Digital, Interconnected Power Plants to Improve Efficiency and Reduce Emissions

Jim Sutton
Senior Manager, GE Power Boiler Services

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Juggling Development Objectives and the Role for Coal after the Paris Agreement

Powers of Perception: The State of the Art and Future of Sensors in Coal Power

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The technology that surrounds us is getting smarter—smart cell phones, smart grids, smart transportation, just to name a few. In fact, smart technologies are changing and shaping our lives in ways of which we are often not aware, as they increasingly become part of the infrastructure impacting day-to-day life.

As a traditional and important energy resource, coal and coal-related sectors are no exception. Smart technologies now encompass the entire coal life cycle. Smart mines and power stations are two examples, which are extensively developed around the world. Advances in sensor technologies over the last decade are giving control systems access to a continuous stream of real-time data from previously inaccessible regions of the plant. Modern advanced coal-fired power stations can be operated and monitored more efficiently and effectively due to the use of smart technology. Research and development are enabling the use of advanced analytics to improve operations in coal-fired power plants dramatically, by reducing fuel consumption, improving reliability, and reducing emissions.

GE has developed a new equipment-agnostic technology called the “Digital Power Plant”. If used globally by every existing coal-fired power plant, this technology could result in lowering greenhouse gas emissions by 500 million tonnes—equivalent to taking 120 million cars off the road. In the U.S., EPRI’s I4GEN (Insight through the Integration of Information for Intelligent Generation) aims to create a digitally connected and dynamically optimized power plant and to identify the tools to enhance performance, reduce failures, increase availability, improve flexibility, and minimize costs.

Smart technologies are now in play even before the coal arrives at the power plant. Smart mining technology makes coal mining more efficient, and safer, for miners and also enables extraction of coal that could not be mined in the past. In Australia, CSIRO has developed a suite of enabling technologies and systems to allow longwall mining equipment of any brand to be automated using inertial navigation system technology.

This issue of *Cornerstone* offers a wide range of articles that discuss coal and smart technologies. I hope it informs and encourages readers to understand the exciting developments happening globally in smart technologies within the coal sector.

This is the first issue with a new editorial team. As Executive Editor of *Cornerstone*, I am fortunate to have three smart new colleagues on board: John Kessels, Executive Editor; Dr. Han Meiling, editor; and Dr. Zhai Xiaoling, editor. It is our great honor to serve in these roles and to continue telling the story of coal.

On behalf of the new editorial team, I would like to take this opportunity to thank Dr. Holly Krutka and her team for their previous contributions.

On behalf of our team, I hope you enjoy this issue.
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GLOBAL NEWS
Covering global business changes, publications, and meetings
Countries around the world face a tremendous challenge in providing ample clean water, sustainable food supplies, and jobs to their citizens, while protecting the environment. Central to this challenge is managing and improving the power production infrastructure. Today, and for the foreseeable future, coal-fired power plants play a pivotal role by providing low-cost electricity to much of the world. Natural gas and renewables are growing in importance and are changing the ways in which traditional power plants operate. The rate of change in the electricity production business is unprecedented and is creating new opportunities for digital, interconnected, more intelligent power plants that are better able to meet these new requirements.

“The rate of change in the electricity production business is unprecedented and is creating new opportunities for digital, interconnected, more intelligent power plants that are better able to meet these new requirements.”

By Jim Sutton
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Product Manager, GE Power Digital
GE believes digital solutions will provide this intelligence, transform the industry, establish new business models, and create unprecedented opportunities to address global energy challenges. Over the next decade, the International Data Corporation has projected that approximately ~US$1.3 trillion of value will be captured as part of this transformation. With software and data analytics, combined with advanced hardware, new digitally enhanced power generation will deliver greater reliability, affordability, and sustainability. This can help lower costs, improve efficiencies, create growth opportunities, and reduce CO₂ output.

Advanced analytics can dramatically improve operations in coal-fired power plants by reducing fuel consumption, improving reliability, and reducing emissions. If deployed at every existing coal-fired power plant globally, this new equipment-agnostic technology, “Digital Power Plant for Steam” software, could eliminate 500 million metric tons of greenhouse gas emissions—the equivalent of removing 120 million cars from the road.

**TECHNOLOGY AS IT STANDS TODAY**

Modern coal-fired power plants rely on a complex network of sensors, actuators, digital controllers, and supervisory computers to operate and coordinate each of the plant subsystems. Hundreds of feedback control systems serve to monitor plant processes and perform appropriate control actions, aiming to maintain optimum operating conditions regardless of system disturbances, such as changes in coal quality or electricity demand. However, the highly interactive nature of power plant parameters—where one parameter can affect many others—means that control is highly challenging, and plants are often not operated to their potential capabilities.

Power plants utilize a distributed control system (DCS)—an automated system that monitors and coordinates different parts of a power plant—to start and keep the plant running amid these changes. DCS is the most commonly used method of controlling the components in a modern plant, having replaced pneumatic, analog, and discrete controls.
DCS-enabled power plant controls perform quite well. Although advanced control is possible, most power plant DCS implementations use a basic scheme known as proportional-integral-derivative (PID) controller. A PID controller continuously calculates an error value, defined as the difference between a measured process variable and a desired set point. The controller attempts to minimize the error over time by adjusting a control variable—such as the position of a control valve, a damper, or the power supplied to a heating element—to a new value based on a mathematical algorithm. This PID control algorithm does not require information about the power plant operational process; it simply reacts to errors and adjusts the controlled elements to minimize errors over time.

The main disadvantage of this controls approach is that it is difficult to implement for the process of optimizing multiple variables. For example, a power plant operator may hope to reduce NO\textsubscript{x} and CO while improving heat rate and superheated steam temperature balance. To achieve this, DCS suppliers have included the provision for operators to “bias” the controls. In this way, basic controls continue to operate well, but power plant operators are able to use their knowledge of the process to fine-tune the controls to meet their operational goals.

### THE PLANT OF THE FUTURE

GE envisions a more comprehensive analytic solution that builds on historic plant DCS and data historians to deliver improved outcomes for plant efficiency, low emissions, and reliable generation. In a recent GE survey of over 100 power generation executives, 94% of those surveyed believe that the internet and improved analytics will transform their industry in the coming years. GE fully agrees and is developing both an overall web-based computer analysis environment (or enterprise tool), called Predix™, and the individual applications that will provide the improvements. Predix™ is GE’s operating system for digital analytics for large machines that will manage data and supply tools to allow developers to easily create beneficial software applications. GE is now delivering many Predix™ applications. For the power industry, and coal-fired power plants in particular, some Predix™ applications are described briefly below.

**Asset Performance Management (APM):** A power plant consists of many assets, such as a boiler, a generator, a turbine, a boiler feed pump, or a coal pulverizer. Each asset has condition data that is already being measured and recorded. The goal of this application is to transform machine sensor data into actionable intelligence by combining robust analytics and domain expertise. This predictive information drives toward the ultimate goal of zero unplanned downtime and an optimal maintenance schedule.

**Operations Optimization (OO):** In any power plant, each of the plant assets must work together to accomplish the overall goal of efficient production at the system level. The goal of OO is overall improvement in client operations with performance visibility across power plant and fleetwide footprints, providing a holistic understanding of the operational decisions that can improve efficiencies, reduce emissions, expand capabilities, and lower production costs. Some of these optimizations can be performed immediately by local interfaces with the plant DCS.

**Business Optimization:** With the increase in complexity of maintaining a stable generating grid, many regions are requiring power producers to correctly forecast and price the power being produced. This is a challenge for the operations team, who may have limited tools. This application provides intelligent forecasting and portfolio optimization to enable trading and operations teams to make smart business decisions that reduce financial risk and maximize the profitability of the fleet.

**Cyber Security:** GE’s advanced defense system is designed to assess system gaps, detect vulnerabilities, and protect the customer’s critical infrastructure and controls in compliance with the various national-level cybersecurity regulations.

**Advanced Controls/Edge Computing:** This application allows plant operators to leverage data and analytics to manage grid stability, fuel variability, emissions, compliance, and other challenges that affect machine performance, as well as to execute fast starts and efficient cooldowns to meet dispatch and market demands. The ability to perform in this manner will be critical in a world that maximizes renewable power sources with their inherent variability.
**Predix™:** As previously described, Predix™ as an overall platform allows application developers to safely and securely access plant information and build apps to improve any aspect of system performance. Predix is an open architecture that allows both GE and independent developers to use built-in analytic tools to quickly build the apps.

Predix Operational Optimization for Boilers™ is one of the many smart technologies being developed and offered by GE that could be useful for many coal-fired power plants and is explored in greater depth below.

“Fast, optimal adjustments can be made using an accurate predictive model of the boiler processes.”

Today, boiler modernization is focused on more than NO\(_x\) reduction or heat rate. Goals are varied and the systems are asked to address a more diverse problem set. For example, boilers are challenged to control emissions, but also to deliver improved fuel efficiency and integrate complex air-staged combustion systems with different types of air quality control systems, such as complex combustion systems, selective catalytic reduction (SCR) systems, or selective non-catalytic reduction (SNCR) systems. Operating envelopes have expanded, intermittent renewables are increasing, and coal-fired power plants are being asked to ramp faster and also to ramp down to lower electricity output than ever before.

Predix Operational Optimization for Boilers™ is an analytic system that models how power plants respond to various inputs. Understanding how the interrelated systems interact allows a software solution to provide control biases—or set-points—to the DCS that improves performance. The software runs on a server at the power plant and communicates directly with the DCS. A coal power plant has multiple objectives: limiting plant emissions, achieving certain steam temperatures, while ensuring that the power plant operates as efficiently as possible. Predix Operational Optimization for Boilers™ understands multiple objectives and reacts much faster and more accurately than a human operator can because of the complex interactions and volume of data that must be assessed.

The basic configuration of the application is shown in Figure 1; the system builds models of power plant performance that predict what the plant’s state will be for the given set of inputs. As one example, the application is able to predict the likely values of the gaseous emission CO based upon current operating conditions. Predix Operational Optimization for Boilers™ can also model the impact of the various parameters on heat rate. With this understanding, the software issues optimal bias-to-set-point signals to the DCS that both improve plant heat and ensure that CO emissions do not exceed plant requirements. This is a considerable improvement over traditional plant controls that typically do not take CO into account or include heat rate as an explicit optimization target.

Fundamental to the operational improvements offered by the software is the ability to build mathematical relationships that model the process behavior. Fast, optimal adjustments can be made using an accurate predictive model of the boiler processes. Several types of models are used in the Predix Operational Optimization for Boilers™ system, as summarized in Table 1.

**CUSTOMER OUTCOMES**

More than 120 installations of this boiler optimization technology have been installed and continue to be supported by GE on coal-fired boilers. Most of these clients are top utilities in the U.S., although there is now significant growth internationally. One example of a successful installation occurred at Calaveras Power, JK Spruce Station Unit Number 1, located near San Antonio, Texas. The unit is a 600-MW tangentially fired coal unit originally manufactured by GE in 1990. The Ovation™ control system was manufactured by Emerson.

The results from the optimization are summarized in Table 2, where several key performance indicators (KPIs) are listed at full load conditions. The first two KPIs are heat rate and boiler efficiency. Heat rate measures how much heat input from the fuel is required to produce a kWh of electricity. A lower heat rate is better as it means less heat input (less fuel) is required to
produce the same amount of electricity. Examining this KPI in the table in more detail, the next column lists the average heat rate achieved by the plant during periods where the optimizer was not running. The next column lists the average efficiency achieved with the optimizer turned on. As can be seen, with the optimizer turned on, the plant was able to achieve a lower net plant heat rate of 9557 Btu/kWh, or a 1.08% improvement in heat rate. The second KPI focuses on the overall boiler efficiency, which looks at boiler performance separate from the overall plant performance.

The next two lines in Table 2 describe KPIs associated with gaseous emissions. Significant improvement was made in reducing NO\textsubscript{x}, a key objective of the optimizer. The average value of CO emissions increased somewhat but CO was reliably maintained below the target maximum value of 125 ppm. The next KPIs are related to the actual superheated and reheated steam produced by the boilers. With the neural net in operation the plant was able to get close to the ideal steam temperature for this plant, 1005°F, without exceeding it. Particularly important is the reduction in the need for reheat spray flows. Reheat spray flows deteriorate plant efficiency. This KPI was improved by 4.25%. Superheat spray flow was increased by 6.99 klb/hr, but this does not impact plant efficiency in the same way as reheat spray.

Figure 2 shows how operation heat rate varies with the
optimizer on versus off at several different loads. With the optimization software off (green), the heat rate is the highest, meaning the boiler was the least efficient. With the software on (blue) the heat rate was improved. As can be seen in the figure, improvement was made at all loads but the biggest gains were at high loads and low loads.

These results were achieved by maintaining proper fuel and air control, which is critical to achieving efficient combustion and cost-effective compliance with environmental regulation. Figure 3 shows how the software can improve efficiency while reducing NOx emissions by controlling the fuel/air ratio.

**OPTIMIZED UPGRADES**

The availability of digital solutions that optimize performance now allows GE to make more comprehensive upgrade offers that give greater value than solely providing the equipment. One example of this is low-NOx upgrades. Previously, GE had been limited to providing OEM low-NOx burner, SCR, and SNCR hardware as stand-alone packages with manual commissioning services. For low-NOx system upgrades, over 700 burner upgrade projects have been commissioned, and over 100 upgrade projects have been successfully implemented for post-combustion SCR and SNCR. With the robust closed-loop optimization system, it is now possible to offer full packages with SNCR and SCR that not only minimize NOx, but allow optimization of boiler heat rate, while minimizing the cost of sorbent needed in the SCR or SNCR.

The robust nature of the neural network software also allows GE to identify wear in key components, such as coal pulverizers. This ability to understand the condition and operating circumstance allows GE to offer more comprehensive multi-year service agreements that provide specified performance and reliability assurances.

**SUMMARY**

Coal-fired power plants are an important part of the global infrastructure to produce electricity and face increasingly challenging operating requirements. In high-growth areas such as China and India, new high-efficiency coal plants are coming online. There is a real need to ensure that these plants, along with the massive installed base, operate with maximum efficiency and minimum emissions throughout their lifetime. Additionally, coal-fired power plants face the increasingly challenging generation mix that includes renewables. More renewables on the grid mean that power plants will need to ramp up and turn down as never before. Tighter emissions regulations also mean that more variables must be tightly controlled. Tomorrow’s smarter power plants can simultaneously address these multifaceted challenges with digital controls.

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**Figure 2.** Optimizer on versus off at different loads

**Figure 3.** Predix Operational Optimization for Boilers™ helps power plants run in their optimal operating window.

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Developing Conventional and Alternative Energy in China

By Zuo Qianming
Chief Analyst of Coal Industry, Cinda Securities Co., Ltd.

Energy is the foundation of China’s economy; thus, it impacts every facet of national, economic, and social development. China’s economy is entering a period of new economic growth and energy demand after a downturn. There are numerous perspectives on the best pathway to develop various sources of energy, especially on how best to increase alternative energy sources instead of fossil fuel-based energy. During China’s energy transition, it is important that various energy strategies be thoroughly considered.

Energy is strategically linked to the development of the global economy and society. In 2014, the global consumption of primary energy grew by 0.9%, lower than the average growth rate of 2.1% over the previous decade. Although China’s energy consumption had been expanding, there was a clear reduction in energy consumption in China as a result of the global economic downturn.

The combustion of conventional fossil fuel energy, especially low-quality coal in unabated systems, can result in air quality issues. In addition, the emphasis on decarbonization is growing. Scientists and policymakers are examining options to develop alternative energy sources. However, alternative energy development is closely tied to policy-based subsidies, which can come at a high cost and impact to the economy. Moreover, intermittent alternative energy sources, such as wind and solar, are not able to be stored economically. Thus, in China, alternative energy sources are used for auxiliary energy and cannot replace fossil fuels, especially coal, at present.

In the “New Urbanization Plan of China (2014–2020)”, an active, steady, firm, and orderly urbanization strategy was proposed. By 2020, the strategy suggests 60% of permanent residents will live in urban areas, and as the pace of industrialization and urbanization quickens, energy demand will rapidly grow. The use of fossil fuel energy and alternative energy sources are not mutually exclusive. Both types of energy can be developed to meet China’s increasing energy demand and will be needed in an increasingly urbanized country.

“A key factor in the long-term plan of meeting energy demand in China is to continue the improvement and deployment of clean coal utilization.”

THE CURRENT LAG IN CHINA’S ENERGY DEMAND IS TEMPORARY

According to the “National Economic and Social Development Statistical Bulletin 2015” published by the National Bureau of Statistics of China, China’s energy consumption for 2015 grew by 0.9% year on year to 4.3 billion tonnes of standard coal equivalent, the lowest growth rate since 1998. The output for raw coal fell for the second consecutive year by 3.3% year on year to 3.75 billion tonnes. Coal consumption fell by 3.7%. Total power generation for the year was 5.81 trillion kWh of power, with 4.24 trillion kWh of coal-fired power, a drop of 2.7% year on year. The national installed capacity for coal-fired power in 2015 was 990 GW. The average plant availability time was the lowest since 1978, falling by 410 hours year on year to 4329 hours.

In my opinion, the current low energy demand is a temporary transition period of the energy mix due to structural adjustments, rather than a long-term trend. The transition from conventional to alternative power conversion reflects the changing lifestyle of people and a move of energy consumption from the manufacturing to the services industry. Emerging
industries are growing in size. The establishment of new businesses is driving innovation in China, especially the services industry. In 2015, China's services industry grew by 8.3% from the previous year, and it contributed 50.5% to the GDP; this figure was 2.4 percentage points higher than the previous year and 10 percentage points higher than secondary industries such as the mining, manufacturing, and construction sectors.

China’s electricity consumption per capita reached 4058 kWh in 2015, significantly above the global average of 3268 kWh. High energy-consuming industries have begun to reach their peak, but electricity consumption is expected to continue to maintain a high level.

Figure 1 shows residential electricity is increasing based on the GDP per capita and power consumption of key representative countries in 2013. These countries’ use of electricity from different sectors such as information technology, transportation, software, and the services industry is increasing. There is reason to infer that China’s future demand for energy will gradually increase with the expansion of the services industry.

China is developing strategies such as the “Silk Road Economic Belt”, and the “21st-Century Maritime Silk Road” initiatives and the “Made in China 2025” plan. As a result, the building of infrastructure for major thoroughfares in the future and the massive replacement of manpower with machines will require additional energy.

Increasing urbanization and improving standards of living with higher demand for modern technology are likely to result in additional consumption of electricity per capita. According to the China Electricity Council, the demand for electricity in China will peak post-2030. Electricity consumption per capita is forecast to at least double from current levels, as summarized in Table 1. Therefore, it is important to make strategic choices in the long-term energy mix.

DEVELOPMENT OF CONVENTIONAL AND ALTERNATIVE ENERGY

The development of more intermittent electricity sources in China will require considerable planning to ensure continued grid stability. Thus, both conventional and alternative electricity sources will play an important role.

