₂). Then, using the water-coal gas transformation reaction, the CO₂ concentration is increased. Hydrogen-rich gas after CO₂ capture can be used for combustion and power generation, and the separated CO₂ can be compressed, purified, and then utilized or sequestered.

IGCC integrates many advanced technologies to achieve higher thermal efficiency and extremely low discharge of pollutants. It is receiving more and more attention from major power companies worldwide. Because of the high pressure and low flow volume of synthetic gases in the IGCC power generation process, the concentration of CO₂ is very high after the transformation reaction. Choosing pre-combustion capture technology will effectively reduce energy consumption and allow for a decrease in equipment size. The IGCC-based pre-combustion CO₂ capture technology is an important technical category in large-scale carbon capture demonstration projects in today’s power generation field. The CCUS plans for the Hypogen (EU), ZeroGen (Australia), and New Sunshine (Japan) projects are all based on IGCC and pre-combustion CO₂ capture.¹¹

“**IGCC integrates many advanced technologies to achieve higher thermal efficiency and extremely low discharge of pollutants.**”

In 2004, Huaneng became the first power enterprise in China to create a “GreenGen” plan for near-zero carbon emissions.¹² This plan studied, developed, demonstrated, and promoted an IGCC-based, coal-gasified hydrogen generation, hydrogen gas turbine combined-cycle power generation, and fuel battery power generation-focused coal base energy system, which would also facilitate CO₂ separation and treatment. This plan will significantly improve the efficiency of coal-fired power generation and realize near-zero emissions of CO₂ and other pollutants in coal-fired power generation.

In 2012, the first stage of “GreenGen” was completed when the Tianjin IGCC demonstration power station began operation. With an installed capacity of 265 MW, the station features the world’s first two-sectioned, dry coal powder pressure, pure oxygen combustion gasification furnace. This technology is Huaneng’s independently developed intellectual property. After a long cycle of demonstrated operation, the emissions performance of the power station has proven significantly superior to conventional coal-fired power generation units. Its major emissions parameters—dust, 0.6 mg/m³; SO₂, 0.9 mg/m³; NOₓ, 50 mg/m³—indicate that the IGCC station has reached the emissions level of a gas turbine power generation unit.

During the design stage of the IGCC power station, Huaneng also began R&D and demonstration of a pre-combustion CO₂ capture system. The technological design model of an IGCC-based CO₂ capture system was established through technical comparison and selection. The technical approach chosen used a sulfur-tolerant shift, MDEA decarbonization and purification, compression, and liquefaction of CO₂. The energy and material balance of the system were calculated using a model; the optimization of the fundamental design plan took into account the characteristics of the site.¹³ The transformation technology of this project adopts a low water-vapor
ratio sulfur-tolerant shift and makes full use of the low water content in the feed gas of the two-sectioned furnace by regulating the inlet temperature of the first section of the furnace and water-vapor ratio. The transformation furnace’s reaction depth can be controlled, achieving partial transformation of high-concentration CO\(_2\) and reduces vapor consumption and increases output. The MDEA desulfurization and decarbonization device uses the technology of sectioned absorption with lean solution and semi-lean solution. The regeneration process combines regeneration of a normal-pressure absorption tower with regeneration of the stripping tower, fully utilizing the physical and chemical absorption properties of the solutions to lower energy consumption.

"Dealing with climate change is receiving increased attention worldwide..."

This device began operation in July 2016. The CO content at the outlet of the transformation section is approximately 1%. The system has been running consistently. Calculations based on on-site operation data indicates the following: the device’s CO\(_2\) capture rate is more than 85%; the system’s energy consumption is lower than 2.5GJ/t CO\(_2\); and the CO\(_2\) capture capacity is 60,000–100,000 t/yr. After the compression and liquefaction of CO\(_2\), the next step is to conduct experiments on increasing the oil recovery rate and applying geo-sequestration. The separated hydrogen-rich gases will be compressed and sent into the gas turbine for mixed combustion. Relevant geological evaluation and research into CO\(_2\) injection is still underway. The pre-combustion CCUS system with the largest capacity internationally. It will be able to conduct various experiments under different loads and operating conditions, accumulating experience for exploration of CCUS technologies with low energy consumption and high recycling rate.