Coal Remains Dominant

Countries consider several factors when comparing energy options, such as energy security, economic, environmental, and social impacts. It is important to maintain a balance that ensures the long-term impact of using China’s domestic energy resources is not detrimental to its economic and social development. China’s coal-based energy mix is defined by its abundance of coal and lack of oil and gas. According to the 2014 National Coal Resource Assessment, China had 5.9 trillion tonnes of potential coal resources. Coal accounts for about 94% of the country’s fossil energy reserves. This figure is far higher than the global average of 55%. For the same calorific value, the price ratio of coal to petroleum and natural gas is 1:8.3:3.2, making coal the most affordable energy source.

The development of alternative energy, including renewable energy, has proven to be relatively slow. In 2015, coal consumption accounted for 64.0%, petroleum 18.1%, and natural gas was 5.9% of the energy mix. The cumulative contribution from all alternative energy sources, including solar, hydro, wind, and nuclear power, accounted for only 12%.

According to the China Electricity Council, during the period of the 13th Five-Year Plan (2016–2020), about 200 GW of installed alternative capacity will be added. The proportion of

### Table 1. Forecast of electricity consumption in China

<table>
<thead>
<tr>
<th>Year</th>
<th>2015</th>
<th>2020</th>
<th>2030</th>
<th>2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>National electric power consumption (TWh)</td>
<td>5550</td>
<td>7700</td>
<td>10,300</td>
<td>12,000</td>
</tr>
<tr>
<td>Electric power consumption per capita (kWh)</td>
<td>4058</td>
<td>5570</td>
<td>7400</td>
<td>9000</td>
</tr>
</tbody>
</table>
alternative energy in the energy mix is predicted to be 15% by 2020. Table 2 shows development remains relatively slow.

A key factor in the long-term plan of meeting energy demand in China is to continue the improvement and deployment of clean coal utilization. The first step in China’s clean coal approach is retrofitting coal-fired power plants using ultra-low emission technologies, which results in reducing the concentration of particulate matter (PM) discharge to as low as 2.7 mg/m³ in comparison to the emissions limit of 5 mg/m³ for gas-fired power plants. The SO₂ concentration is also being reduced to 23.2 mg/m³—again lower than the emission limit of 35 mg/m³ for gas-fired power plants. Similarly, the concentration of NOₓ is made as low as 31 mg/m³, in comparison to the emissions limits of 50 mg/m³ for gas-fired power plants.

In eastern China, the cost of power generation in coal-fired power plants with ultra-low emissions is 0.45 yuan/kWh, and the cost of power generation by natural gas is 0.9 yuan/kWh. Although the modifications with ultra-low emission technologies increased the cost of power generation from coal-fired power plants by 1.8–2.6 yuan cents/kWh, the plants remain highly competitive in the market.

For new plants, the latest industrial pulverized coal boiler system has an average efficiency of 90%, only 11 mg/m³ of PM is discharged, and no more than 100 mg/m³ of SO₂ is discharged. NOₓ emissions are limited to 200 mg/m³, and the advantages are significant as compared to conventional chain grate boilers. In addition, technologies are also being developed for coal-water slurry, briquette, lignite, and CO₂ capture, use, and storage.

Therefore, a coal-dominated energy mix can fit into China’s current and future development. As the “golden decade” for growth in coal consumption closes it is clear that the coal industry will remain and play a vital role in sustainable development through higher efficiency and lower emissions.

### Increasing Alternative Energy in China’s Energy Mix

In the long term, fossil energy is non-renewable. China’s massive economy is highly reliant on energy, thus alternative energy, including renewables, must be developed to maintain the economy.

China’s commitment to peak CO₂ emissions by 2030 is a challenging one. Increased renewable energy and non-fossil energy can help achieve this peak. China aims to enhance the proportion of these energy sources to 20% in its energy mix by 2030. Recognizing the longevity of coal’s role, in the “Energy Development Strategy Action Plan (2014–2020)”, China will simultaneously continue the development of high-efficiency, low-emissions fossil energy and gradually reduce the percentage of coal consumption. For example, by 2020 coal consumption will be kept within 62% of total primary energy consumption.

There will be a higher percentage of alternative energy consumption in the future. Meanwhile, to some extent the total consumption of conventional energy will continue to increase. The meaning of development is not merely presented in terms of “quantity”; there are other important elements to consider such as system reform, structure optimization, higher efficiency, and industrial progress. Other factors considered in China’s energy planning and development are the energy mix, stage of development, environmental requirements, carrying capacity of resources, as well as technical and economic feasibility.

### Complementary Development of Energy Resources

The reform of the power sector with the development and deployment of smart technologies for the energy sector will require increased coordination to complement the use of various energy resources.

Solar, nuclear, and wind energy can be complementary with coal-based polygeneration. For instance, in coal-based poly-generation, a large amount of hydrogen is required. This hydrogen could be obtained from these alternative energy sources to power technologies such as the electrolysis of water, thermochemical water-splitting cycles, and high-temperature pyrolysis in nuclear reactors. Achieving onsite utilization of clean energy can result in avoidance of energy grid integration network problems that can result from intermittent renewables. The supply of energy can be made more stable and sustainable by building auxiliary service mechanisms and thereby achieving “load shifting”. Coal-fired power could even be backed up through auxiliary services.

### TABLE 2. Power generation capacity of alternative energy to 2020 in China

<table>
<thead>
<tr>
<th>Energy generation source</th>
<th>2015 Installed capacity (GW)</th>
<th>2020 Installed capacity (GW)</th>
<th>Average annual growth (GW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydropower</td>
<td>300</td>
<td>350</td>
<td>10</td>
</tr>
<tr>
<td>Wind power</td>
<td>130</td>
<td>200</td>
<td>14</td>
</tr>
<tr>
<td>Photovoltaic solar power</td>
<td>43.18</td>
<td>100</td>
<td>11.36</td>
</tr>
<tr>
<td>Nuclear power</td>
<td>26.08</td>
<td>58</td>
<td>6.40</td>
</tr>
</tbody>
</table>
In some cases, coal production sites may need to utilize alternative energy. In 2015, China specified in its electric power system reform scheme that power generation will be included from renewable energy, such as wind and solar energy. The coal industry can also leverage its advantages of high power consumption in coal mines, stable loads and available grids by making use of abandoned industrial sites, land surface of mines and its surrounding areas to actively explore and develop wind and solar power generation. Maximizing the use of land resources effectively can reduce the cost of power generation.

The State Council of China recently published “Opinions on Reducing Overcapacity in the Coal Industry to Achieve Development by Solving the Difficulties”. The following is stated in the document: “We will promote industrial adjustment and transformation, and encourage the use of abandoned coal industrial sites and their surrounding areas to develop wind power and photovoltaic power generation as well as modern agriculture.”

CONCLUSIONS

In summary, taking into account various factors, such as the country’s stage of development, energy resource endowment, and energy costs, the development of alternative energy and conventional energy should be coordinated to provide a stable and reliable energy supply to support the sustainable development of China’s economy and society. An energy directive for “coal-based, diversified development” is needed. The low-emissions utilization of conventional fossil energy and push to increase the proportion of non-fossil energy through developing renewables, nuclear, and hydrogen as supplements is an optimal strategic choice. This strategy will enable China to follow a path of sustainable development while ensuring energy security and meeting long term energy demand and supply.

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The Essential Role of Coal in Past and Future Economic Growth

By Roger Bezdek
President, Management Information Services, Inc.

The recently published book *The Rise and Fall of American Growth*, by Dr. Robert Gordon, has taken the policy establishment in Washington, D.C., by storm. An eminent economist at Northwestern University outside of Chicago, Gordon’s thesis is that the incredible technological innovations of the period 1870–1920 were a “one time in history” series of events that cannot be replicated. Innovations such as electricity, telephones, indoor plumbing, air conditioning, cars, airplanes, radio, sanitation, and refrigeration transformed the U.S. and the world. They were responsible for the extraordinary growth in GDP and incomes in the U.S. and globally over the past 150 years—especially the “golden period” of 1945–1970. According to Gordon, no other period in history has brought similar comparable progress, or is likely to again.

His controversial conclusion is that U.S. growth has been much slower since 1970 and will continue to be slow in the future. Thus, the U.S. and the rest of the world should become accustomed to productivity and growth rates of less than 1% annually instead of nearly 3%—a huge difference. Further, he contends that governments can take little action in terms of monetary, fiscal, tax, or other policies to measurably change this.

This is a pessimistic message with profound economic, social, and political implications. The debate Gordon has generated focuses on whether he is correct that the world faces an inevitable future of weak economic growth, or if the “techno-optimists”, such as Brynjolfsson and McAfee, predicting a bountiful future (robots, artificial intelligence, nanotech, space colonies, flying cars, etc.) are correct.

A key implication of Gordon’s work, which, unfortunately, he does not recognize, is the essential role of fossil fuels in economic growth. The extraordinary world economic and technological progress over the past two centuries would not have been possible without the use of coal and other fossil fuels.

THE MISSING LINK

A critical issue not being discussed is that nowhere in Gordon’s book does he give credit to fossil fuels or coal for the economic miracle of the past 200 years. None of the disruptive, revolutionary economic and technological innovations he identifies would have been possible without abundant, reliable, affordable energy. This is especially true of the electricity generated from coal, which powered the 19th and 20th centuries and will continue to power the 21st century, albeit likely at a lower percentage of the total energy mix in the U.S. and most other developed nations.

Gordon combined the historical UK/U.S. growth record with a forecast and overlaid a curve showing growth steadily increasing to the mid-20th century and then declining to 0.2% annually by 2100 (see Figure 1). He translated these growth rates into corresponding levels of per capita income, which for the U.S. in 2007 was $44,800 (2005 US$). The per capita income for the UK in 1300 was $1150 (2005 US$), and it took five centuries for that to triple to $3450 (2005 US$) in 1800, and over a century to then double to $6350 (2005 US$) in 1906—his transition year from UK to U.S. data. Even with the slowdown in the growth rate after 1970, the forecast level implied in Figure 1 for 2100 is $87,000 (2005 US$), almost double that of 2007.

A key implication of Gordon’s work, which, unfortunately, he does not recognize, is the essential role of fossil fuels in past and future economic growth.
fuels—especially coal—in this economic miracle over the past two centuries (see Figure 2). Between 1850 and 2010, the world population increased 5.5-fold; world energy consumption increased 50-fold; coal consumption increased over 700-fold; world per capita energy consumption increased eight-fold; and nearly all of the world’s increase in energy consumption was comprised of fossil fuels.3

Comparing Figures 1 and 2 shows that without adequate supplies of accessible, reliable, and affordable fossil energy, little of the technological and economic progress of the past two centuries would have been possible.

Notably, even with Gordon’s pessimistic assumption that economic growth will decrease to 0.2% annually by 2100, the forecast line in Figure 1 rises rapidly. Further, although GDP is becoming more energy efficient in most countries, even modest economic growth will require large increases in energy supplies both in the U.S. and, especially, in developing nations. World economic growth over the past two centuries was powered largely by coal and other fossil fuels. This raises the question: What energy sources are required to enable the world to continue to increase income, wealth, productivity, and standards of living and to lift billions of people worldwide out of poverty?

FOSSIL FUELS AND COAL AS THE KEY TO FUTURE GROWTH

The answer to the question is that fossil fuels, including coal, will remain essential global energy sources. Population and income growth are the major drivers behind the growing demand for energy. World population is forecast to reach 8.8 billion by 2035, world GDP is forecast to double, and an additional 1.5 billion people will require access to energy.4 As the world economy grows, in excess of one-third more energy will be required over the next two decades to meet the increased level of demand. According to the International Energy Agency (IEA)5 and the U.S. Energy Information Administration (EIA), fossil fuels, including coal, will continue to meet most of the world’s increasing energy needs over the next two decades. These fuels, which represented 81% of the 2010 primary fuel mix, will remain the dominant source of energy through to 2040 in all of the IEA scenarios and account for about 80% of total energy supply in 2040. The demand for coal is projected to increase substantially in both absolute and percentage terms over the next several decades. This provides the opportunity for continual global economic growth, increased incomes, higher living standards, and poverty reduction.

The electric power sector is forecast to remain among the most dynamic areas of growth among all energy markets. Electricity

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**Figure 2. World population and per capita and total energy consumption, 1850–2010, as a percentage of 2010 levels**

- Population: 5.5 times
- Per Capita Consumption: 8.9 times
- Total Consumption: 49 times

89% Non-Renewable
is the world’s fastest-growing form of end-use energy consumption, as it has been for many decades. Power systems have continued to evolve from isolated, noncompetitive grids to integrated national and even international markets. The strongest growth in electricity generation is forecast to occur among the developing, non-OECD nations. Increases in non-OECD electricity generation are expected to average 2.5% annually from 2012 to 2040, as rising living standards increase demand for home appliances and electronic devices, as well as for commercial services, including hospitals, schools, office buildings, and shopping malls. Developing countries will use the least expensive form of electricity that is available, which is usually generated from coal. Thus, we are witnessing the work of coal in action to help develop economies around the world, which is what Gordon missed in his book.

As shown in Figure 3, EIA forecasts that world net electricity generation will increase 70%, from 22 trillion kWh in 2012 to 37 trillion kWh in 2040. The world’s energy growth will continue to be in the power sector as the long-run trend toward global electrification continues. Figure 4 shows that the global share of energy used for power generation is forecast to increase from 28% in 1965 to 45% by 2035. More than a third of the growth in power generation takes place in regions where a large part of the population lacks modern access to electricity—India, other developing Asia, and Africa. These regions and countries are deploying coal for their electricity needs, thus coal will remain a key source for electricity production.

Indeed, greater utilization of fossil fuels may be required than is currently forecasted. For example, the IEA states that, even with the anticipated increase in economic growth and fossil fuel utilization, in 2030 nearly one billion people will be without electricity and 2.3 billion people will still be without clean cooking facilities.

In his concluding chapter, Gordon discusses various factors that may inhibit future global economic growth, including changing demographics, excessive debt levels, and faltering educational systems. He also identifies several policies that may increase economic growth, including less regulation. Unfortunately, none of the regulatory reforms he recommends deal with energy, energy access, or energy innovation. For example, he never discusses the harmful impact of the increasing widespread trends in the U.S. and globally toward constraining fossil fuel development, deployment, and utilization. He thus errs by failing to recognize the threat that increasing, harmful energy regulations could have on future fossil fuel production, energy costs, technological innovation, and economic growth.

“Reliable and affordable energy alone may not be sufficient for creating the conditions for economic growth, but it is absolutely necessary.”
It is impossible to operate a factory, run a store, grow crops, or deliver goods to consumers without using some form of energy, and energy means fossil fuels both now and in the future.

Access to electricity is particularly crucial to human development as electricity is indispensable for basic industrial, commercial, and residential activities, and cannot easily be replaced by other forms of energy. Individuals’ access to electricity is one of the most clear and undistorted indications of a country’s energy poverty status. Long-run causality exists between electricity consumption and five basic human development indicators: per capita GDP, consumption expenditure, urbanization rate, life expectancy at birth, and the adult literacy rate. In addition, the higher the income of a country, the greater is its electricity consumption and the higher is its level of human development and, further, as income increases, the contribution of electricity consumption to GDP and consumption expenditure increases. Thus, electricity access is increasingly at the forefront of governments’ preoccupations, especially in the poorest countries, and Figure 3 shows that fossil fuels, including coal, will continue to be required to generate the world’s electricity.

There are strong energy, environmental, and financial rationales for upgrading coal-fired power plants to achieve higher efficiencies, reduced CO$_2$ emissions, lower criteria emissions, and increased flexibility. One technology for achieving this is carbon capture and storage (CCS), which can capture up to 90% of the CO$_2$ produced by coal-fired power plants. The CO$_2$ is captured at the plant and then transported by pipeline for storage in geological rock formations. Another way to achieve these objectives is to improve plant control systems, and recent advances in sensor hardware and control software have made control system upgrades feasible. According to the IEA Clean Coal Centre, state-of-the-art process control software can produce significant efficiency improvements, 20% lower NO$_x$ emissions, and improved load dynamics and steam temperatures and result in rapid payback times for coal plant investments. Similarly, the U.S. Department of Energy has estimated that, applied to the U.S. coal fleet, incremental improvements in plant efficiency and reliability provided by control system upgrades will generate significant annual savings and reduced CO$_2$. 

"Incremental improvements in plant efficiency and reliability provided by control system upgrades will generate significant annual savings and reduced CO$_2$."

A modern high-efficiency, low-emissions coal-fired power plant.
CONCLUSIONS

Robert Gordon has convincingly shown that the process of economic growth and increasing standards of living is not a given and that maintaining the economic progress that the world has become accustomed to may be much more difficult than is generally assumed. Gordon’s otherwise commendable book is marred by three serious flaws: He fails to identify the critical role of energy in past economic growth, he fails to appreciate the essential role of energy in future economic growth, and his recommendations for regulatory reform fail to identify the reforms necessary to prevent fossil fuels from being artificially constrained in the future.

The extraordinary world economic and technological progress over the past two centuries would not have been possible without the use of coal and other fossil fuels. Further, vast increased quantities of coal and fossil fuels will be required in the coming decades both to sustain continued economic progress and to lift billions of people out of poverty. Coal was the essential energy source of the 20th century and it will continue that role in the 21st century. Just as the developed nations once relied on the most affordable and reliable energy to which they had access, the developing nations in the world are doing so. A major threat to continued global technological and economic progress is regulation that may restrict coal development and utilization resulting in billions of people continuing to be forced to live with energy deprivation and economic poverty.

NOTES

A. Although his focus is primarily on the U.S., Gordon also compares developments in the U.S. with those in other nations.

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Juggling Development Objectives and the Role for Coal After the Paris Agreement

By Milagros Miranda R.
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As of 2015 the world has a new global framework for sustainable development, supported by these four pillars: the Paris Agreement on climate change, the UN 2030 Agenda for Sustainable Development, the Sustainable Development Goals (SDGs), and the Addis Ababa Action Agenda on Finance for Development (AAAA). There are crucial and supportive links between these as the new framework calls for a holistic and integrated approach to guide actions toward achieving sustainable development.

Adopted in December 2015, the historic Paris Agreement has 178 signatures. To enter into force, however, the agreement requires ratification by 55% of countries that represent at least 55% of the global emissions reductions. Currently, only 19 countries, representing 0.18% of global emissions, have ratified the agreement.1 Notably, a second UN assessment report on the Individual Nationally Determined Contributions (INDCs) filed by each country indicates that implementation of the current INDCs would not fall within the scope of the 2°C scenario by 2025 and 2030.2 In reality, the global emissions levels as a result of these INDCs are expected to be higher compared with global emissions levels in 1990, 2000, and 2010.

The Paris Agreement’s aim is to set a low-emissions path by which the world should hold the increase in the global average temperature to well below 2°C above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5°C above such levels. This goal is further stressed in Decision 1/CP.21, which adopts the Paris Agreement and emphasizes the urgent need to address the significant gap between the aggregate effects of parties’ mitigation pledges in terms of global annual emissions of greenhouse gases by 2020 and aggregate emission pathways consistent with the agreement’s goal.1

“Fossil fuels will continue to dominate primary energy consumption for the foreseeable future increasing the urgency of CCS deployment.”

Achieving both a low-emissions path and the goals in the Paris Agreement will require countries reliant on coal to implement high-efficiency low-emissions (HELE) and carbon capture and storage (CCS) technologies.

The success of the agreement relies on the implementation of the INDCs that develop into NDCs once a country ratifies the agreement. To achieve a successful, real, and effective Paris Agreement, implementation must be ambitious and efficient. The international community should focus primarily on support and assistance to coal-reliant countries with limited resources in implementation of HELE technologies. The provision of adequate technological and economical resources will allow those countries to achieve and scale up their mitigation ambitions.

The Paris Agreement and Decision 1/CP.21 request parties with INDCs containing a time frame up to 2025 or 2030 to submit new NDCs by 2020, and to periodically increase their ambitions. In 2018, parties will meet to assess all efforts undertaken to peak global greenhouse gas emissions. These
events will mark important stepping stones toward increasing the ambitions of the NDCs.

The INDCs submitted by many countries are conditional, stating that if adequate technological and financial support is not forthcoming they will be unable to fulfill their current pledges or offer more ambitious pledges in the future.

Climate finance, technology transfer, and capacity building were potential deal-breakers to adoption of the Paris Agreement. Failure to address technological and financial support issues is likely to result in the unsuccessful implementation of the Paris Agreement. Those same issues also present difficulties for achieving the SDGs and the UN Agenda for Sustainable Development.

“Developing countries are forecast to increase their coal use to meet electrification needs.”

ENERGY AND CLIMATE ARE COMPLEMENTARY PRIORITIES

Energy is an essential enabler of development. However, 1.1 billion people globally lack access to electricity. This reality is one of the greatest challenges of our time.

Climate change and energy access are embedded in SDG 13 (take urgent action to combat climate change and its impacts) and SDG 7 (ensure access to affordable, reliable, sustainable, and modern energy for all), respectively. As countries work toward those goals, they are simultaneously working to address other development needs and priorities—some of which are embedded in other SDGs and some in their INDCs concerning mitigation and adaptation objectives.

Coal continues to play a critical role in the world economy. Globally, coal accounts for around 29% of primary energy supply and 41% of electricity generation. It is an essential raw material in the production of 70% of the world’s steel and 90% of the world’s cement, and its use will remain critical in supporting infrastructure, modernization, and urbanization efforts in the world, especially in emerging economies.

Climate change and energy are not competing priorities. Rather, climate and energy action are complementary and can be mutually reinforcing. With HELE technologies, countries can use coal more efficiently to reduce emissions while increasing energy efficiency in the electricity generation sector. Utilization of HELE technologies will enable countries to improve energy access without undermining their climate objectives. In that way, policies supporting access and deployment of modern and cleaner coal technologies will actually address climate and energy objectives.

Developing countries are forecast to increase their coal use to meet electrification needs. According to the International Energy Agency (IEA), even with a significant increase in use of renewables, coal will still be a substantial source of energy in 2040, accounting for 30% of global electricity generation. Despite reducing its share of electricity generation from 41% to 30%, coal will increase in terms of total electricity generated, reaching almost 24% growth in absolute terms by 2040.

Growth in coal power generation is driven almost exclusively by Asian economies. According to the IEA, coal is the fuel of choice in Southeast Asia, where energy demand will increase from current levels by 80% by 2040.

“One size fits all” does not apply when dealing with mitigation objectives. Availability, reliability, affordability, and energy security are the key factors that influence countries’ energy mix. Depending on national priorities and circumstances, countries will apply different policies and technologies to achieve their energy and development objectives.

Coal-using countries will continue to use it because it is affordable, reliable, and available. This is particularly true with developing and emerging economies. A major challenge for those countries is developing policies compatible both with a sustainable development path and their INDC mitigation objectives.

The IEA forecasts that, by 2040, India’s energy consumption will be more than OECD Europe combined. India, as China did before it, will fuel its economic growth with coal, because it is affordable and available. India’s INDC highlights that coal will continue to dominate power generation in the future. Its government is implementing several initiatives to improve the efficiency of its coal power plants, and future policies will focus on developing and deploying cleaner coal technologies such as supercritical and ultra-supercritical. As India’s INDC states, “Given the current stage of dependence of many economies on coal, such an effort is an urgent necessity.”

In China, India, and other developing countries, coal contributes substantially to the baseload electricity that is critical to economic growth and energy access. Moreover, coal-fired power plants can support renewables deployment, making it more viable and counteracting its intermittent nature.
Hence, moving away from coal is not a realistic solution to the climate challenge faced by developing countries which must juggle other priorities simultaneously: energy access, growing electrification rates, energy security, poverty alleviation, and other environmental objectives. Implementation of HELE and CCS technologies, however, can offer realistic options to developing countries. According to the IEA’s Coal Industry Advisory Board, “Coal-fuelled power plants are indispensable in the near future and thus more focus should be put on making coal technology more efficient and clean. It is a false notion, at least for the next 50 years, that coal-fuelled power plants can be completely replaced with non-conventional technology.”

A ROLE FOR COAL IN A LOW-EMISSIONS PATH WITH HELE AND CCS

HELE coal technologies increase the efficiency of coal-fired power plants and substantially reduce CO$_2$, NO$_x$, SO$_2$, and particulate matter (PM) emissions. A one-percentage-point improvement in the efficiency of a conventional plant results in a 2–3% reduction in CO$_2$ emissions. With supercritical and ultra-supercritical HELE technologies, power plants can achieve efficiencies of up to 42% and 45% (LHV), respectively.

China offers an example of how countries can change the way they use coal. Measures implemented in China include the adoption of high-efficiency advanced boiler technology and emissions standards for coal-fired power stations. Using supercritical HELE technologies, Unit 4 at the Zhoushan power station achieved thermal efficiency levels equal to or even better than levels achieved in some ultra-supercritical units. Similarly, the Ninghai power station utilizes supercritical and ultra-supercritical HELE technologies—and releases almost five times less SO$_2$, NO$_x$, and PM than the average coal-fired power station in China. Table 1 shows the saving rates of both plants concerning CO$_2$, SO$_2$, NO$_x$, and PM emissions.

Nineteen developing countries have recognized the importance of HELE technologies as mitigation tools by committing to their use in reducing emissions from coal-based energy generation in their INDCs. Collectively these countries are responsible for 44% of the world’s emissions and include Bangladesh, China, India, Egypt, Japan, the Philippines, and Vietnam, among others.

According to an article published in the Proceedings of the U.S. National Academy of Sciences, increase in energy demand might be driving a “renaissance of coal” in developing countries, “which is not restricted to a few particular cases but instead is a general phenomenon occurring in a broad set of countries”.

China and India are the two largest fast-growing developing countries that have increased use of coal to meet energy and electricity demand, and have also begun to switch from subcritical to supercritical and ultra-supercritical HELE technologies. Other coal-producing and consuming countries in the developing world following suit include South Africa, Indonesia, Kazakhstan, Thailand, Colombia, and Malaysia. It will be particularly important that the rest of Asia follows at a rapid pace.

Bangladesh, for example, has 121,160 MW$_e$ of coal-fired power generation capacity planned or under construction post-2015, of which 5440 MW$_e$ is planned to be ultra-supercritical. In its

### TABLE 1. Annual emission reductions of SO$_2$, NO$_x$, PM, and CO$_2$ in Zhoushan Unit 4 and Ninghai Units 5 & 6 power station in China

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<th>Zhoushan Unit 4</th>
<th>National average</th>
<th>Potential improvement amount</th>
<th>Units of saving or reduction based on 500 TWh</th>
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<tr>
<td>Heat rate (MMBtu/MWh)</td>
<td>7.77</td>
<td>9.47</td>
<td>30.62</td>
<td>million tonnes standard coal</td>
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<tr>
<td>SO$_2$ (kg/MWh)</td>
<td>0.009</td>
<td>5.571</td>
<td>2.78</td>
<td>million tonnes of SO$_2$</td>
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<tr>
<td>NO$_x$ (kg/MWh)</td>
<td>0.110</td>
<td>3.044</td>
<td>1.47</td>
<td>million tonnes of NO$_x$</td>
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<tr>
<td>PM (kg/MWh)</td>
<td>0.010</td>
<td>1.631</td>
<td>0.81</td>
<td>million tonnes of PM</td>
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<tr>
<td>CO$_2$ (kg/MWh)</td>
<td>774.94</td>
<td>994.57</td>
<td>84.82</td>
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<th>Ninghai Units 5 &amp; 6</th>
<th>National average</th>
<th>Potential improvement amount</th>
<th>Units of saving or reduction</th>
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<tr>
<td>Heat rate (MMBtu/MWh)</td>
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<td>9.47</td>
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<td>SO$_2$ (kg/MWh)</td>
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<td>5.571</td>
<td>2.7</td>
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<tr>
<td>NO$_x$ (kg/MWh)</td>
<td>0.622</td>
<td>3.044</td>
<td>1.2</td>
<td>million tonnes of NO$_x$</td>
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<tr>
<td>PM (kg/MWh)</td>
<td>0.044</td>
<td>1.631</td>
<td>0.8</td>
<td>million tonnes of PM</td>
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<tr>
<td>CO$_2$ (kg/MWh)</td>
<td>765.21</td>
<td>994.57</td>
<td>89.7</td>
<td>million tonnes of CO$_2$</td>
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INDC, Bangladesh has pledged that 100% of new coal-based power plants will use supercritical technologies by 2030. For this to happen, Bangladesh has estimated that an investment of US$16.5 billion is required.13

“Over the last 20 years, CCS has been applied to many uses and with multiple processes and fuels.”

Clearly, the transition pace from older, less efficient, and higher emission subcritical technology to more advanced HELE technology must be accelerated. However, without the needed support, the INDC pledges will not be implemented and countries will continue to allocate economic resources to subcritical capacity, thus missing a vital opportunity to slow emissions growth. Figure 1 depicts the projected CO₂ emissions reductions achievable by switching from subcritical to ultra-supercritical technologies, in India, China, and other Asian countries.

World Coal Association studies indicate it will cost US$31 billion to convert 400 GW of coal capacity from subcritical to HELE technologies in non-OECD countries by 2040, saving around six billion tonnes of CO₂ from 2015 to 2040.14

HELE coal technologies are also critical precursors to CCS. Without CCS, achieving the goals in the Paris Agreement will be more expensive.15 According to the IEA, “CCS is a critical component in a portfolio of low-carbon energy technologies aimed at combatting climate change. Fossil fuels will continue to dominate primary energy consumption for the foreseeable future increasing the urgency of CCS deployment.”16 The Boundary Dam coal-fired power station in Canada demonstrates that CCS can achieve 90% CO₂ emissions reduction.1

Over the last 20 years, CCS has been applied to many uses and with multiple processes and fuels. Industrial applications of CCS are equally important within a low-emissions path.

The IEA forecasts that, by 2050, emissions from coal-fired electricity generation need to be reduced by around 90% if the world is to achieve a 2°C scenario.17 This is doable only with implementation of HELE and CCS. All sources of energy and a varied portfolio of low-emission technologies will need to be implemented with countries’ forthcoming NDCs to achieve electricity for all.

FIGURE 1. IEA-CCC study on potential HELE impacts in Asia12

CONCLUSIONS

Governments and policymakers in countries reliant on coal and with ambitious INDC pledges will need to use and promote HELE and CCS technologies. Without their use, any transition toward a sustainable and low-emissions energy system will be difficult. International financial and technical institutions also play a critical and catalytic role in accelerating that transition. Without technical and finance support, decision makers will be reluctant to invest in the best available technologies, due to upfront capital investment costs. As indicated by the Addis Ababa Action Agenda on Finance for Development, public-private partnerships must ensure that HELE and CCS are part of national investment plans and decisions, to avoid unnecessary delays in achieving mitigation objectives.

“The Paris Agreement established a Technology Framework to provide overarching guidance to the Technology Mechanism of the Convention in facilitating technology development and transfer. One key area of work will be the provision of enhanced financial and technical support for the implementation of the Technology Needs Assessment and Technology Action Plans.

As many developing countries have included HELE coal technologies in their INDCs, those technologies will be part of their Technology Action Plans and most likely require the new Technology Framework to facilitate the required technology transfer and financial support.
UN financial and technological institutions such as the Green Climate Fund and Climate Technology Centre and Network are technology-neutral. These institutions should provide the necessary support for the development of HELE and CCS technologies when countries request it.

A different approach will neglect the reality of the global electricity generation system and result in the likely failure of implementing and achieving the Paris Agreement’s goals. As Yvo de Boer, former Executive Secretary of the UN Framework Convention on Climate Change, has warned: “Without support for new highly efficient coal plants, the world may end up with something much worse.”

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We’re in the process of planning the editorial schedule for 2017.

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

We’re looking for any and all feedback from our readers.

Cornerstone aims to be inclusive to all things related to coal and energy, especially those pieces that are focused on scientifically derived solutions for the challenges associated with ever increasing energy demand. Our goal is to include diverse material, such as interviews, letters, op-ed editorials, technical articles, 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 cornerstone@wiley.com (English) or cornerstone@shenhua.cc (Chinese)
The most impactful action the U.S. can employ to reduce CO₂ emissions is to incentivize the rapid deployment of carbon capture and storage (CCS) technologies. Unfortunately, to date U.S. federal and state policies have severely tilted the energy playing field. Existing incentives for CCS are simply too small to bridge the gap between the cost and the risk of promising, but immature, CCS technologies vis-à-vis other low-emissions technology options. While the U.S. Department of Energy has stewarded a successful research and development program to spur early development of CCS technologies, insufficient overall support has hindered commercial deployment.

Other low-emissions technologies have benefited from substantial government support. The success of policy and financial incentives afforded to the renewable energy industry in the U.S. provides ample evidence that government support can be the critical enabler for bringing scale and speed to clean energy technology deployment.

The National Coal Council white paper on low-emissions policy parity offered several recommendations to advance CCS technology development and deployment.

**Policy Parity for CCS Would Move the U.S. Closer to Its Climate Goals**

By Janet Gellici
Chief Executive Officer, National Coal Council

Policy initiatives must provide positive economic signals for deployment of CCS technologies, recognizing that these technologies are still immature and not yet commercially available in the power sector.”

**THE IMPORTANCE OF PARITY**

The guiding principle in advancing a level playing field for various low-emissions energy resources is to ensure that U.S. citizens and businesses have access to reliable, low-cost electricity that can meet various regulatory drivers. Parity connotes a concept of fairness and an assurance that the same set of rules apply to all players. A metaphorical playing field is said to be level if no external interferences affect the ability of the players to compete fairly. Policies and incentives that grease the skids for one resource and/or erect hurdles for others impede our nation’s economic and environmental objectives while imposing undue economic hardship on our citizens.

Policy parity is important to meeting the diverse set of U.S. energy policy objectives. Those objectives have consistently focused on providing a reliable, secure, and low-cost supply of energy, and in recent years have increasingly directed energy...
production and consumption toward environmental goals. CCS is essential to meeting each of these objectives.

“Not including CCS as a key mitigation technology is projected to increase the overall costs of meeting CO₂ emissions goals by 70% to 138%.”

CCS technologies provide the most impactful opportunity to capture, use, and store a significant volume of CO₂ from stationary point sources. Such technologies can be used to reduce CO₂ emissions from electric generation as well as from key industrial sectors, including cement production, iron and steel making, oil refining, and chemicals manufacturing. CCS technologies help maintain electric reliability in a carbon-constrained world by supporting baseload generation that enables the grid to maintain voltage, frequency, and other attributes essential to reliable power supply.

Additionally, CCS technologies significantly reduce the costs of decarbonization. Not including CCS 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 CCS preserves the economic value of fossil fuel reserves (coal and natural gas) and associated infrastructure.

Other energy technologies have benefited greatly from substantial government support (see Figure 1). In 1992 when Congress enacted the Section 45 renewable energy tax credit, the U.S. had less than 2000 megawatts (MW) of installed wind-generating capacity. Today, there are 69,471 MW of installed wind capacity. Wind energy prices have dropped from more than $50/MWh in the late 1990s to less than half that cost in 2014. The industry credits government policy for its success: “With a two-thirds reduction in the cost of wind energy over 1992–2013, the industry credits government policy for its success.”

FIGURE 1. Public policy drives investment.
Source: Carbon Capture and Storage: Perspective from the IEA
Ellina Levina, Sydney, Australia, 2 September 2014
the last six years, the renewable production tax credit (PTC) is on track to achieving its goal of a vibrant, self-sustaining wind industry.”

Policy and financial incentives have brought scale and speed to renewable energy deployment and helped reduce the cost of these technologies. In contrast, policies that disadvantage fossil fuels have had a suppressing effect on deploying CCS technologies. Policy initiatives must provide positive economic signals for deployment of CCS technologies, recognizing that these technologies are still immature and not yet commercially available in the power sector.

Commercializing CCS requires a level playing field and a correction to the existing “dis-parity” that exists between CCS and renewables.

POLICY DIS-PARITY BETWEEN CCS AND OTHER LOW-EMISSIONS RESOURCES

In March 2015, the U.S. Energy Information Administration (EIA) produced a report valuing subsidies and incentives provided to various forms of energy. The report shows that the single largest recipient of federal energy subsidies is, by far, renewables, which, in 2013, received more than 12 times the subsidies received for coal—$13.227 billion for renewables versus just $1.085 billion for coal. It also revealed that renewables received 72% of total subsidies while coal received just 6%. As shown in Table 1, U.S. government support to launch CCS is not remotely comparable to that given to renewables.

The Congressional Research Service (CRS) also released a report in March 2015 assessing the value of energy tax credits for various fuel resources. CRS noted that, in 2013, the

| TABLE 1. Incentives for renewable electricity generation compared with electricity generation with CCS |
|-----------------------------------|----------------|----------------|
| **Incentive**                     | **Renewables** | **CCS**        |
| **DOE Budget (2012–2016)[9]**     |                |                |
| FY 2016 (requested)              | $645 million   | $224 million   |
| FY 2015                          | $456 million   | $188 million   |
| FY 2014                          | $450 million   | $200 million   |
| FY 2013                          | $480 million   | $186 million   |
| FY 2012                          | $480 million   | $182 million   |
| **Total DOE Budgets:**           | **$2.5 billion** | **$980 million (CCS demonstration: $0)** |
| **Tax Credits (2010–2014)[10]**  |                |                |
| Investment tax credit            | $2.1 billion   | $1 billion     |
| Production tax credit            | $7.6 billion   | $0             |
| ARRA §1603 grants in lieu of credit | $24 billion | $0             |
| Investment in advanced energy property | $2.1 billion | $0             |
| Accelerated depreciation for energy property | $1.5 billion | $0             |
| **Total revenue cost:**           | **$37.3 billion** | **$1 billion** |
| **Other Federal Programs**       |                |                |
| Loan guarantees (EPAct ‘05 §1703) | Yes ($13.9 billion) | Yes ($0)         |
| Mandatory purchase requirement (PURPA § 210) | Yes | No |
| Siting and interconnection preferences (e.g., FERC Order 792) | Yes | No |
| Clean energy Credits (EPA, 111(d) Existing Power Plant Rule) | Yes | No |
| **State Programs**               |                |                |
| Net metering                      | 44 states      | 0 states       |
| Renewable energy standards        | 29 states      | 5 states (CCS applied to standard: 0) |

Note: DOE issued a solicitation for up to $8 billion in loan guarantees for advanced fossil energy projects on 12 December 2013. To date, no loan guarantees have been made for an advanced fossil energy project. It is unclear whether any applications have been submitted.
value of federal tax-related support for the energy sector was estimated to be $23.3 billion, of which $13.4 billion (57.4%) supported renewable energy and $4.8 billion (20.4%) supported fossil fuels.