CONCLUSIONS

Dealing with climate change is receiving increased attention worldwide, but the sustainable development of traditional fossil fuel power generation technologies are facing a bottleneck. CO\(_2\) capture technology provides a new approach for power enterprises’ carbon emissions. Huaneng Group was the first in China to carry out research into capture technologies for coal-fired power plants. They are executing near-zero emissions projects with pre-combustion capture technologies and have carried out industrial demonstration of post-combustion capture in power plants. Focusing on the critical issue of reducing energy consumption and cost, Huaneng conducts application experiments on new technology and continuous operation demonstration projects of various sizes. Relevant technologies have reached an advanced standard worldwide, laying a solid foundation for Chinese power plants to use the technologies in the future.

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Coal is utilized in three ways in China: direct combustion (through coal-fired power plants and industrial boilers), coking, and gasification. Among these three methods, coal gasification is the cleanest option, and the most complex. Coal gasification accounts for 5% of China’s total coal consumption; it is a core technology in efficient and clean coal conversion, and important in the development of coal-based bulk chemicals (chemical fertilizers, methanol, olefins, aromatics, ethylene glycol, etc.), coal-based clean fuel synthesis (oil, natural gas), advanced integrated gasification combined-cycle (IGCC) power generation, polygeneration systems, hydrogen production, fuel cells, direct reduction iron-making, and other process industries. Coal gasification is not only the foundation for the modern coal chemical industry, and widely used in the oil refining, power generation, and metallurgical industries, it is the common key technology of these industries.¹

R&D PROCESS FOR COAL GASIFICATION TECHNOLOGY IN CHINA

Research and development on China’s coal gasification technology began in the late 1950s. Government support has resulted in many new developments over the last 30 years, including:

- Coal-water slurry gasification technology and the construction of a pilot plant in the Northwest Research Institute of Chemical Industry;
- IGCC key technologies (including high-temperature purification) project;
- A Pyrolysis, Gasification and High-Temperature Purification of Coal project completed in 1999;
- Large-Scale and High-Efficiency Entrained-Flow Coal Gasification Technology project completed in 2009;
- Large-Scale and High-Efficiency Clean Gasification of Coal and Other Carbonaceous Solid Raw Materials project completed in 2014.

During the 9th–12th Five Year Plans the East China University of Science and Technology carried out several coal gasification projects, including:

- Development of a new model (Opposed Multi-burner, OMB) of coal-water slurry gasifier (coal consumption 22 tons of coal per day, t/d) using a pilot plant that was built in 2000 in cooperation with Lunan chemical fertilizer plant and China Tianchen Engineering Corporation (TCC); ²
- “New Technology of Coal-Water Slurry Gasification,” supported by the National High Technology Research and Development Program of China (863 Program). Two industrial demonstration plants for the OMB coal-water slurry gasification technology were built in Shandong Lunan and Shandong Dezhou, respectively. The successful operation of the 1000-ton industrial demonstration plant of Yankuang Cathay Pacific Chemical Co., Ltd. (single gasifier

The Inner Mongolia Rongxin Chemical Company Plant with the largest coal-water slurry single gasifier capacity in the world.
with a capacity of 1150 t/d of coal, 4.0 MPa), as well as the domestic large-scale fertilizer project of Shandong Hualu Hengsheng Chemical Co., Ltd. (single gasifier with a capacity of 750 t/d of coal, 6.5 MPa) demonstrated engineering feasibility of this technology;

- “New Coal-Water Slurry Gasification Technology for 2000-t/d of Coal”, supported by the 863 Program, is being used in a large-scale fertilizer plant;

- “Research and Development and Demonstration of 3000-t/d Large-Scale Coal Gasification Key Technology”, also supported by the 863 Program, is another important advancement in coal gasification technology with China’s independent intellectual property rights;

- “Research and Development of New Technologies for the Preparation of Synthesis Gas by Pulverized Coal Pressurized Gasification” project, a refractory-wall-type gasifier pilot plant, for which the operations and assessment were completed in 2004. Following this, the successful operations of the membrane-wall-type gasifier pilot plant were completed in 2007.