Financial support outside typical funding mechanisms for energy has also favored renewables over other fuel sources. Funds for renewable projects under the American Recovery and Reinvestment Act (ARRA) were $20 billion versus $3.4 billion for coal.²

In addition to financial support, renewables have benefited significantly from regulatory mandates creating a guaranteed market for wind, solar, biomass, and other alternatives to fossil and nuclear power. These renewable energy standards obligate utilities to obtain a specified percentage of their electricity from renewable energy sources.

**MEASURES FOR LEVELING THE PLAYING FIELD**

Leveling the playing field for CCS will require a combination of financial incentives, regulatory improvements, and research, development, and demonstration catalysts, as well as international collaboration. It will also require that U.S. and global policymakers demonstrate a firm understanding that fossil fuels will be used in the coming decades to a greater extent than today, resulting in an urgent need for CCS deployment.

**Financial Incentives**

Financial incentives for CCS must be substantially increased and broadened to include incentives available to other low-emissions energy sources. Up-front incentives that reduce risk to capital should be emphasized and designed with a recognition—as with wind and solar in the 1990s—that CCS is an immature technology with up-front risks and high initial capital costs. Operating incentives are important to ensure a steady long-term revenue stream and lessen direct costs to consumers.

Perhaps the single-most important mechanism to spur CCS deployment may be the use of a “contracts for differences” (CFD) structure. This approach would provide for a limited number of projects to bid to the federal government for financial support using a combination of proposed incentives, including:

- Limited guaranteed purchase agreements
- Market set asides (similar to state renewable energy requirements)
- Clean energy credits
- Production tax credits

**Regulatory Improvements**

NCC recommends DOE take the lead, working with sister agencies, in developing a regulatory blueprint to remove barriers to the construction and development of projects with CCS, including industrial and power generation plants, transportation options, and injection sites. The regulatory barriers that could be addressed include:

- Injection Barriers—The EPA’s 111(b) and 111(d) regulations impose reporting rules discouraging, as opposed to encouraging, CO₂ utilization.
- New Source Review—Requirements discourage retrofits of CO₂ and other carbon reduction technologies to existing plants.
- Infrastructure Siting—Granting authority, similar to provisions under the Natural Gas Act, for federal eminent domain for siting and construction of CO₂ pipelines.
- Storage Siting—DOE should identify and certify at least one reservoir capable of storing a minimum of 100 million tons of CO₂ at a cost of less than $10/ton in each of the seven regions covered by the agency’s Regional Carbon Sequestration Partnership program.

**Research, Development, and Demonstration**

NCC recommends DOE substantially increase its budget for RD&D funding for CCS. In concurrence with the CURC-EPRI Roadmap,¹¹ NCC recommends fully funding 80% federal cost...
share for early-stage RD&D, 100% federal cost share for large-scale pilots, and 50% cost share for commercial demonstration projects.

“The U.S. increases its chance of success in meeting its global CO₂ emission reduction goals when it commits with urgency to the deployment of CCS technologies.”

Communication and Collaboration

NCC encourages DOE to propose an international pool of funds specifically set up for the implementation of 5–10 GW of globally based CCS demonstration projects at scale.

Finally, NCC recommends that DOE be a tireless advocate in all venues for recognition that fossil fuels will be used in coming decades to a greater extent than today to fuel a more populous, developed, urban world. Acknowledgment of the continued global reliance on fossil fuels will enhance the likelihood of support for efforts to achieve meaningful CO₂ emissions reductions.

CONCLUSION

The U.S. increases its chance of success in meeting its global CO₂ emission reduction goals when it commits with urgency to the deployment of CCS technologies. Such a commitment begins with the establishment of policies and incentives to level the playing field for CCS.

NOTES

A. The term “CCS” as used in this article denotes both carbon capture and storage (CCS) and carbon capture utilization and storage (CCUS).

B. Budgets for “Renewables” reflect funds budgeted to the Office of Energy Efficiency and Renewable Energy for the line items “Solar Energy”, “Wind Energy”, “Water Energy”, and “Geothermal Technologies”. Budgets for “CCS” reflect funds budgeted to the Office of Fossil Energy for the line items “Carbon Capture” and “Carbon Storage”. As noted in the chart, no funds were budgeted for CCS demonstration projects (i.e., CCPI). The budget for CCS does not reflect funding for technologies not under the CCS budget that have application beyond electric generation, such as oxy-combustion and chemical looping. Budgets available at www.energy.gov/budget-performance

C. While approximately $30 million of this credit has been claimed, no evidence could be found of the credits being claimed by power projects with CCS.

REFERENCES


The U.S. utility industry has already installed mercury (Hg) emissions controls at hundreds of coal-fired power plants to meet the Mercury and Air Toxics Standards (MATS) that went into effect in spring 2016. Meanwhile, utility operators in the developing world are focusing on recent or impending regulations on particulates, SOX, and, perhaps, NOx. This is unfortunate because the global distribution of anthropogenic Hg emissions shows that the strongest sources of this air toxin coincide with a heavy reliance on coal for electricity generation. The situation is actually more complex because, taken together, artisanal and small-scale gold mining and coal combustion account for 60% of all anthropogenic Hg emissions, with gold mining’s contribution being about 50% greater than that of coal combustion. Whereas Hg control technologies are already being applied to power plants in developed countries, they will also need to be applied in developing countries to effectively reduce global emissions.

The United Nations Environment Programme (UNEP) has led global efforts to rein in Hg emissions from all sources, including establishing the multilateral Minamata Convention on Mercury. On the technical side of Hg emissions control, UNEP distributes the Mercury Inventory Toolkit that brings the skills and tools to monitor Hg emissions to local field testing teams, and has already guided teams at power plants in Russia, South Africa, India, China, Thailand, Indonesia, and Vietnam. UNEP supports statewide, regional, and local estimates for Hg emissions from power plants, and supports strategic planning on Hg emissions control at the scale of individual power plants. That’s the specific goal of its Interactive Process Optimization Guidance (iPOG) program. This user-friendly computer program gives nonspecialists and experts alike a simple means to estimate Hg emissions for actual and hypothetical fuels and gas-cleaning units at a specific power plant, based on the huge database of field test data recorded by U.S. utility companies. This article reviews the look-and-feel of the program, the input data requirements, and a case study that demonstrates iPOG’s capabilities.

“...This user-friendly computer program gives nonspecialists and experts alike a simple means to estimate Hg emissions for actual and hypothetical fuels and gas-cleaning units at a specific power plant...”

THE EVOLUTION OF MERCURY EMISSIONS

Three forms of Hg are found in coal-derived flue gas: elemental mercury (Hg⁰); oxidized mercury (Hg²⁺), which is combined with chlorine or bromine; and particulate mercury (HgP), which is bound to fly ash. Flue gas contains suspended solids called fly ash that originate in two sources, either in the mineral matter embedded in the coal and released during combustion or as the unburned carbon (UBC). Only UBC has strong affinities for both Hg⁰ and Hg²⁺, and only in the presence of chlorine or bromine vapors. The imperative in Hg emissions...
control is to operate the cleaning system to convert as much Hg\(^0\) as possible into HgP and Hg\(^{2+}\). Particulate Hg is desirable because essentially all Hg adsorbed onto suspended particles in the flue gas stream is readily captured in a particle collection device. Whether a plant uses an electrostatic precipitator (ESP), a fabric filter (FF), or a venturi wet scrubber, it collects all the Hg that enters it.

An abundance of Hg\(^{2+}\) is preferable because the flue gas desulfurization (FGD) scrubbers that capture sulfur dioxide also collect all the Hg\(^{2+}\) entering with the flue gas, but none of the Hg\(^0\). Mercury captured this way ends up sequestered in the finest particles of gypsum, which is often a saleable byproduct in coal-fired electricity generation. So the keys to controlling Hg emissions are to (1) oxidize as much Hg\(^0\) into Hg\(^{2+}\) upstream of the FGD scrubber and (2) bind as much Hg\(^0\) and Hg\(^{2+}\) as possible into HgP upstream of the particle collector.

"iPOG estimates the proportions of Hg\(^0\), Hg\(^{2+}\), and HgP at the inlets and outlets of every pollution control device in a gas-cleaning system."

Controlling Hg emissions is a challenge for several reasons. Typical levels of coal-Hg are only about 100 ppb, and these levels are diluted by roughly a factor of 10 by the combustion process. To get a sense of how small such concentrations really are, imagine that a large football stadium was filled to the rafters with white ping pong balls. If a few handfuls of black balls are added to the stadium mix, they would be present at a concentration as it moves from the furnace into a gas-cleaning system. Mercury emissions control is like capturing only the black balls while the stadium is quickly evacuated through the gates.

Another obstacle is the daunting number of furnace and cleaning conditions that determine how much of the coal-Hg is captured or emitted (as explained in detail elsewhere\(^5\)). If the level of chlorine in coal is not sufficient to bind the mercury to the UBC particles before the stream reaches the particle collector, or the chlorine and UBC in the flue gas are not in the proper proportions to maximize the conversion to HgP, then an operator may consider spraying a bromine solution onto the coal before it is fed into the furnace. Activated carbon can also be injected into the gas upstream of the particle collector to compensate for deficient UBC.

The third obstacle is that several technical approaches could potentially meet an emissions target, but at markedly different cost. The pace and depth of current and impending emissions regulations usually dictate whether the units that control particulates, NO\(_x\) and SO\(_x\) will be able to meet the regulations on Hg emissions with only minor adjustments and additives, or whether dedicated Hg control technologies will be needed. The first scenario takes advantage of so-called co-benefits for Hg emissions control, whereas the second uses dedicated or external Hg emissions controls. Both forms of control can be analyzed with iPOG.

**THE SCOPE OF IPOG CALCULATIONS**

iPOG estimates the proportions of Hg\(^0\), Hg\(^{2+}\), and HgP at the inlets and outlets of every pollution control device in a gas-cleaning system. Users start with calculations for their current gas-cleaning configuration, and the properties of their current fuels. Once the baseline Hg emissions have been estimated, users can quickly estimate the emissions reductions for a broad assortment of control strategies. They can evaluate coal pretreatments based on washing or float/sink separations, and consider different fuel-blending strategies, and fuel switching. Either chlorine or bromine compounds can be virtually added to the fuel stream as it enters the furnace. Furnaces are specified by their burner arrangements, megawatts of electricity output, and overall thermal efficiency, plus the amounts of excess air and the percentage of UBC in fly ash. The flue gas-cleaning configurations can have any arrangement of a selective catalytic reduction (SCR) reactor for NO\(_x\) control, particle control units (ESP, FF), and a FGD scrubber. Units also can be added or omitted at will, to assess the co-benefits for Hg emissions control from better controls on particulates, NO\(_x\), and SO\(_x\). The dedicated Hg emissions controls cover injection of chlorine or bromine compounds, and conventional or brominated activated carbon at any point along the gas-cleaning system.

The output screen in Figure 1 illustrates a typical calculation sequence. The flow diagram along the lower portion illustrates the user’s entries for the cleaning configuration. This case shows coal being fed into a 750-MW wall-fired furnace without any additives. The flue gas leaves the furnace and passes through an SCR for NO\(_x\) control, an air preheater, ESP to remove fly ash, and a wet FGD scrubber for SO\(_x\) control, before it enters the stack. Along the bottom, the diagram gives the Hg withdrawal rates in ash from the bottom of the furnace, in fly ash captured by the ESP, and in the scrubber solution from the FGD. In this case, hardly any Hg was withdrawn from the furnace, whereas almost 16% was collected with the fly ash, and 88% of the Hg coming into the FGD was retained in the wastewater.
Overall capture efficiencies are shown along the top of the screen in the figure. For these cleaning conditions, 95% of the Hg is oxidized along the catalyst in the SCR, so 95% of the flue gas entering the FGD is in the oxidized state. Stack emissions rates are given in g/h and g/TJ, along with the proportions of Hg\(^0\) and Hg\(^{2+}\) from the stack, and the overall Hg removal efficiency.

**CASE STUDIES**

Gas-cleaning systems on coal-fired plants vary dramatically, and programs to estimate Hg emissions must describe all the popular configurations. Suppose, for example, that a newer 750-MW furnace operates at full load with a high-sulfur bituminous coal, and with an ESP to capture particulates but no other pollution controls. The UBC level in the fly ash is 3.5 wt%, which is a modest level, and the flue gas contains about 50 ppm chlorine. The plant operators are currently procuring a wet FGD to control SO\(_x\) emissions, and contemplating an SCR for NO\(_x\) control. The iPOG estimates the Hg removal co-benefits of these additional pollution control units, and can also evaluate coal washing and bromine addition to the coal feed. The estimated stack Hg emissions rates and overall Hg capture efficiencies for relevant iPOG runs are compiled in Table 1.

Without any Hg capture, the emissions rate would be 47 g/h. The current ESP-only system emits 41 g/h, for a capture efficiency of only 14%. This Hg capture efficiency is not limited by the availability of coal-chlorine, since equal proportions of Hg\(^0\) and Hg\(^{2+}\) are released from the stack. Rather, it is limited by the availability of UBC to capture the Hg species before the flue gas enters the ESP. Washing the coal only lowers the emission rate to 38 g/h, and raises the capture efficiency to 19%. After the wet FGD is installed, the emissions rate decreases to 24 g/h, while the capture efficiency surges to 50%, because the scrubber captures the substantial portion of Hg\(^{2+}\) that...
would otherwise enter the stack. If a bromine solution were sprayed on the coal feed, however, the Hg emissions would slightly diminish to 20 g/h for a capture efficiency of 58%. However, the impact of adding an SCR is dramatic. The rate diminishes to only 5 g/h for a capture efficiency of just below 90%. Indeed, SCR catalysts are the most effective means to oxidize Hg\(^0\), which explains why SCR/ESP/FGD cleaning configurations provide the greatest co-benefits for Hg control.

iPOG allows users to formulate case studies on fuel switching and fuel blending, which is becoming more common throughout Asia where native coal supplies are outpaced by surging demand for electricity. Users can also delve deeper into the connections among coal properties, furnace performance, and Hg capture efficiencies. Policy analysts use iPOG to run numerous “What if?” scenarios across local and regional facilities. Ultimately, numerous case studies can be synthesized into a strategy to achieve the greatest Hg emissions reductions for the lowest cost that are compatible with specific constraints on coal quality and gas-cleaning configuration, and the timetable of impending Hg emissions regulations. From environmental managers, to fuel procurement specialists, to project engineers, to technology manufacturers, the numerous scenarios provided by iPOG streamline the path toward the most cost-effective approach to reducing Hg emissions. All stakeholders can obtain a copy of the program free of charge by contacting the Mercury Section at UNEP.

LIMITATIONS ON THE ESTIMATES

The statistical uncertainties on iPOG estimates have been analyzed in detail. The most general limitation is that the iPOG estimates are based on regressions of field test data, so they are no more accurate than the qualified measurement uncertainties, which are 10–15% of the total Hg inventory in each test. Differences among cases that are smaller than these tolerances are statistically insignificant and should be ignored. Since the input data requirements have been streamlined, iPOG cannot depict the distinctive features of particular gas-cleaning systems. This is particularly important in the results from activated carbon injection, which does not account for interference by adsorbed sulfur trioxide. Similarly, for oxidation of Hg\(^0\) along SCR catalysts, iPOG does not account for variations among the SCR design specifications and in the reactivities of the catalysts from different manufacturers and for different lifetimes in service. Users who reach a point in their analyses with iPOG where these limitations are hindering their development work on Hg control strategies can consider more comprehensive simulations.6

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India’s Dash for Coal Loses Pace

By Jeremy Bowden
Contributing author, Cornerstone

India has huge potential for growth in energy demand. It hosts one sixth of the world’s population and boasts the third-largest economy in purchasing power parity terms, but currently accounts for only 6% of global energy use, while 20% of the population—240 million people—still lack access to electricity. The World Bank suggests India’s GDP will grow by 7.9% in 2016, more than twice the global average. This growth, combined with modernization, urbanization, and government policies to assist those affected by energy poverty, are all expected to help drive electricity-sector growth, which has averaged 6.34% since 2009. Figure 1 depicts the steady growth in India’s electricity production since 2009.

As a result, the International Energy Agency (IEA) estimates that India will add a quarter to current global energy demand by 2040, overtaking OECD Europe, and nearing consumption levels of the U.S. To achieve this, its power sector needs to almost quadruple in size, which will require an estimated US$2.8 trillion of investment by 2040. According to the IEA, the use of coal in power generation and industry is expected to rise sharply, increasing demand for coal and making India by far the largest driver of growth in global coal use. India is also expanding renewables and nuclear, targeting a 40% share of non-fossil fuel capacity in the power sector by 2030.

The IEA also expects India to be the world’s largest coal importer by 2020, overtaking Japan, the EU, and China, due to the rapid expansion of its use in the energy and industrial sectors as part of the country’s broader economic policy. However, recent events cast some doubt over the IEA predictions. First, imports have been falling for over a year (after having risen sharply, as expected, into early 2015), partly due to higher domestic production and stocks, but also due to lower peak power shortages, low thermal power utilization rates, and, since COP21, perhaps a greater emphasis on renewables.

“India will add a quarter to current global energy demand by 2040, overtaking OECD Europe, and nearing consumption levels of the U.S.”

Analysts disagree over whether the dip in imports is temporary. The Global Institute of Energy Economics and Financial Analysis claims imports will soon cease completely: “The country is now firmly on track to meet its publicly-stated goals of ceasing thermal coal imports by 2017-18,” it said in an April article. However, a report from the Fitch Group firm BMI Research in January stated that “coal imports will remain strong over the coming quarters as India will continue to be unable to meet domestic coal consumption.” It claimed India had a structural deficit of 187 mnt in 2015. Over the long term, as India attempts to hit its ambitious plans of doubling production by 2020, and production from its auctioned coal mines finally comes online, then we expect imports to fall.”

Second, cutbacks for coal-fired capacity have been announced. India currently has a thermal power capacity of 211 GW, after 20.8 GW was added in 2014 and 2015—the highest on record and well above the target of 17.8 GW. The plan was to add an additional 113 GW of new coal capacity by 2022, most of which...
is already under construction. In addition, India currently has a further 289 GW of coal capacity in the planning stages. The IEA estimated that this would require around US$1.2 trillion investment by 2040. However, the financing available for new capacity is restricted by high network losses—both to illegitimate users and sub-optimal network operation—among India’s local distribution utilities, which reduces revenue.

**BACKSLIDING ON COAL CAPACITY**

In April 2016, the Ministry of Power announced it had scaled back its projected thermal power capacity growth forecast by 50 GW, reducing the target from 289 GW to 239 GW by 2022. Then in May 2016, the chairman of the Central Electricity Authority announced plans to close up to 37 GW of antiquated subcritical coal plants—equal to 20% of India’s current coal fired power fleet, or 12% of the total system capacity. These units can produce electricity at a relatively low cost and their closure is opposed in some regions where the cost of electricity is a particularly sensitive and politically charged issue.

These moves reflect a change in tone among many national politicians since the COP21 deal was signed in Paris last December. The 2015 statement by Piyush Goyal, Minister of State for Power, Coal and New & Renewable Energy, that “universal and affordable energy access 24/7 ... is the mission of this Government under Prime Minister Modi” has been replaced by less bullish comments such as this from Mr. Dubey, chairman of the Central Electricity Authority, speaking in May of this year: “Our first concern is emissions ... We also want plants to be more efficient in use of resources.”

The change in emphasis was reinforced in June, when Prime Minister Modi, speaking in the U.S., made clear that the focus on driving Indian economic growth at 7.6% must “be achieved with a light carbon footprint, with greater emphasis on renewables.” In his meeting with President Obama, Modi also confirmed India would ratify the Paris COP21 Agreement this year. India pledged to cut its GDP carbon intensity by 33–35% compared to 2005 levels and bring renewable and nuclear capacity up to 40% of the total by 2030. Subsequently S&P Global Platts forecast that India’s reliance on coal-fired power generation would drop from an estimated 69% share in 2020 to just 60% by 2030—compared to a peak of 75% in 2015.

After Modi’s visit to the U.S., the Indian Energy Ministry announced the cancellation of four ultra-mega power plants (UMPP) in the states of Chhattisgarh, Karnataka, Maharashtra, and Odisha, with a combined capacity of 16 GW. These four proposed plants had been in the planning, preparation, and land acquisition stage for eight years. Community resistance to compulsory land acquisition and forced resettlement combined with electricity power surpluses helped persuade the government to cancel. It had been expected that the UMPPs would facilitate the proposed closure of 37 GW of old coal-fired capacity, and India appears to be going ahead with the closures even without these new coal plants.

**SUPERCRITICAL TECHNOLOGY CRITICAL TO LIMITING EMISSIONS**

The news of the UMPP cancellations has been complemented by signs that the government appears to be preparing the 13th Five-Year Plan (2017–2022) to call for the development of 100% supercritical technology for those plants that do get built. Anil Razdan, the former Secretary for Power, said an “efficiency tax” might be levied to encourage operators to upgrade their capacity. He also suggested that the coal levy (currently Rs 400/t or $6/t), which contributes to the Clean Environment fund, could be expanded to include clean coal technologies.

Cost differences, however, could still impact developers’ choices. Analysis show that if all coal plants built from 2020 on were ultra-supercritical, total capital expenditure would reach US$500 billion by 2040, compared to around US$387 billion if all coal plants built from 2020 onward were subcritical.

Supercritical clean coal technologies are an important component in India’s INDC (Intended Nationally Determined Contribution) for the COP21 agreement. If India is to drive economic development as planned through electrification, with 290 GW of coal-fired plants under construction or in the pipeline, a wholesale switch to supercritical plants is essential if emissions are to be kept down.

CO₂ emissions are 25–30% lower in a supercritical plant, making them a long-term, cost-effective option to reduce emissions. In
addition, the technology lays the groundwork for carbon capture and storage (CCS). A report by the World Coal Association in late 2015 claims the cost of saving a tonne of CO₂ would work out at around $10 per tonne by replacing subcritical (old) plants with supercritical and ultra-supercritical technology—making it the most cost-effective form of CO₂ abatement, allowing economic development and poverty alleviation efforts through electrification to continue at lowest cost.

LATEST DEVELOPMENTS

Power: Sector Targets Higher Utilization and More Renewables and Nuclear

With the utilization rates of the average coal-fired power plant at multiyear lows of 61.6% in 2015/16, having fallen steadily since 2008, the government believes part of the reduction in coal-fired expansion plans can be covered by increasing utilization rates at existing plants. Among the factors constraining utilization are coal supply bottlenecks. A more reliable source of coal is needed, which could mean a shift in demand toward imports, which are often higher quality and more reliably delivered than the coal produced in India.

In addition, peak shortages have been falling quickly over recent years according to the Ministry of Power, indicating that supply is coming more in line with demand across the country. Anecdotal evidence, however, suggests the official figures may be overoptimistic, with blackouts and brownouts still common across the subcontinent. Nevertheless, the ministry said in June 2016 that this decline in peak shortages indicates it would not need any new thermal capacity for the next three years beyond what was already under construction. Figure 2 shows both the fall in utilization rates and peak shortages since 2006.

Coal generation will face more competition from alternatives. India plans to ramp up solar power from 7.5 GW now (up from 10 MW in 2010) to 100 GW of capacity installed by 2022. This is a sharp increase in the 2009 target for 2020 of 20 GW, but could be attainable due to high solar intensity, cheap land, falling solar panel prices, and strong regional and central government support. In June the World Bank Group (WBG) announced more than US$1 billion in loans over FY 2017, the bank’s largest-ever support for solar power in any country. This stands in stark contrast to its decision not to support India’s higher efficiency supercritical coal-fired units. The WBG is also backing the India-led International Solar Alliance, aimed at promoting solar use globally by mobilizing US$1 trillion in investments by 2030.

While in Washington, Prime Minister Modi also agreed to Westinghouse’s plan to build six AP1000s nuclear plants in India, which could represent as significant a challenge to coal as intermittent solar. Nuclear power produces a steady baseload that has the potential to produce electricity less expensively than coal or solar. This is, however, conditional on the plants being built, and construction times and costs so far are longer and less certain than easily constructible coal-fired plants, adding substantial uncertainty to nuclear investment.

This deal is the first such opportunity for a U.S. company since the countries signed a civil nuclear agreement in 2008, partly due to the 2010 Indian law on nuclear liability (now remedied through India’s ratification of the Convention on Supplementary Compensation for Nuclear Damage). It could pave the way for further nuclear agreements between India and overseas investors.

A weaker international gas market could also present a challenge to coal. For instance, Essar Power, one of India’s largest private-sector power companies, is planning to restart two gas plants in western India that have been idle for three years. Essar expects lower gas prices to last for 5–8 years, although currently prices remain above the price of coal on a unit energy basis.

Coal: Rising Coal Stocks, Surplus Production, and Falling Imports

The state-controlled dominant producer, Coal India Limited, and its customers are facing a massive coal stockpile of 97

![FIGURE 2. Falling utilization rates and narrowing supply deficits](image-url)
mnt, which needs to be consumed quickly to avoid fire risks. Figure 3 shows the rise in stocks since 2006. The total includes 58 mnt at Coal India’s mines and a further 39 mnt at its customers’ power plants. The company has cut prices of higher grade coal to encourage buying, but so far has been unable to shift the surplus, due to a lack of demand from plants. This lack of demand could be due, in part, to the ongoing drought that has seen a number of water-cooled coal plants shut down. Problems with domestic distribution, partly due to Indian coal’s high ash content, also make transportation more problematic.

“The continuing fast-growing economy is likely to drive power demand sharply higher.”

Early in March, a senior official at Coal India said: “The power companies are not in a position to take any additional coal and we are being requested, both officially and unofficially, to cut supplies, which has prompted us to scale down production at several other mines apart from the ones where we have stopped production temporarily.” Around the same time, another Coal India executive was quoted as saying that cutting the price of coal to boost sales would have “far-reaching unfavourable implications” for the company’s profitability. Prices have been cut by 10–40% until the end of March 2017, as the company attempts to reduce stockpiles.

The price cuts could also provide a further challenge to coal imports, which fell by 15% to 132.3 mnt tonnes in nine months to January this year, from 155.4 mnt a year ago. For the second year running, NTPC, India’s largest power generator and coal consumer, will not import any coal this year. It plans to source its entire requirement of 155 mnt from domestic resources. In early July, the Ministry of Finance sought a presentation on the feasibility of power projects running on imported coal from the Ministry of Power, expressing concern that the cost of such projects could be subject to changes in law internationally following the COP21 agreement.

The situation could threaten the remaining plans to develop overseas mines for the Indian market, such as the Adani Group’s proposed 60-mnt Carmichael low-grade thermal coal mine in Australia. Before the recent price slump, a number of Indian companies—including Adani, Jindal, Reliance, and the ICVL consortium of NTPC, Coal India, and others—had begun plans for mines in Australia, Indonesia, South Africa, and Mozambique. But by undermining imports with low prices, Coal India should be well placed to take advantage of future growth, provided it can prove itself a reliable provider.

FIRST MOVES TO BREAK UP COAL INDIA MONOPOLY

While Coal India attempts to undercut imports and shift stock, many smaller industrial consumers remain short of coal. In an attempt to overcome such bottlenecks, the Ministry of Coal has recently earmarked 16 coal mines to be allocated to states for sale to private companies—an important step in dismantling Coal India’s monopoly.

The states will then mine and sell coal to their own industries, helping curb the black market for coal that results from the supply shortfall. The ministry is in the “last lap of designing” a guiding mechanism for transparent mining and sale of coal by the states. So far, coal blocks allotted to the states under the new mechanism have stipulated end-use, and no sale of coal was allowed. Any commercial mining will have strict guidelines.

Depending on how successfully policy emphasis continues to move toward environmental priorities, the ambitious
production target of one billion tonnes per year by Coal India by 2020 may not all be needed, and imports could be squeezed further. However, the current slide in imports and hiatus in coal plant construction is unexpected and may only be a temporary factor. The continuing fast-growing economy is likely to drive power demand sharply higher. This should increase utilization, absorb stocks, and provide a growing market for rising temporary factor. The continuing fast-growing economy is likely to drive power demand sharply higher. This should increase utilization, absorb stocks, and provide a growing market for rising domestic coal production, while maintaining space for some imports—for the supercritical coastal plants at least.

REFERENCES

Coal and Clean Coal Technologies in Turkey

By Mücella Ersoy
Chief Mining Engineer, Turkish Coal Enterprises (TKI)

Coal is Turkey’s most important domestic energy resource. Although the country has large reserves of low-grade lignite and some hard coal resources, its oil and natural gas resources are quite limited. In recent decades Turkey has relied less and less on its domestic resources, leading to concerns about the country’s energy security.

Turkey also has one of the fastest growing economies in the world due to a growing population and increasing industrialization. This has led to expanding energy demand, which increased by nearly a factor of six between 1970 and 2014. In 1970, the share of domestic resources in Turkey’s energy consumption was 77%. The high energy consumption rate, delays in realization of investments for domestic resources, and increasing imports of energy resources resulted in a reduction of 25% in the domestic share by 2014 (see Figure 1).

Coal’s share, including lignite, in Turkey’s total primary energy supply (TPES) decreased from 24% in 1970 to 13% in 2014. Since 1986, coal has accounted for more than 50% of domestic energy production (see Figure 1). In 2014, the TPES by fuel share (123,937 ktoe) was coal 29.1% (hard coal 16.3%, lignite 12.3%, ashpaltite 0.3%, coke 0.2%), other solid fuels 4.9%, oil 26.2%, natural gas 32.4%, hydro 2.8%, geothermal 2.8%, wind 0.6%, solar 0.6%, biofuel 0.1%, and electricity 0.4%.

Several recent energy strategy papers published in Turkey have focused on policies to reduce energy import dependency. A common theme among the papers is the importance of prioritizing the use of domestic resources, particularly lignite, for electricity generation. Several objectives were set that aim to reduce energy import dependency, including:

- Increasing domestic coal exploration
- Accelerating the installation of power plants using domestic lignite and clean coal technologies
- Maintaining the momentum of R&D on coal (particularly on coal gasification and liquid fuel production technologies)
- Improving investment incentives for coal-fired power plants
- Retrofitting existing coal-fired power plants

THE HISTORIC PRODUCTION, IMPORT, AND USE OF COAL

Hard coal reserves are concentrated in the Zonguldak Region on the western Black Sea with lignite reserves scattered throughout the country. Hard coal reserves were estimated at 1.3 Bt. As a result of increased exploration, lignite reserve estimates were increased from 8.3 Bt in 2005 to 15.7 Bt in 2015. The largest lignite deposits are in Afsin-Elbistan, Konya-Karapinar, Eskisehir-Alpu, Afyon-Dinar, Manisa–Soma, Ankara-Cayirhan, and Kütahya-Tunçbilek, covering the Anatolian plateau from west to east (see Figure 2).

Lignite gained prominence as a domestic energy resource in Turkey after the oil crisis in the 1970s. Lignite production increased from 14.5 Mt in 1980 to 42 Mt in 1986, principally...
to meet the demand of lignite-fired power plants installed during this period. Production reached a peak of 76.2 Mt in 2008 and then decreased. In 2014, 62.6 million tons of lignite were produced, which ranks Turkey as the fifth largest lignite producer country in the world. According to the Turkish Statistical Institute, lignite production decreased to 42 Mt tons in 2015. The decrease can be attributed to the closure of mines due to accidents and increasing operating costs. Hard coal production decreased from 4.6 Mt in 1970 to 2.2 Mt in 1995 and remains relatively unchanged with an annual production of around 2 Mt (see Figure 3).

In order for Turkey to meet domestic energy demand, it has been importing hard coal since the 1980s (30 Mt in 2014), mostly from Russia, Columbia, the U.S., South Africa, and Australia (see Figure 3). Hard coal is used for electricity generation, steelmaking, cement production, and heating, while lignite is mainly used for electricity generation and, on a minor scale, for heating and industrial purposes.

Reliance on imported coal has increased to meet the demands of new coal-fired power plants. Total coal consumption in 2014 was 97.2 Mt, of which 31.5 Mt was hard coal, 64.7 Mt lignite, 0.771 Mt asphaltite, and 0.347 Mt coke.

**COAL USE FOR POWER GENERATION IN TURKEY**

Table 1 shows the current operating status of coal-fired power plants in Turkey. In July 2016, 64 units in total (only those having generation capacity >100 MW are counted) were operating, 10 of which (3115 MW) belong to the state-owned electricity generation company, EUAS.

As a part of creating a competitive energy market in Turkey, the privatization of power plants has been ongoing for several decades. Since 2013, 24 units of EUAS-owned coal-fired power plants (totaling 4302 MW) have been privatized.
In 2015, coal, including lignite and asphaltite, generated 28.5% of Turkey’s electricity (259.7 GWh). The share of lignite in electricity generation peaked at 47% in 1986. Domestic lignite demand for electricity generation has decreased due to an increase in the number of power stations relying on imported natural gas. However, between 2004 and 2009, lignite’s share of electricity increased to 20.1%, by commissioning of new domestic lignite-fired power stations at Can (2 x 160 MW) in 2003 and Elbistan B (4 x 360 MW) in 2009. Several domestic lignite-fired power plants are also currently under construction. From 2009 to the end of 2015, no additional power plants were commissioned and, as a result, power from lignite decreased to 12%. However, this may change with Tufanbeyli (3 x 150 MW), Bolu-Göynük (2 x 135 MW), and Yunus Emre (1 x 145 MW) starting operation at the end of 2015 and in 2016 (see Figures 4 and 5). The use of imported coal for coal-fired power plants since 2004 has increased in order to meet power demand in Turkey. Due to the low prices of imported coal in comparison to natural gas, imported coal-fired power plant investments in Turkey are attractive for investors. The use of imported coal reached almost an equal share with lignite in 2013 and a higher share (15%) than lignite in 2015.

### TABLE 1. Coal-fired power plants in Turkey ( >100 MW, end of July 2016)

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Source</th>
<th>Technology</th>
<th>Public (# of units)</th>
<th>Private (# of units)</th>
<th>Total (# of units)</th>
<th>Installed Cap. (MW)</th>
<th>ESP (# of units)</th>
<th>FGD (# of units)</th>
<th>DeNOx (# of units)</th>
<th>Age (min-max year)</th>
<th>Thermal Eff. (min-max %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lignite</td>
<td>Domestic</td>
<td>PC (Subcritical)</td>
<td>8</td>
<td>28</td>
<td>36</td>
<td>7652</td>
<td>36</td>
<td>18</td>
<td>0</td>
<td>7-43</td>
<td>28-39</td>
</tr>
<tr>
<td>Lignite</td>
<td>Domestic</td>
<td>CFB</td>
<td>2</td>
<td>6</td>
<td>8</td>
<td>1185</td>
<td>8</td>
<td>6</td>
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<td>35-41</td>
</tr>
<tr>
<td>Total lignite</td>
<td></td>
<td></td>
<td>10</td>
<td>34</td>
<td>44</td>
<td>8837</td>
<td>44</td>
<td>24</td>
<td>6</td>
<td>1-13</td>
<td>35-41</td>
</tr>
<tr>
<td>Hard coal</td>
<td>Domestic</td>
<td>PC (Subcritical)</td>
<td>0</td>
<td>2</td>
<td>2</td>
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<td>2</td>
<td>0</td>
<td>0</td>
<td>25-27</td>
<td>34</td>
</tr>
<tr>
<td>Asphaltite</td>
<td>Domestic</td>
<td>CFB</td>
<td>0</td>
<td>3</td>
<td>3</td>
<td>405</td>
<td>3</td>
<td>3</td>
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<td>49</td>
<td>27</td>
<td>9</td>
<td>1-7</td>
<td>36</td>
</tr>
<tr>
<td>Hard coal</td>
<td>Imported</td>
<td>PC (Subcritical)</td>
<td>0</td>
<td>3</td>
<td>3</td>
<td>1510</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>4-12</td>
<td>34-39</td>
</tr>
<tr>
<td>Hard coal</td>
<td>Imported</td>
<td>PC (Supercritical)</td>
<td>0</td>
<td>8</td>
<td>8</td>
<td>4680</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>1-6</td>
<td>41-42</td>
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<tr>
<td>Hard coal</td>
<td>Imported</td>
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<td>Total PC</td>
<td>Subcritical</td>
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<td>41</td>
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<td>1-6</td>
<td>41-42</td>
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<tr>
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<td></td>
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<td>49</td>
<td>14142</td>
<td>49</td>
<td>29</td>
<td>11</td>
<td>1-6</td>
<td>41-42</td>
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<tr>
<td>Total CFB</td>
<td></td>
<td></td>
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<td>13</td>
<td>15</td>
<td>2155</td>
<td>15</td>
<td>13</td>
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<td>1-6</td>
<td>41-42</td>
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<tr>
<td>GENERAL TOTAL</td>
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<td></td>
<td>10</td>
<td>54</td>
<td>64</td>
<td>16297</td>
<td>64</td>
<td>42</td>
<td>24</td>
<td>1-13</td>
<td>35-41</td>
</tr>
</tbody>
</table>

Notes. *Total coal-fired installed capacity <100 MW is 325.3 MW. †ESP: electrostatic smoke precipitator. ‡FGD: flue gas desulfurization. §Data for public and privatized domestic coal-fired power plants are from EUAS. Other data are from M. Basaran. †PC: pulverized combustion; ‡CFB: circulating fluidized bed.
CLEAN COAL TECHNOLOGIES IN TURKEY

Clean coal technologies have been developed and deployed globally to reduce the environmental impact of coal utilization over the past 30 to 40 years. Initially, the focus was to reduce emissions of particulates, SO$_2$, NO$_x$, and mercury. Focus has now moved to the development and operation of low and near-zero GHG emission technologies, such as CO$_2$ capture and storage (CCS).