Moreover, Thermal Power Research Institute of State Power Corporation and others have further developed dry pulverized coal gasification technology with an industrial demonstration plant using a 2000-t/d single gasifier for power generation with a 250-MW IGCC.

The Institute of Coal Chemistry, Chinese Academy of Sciences, has developed an industrial demonstration plant for fluidized bed oxygen/steam-blown synthesis gas (syngas) production. Its bituminous coal capacity is 200 t/d (normal pressure).

Tsinghua University has also established an experimental unit for multi-stage oxygen-fed entrained bed gasification. Tsinghua University and Shanxi Fengxi Fertilizer Industry (Group) Ltd. have jointly developed the Tsinghua gasifier. The first-generation gasifier adopted the refractory brick structure and oxygen stage-fed entrained bed gasification, with seven gasifiers that are in or are about to enter operation; the second-generation gasifier adopted a membrane wall structure that reduces operating costs and broadens coal adaptability. Currently, 28 gasifiers are under construction and 7 gasifiers are operating.

At present, the OMB coal-water slurry gasification technology is the most widely used, especially in China; this is also China’s first large-scale domestically built coal gasification system.

**OPPOSED MULTI-BURNER COAL-WATER SLURRY GASIFICATION TECHNOLOGY**

East China University of Science and Technology established China’s first large-scale cold-model entrained-flow gasifier unit with the support of government and industry. Researchers studied the refractory brick, burner, and other issues, gaining an in-depth understanding of the principle, flow field, mixing process, and burner atomization mechanism of the coal-water slurry gasification process. This research resulted in a proposal to develop a multi-burner coal-water slurry gasification technology plan. Figure 1 depicts a schematic of the OMB coal-water slurry gasification process. The technology involves processing syngas from raw materials such as pure oxygen and coal-water slurry. The technical characteristics of the technology include: (1) OMB coal-water slurry entrained-flow gasifier and compound-bed gas washing and quenching equipment; (2) three-unit combination comprising the mixer, cyclone separator, and water scrubber of the preliminary purification process for syngas; (3) direct heat exchange-type wastewater treatment and heat recovery technology for evaporative separation.

**Gasifier**

The OMB coal-water slurry gasifier (Figure 2) has four symmetrical burners, located at the upper part of the gasifier chamber. This type of opposed impact gasifier overcomes the flaw of irrational residence time distribution in the single-burner coal-water slurry gasifier, as well as short residence time of partial reaction materials in the gasifier. The result is an improvement in gasification efficiency. Evidence from the research shows improvements with a high carbon conversion rate, low oxygen consumption, and less coal consumption.

In comparison to the single-burner gasifier, the OMB gasifier has obvious advantages in large-scale gasification. At present, the OMB coal-water slurry gasifier has been adopted for the Inner Mongolia Rongxin Chemical Company, the largest-scale coal-water slurry gasification plant in the world.
Process Burner

The pre-filmed structure is adopted for the process burner of the OMB gasifier. In comparison to the GE (Texaco) burner, the biggest difference is that the pre-filmed burner avoids the premixing of central oxygen and coal-water slurry in the secondary channel by reducing the central oxygen channel. The pre-filmed burner’s advantages are good atomization performance, simple structure, low velocity of coal-water slurry outlet, and its ability to reduce or avoid wear and tear. The demonstration proves this new type of burner has excellent technological results and long service life. At present, the service life of pre-filmed process burners can reach about 90 days on the average. At Yankuang Cathay Pacific Co., Ltd, the longest service life of such a burner was 152 days.

Syngas Washing and Quenching System

Raw syngas produced in the gasification process at a high temperature with a large quantity of slag enters the washing and quenching chamber located below the gasification chamber for quenching, washing, and humidification. The compound-bed washing and cooling chamber contains a spray bed and a bubbling bed. The spray bed is formed by the washing and quenching ring and the dip tube, and the bubbling bed formed between the bubble breaker and the metal shell. This type of washing and quenching chamber abandons the traditional riser. With several bubble breakers installed in the bubbling area, the effects of air bubble breakup and gas-phase dispersal are realized, promoting the formation of a homogeneous gas-liquid mixture, the reduction of liquefied gas, and slag separation through sedimentation. Industrial plants demonstrate the advantages of the spray-bubbling compound bed in terms of washing and cooling efficiency, load adaptability, and operational stability.