Key Drivers for Clean Coal Technologies in Turkey

The key drivers for clean coal technologies in Turkey include:

- Increasing the use of existing domestic coal resources for energy security
- Developing domestic coal technologies to reduce high-technology import dependency
- Competing with imported energy resources, such as natural gas
- Efficient use of low-quality coal to protect the environment and combat climate change

Climate Change Policy Measures

Turkey is a party to the UN Framework Convention on Climate Change and a signatory to the Kyoto Protocol and Paris Agreement. It submitted its Intended Nationally Determined Contribution (INDC) within the context of the Paris Agreement with an aim to reduce emissions by 21% from the current business-as-usual level by 2030.

Harmonization of Turkish legislation with EU legislation in the coal sector is also underway. In 2010, the EU Directive on Large Combustion Plants (LCPD) was harmonized, under which emission limits for both new and existing plants were established and put into effect in Turkey. A twinning project was also initiated to harmonize Turkey’s policies with those of the EU Industrial Emission Directive (2010/75/EU). Accordingly, LCPD emission limits were included in the Turkish Industrial Pollution Prevention and Control Directive (IPPC) at the end of 2014 and the LCPD was repealed. New coal-fired power plants must now comply with the commitments of the amended IPPC directive. By the end of 2019 existing public and privatized old subcritical coal power plants must also comply. Therefore there is a need for investment to retrofit them to comply with the new emission limits.

Efficiency Improvements for New Coal-Based Power Plants

Turkish policies support efficiency improvements for new domestic lignite coal use. Circulating fluidized beds (CFBs) are preferred for lignite and asphaltite power plants, as they are more readily able to comply with the emission limits of the amended IPPC directive. Efficiency improvements have several benefits:

- Prolonging the life of coal reserves and resources by reducing consumption
- Reducing emissions of CO$_2$ and conventional emissions (1% efficiency improvement provides 2.5% CO$_2$ emission reduction)
- Increasing a plant’s power output
- Potentially reducing operating costs

Currently, 49 pulverized coal including lignite power plants are operating. A total of 41 units, or 9.5 GW, are subcritical and were installed prior to the LCPD Directive (2010). The remaining eight units (4.7 GW) use supercritical steam conditions with thermal efficiencies of 41–42%, and are already meeting emission limits.

Emission Control Technologies

The 1986 air quality directive established emission limits for \( \text{SO}_2 \), \( \text{NO}_x \), and particulate matter (PM). As a result, new power plants were built with flue gas desulfurization (FGD). In addition, some older plants were retrofitted with FGD. Prior to 2010, NO\(_x\) emission limits were met through the use of tangential burners in lignite-fired power plants.\(^{13}\) More stringent limits have resulted in the use of de-\( \text{NO}_x \) technologies in new plants. Electrostatic smoke precipitators (ESP) are also used for mitigating PM emissions in all coal-fired power plants in Turkey (see Table 1).

Coal Upgrading

Coal upgrading includes coal washing, drying, and briquetting.\(^{11}\) In the last decade Turkey has increased its coal-washing capacity. State-owned coal-producing companies—TKI, EUAS, and Turkish Hard Coal Enterprises (TTK)—and their contractors have a total coal-washing capacity of 5780 tonnes/hr. A pilot-scale coal drying and enhancement (CDE) system was successfully designed, built, and tested at Afsin-Elbistan Power Plant. Tests have shown that the moisture in lignite has been reduced by 10% point and calorific value has been increased by 30%.\(^{14}\)

"Turkey is considering funding a 10-MW\(_{th}\) IGCC pilot plant".

Lignite Gasification Projects

Integrated gasification combined-cycle (IGCC) is a promising technology based on its environmental performance, especially regarding the ability to carry out pre-combustion \( \text{CO}_2 \) capture. IGCC plants also have very low \( \text{SO}_2 \), \( \text{NO}_x \), PM, and mercury emissions. Although most IGCC studies have focused on bituminous coal, lignite has been successfully gasified.\(^{15}\)

Turkey is involved in several R&D projects on lignite gasification, focused on investigating low-quality lignite gasification characteristics using different gasifiers. TKI and Hacettepe University in Ankara are part of the EU’s 7\(^{th}\) FP project “Optimizing gasification of high-ash coal for electricity generation (OPTIMASH)” in collaboration with India, France, and Netherlands. That project aims to design, install, and test a 1-MW\(_{th}\) IGCC plant in India using pressurized CFB technology operating at a pressure of 10 bar. Based on the success of this initial project, Turkey is considering funding a 10-MW\(_{th}\) IGCC pilot plant.\(^{16}\)

Other gasification projects include a pilot-scale (250 kg/hr) entrained-flow gasifier to produce methanol and a lab-scale (20 kg/hr) CFB gasifier in TKI’s Tunçbilek Area. A pilot-scale coal and biomass to liquids plant with 1.1-MW\(_{th}\) capacity in TKI’s Soma Area and a lab-scale plasma-aided gasification facility are other ongoing projects.

CCS

CCS is also being investigated in Turkey. Several lignite gasification R&D projects have a \( \text{CO}_2 \) capture component (e.g., liquid production from a coal and biomass blend project). There is
also a project to assess CO₂ storage potential in Turkey, as well as a modeling and prefeasibility study for injection of CO₂ into an oil field.17,18

CONCLUSIONS

Turkish energy policies and strategies are driven by increasing energy demand and dependency on importing energy resources and technologies. Turkey has considerable low-quality lignite reserves. Continuing to use lignite will require clean coal technologies to comply with environmental regulations and climate change commitments.

The future of coal in Turkey will be driven by the domestic use of lignite. The Turkish government aims to continue to use lignite for power generation. This is evident in its commitment to further exploration, investment incentives, improving environmental regulations, and supporting research into more efficient use of lignite. In line with those goals, development and deployment of more efficient coal-fired power plants, and research on gasification and CCS, will continue to be pursued by the country.

ACKNOWLEDGMENT

The author wishes to thank Dr. İskender Gökalp for his valuable contributions to this article.

NOTES

A. The analysis in the article is based on the energy balance sheets of the Ministry of Energy and Natural Resources (MENR); all electricity generation data are from the Turkish Electricity Transmission Company (TEIAS) unless otherwise stated.
B. The reserve classification system used in Turkey is exclusively based on the geological assessment; this means that not all of the reported reserve estimates are economically recoverable quantities.
C. Production data for 1970–2014 are from MENR Energy Balance Sheets; 2015 production is taken from the provisional data from Turkish Statistical Institute.

REFERENCES

Powers of Perception: The State of the Art and Future of Sensors in Coal Power Plants

By Toby Lockwood
Technical Author, IEA Clean Coal Centre

Coal plant operators are increasingly constrained by a wide range of conflicting objectives, as they seek to maximize efficiency, profit, availability, and plant lifetime, while minimizing emissions and water consumption. The best set of operational parameters required to satisfy these demands can also be subject to constant change, as growing grid-connected capacities of intermittent wind and solar power oblige thermal power stations to ramp their output, and economic and environmental incentives encourage switching of coal type or biomass co-firing. To face these challenges, automation and more intelligent control systems able to optimize plant operation faster and more effectively than human operators are in increasing use; yet such systems rely on sensors to provide accurate data from the processes they control. Whereas in the past much of the operational data available to coal-fired power plant operators derived from imperfect, periodic measurements used to set long-term operating parameters, advances in sensor technologies over the last decade are now giving control systems access to a continuous stream of real-time data from previously inaccessible regions of the plant. This allows for human operators or the automated control system to take action based on considerably more information. As well, online sensors can also play an important role in monitoring the condition and performance of plant components and identifying when maintenance is required. This is particularly important given the unfamiliar and challenging operating regimes associated with frequent load following or non-design fuels.

SHEDDING LIGHT ON COMBUSTION

The fundamental control problem faced by pulverized coal-fired power plants is that of achieving uniform and optimized combustion throughout the furnace by optimizing the fuel-to-air ratio. While a certain amount of excess air is required for complete coal combustion, excessive air leads to increased NOX formation and a reduction in boiler efficiency due to increased heat loss in the larger volume of flue gas. In the absence of detailed data on the combustion process, many plants operate with excessive levels of air in order to ensure complete combustion and avoid corrosive, reducing conditions in the boiler. Such plants, said to be operating in a comfort zone rather than an optimum zone, incur an efficiency penalty and an increased demand on downstream NOX abatement (see Figure 1).

"Advances in sensor technologies now allow operators to “see” inside the furnace itself..."

The overall fuel-to-air ratio is typically set using one or two oxygen sensors at the economizer exit to measure excess air levels, together with carbon monoxide (CO) monitoring at the stack. Rising CO levels are a sensitive indicator of incomplete combustion which can be countered by increasing the excess air. However, in large furnaces with multiple burners, regions of locally poor combustion can easily occur, leading to localized flue gas columns with high CO or NOX, which are difficult to measure. As a result, greater volumes of air than are necessary may be fed to the boiler to eliminate high CO levels generated by a single burner.

As many of these combustion optimization problems ultimately derive from an uneven distribution of coal and air between burners, online mass flow sensors are increasingly taking the place of the periodic, isokinetic sampling measurements previously used to monitor and tune coal distribution between pipes. With a variety of pipe lengths and geometries...
typically used to convey coal from mills to burners, imbalances in coal flow are common, but achieving accurate flow data in these turbulent and erosive conditions is challenging.²

Several commercial technologies are now available that use a variety of different measurement principles, including microwaves, light, and the electrostatic charge developed by the coal particles.³ For example, Greenbank’s PFMaster consists of two electrode rings which sit flush with the coal pipe for minimal intrusion, and correlate unique charge signals from the coal particles passing each electrode to determine their time-of-flight and velocity (Figure 2).¹ Together with the magnitude of the charge and knowledge of the total coal feed rate, the distribution of mass flow over each pipe can be determined and used to “balance” the fuel-to-air ratio across the furnace. German manufacturer Promecon’s Mecontrol sensor combines a similar cross-correlation principle with a microwave-based technique to obtain coal density and, thus, an absolute value of mass flow, whereas EUcoalflow from EUtech uses an entirely microwave-based method to measure the coal particle velocity.

Installation of these devices, often in combination with specialized actuators for evenly distributing coal between pipes, has been shown to lead to significant efficiency improvements and NOₓ reductions associated with minimizing the excess air required for complete combustion. For example, installation of PFMaster at Datong power plant in China resulted in a boiler efficiency increase of up to 0.8% points and a 25% reduction in NOₓ emissions. At Yeongheung plant in South Korea, Mecontrol was used to effectively ease the switch to a lower grade sub-bituminous coal that was previously creating poor combustion and operational issues such as fan stalls.³

Optimizing coal flow can still be problematic if coal particles are too coarse to approach fluid-like flow behavior, either as a result of incorrect pulverizer mill parameters or grinding elements in poor condition. A range of complementary sensors is therefore also available for online measurement of particle size distribution, usually based on imaging with lasers or white light followed by rapid image analysis. The information from these sensors can be used to adjust and calibrate coal flow data, control the mill classifiers that regulate particle size, or alert operators to poorly performing mills.

The difficulty of obtaining data from the hostile environment of the furnace previously reduced it to the status of a “black box”, into which fuel and air are fed and from which only the cooled combustion products can be analyzed. Advances in sensor technologies now allow operators to “see” inside the furnace itself and map variations in temperature and gas concentrations in real time, providing an invaluable tool for balancing and optimizing combustion and avoiding problems such as excessive slagging. Installed at over 60 sites, the ZoloBOSS system from Zolo Technologies employs a grid of infrared lasers that crisscross the furnace, using a technique known as tunable diode laser absorption spectroscopy to map concentrations of NOₓ, CO, and O₂, as well as temperature data derived from water absorption peaks (Figure 3).³ This spatial resolution allows localized regions of CO or NOₓ from poorly tuned burners to be easily identified and coal and air flows to be redistributed accordingly, either as part of a manual tuning process at steady state or by feeding data to an automated combustion optimization program for dynamic operation. The accurate furnace temperature data can also be usefully applied to intelligent soot blowing systems, which often rely on basic measurements of furnace exit gas temperature taken at a single point by optical pyrometers.

**SMALLER AND SMARTER**

The value of advanced sensor technologies for upgrading the fossil fuel fleet has been fully recognized by the U.S. Department of Energy (DOE), whose Crosscutting Technology Research program funds research into a host of novel sensor concepts under development by academic institutes and the private sector.⁴ This program has particularly focused on sensors which will be able to survive in the even harsher conditions likely to be encountered in future coal plants, such as the high-temperature, reducing atmospheres of gasifiers.
used in integrated gasification combined-cycle plants or the elevated advanced ultra-supercritical steam temperatures.

Many of the sensors being developed are miniaturized, solid state devices which can be packaged and deployed in large numbers to maximize data flow from the process. However, traditional silicon-based chips cannot withstand the temperatures of over 1000°C encountered in coal furnaces, gasifiers, and gas turbines. Novel materials such as high-temperature ceramics or silicon alloys are instead being employed for the fabrication of more robust devices, with new gas sensor designs even making use of high-surface-area nanomaterials to enhance their performance.1

A key component of high-temperature sensor research in the U.S. and elsewhere is the use of optical devices which use light instead of electrons as their medium for sensing and transmitting information. Not only can optical fibers be made from materials with high thermal stability, such as sapphire, they are immune to signal interference from the widespread electromagnetic noise in power plants, and miniaturized devices can be created by engineering or coating short sections of fibers to modulate light according to the temperature, pressure, or chemistry of their environment.1 Using a micromachined sapphire tip on an optical fiber to act as a miniature interferometer, a commercial optical sensor from Oxsensis (UK) can achieve integrated temperature and pressure sensing up to 1000°C, and has been applied to condition monitoring and control of gas turbines.5 Optical fibers can also be interrogated to yield information on the environment along their entire length. Known as distributed sensing, this is widely used for monitoring large structures in civil engineering or characterizing oil wells. There are also high-temperature versions of these devices being developed for the power industry. A novel concept being investigated by the University of Massachusetts is to surround a coal furnace with optical fibers engineered to both generate and detect sound waves, allowing the temperature profile of the whole space to be mapped out in 3D by acoustic pyrometry (Figure 4).6

To protect these sensors without the need for costly packaging, and to bring them closer to the processes they are used to monitor, researchers are also attempting to embed them into power plant components, such as steam pipes and turbine blades, using additive manufacturing techniques (Figure 5). Metal parts can be built up using targeted lasers to selectively fuse together layers of a powder or foil sheets; ceramic parts, such as refractory material, can be manufactured by extrusion and solidification of a precursor paste, allowing the optical fiber sensor to be placed directly within the component at the appropriate stage. As part of the EU-funded project OXIGEN, researchers at Herriot-Watt University in the UK incorporated optical fiber sensors within turbine blades to produce a “smart part” able to report on its strain and temperature and thus preempt material failure.7

FIGURE 4. The optical fiber-based acoustic pyrometry concept developed by the University of Massachusetts6
Several U.S. universities are collaborating to develop boiler tubes, turbine blades, and refractory materials with embedded optical fibers capable of distributed strain sensing. A key challenge for these projects is achieving good adhesion between the sensor and the host material.8

These developments point toward an emerging future for fossil-fueled power plants, wherein an army of sensors provides a constant stream of data on the performance of each process and the condition of every component. How to best handle and exploit this potential flood of data is another challenge for researchers, which may require a fundamental rethink of power plant control systems. “Smarter” sensors with embedded processing power can be combined with wireless communication to create highly interconnected networks, able to take control decisions without the higher-level supervision found in traditional, hierarchical systems. This kind of distributed intelligence network can begin to mimic the emergent behavior found in biological systems, potentially offering greater capability for adapting and meeting competing plant objectives, and could be key to effectively managing the larger, more complex power systems of the future.9

CONCLUSIONS

As the growing operational demands on modern power stations emphasize the need for more accurate, real-time data from all areas of the plant, sensors are coming to represent the cutting edge of coal power research. Rapid advances in novel technologies such as nanomaterials, optics, and additive manufacturing are outpacing the rate at which they can be implemented in commercial sensors. The industry is only beginning to exploit the potential benefits they can bring to process control and predictive maintenance. Although attention has often focused on the development of new materials to increase plant efficiencies and availability, advanced sensors can offer an effective and economic means of achieving the same goals. Given the size of the world’s coal power fleet, such incremental gains in efficiency and component lifetimes can represent significant reductions in emissions and huge financial savings. In fact, the U.S. DOE estimated potential yearly savings of over $350 million and 14 million tons of CO$_2$ from control system upgrades in the U.S. alone.4 There is, therefore, every incentive for coal power to embrace the information age.

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Using Automation to Increase Mining Safety and Productivity

By Hua Guo
Research Director, Coal Mining Research Program, CSIRO

Improving longwall mining safety, and with it productivity, is a priority for Australia’s leading applied research agency, the Commonwealth Scientific and Industrial Research Organisation (CSIRO). CSIRO’s Coal Mining Research Program, based at the Queensland Centre for Advanced Technologies, is made up of some 70 specialists who work with industry to improve ground stability and mine gas and fire control, and to develop advanced technologies that enhance workplace safety and productivity.

The team is credited for the development of an automation technology known as LASC (Longwall Automation Steering Committee), which is used by the majority of longwall mining operations in Australia. Its implementation has arguably improved longwall mining safety and productivity more than any other innovation in the last decade. The technology automates the longwall mining process and has improved safety by moving people away from the hazards of the mine’s working face. At the same time, LASC has delivered productivity gains of up to 10% during peak operating periods. Over the long term, this translates to a productivity gain of 5%, saving mine operators millions of dollars each year.

Today CSIRO is close to even more innovative advancements in its automation technology, by adapting this technology to the continuous miner (CM) operations used to develop underground coal mine roadways. This adaptation will again protect lives and boost productivity in an area that is widely considered a bottleneck in the coal supply chain.

A DESCRIPTION OF LASC TECHNOLOGY

LASC is a suite of enabling technologies and systems that allows longwall mining equipment of any brand to be automated using inertial navigation system (INS) technology. The INS technology allows the 3D position of the major elements of the longwall mining system to be measured accurately for the autonomous operation of mining systems underground.

“The technology automates the longwall mining process and has improved safety by moving people away from the hazards of the mine’s working face.”

The LASC suite automates the hazardous manual tasks of face alignment and steering, as well as horizon control. Thanks to a WiFi-enabled shearer communication system, a world’s first in the LASC project, the whole process can be controlled remotely.

Four technologies were developed to achieve automation and make up the LASC suite:

1. Shearer Position Measurement System (SPMS)—a combination of software and hardware that measures and communicates the 3D position of the shearer, and processes the raw data to a meaningful format.
2. Automated Face Alignment—software that allows the user to monitor and adjust the position of the shearer by sending corrections to the roof support control system to maximize production by keeping the longwall face straight.
3. INS-Based Automated Horizon Control—a combination of software that manages the transfer of horizon information to the original equipment manufacturer’s (OEM) shearer control system and provides an interface for users to control, monitor, and adjust the shearer’s cutting horizons.
4. Automated Creep Control—a system comprised of sensors mounted adjacent to the main gate to measure the cross gate road creep distance of the main gate hardware, and supporting software that displays the information and computes corrections.

Longwall mining shearer
INS ENABLING TECHNOLOGIES CONSTITUTE THE KEY BREAKTHROUGH

The key to achieving automation was developing effective enabling technologies that would open up the use of high-accuracy INS underground. The idea in itself was not new, and during the 1990s CSIRO demonstrated that it was possible to guide highwall mining machines using inertial navigation. Realizing that the principle could also be applied to measuring and controlling the motion of a longwall shearer, CSIRO began developing strategies that would allow an INS to be effectively used underground.

An INS calculates the position of a moving object based only on its motion without the need for an external reference, but a small error in the measurement is always present. This error increases over time and makes the INS unusable, so, from time to time, INS information needs to be checked against other navigation methods.

Above ground, almost all navigation systems use GPS to provide position information to correct or minimize measurement errors. It’s a different story underground, where GPS is unavailable, and the rough, dusty, and hazardous conditions hamper the use of other assistive methods.

CSIRO achieved long-term INS stability by using very high-quality, accurate, low-drift inertial measurement systems and then by ensuring the SPMS included a calculation of the (almost) closed path of the shearer throughout each shear cycle. The horizontal closing distance is used in a patented approach in the automated face alignment system to back-correct the shearer path at the completion of each shear cycle.

The result was a world-first system that could provide 3D measurement of the longwall shearing machine with constant, centimeter-order position accuracy, which is now widely used in the industry.

OTHER FACTORS THAT INFLUENCED THE SUCCESS OF LASC

Finding a way to track the 3D path of the shearer by developing multiple and diverse sensing technologies to support INS underground was a key technology breakthrough.

Other factors that contributed to LASC’s success include:

- Its design as an open-source platform, with freely available interconnection specifications allowing seamless integration with any brand of mining equipment
- A unique commercialization model with OEMs, based on a nonexclusive technology license
- The provision of guaranteed technical assistance to OEMs during the initial roll-out, including detailed implementation guides and access to upgrades
- The nonexclusive technology license, critical to LASC’s success, was brokered largely because mine operators led the push for automation

The technology development could not have occurred without collaborative support. The coal mining industry, through the Australian Coal Association Research Program (ACARP), provided funding for CSIRO’s automation research and development program, and viewed the resulting technology as a must-have safety feature. Industry participants required a nonexclusive technology license so that they could access it through any OEM industry supplier. OEMs supported this unique arrangement in recognition of the existing market interest, and the savings they had made on research and development activities.

ASSESSING THE EFFECTIVENESS

The fact that two thirds of Australian longwall mines are using LASC technology is a testament to the safety and productivity benefits it delivers. Exact figures are hard to obtain due to the commercially sensitive nature of the information; however, an independent evaluation conducted in 2014 by ACIL Allen Consulting found that LASC:

- contributes to improving the working conditions and safety of coal mine employees as it moves them away from the hazards of the longwall;
- will likely save mining firms millions of dollars annually as a result of improved safety;
- delivers productivity increases of up to 10% during peak periods, and, significantly, up to 5% over the long term.

LASC is able to directly improve productivity by up to 10% during peak periods because it facilitates consistency in the longwall mining machine. Over the long term, a 5% increase in productivity can be gained because LASC technology requires
all other systems and machines in the mining operation to be in peak condition for automation to be achieved consistently.

When combined with the lower risk of accident and injury, this means fewer process delays and greater efficiency in the entire mining operation.

**THE FUTURE OF LASC TECHNOLOGY**

In just seven years since its commercialization, LASC technology has been adopted by the majority of OEMs—Joy Global, Caterpillar, Eickhoff, Kopex, and Nepean Longwall—for use in their mining machines.

With the strong uptake in the Australian market, CSIRO is now focused on international opportunities. One OEM has taken the technology to global markets and CSIRO is currently working with a number of others active in the Chinese and European markets.

CSIRO’s research team continues to make refinements to the performance of the overall system, particularly in the development of improved mining horizon-sensing strategies using techniques like thermal imaging for coal seam tracking. Improved horizon control will lead to further economic and new environmental benefits for mine operators through a reduction in the amount of ash. This ultimately results in a cleaner coal product.

Perhaps the most exciting recent developments are based on CSIRO’s ongoing investigations into enhanced inertial system mining applications. In research which is now near commercialization, extra performance has been extracted from inertial systems so that the back-correction step referred to earlier for shearer position measurement is not required, paving the way for “real-time LASC”, which will deliver even more productivity improvement for longwalls.

CSIRO is nearing the end of a four-year research and development project aimed at delivering a “self-steering capability, called “LASCCM” guidance technology, that will enable a continuous miner (CM) to maintain 3D position, azimuth, horizon, and grade control within a variable seam horizon under remote monitoring and supervision.

Inertial navigation is again central to the design of LASC-CM. Thus, CSIRO has been working to develop aiding strategies to mitigate the effects of INS time-dependent position drift that will work in the roadway development setting, which is less structured than in longwall mining.

CSIRO’s experimental trial involved modifying a skid steer remote control vehicle so that it mimicked most of the CM dynamics in terms of motion profile, wheel slip, and vibration characteristics. This meant that the technology suite could be tested above ground, on a representative surface, which was important because gaining access to a working mine for extended prototype testing is impractical. The vehicle was fitted with CSIRO’s LASC-CM technology, as well as a high-performance GPS system. This allowed the positioning performance of LASC-CM to be compared with an accurate GPS-derived position.

In the trial, the vehicle was programmed to autonomously mimic the action of a CM developing a two-heading drive with cut-throughs. The practical accuracy of the LASC-CM system is demonstrated in Figure 1, which displays a waypoint during a trial. This and other trials have provided a high level of confidence in CSIRO’s approach.

Importantly, the results obtained show that decimeter 2D position accuracy can be achieved with an INS supported by

**PROMISING RESULTS FOR CONTINUOUS MINER APPLICATIONS**

Roadway development has not experienced the same rate of innovation as other areas of longwall coal-mine production and, as a consequence, it continues to be a bottleneck in the coal supply chain. The application of automation technology in this context will speed up roadway development, with huge gains for productivity and personnel safety.
CSIRO’s combination of aiding strategies over long distances, including sharp turns, reversing, and vibration. CSIRO’s work continues to improve the underlying navigation performance of the LASC-CM system, as well as its deeper system integration.

“A new high-quality miner position information can be used for performance analysis and improvement of existing manual processes.”

A field trial of the navigation technology during roadway development at an operating mine has now been completed. In this trial, conventional manual roadway development was carried out according to a mine plan and the position of the continuous miner was logged using CSIRO’s system. Results of the trial are shown in Figure 2. Extremely close agreement was obtained between the mine plan and the measured machine position.

Already the new high-quality miner position information can be used for performance analysis and improvement of existing manual processes. Thus, in the near future, full automation of the process becomes a real possibility because the miner position can be measured robustly with unprecedented accuracy. In a technology transfer process similar to LASC for longwalls, CSIRO will work with leading continuous miner manufacturers on licensing arrangements to deploy the LASC-CM technology commercially.

CONCLUSION

CSIRO’s research into longwall automation and the subsequent development of commercially available LASC automation technologies have produced clear productivity and safety benefits for longwall mining, and have opened the way to automation of continuous miner operations. Although the basic problems of machine positioning and process control are now close to being solved, barriers to fully autonomous mining operations still remain. Much work remains to be done in machine sensing of the mining environment and consistent automated management of the interaction of the mining process with ground conditions, before the process can be truly autonomous and workers can be removed from underground hazards. CSIRO’s ongoing research is concentrating on resolving these outstanding issues and will contribute significantly to the mining industry’s ultimate goal of zero harm to its people.

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Coal provides enormous benefits to society and continues to be a major energy source for power generation because of its large reserves, ease of transportation and storage, and low price. Coal-fired power generation also is one of the largest contributors to CO$_2$ emissions. One promising technology for CO$_2$ mitigation is oxy-combustion. However, first-generation oxy-combustion technologies, which operate under atmospheric pressure, suffer from a significant penalty in net generating efficiency—over 10 percentage points—primarily due to the auxiliary energy consumption from the air separation unit (ASU), flue gas recirculation (FGR), and gas processing unit (GPU). A promising new technology is pressurized oxy-combustion (POC), which can increase the plant efficiency by recovering the latent heat in the flue gas moisture and coupling it back into the steam cycle. An advanced POC technology is currently being developed at Washington University in St. Louis (WUSTL), Missouri, U.S.A. This technology can achieve an increase of more than six percentage points in net generating efficiency over the first-generation oxy-combustion process and is paving the way for low-cost carbon capture.¹

BACKGROUND ON PRESSURIZED OXY-COMBUSTION (POC)

In the simplest sense, pressurized oxy-combustion is oxy-combustion occurring within a pressurized vessel with a condensing heat exchanger downstream. There are several justifications for this added complexity. First, the large white plumes emitting from the stacks of a power plant, as seen from Figure 1, represent a large amount of moisture. When this moisture condenses in the atmosphere, the heat being released has no benefit to the power cycle. Thought of another way, the amount of energy needed to evaporate water to form this plume is quite large and this energy is lost to the power plant. POC harnesses this energy.

“Pressurized oxy-combustion, with the potential to capture over 90% of the CO$_2$ at high efficiency and affordable costs, is poised to transform coal-based power.”

Since carbon capture and storage (CCS) requires pressurization of CO$_2$, there is no change to net loss of efficiency to pressurizing the combustion process. When the flue gases are at an elevated pressure, the condensation temperature for the moisture can be high enough that the latent heat can be captured and fed into the steam cycle, increasing the efficiency of the process. Although a pressure of 10–16 bar is sufficient to recover most of the latent heat, pressures up to 80 bar have been proposed.²,³

The basic flow sheet for POC is similar to that of atmospheric pressure oxy-combustion, which includes the ASU, FGR, and GPU, but it also includes a condensing heat exchanger to capture the latent heat of the moisture. The ASU supplies oxygen at around 95% purity to the boiler. FGR is a widely accepted method in oxy-combustion for moderating combustion temperature and boiler wall heat flux, and FGR may also be employed as carrier gas to deliver pulverized coal to the boiler. Even though coal water slurry feeding has been proposed for pressurized coal delivery,⁴ dry feeding of pulverized coal yields higher boiler efficiency and has been widely used in gasifiers at pressures up to 40 bar.⁵ After
the warm flue gas leaves the boiler(s), particulates are removed using a filter. The warm particle-free gas then enters a condensing heat exchanger designed to recover the latent heat of the flue gas moisture and feed it into the steam cycle. Pressurization allows for simultaneous removal of SO\textsubscript{x} and NO\textsubscript{x} and the capture of latent heat in one device. The CO\textsubscript{2} is further compressed and purified in the GPU before it is pipeline ready.

**BENEFITS OF PRESSURIZED OXY-COMBUSTION**

The primary benefits of POC include:

1. capturing the latent heat of condensation and utilizing it to increase cycle efficiency;
2. reducing the efficiency penalty associated with using high-moisture fuels, since latent heat is recovered, thereby making low-rank coal more valuable;
3. simplifying the capture of SO\textsubscript{x} and NO\textsubscript{x} because pressure allows for co-capture of these pollutants in a simple water wash column;
4. greatly reducing gas volume, thereby reducing the size and cost of equipment;
5. avoiding air ingress, thereby reducing the GPU purification cost, and
6. increasing the optical thickness in the boiler, which allows for optimization of radiant heat transfer and reduced flue gas recycle.

The first few benefits are explained in more detail below.

**High Efficiency Through Latent Heat Recovery From Flue Gas**

The primary motivation to use POC, rather than atmospheric oxy-combustion, is to utilize the recovered latent heat from the flue gas, which compensates for the parasitic energy consumption of carbon capture. The temperature at which phase change occurs is strongly dependent on operating pressure. For example, at atmospheric pressure the flue gas moisture condenses at 50–55°C. At a pressure of 80 bar, condensation occurs at 150–200°C. The significant increase in condensation temperature makes it feasible to utilize the latent heat. Both direct-contact and non-contact heat exchangers could be used for latent heat recovery.

The latent heat that is captured can be utilized in the steam cycle by heating boiler feed water. This approach leads to replacement of roughly half of the steam extraction from the turbines. Less extraction allows more steam flow through the turbine and, thus, an increase in gross power.\textsuperscript{5}

**Integrated Emissions Removal**

Higher pressure enables integrated emissions control, which can replace traditional and expensive emission control equipment such as the Selected Catalytic Reduction (SCR) for NO\textsubscript{x} and Flue Gas Desulfurization (FGD) for SO\textsubscript{x}. Earlier studies have demonstrated that when flue gases are compressed in the presence of water, conversion of gaseous pollutants to weak sulfuric and nitric acids is enhanced by chemical interactions between S- and N-containing species. This occurs at elevated pressure, but not atmospheric pressure. While the precise chemical reaction mechanism that occurs under pressure is still a subject of study, the process is loosely referred to as the “lead chamber” process, which is a well-known process for manufacturing sulfuric acid. Test results have shown that almost all the SO\textsubscript{x} and about 80% of NO\textsubscript{x} is removed at 15 bar. An extra column operating at about 30 bar may also be employed for a more complete removal of NO\textsubscript{x}.\textsuperscript{7} The key requirements for the process are that the NO\textsubscript{x}/SO\textsubscript{x} ratio is greater than about 0.5, the pressure is greater than 15 bar, and the process occurs in the presence of liquid water.\textsuperscript{8, 9}

This process of emissions capture can be combined with the process of flue gas moisture condensation and latent heat recovery in a single counter-flowing water wash column, as illustrated in Figure 2. Wet flue gas at a temperature greater than the acid-gas dew point (≥300°C) flows into the gas-liquid reactor column from

**FIGURE 2. Direct contact cooler (DCC) column for flue gas cooling, latent heat recovery, and SO\textsubscript{x} and NO\textsubscript{x} capture**
the bottom. The flue gas flows against a stream of cooling water, thereby reducing the flue gas temperature. When gas temperature decreases to the dew point, condensation of the flue gas moisture occurs, releasing the latent heat, which is captured in the cooling water. Dew point increases with pressure, and thus the temperature of the water leaving the column increases with pressure. At 16 bar the value is about 167°C, which is sufficiently high to allow the heat to be used for boiler feed water heating.

When applied in a POC system, this approach includes the following benefits:

1. Unlike the protocol for atmospheric pressure oxy-combustion systems, the flue gas need not be compressed because it is already at elevated pressure; thus, the challenges of avoiding corrosion when compressing a sour gas is eliminated.
2. The capture of flue gas latent heat occurs along with SO\textsubscript{x} and NO\textsubscript{x}, which is more economical as compared to separate capture systems.
3. Acid gas condensation occurs in a single device, reducing the chance of corrosion in other parts of the system.
4. Because no cooling is necessary before the flue gas enters the DCC, the overall efficiency of the process is maximized.

**STAGED, PRESSURIZED OXY-COMBUSTION**

An extension of POC, the novel staged, pressurized oxy-combustion (SPOC) process, can reduce the efficiency penalty for carbon capture in coal-fired power plants by over half. The SPOC process incorporates a unique boiler configuration to enable combustion of pulverized coal at elevated pressure (approx. 15 bar) with minimal flue gas recycle.

**Features**

The SPOC process is depicted in Figure 3. A key feature, as compared with the traditional oxy-combustion processes, is that two or more pressurized boilers are connected in series on the gas side. In addition to allowing for reduced FGR, the use of multiple boiler modules also provides added flexibility in plant design and operation under variable loads. Although four boilers, or stages, are shown in the figure, fewer stages may be employed by increasing the amount of flue gas recycle. The optimum operating pressure of the SPOC boilers is around 15 bar.\textsuperscript{10} Coal is fed to the centerline at the top of each boiler, and burns as it flows through each of the respective boilers. The products of the upstream boiler, including any excess oxygen, are passed to the following stage, wherein more coal is introduced. The process repeats until nearly all of the oxygen is consumed in the final stage. The temperature of the products is further reduced in a convective heat exchanger, followed by ash removal. The flue gas is then cooled in a direct contact cooler (DCC), where moisture is condensed, the latent heat is captured, and SO\textsubscript{x} and NO\textsubscript{x} are removed. The majority of flue gas then goes to the GPU where it is further purified to meet the stringent specifications for storage or EOR.

**Higher Net Generating Efficiency**

The SPOC process has several other benefits to increase efficiency and reduce capital and operating costs: (1) FGR is minimized, which decreases flue gas volume, equipment size, and parasitic pumping loads, and increases boiler efficiency; (2) a high gas temperature is maintained to maximize the overall amount of radiative heat transfer, as compared to convective, thereby minimizing the amount of heat transfer.
surface area and reducing boiler exergy losses; and (3) moisture condensation and emissions removal are combined in a compact DCC device to remove SO\(_x\) and NO\(_x\) while recovering latent heat, which minimizes equipment size and cost.

As shown in Table 1(a), the net generating efficiency of the SPOC process can be over six percentage points greater than that of first-generation atmospheric pressure oxy-combustion. The penalty associated with carbon capture on net generating efficiency can be as low as three percentage points, as compared with the traditional air-fired power plant. The improvement in net generating efficiency over the reference atmospheric pressure case is due to a number of factors, but most of the savings are related to the SPOC process.

The capture of latent heat in the DCC is a major contributor to the increase in net generating efficiency of the SPOC process over atmospheric pressure oxy-combustion, adding 10% more heat to the steam cycle. The increase in efficiency and reduction in equipment costs translate into substantial reduction in the added cost of electricity (COE) associated with carbon capture, thereby showing potential to meet the U.S. Department of Energy’s target of less than 35% increase in COE.\(^{13}\) Électricité de France independently evaluated the SPOC process and an alternative pressurized oxy-combustion process and compared them with atmospheric pressure oxy-combustion and air-fired combustion (Table 1(b)).\(^{14}\) The goal was to understand the advantages and disadvantages of the different approaches to pressurized oxy-combustion from an energetic and exergetic standpoint. This study showed that the increase in radiative heat transfer relative to convective heat transfer in the SPOC process increases the overall exergy transfer from the flue gas to the steam cycle, which increases the plant efficiency. In addition, since the SPOC process required less FGR, the auxiliary load was lower, further increasing the plant efficiency.