Preliminary Purification System for Syngas

The preliminary purification of syngas based on the OMB gasification process adopts the idea of purification in stages; the ash carried by the syngas is passed through the mixer and the cyclone separator for elementary separation. Subsequently, the ash undergoes further separation of fine particles in the water scrubber. This reduces system pressure drop, prevents clogging of the purification system, and greatly reduces the solid content (<1 mg/Nm³) of the syngas in the system. The operation results indicate a system pressure drop upon preliminary purification of the syngas in stages of ≤0.1 MPa. The amount of ash content in the syngas from the scrubber is low and it can directly enter the transformation section without any pre-transformation after the separation of coarse particles in the cyclone separator. Other benefits are improving the water quality at the bottom of the washing tower without any blockage of the quench ring, and preventing the phenomenon of pressure drop increasing in the conversion furnace catalyst.

Wastewater Treatment System

The evaporative hot water tower is key equipment for the wastewater treatment system in the OMB gasification process. The black water undergoes flash evaporation upon a reduction in pressure in the evaporation room of the hot water tower. The steam enters the hot water chamber for direct heat transfer with the gray water and results in an improved heat transfer effect. In addition, this prevents fouling. The operation results show that the temperature between the flash steam exported from the evaporative hot water tower and high-temperature gray water is with a temperature difference of <4°C. The smaller design of the system reduces the need for pumping. Consequently, in comparison to single-burner gasification process, there is less rotating equipment which improves operational reliability.

Continuous Feeding Operation Under Pressure and Online No-Fluctuation Switching of Gasifiers

A set of independent feed systems (including an oxygen and a coal slurry feed) is used for each set of opposed process burners of the OMB coal-water slurry gasifier. When a pair of burner feeding systems malfunctions, the work can be suspended to carry out repairs, and the pair of feeding systems can reoperate again after the malfunction is fixed. Throughout the entire process, the other pair of burner feeding systems maintains normal operation, and ensures that the gasifier
is only working under a reduced-load condition without the need to fully stop the whole process, thereby greatly reducing the risk of stoppage.

The online no-fluctuation switching of the gasifiers can realize no fluctuations in the upstream and downstream load capacities during switching operations. During the switching process, the continuous feed feature under pressure using this type of gasification technology has advantages. Stoppage and commencement of operations for the two pairs of burners can be carried out successively through the in-operation gasifier and the active-standby gasifier, thus achieving the switching of gasifiers. This mode of operation greatly improves the operational stability of the gasification system and significantly reduces the consumption of raw materials in the switching process.

Figure 3 depicts a typical load variation curve of two OMB coal-water slurry gasifiers (one in operation and one on standby) in the switching process. The figure shows that, where there is an increase of approximately 15% production capacity in the air separation unit, the gasification plant can guarantee the completion of the switching operation between two sets of gasifiers under a minimum production capacity of 85% of the downstream gas supply. The entire system is smooth and controllable throughout the switching process.

For each numbered point:

1. A (operating) gasifier starts to ramp down from 100%
2. The air separation unit (ASU) starts to ramp up from 100%
3. ASU with 115% production rate
4. ASU starts to ramp down
5. ASU back to 100% production rate
6. B gasifier starts to 100% production rate
7. A gasifier with 85% production rate
8. A gasifier shuts down 2 (opposed) burners
9. B gasifier with 4 burners operating
10. A gasifier shuts down other 2 burners (all burners shut down)
11. B gasifier starts up with 30% capacity (60% of design capacity of single burner), operating pressure starts to increase
12. B's pressure reaches designed pressure value, B's syngas combined with A's syngas and flow downstream
13. A gasifier totally shuts down

**Application of OMB Coal-Water Slurry Gasification Technology Project**

China’s first large-scale coal gasification technology project was established in Yankuang Cathay Pacific Chemical Co., Ltd. in 2005. Using OMB technology provided a viable alternative and reduced the monopoly on advanced coal gasification technology by international multinational companies.

In 2014, the Inner Mongolia Rongxin Chemical Company conducted a successful test run of its gasification plant. The plant has three OMB coal-water slurry gasifiers with single furnace capacity of 3000 t/d of coal. This coal-water slurry gasification gasifier has the largest coal capacity per gasifier in the world. Since 2015 two gasifiers have operated at full capacity and are currently operating without any gasifier problems.

Compared to other coal-water slurry gasification technologies from overseas, the OMB coal-water slurry gasification technology has greater advantages in areas such as large-scale single-furnace processing, system performance indicators, stability and reliability, and patent licensing fees. The OMB technology is operating with 60 coal-water slurry gasifiers with a further 68 under construction in China and in the U.S. and South Korea. The maximum design capacity of a single gasifier has reached 3150 t/d of coal (dry basis).

East China University of Science and Technology concluded a technology licensing contract with Valero Energy Corporation, the largest oil refining company in the U.S., in 2008.
technology licensing fee amounts to more than RMB100 million.\(^7\) In September 2016, another technology license was implemented with Korea’s TENT Company.

The OMB coal-water slurry gasification technology advantages include high carbon conversion rate, facilitation of large-scale processing, and stable and safe operations. The OMB coal-water slurry gasification technology is one of the three internationally recognized coal gasification technologies, ranking with those of Shell and GE.\(^8\)

### PULVERIZED COAL GASIFICATION TECHNOLOGY

Coal-water slurry gasification technology requires coal with better slurry flowing compared to pulverized coal gasification technology, which is more adaptable to a wider range of coals. China has also been developing pulverized coal gasification technology.

### Pressurized Two-Stage Pulverized Coal Gasification Technology

Pressurized two-stage pulverized coal gasification technology was developed by Xi’an Thermal Power Research Institute Co., Ltd, which built a 36-t/d pilot plant built in 2005. A demonstration of 2000-t/d dry pulverized coal gasification technology was carried out at the Tianjin 250-MW IGCC Project which began operating in 2012.

### Aerospace Furnace (HTL) Gasification Technology

The HTL gasifier employs the single-burner pressurized pulv-

### Pressurized Coal Gasification Technology of SE Gasifier

East China University of Science and Technology and Sinopec Group jointly developed the single-burner membrane wall pul-

### CONCLUSION

China’s research and development of coal entrained-bed gasification technology, as well as engineering demonstration, long-term and efficient operation, and further large-scale projects, strongly supported the development of modern coal chemical industry. China possesses the largest coal-slurry gasifier in the world, and coal gasification technologies are internationally recognized. The establishment of large coal-water slurry gasification plants with a daily capacity of 3000 tons of coal is a prelude to a larger-scale demonstration of coal gasification technology. Past, present, and future research has enhanced, and continues to enhance, industrial application of coal gasification technology in China.

### REFERENCES

Shenhua Group. The new research facility is tasked with developing and commercializing technology on shale gas conversion to value-added chemicals, carbon capture, utilization, and sequestration (CCUS), energy internet, and hydrogen energy. In addition, the new facility allows NICE to partner with leading U.S. academic/research institutions and enterprises to accelerate its clean energy development strategy.

International

In a recent article in the Indian newspaper *The Hindu*, the World Coal Association’s Chief Executive, Benjamin Sporton, highlighted that the World Bank and other global development lenders such as the Asian Development Bank are not financing clean coal projects. He pointed out that not investing in supercritical and ultra-supercritical plants is resulting in countries building less efficient subcritical plants with much higher CO₂ and particulate matter emissions. He also noted that, without financial support from international global lenders, India and other developing countries would be unable to meet their Paris Agreement targets. Mr. Sporton stated: “India’s Paris commitment includes building more supercritical and USC plants and the international banks must help them do that. The Intended Nationally Determined Contributions submitted by 19 countries—India included—said they were going to use coal.”