![FIGURE 4. Illustration of “radiative trapping” in SPOC furnace](image)

**Controllable Radiation Heat Transfer**

Pressurization of the combustion process enables operation at higher combustion temperature and, thus, reduced FGR, to a degree that is not possible at atmospheric pressure. This is because at sufficient pressure, radiation heat transfer is dramatically altered since the combustion gas, which contains char and ash particles, becomes optically dense. Recognizing this, the team has developed, through CFD-aided design and fundamental studies, a unique approach to pressurized boiler design that can provide control of wall heat flux under very high flame temperatures.\(^{15,16}\) This approach is called “radiative trapping” as it utilizes the optically dense medium to trap the radiative energy emitted by the high-temperature flame within the reactor core (Figure 4) and control the heat transfer to the boiler tube surfaces. The SPOC boilers have additional design features to ensure that there is no flame impingement on the water wall. The ash deposition rate is substantially

### TABLE 1. Comparison of the net generating efficiency of air-fired, atmospheric-oxy, and pressurized-oxy combustion power plants

(a) supercritical steam conditions, net power output = 550 MW\(^{11,12}\)

<table>
<thead>
<tr>
<th>Coal type</th>
<th>Air-Fired</th>
<th>Atmos. P Oxy-Combustion</th>
<th>SPOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net generating efficiency, HHV (%)</td>
<td>39.3</td>
<td>29.3</td>
<td>36.7</td>
</tr>
</tbody>
</table>

(b) independent study comparing two pressurized oxy-combustion processes\(^{14}\)

<table>
<thead>
<tr>
<th></th>
<th>Air-fired</th>
<th>Atmos. P Oxy-Combustion</th>
<th>Pressurized Oxy-Combustion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net generating efficiency, LHV (%)</td>
<td>46.1</td>
<td>36.1</td>
<td>39.1</td>
</tr>
</tbody>
</table>
lower than that of a traditional air-blown boiler, and ash fouling and slagging are minimized.

Research Facility

WUSTL has recently completed construction of a lab-scale (approx. 100-kWth) pressurized combustion facility, shown in Figure 5. The facility will be utilized to demonstrate the staged oxy-combustion approach and obtain key experimental data to validate the computational fluid dynamics results.

CONCLUSIONS

Pressurized oxy-combustion, with the potential to capture over 90% of the CO2 at high efficiency and affordable costs, is poised to transform coal-based power generation. Through the recovery of flue gas moisture latent heat and the minimization of flue gas recycling, staged, pressurized oxy-combustion is able to achieve a net generating efficiency of 36.7% (HHV, supercritical conditions) with only about 3% penalty on net generating efficiency. Further improvements are anticipated as advances are made in ASUs and CO2 purification technology, and in the development of modular boilers for pressurized coal combustion. ☞

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Cisco estimates 21 billion devices will connect to the Internet by 2018 (three times the world population and up from 14 billion in 2013). This number will include sensors and other devices that aid in the supply and use of electricity. The proliferation of these sensors, the data they collect, and sophisticated new technologies that enable transformational applications of that data will profoundly change society, including the way we generate, distribute, and use electricity.

There are, however, some challenges. They include the sheer volume of data; proprietary legacy systems; the need for enhanced security; inconsistent life-cycle timescales of utility assets and connectivity technologies; rapid technological change; and effective integration of technologies into the power system, including intelligent devices, sensors, advanced metering, and even customer technologies. Fortunately, these challenges also bring opportunities spanning the energy value chain. A digital world full of new technologies with vast potential for addressing most needs via a pocket-held device offers an as-yet untapped arsenal of tools that could meet these challenges and transform the industry’s generating assets.

The bottom line is this: The power plant of tomorrow is likely to generate electricity in much the same way it has in the past, but the way in which the plant is controlled and operated—using digital technology—will change dramatically. And these changes will be driven by new, advanced sensors and data analytics.

“The future power plant operating workforce will use a digital platform in which information produced in real time is used...”

THE CURRENT STATE

Today’s typical large-scale power plants have existing systems, communication capabilities, and work processes. Some of these processes are paper based and communication occurs through a variety of disconnected, ad hoc channels such as e-mail, phone, text, radio, paper, and electronic data/entry into various software-based solutions/data management...
tools. Considerable time is wasted seeking, assembling, and aggregating data, as well as re-entering data in disconnected systems, which limits the amount of time available to analyze data and develop a comprehensive understanding of an issue or solution.

THE FUTURE STATE

The future power plant operating workforce will use a digital platform in which information produced in real time is used to estimate equipment condition, and algorithms are used to forecast a set of operating conditions. The connected and integrated digital networks automatically integrate data and produce the information for various systems, functions, analysis, personnel, and actions. The computation, communication, and linking of systems are embedded with interfaces that are easy to use, but secured at various levels within the network. An open-architecture modular system allows for “plug and play” of new devices, software, and other algorithms regardless of the developer or vendor.

The Electric Power Research Institute (EPRI) and other companies are developing detailed visions of tomorrow’s power plant with seamless integration of data, autonomous communication of information, and corresponding response, action, or control. EPRI’s I4GEN (Insight through the Integration of Information for Intelligent Generation) concept is a holistic approach that creates a digitally connected and dynamically optimized power plant by using a modular and scalable platform of tools, techniques, and technologies that integrate the business, maintenance, and operational aspects of generating power. The goal is to enhance performance, reduce failures, increase availability, improve flexibility, and minimize cost. Dynamically optimizing a plant requires collection and aggregation of data and production of real-time information; embedded distributed and adaptive intelligence that supports decision-making; and identification of actions and responses to account for risk, reward, and uncertainty.

The I4GEN concept is to optimize the use of all available information to make better decisions for the plant, be it autonomous or by the plant operator. Emerging data analytic algorithms are intended to detect degradation at early stages, diagnose the most likely cause of degradation, and estimate the remaining time to take action before an operability limitation will be reached. Successful development and deployment of detection and diagnosis algorithms can result in increased plant reliability, decreased plant O&M costs, reduced forced outages, more efficient use of O&M resources, and minimization of the impact resulting from flexible operations. This is performed through many different avenues. Data can come from operating data from instrumentation in the plant; external sources such as weather conditions, expected demand on the plant and plant flexibility; archived data; and subject-matter expert (SME) specifications and guidelines.

Successful collection and analysis of the most appropriate data enables important advances such as prognostics—doing the right work at the right time—maintaining, repairing, or replacing equipment when needed, instead of when recommended.
based on hours of service or other, less precise metrics. This enhanced diagnosis of component condition and remaining life can come from optimizing sensor suites. Information is then gathered where needed and vital type and location sensors are identified (what types, how many, where they are located, reduced redundancies); sensor groupings and embedding intelligence into sensors so that they continue to retrieve valuable information even as sensor data drifts or certain sensors fail; and data analytics, statistical methods, model-based methods, SME input (when needed), and machine learning.

The ultimate goal of I4GEN is to make the most useful information available to a person at the time it is needed to make a decision or perform an action. A power plant using I4GEN produces, shares, manages, and manipulates information at the appropriate time, within proper context, and at a level of detail sufficient to support a response. It is enabled through an open-architecture communication framework that is scalable, modular, and secure. Its foundation relies on dense and distributed data collection, aggregation, and computational analytics to generate actionable information. Optimization and effectiveness are the result of having actionable information in context and at the appropriate time to achieve an objective.

The drivers for adopting the new digital technologies for power generation envisioned in I4GEN are many:

- **Grid modernization and integration**: As part of an integrated grid, power will be generated from a range of sources; the mix of types, sizes, locations, and intermittent operations adds layers of complexity to the grid control. Dynamic, fully integrated generation assets are required to achieve the full benefits of the integrated grid.

- **Critical cost-competitiveness**: Maintaining the reliability and availability of power generation is paramount when introducing new facets of flexible operation. Quantifiable benefits from implementing and adapting the I4GEN architecture/framework would be specific to the generating asset, how it is used within a fleet, and how it is used for a region’s dispatch to the grid.

- **Changes in the generation resource portfolio and the need for operational flexibility**: The mix of generating assets is changing as the portfolio becomes more diverse with the advent of advanced power cycles, renewables, energy storage, microgrids, and other distributed generating assets.

- **Changing workforce**: Highly skilled and experienced workers are either retiring or preparing to retire from the

"Maintaining the reliability and availability of power generation is paramount when introducing new facets of flexible operation."

Workflow is optimized and automated through connectivity of all needed information. (Courtesy EPRI)
power industry. The new workforce brings a different set of skills and capabilities, including an in-depth familiarity and expertise with digital technologies. Plants facing a significant turnover with staff and a potential loss in expertise may also view an investment in digital technologies as a means to capture and automate the expertise, facilitate training of new personnel, and reduce risk associated with staff turnover.

- Inherent value in owning, managing, and controlling data and information: Generating plants produce vast amounts of data: Managing and sharing that data is a critical function for moving from a reactive state to a more proactive state. As organizations recognize and assign value to plant data and information, similar to how they currently treat financial data, the opportunities, benefits, and drivers associated with this valuation emerge.

**“Real-time data on component status will identify developing problems and support condition-based maintenance to help prevent failures and avoid outages.”**

**EMERGING TECHNOLOGIES THAT SUPPORT I4GEN**

The I4GEN concept can be applied to all types of generating assets. Remotely located generating assets, such as hydroelectric and wind, which do not maintain large, onsite staffs may develop highly advanced monitoring and diagnostics to support more effective use of onsite inspection and maintenance. Slightly different drivers and emphasis may be placed on large-scale central power stations in which enhancements in process controls may be needed to support operational flexibility.

Besides producing electricity, all these generating assets have something in common, the two keys to success in their transition to the generating plants of tomorrow: advanced sensors and the data analytics needed to realize the value of the information they provide. After the sensor suite has been developed, the sensors are able to communicate, and data is being fed into the data analytics suite, the plant should be able to detect, diagnose, and act rapidly with much less downtime than current methods allow.

The I4GEN concept requires connectivity and communication between systems, hardware, and software users. This requires an increase in data collection; autonomous data integration; methods for massive data management; ability to reconfigure data integration and analysis; incorporation of advanced query capabilities; and application of intelligence algorithms (e.g., cognitive, analytics, artificial intelligence, etc.). Enabling technologies include component and system modeling, augmented reality, visualization, and networked systems (hardware and software) to provide real-time information, distributed and adaptive intelligence, and action and response.

Real-time data on component status will identify developing problems and support condition-based maintenance to help prevent failures and avoid outages. Improved situational awareness will allow operators to extend maintenance intervals and maximize asset utilization, helping reduce costs and improve productivity without affecting safety and reliability. The ability to monitor key parameters in areas that could not previously be accessed—or only accessed with significant cost and safety implications—will enable operating and maintenance interventions to address incipient problems and otherwise improve the performance of electricity infrastructure.

EPRI’s Technology Innovation (TI) program is pursuing novel sensor designs for steam turbine and combustion turbine compressor blades and pressure-retaining components, as well as overhead transmission lines, transformers, underground distribution cables, and other applications. This effort also focuses on core technologies for data analysis, decision support, and power harvesting for self-powered sensor technologies.
Three examples of sensor technology developments specific to power generation that are supported by EPRI TI projects include blade vibration sensors, laser-based sensors for coal gasifiers, and fiber Bragg grating (FBG) sensors for nuclear plant applications. Since 2009, EPRI has been leading efforts to create a microelectromechanical (MEM) sensing system for direct online vibration monitoring of large blades in low-pressure steam turbine stages to detect incipient damage and avoid catastrophic failure, which poses major cost and safety risks at thermal power plants. The system is also applicable for combustion turbine compressor blades.

"Adopting the I4GEN approach in totality will be a large undertaking."

The shaft systems on large grid-connected steam turbine generators can be subjected to dynamic torque (or “twisting”) oscillations caused by negative sequence currents in the generator. To date, prototype EPRI torsional sensors to detect these oscillations have been installed and field tested on three shaft locations on two separate generating units. The accumulated operating time represents a total of 11 unit-months of operation without failure of the shaft sensors, circuit boards, or the stationary antenna assemblies. Compared to earlier technologies, the system is highly sensitive and provides more data, with a higher degree of granularity, making it easier to tell where the torsional peaks are. The data provides an accurate picture of each individual torsional node, enabling assessments of the failure mechanisms. It is anticipated that highly sensitive and low-noise shaft strain monitoring will be the basis for advances in a range of new condition-monitoring applications on a wide array of power generating equipment.

Reliability problems challenge the economics of integrated gasification combined-cycle (IGCC) plants, creating the need for a system to prevent the temperature excursions that damage refractory linings. Based on exploratory research initiated in 2000, EPRI demonstrated the feasibility of applying tunable diode laser (TDL) technology for this application. An initial prototype delivered accurate temperature readings and the first direct, real-time measurements of key chemical species in the high-temperature, high-pressure, particulate-laden gasifier environment. Follow-on scale-up experiments supported development of a TDL sensor system incorporating advanced spectroscopy techniques and multiple diodes tuned to the wavelengths of targeted species. Commercial TDL sensors are expected to provide real-time data for precise monitoring and control of the gasification process to improve reliability, conversion efficiency, and environmental performance at IGCC plants. Other EPRI TI advanced sensors and data analytics projects include:

- **Transient analysis methods**: Much like autos running at highway speed, most bulk power generation assets operate most efficiently in steady states at high capacity. Their components are under the most stress during start-up, load change, and shut-down cycles. EPRI has explored use of transient analysis methods to uncover data anomalies and trends that indicate the onset of aging or failure. In a proof-of-concept study, aging-related performance degradation of a high-speed motor not evident in steady-state data was clearly detected in start-up data. Follow-on work has established a novel method, sharp time distribution mapping, as a generalizable approach for applying transient sensor data to improve anomaly detection for power generation and delivery system components.

- **Decision-support technologies**: EPRI is creating a knowledge and capability base to enable accurate and timely decision-making in power plant and grid control centers where personnel are challenged to handle large amounts of complex and diverse data from sensors and other sources with support from growing amounts of automation. A long-term, multidisciplinary research plan has been defined for addressing the industry’s decision-making needs with interactive human–system interface (HSI) technologies, including analysis, visualization, and simulation tools. In addition, based on advanced HSI test cases, design guidelines have been developed to ensure that decision-support technologies meet application-specific needs while avoiding loss of situation awareness and other new types of errors associated with increased automation. The guidelines will aid in the design of user-centered HSIs, responsibilities, and workloads to support decision-making in environments where cognitive processing is essential, such as control rooms, control centers, and monitoring and diagnostics centers.

- **Power harvesting and storage**: A number of promising methods have been identified for exploiting ambient energy sources to support the autonomous operation of sensors and associated electronics within power generation and delivery infrastructure. A laboratory test bed for evaluating harvesting technologies has been constructed, and this project continues to focus on applications of self-powered sensors in nuclear, fossil, and renewable generation systems and on the transmission and distribution grid.

**PROSPECTS FOR ADOPTION**

Adopting the I4GEN approach in totality will be a large undertaking. In many cases, adoption of selected digital technology platforms and capabilities over time, with short-term returns on investment and measurable benefits, is a more likely
scenario. Near-term development and demonstration opportunities that offer tangible benefits and utilize many of these enabling technologies include:

- **Digital worker**: Tablets, smart phones, laptops, wearable monitoring devices, headsets, and augmented reality devices can be used by staff to carry out or complete a given job function. Wireless communication capabilities; developing relevant information, procedures, guidance, equipment tagging, operator rounds, and work order entries in a digital format that is easy to access and intuitive; and ergonomics, safety, and impact on situational awareness need to be evaluated under different scenarios.

- **Virtual reality and simulated plant analytics and operation**: 3-D interactive images of workspaces and equipment layouts support training and assists in work planning and can be linked to digital devices to support work execution. A plant process simulation running in near time using data from the plant can be used to assist in optimization of the process and provides a safe environment to forecast a number of operating conditions to aid the plant in performance.

- **Low-cost sensing and monitoring**: Additional data can help produce information and insights about the process, equipment and component conditions, and other operational aspects, but the cost to purchase, install, and maintain these sensors can be a challenging hurdle. Many new types of sensors are entering the market that are both low-cost and wireless; installation costs can be comparably less if a wireless network is available and powering the sensors can be managed cost-effectively. A number of low-risk opportunities exist to demonstrate new sensor technology and evaluation of additional data may bring in greater insights and proactive operations and maintenance.

EPRI plans to develop and implement the I4GEN technologies discussed above that will support power generation companies at various stages of maturity. Whether an organization is at the beginning stages of learning about I4GEN-associated technologies and applications or have already invested in advanced remote monitoring centers, digital worker applications, etc., this development and implementation will provide opportunities for collaboration, technology transfer, and development of industry guidelines to further work in this area.

**REFERENCES**

GLOBAL NEWS

Movers & Shakers

Paul Flynn, Managing Director and Chief Executive Officer of Whitehaven Energy, and Jianjun Gao, President of China Coal Energy Co Ltd, have been appointed to the World Coal Association Executive Committee.

Recent Select Publications

World Energy Outlook Special Report 2016: Energy and Air Pollution — International Energy Agency (IEA) — In June the IEA launched its Special Report on Energy and Air Pollution. The report notes that around 6.5 million people die each year as a result of air pollution. The IEA proposes a pragmatic, tailored solution: A Clean Air Scenario (CAS). The report identifies three key areas for government action, including long-term air quality goals, a package of clean air policies for the energy sector, and effective monitoring, enforcement, evaluation, and communication. The full report can be downloaded free of charge from www.iea.org/publications/freepublications/publications/weo-2016-special-report-energy-and-air-pollution.html

The Potential for Equipping China’s Existing Coal Fleet With Carbon Capture and Storage — International Energy Agency (IEA) — The report, part of IEA’s Insight Series 2016, identifies 310 GW of existing coal-fired power capacity that could be retrofitted. Further information about the criteria used to identify the potential plants, including costs, are in the report, which can be accessed for free from www.iea.org/publications/insights/insightpublications/ThePotentialforEquippingChinasExistingCoalFleetwithCarbonCaptureandStorage.pdf

The Role of Coal for Energy Security in World Regions — IEA Coal Industry Advisory Board (CIAB) — The CIAB has published a report based on its study of the role coal plays globally in several important world regions: the EU-28, the U.S., Canada, Australia, Japan, China, India, and South Africa. The report found that applying of high-efficiency, low emission (HELE) technologies provide significant CO₂ emission reductions. A further key finding is that coal provides energy security and plays an important role in balancing the relatively unpredictable feed-in of wind and solar energy. The whole report (including all country chapters) can be accessed from www.iea.org/ciab/The_role_of_coal_for_energy_security_in_world_regions.pdf
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

<table>
<thead>
<tr>
<th>Conference Name</th>
<th>Dates (2016)</th>
<th>Location</th>
<th>Website</th>
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<tbody>
<tr>
<td>IEA Clean Coal Centre 1st Coal Quality Workshop</td>
<td>9–10 Nov</td>
<td>New Delhi, India</td>
<td><a href="http://www.iea-coal.org.uk/site/2010/conferences/coal-quality?LanguageId=0">www.iea-coal.org.uk/site/2010/conferences/coal-quality?LanguageId=0</a></td>
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<tr>
<td>IEA GHG R&amp;D Programme 13th Greenhouse Gas Control Technologies Conference</td>
<td>14–18 Nov</td>
<td>Lausanne, Switzerland</td>
<td><a href="http://www.ghgt.info">www.ghgt.info</a></td>
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There are several Coaltrans conferences globally each year. To learn more, visit www.coaltrans.com/calendar.aspx
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The power plant of tomorrow is likely to generate electricity in much the same way it has in the past, but the way in which the plant is controlled and operated—using digital technology—will change dramatically.