On 29 November 2016, the ASEAN Centre for Energy (ACE)—an independent intergovernmental organization within the Association of Southeast Asian Nations’ (ASEAN) structure that represents the 10 ASEAN Member States’ (AMS) interests in the energy sector—held a webinar titled “Coal in ASEAN After the Paris Agreement”. A blend of regional and international perspectives was shared by the panelists from the Ministry of Energy and Mineral Resources of Indonesia, Chulalongkorn University on behalf of Ministry of Energy of Thailand, the World Coal Association, and Global CCS Institute. The ASEAN region is one of the fastest growing economic regions in the world. The ASEAN region will continue to depend on fossil fuels, with coal as the main energy source to meet the increasing electricity demand, due to its high availability and low costs. A key message from the webinar was that there is a need for international community support to implement high-efficiency, low-emissions (HELE) and CCS technologies in ASEAN, so the region can contribute to the Paris Agreement while meeting the needs of its economic growth. The recording video, presentations, and related materials from the webinar can be accessed at www.aseanenergy.org

International Outlook

China

The National Key Research and Development Plan “Ultra-supercritical Circulating Fluidized Bed Boiler Technology Research and Development and Demonstration Project” started in Beijing in October. The four-and-a-half-year project is led by Shenhua Group, with 16 organizations in China participating in research and development. This project will research improvements for 660-MW ultra-supercritical circulating fluidized bed boilers and furnaces. The aim of the project is to promote large-scale clean combustion of China’s low-grade coals.

United Arab Emirates

In the United Arab Emirates (UAE), construction has begun on the US$1.8 billion Hassyan clean coal plant. The first phase of the project will be the construction of 1.2 GW. The first 600-MW unit is expected to be operational in 2020, with the second 600-MW unit coming online a year later. By 2023 a total of 2.4 GW will be generating electricity. The Dubai Electricity and Water Authority plant will provide a 12.5% boost to Dubai’s current grid capacity on completion. The aim is that 7% of electricity in Dubai will be generated by coal by 2030.

U.S.

The election of Donald Trump as President and the Republican majorities in Congress have the potential to change the energy regulatory landscape in the U.S. As a candidate, Trump indicated his administration would not implement the Clean Power Plan advanced by the Obama administration. Specific changes in policy remain to be seen as Trump assembles his leadership team.

The opening ceremony for NICE America Research Inc. was held in Mountain View, California, in October. Dignitaries from the Shenhua Group, Consulate-General of the People’s Republic of China in San Francisco, U.S. Department of Energy, NICE headquarters, and the local government were in attendance. Dr. Yuzhuo Zhang, Chairman of Shenhua Group, addressed the audience, articulating his vision for the center and his excitement for the opening of NICE’s first international facility. After the ribbon-cutting ceremony, NICE signed memoranda of understanding with General Electric and Air Products to explore collaboration on fuel cells and hydrogen fueling, respectively.

NICE America Research Inc. will be the U.S. headquarters of the National Institute of Clean and Low-Carbon Energy (NICE), a R&D institute funded and administered by the Shenhua Group. The new research facility is tasked with developing and commercializing technology on shale gas conversion to value-added chemicals, carbon capture, utilization, and sequestration (CCUS), energy internet, and hydrogen energy. In addition, the new facility allows NICE to partner with leading U.S. academic/research institutions and enterprises to accelerate its clean energy development strategy.
Globally there are numerous conferences and meetings geared toward the coal and energy industries. The table below highlights a few such events. If you would like your event listed in Cornerstone, please contact the Executive Editor at cornerstone@wiley.com

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There are several Coaltrans conferences globally each year. To learn more, visit www.coaltrans.com/calendar.aspx

Recent Select Publications

20 Years of Carbon Capture and Storage – Accelerating Future Deployment — International Energy Agency — This report reviews progress with CCS technologies over the past 20 years and examines their role in achieving 2°C and well-below 2°C targets. Based on the International Energy Agency’s 2°C scenario, it also considers the implications for climate change if CCS was not a part of the response. And it examines opportunities to accelerate future deployment of CCS to meet the climate goals set in the Paris Agreement. The full report is available at www.iea.org/publications/freepublications/publication/20YearsofCarbonCaptureandStorage_WEB.pdf

Ribbon-cutting ceremony for NICE America Research Inc.
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CCS can achieve significant decarbonization when applied to fossil fuel power generation technology…

(Image Courtesy of Styrk Tronsen)