Coal is plentiful in the United States, but technologies must be developed to make it burn more efficiently and to sequester the carbon dioxide it generates.

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The United States is, by any measure, the “Middle East” of coal resources. The readily available (least expensive to recover) portion is estimated to be close to 400 billion tons, enough to generate electricity as well as produce fuels for about 250 years. Today, coal combustion accounts for more than half of the nation’s electric power generation. However, burning coal produces large amounts of ash and carbon dioxide, and sulfur-containing coal emits sulfuric acid, the main constituent of acid rain. To address these issues, the U.S. Department of Energy has collaborated with industrial partners and university researchers to develop a range of technologies that improve plant efficiency and reduce emissions. They are also working on coal technologies that can produce hydrocarbon fuels for vehicles. This article discusses fluidized bed combustion, coal gasification, coal liquefaction, and carbon dioxide sequestration.

Fluidized bed combustion
Fluidized beds suspend solid fuels on upward-blowing jets of air during the combustion process (Fig. 1). The result is a turbulent mixing of gas and solids. The tumbling action, much like a bubbling fluid, provides more effective chemical reactions and heat transfer. The mixing action of the fluidized bed brings the flue gases into contact with a sulfur-absorbing chemical such as limestone or dolomite. More than 95% of the sulfur pollutants in coal can be captured inside the boiler by the sorbent. Fuel is burned at temperatures of 760 to 925°C (1400 to 1700°F), well below the threshold where nitrogen oxides form. (At ~1370°C (2500°F), the nitrogen and oxygen atoms in the combustion air combine to form nitrogen oxide pollutants).

The popularity of fluidized bed combustion is due largely to the technology’s fuel flexibility and the capability of meeting sulfur dioxide and nitrogen oxide emission standards without the need for expensive add-on controls. Almost any combustible material can be burned, from coal to municipal waste.

• First Generation: The DOE Clean Coal Technology Program (www.fossil.energy.gov) led to the initial market entry of First-Generation pressurized fluidized bed technology, with an estimated 1000 megawatts of capacity installed worldwide. These systems pressurize the fluidized bed to generate sufficient flue gas energy to drive a gas turbine and operate it in a combined cycle.

The First Generation pressurized fluidized bed combustor is based on a “bubbling-bed.” A relatively stationary fluidized bed is established in the boiler, in which low air velocities fluidize the material, and a heat exchanger immersed in the bed generates steam. Cyclone separators remove particulate matter from the flue gas prior to entering a gas turbine, which is designed to accept a moderate amount of particulate matter.

• Second Generation: The pressurized fluidized bed combustor is based on “circulating fluidized-bed” technology, as well as several measures to enhance efficiency. Higher air flows entrain and move the bed material, which is recirculated with adjacent high-volume, hot cyclone separators. The relatively clean flue gas goes on to the heat exchanger. This approach theoretically simplifies feed design, extends the contact time between sorbent and flue gas, and reduces likelihood of erosion in heat exchanger tubes. It also improves sulfur dioxide capture and combustion efficiency.

Another innovation is the integration of a coal gasifier (carbonizer), which produces a fuel gas that is burned in a “topping combustor.” The gasified coal adds to the combustor’s flue gas energy.
as it enters the gas turbine, which is the more efficient portion of the combined cycle. The topping combustor must exhibit flame stability in combusting low-Btu gas, and must demonstrate low-NOx emission characteristics.

• Materials developments: Tests of promising new hot-gas filter components and systems are continuing at the Power Systems Development Facility (PSDF) in Wilsonville, Alabama. (http://psdf.southernco.com/tech_papers.html) Advances made to date in this critical technology area include the development of clay-bonded silicon carbide candle filters and the associated filter vessel. Efforts are currently focused on improved candle filter materials for enhanced durability under extreme temperatures and a highly corrosive environment. New ceramics and ceramic-metallic composites show promise in this area.

Coal gasification

An alternative to coal combustion is coal gasification. Rather than burning coal directly, a coal gasifier reacts coal with steam and controlled amounts of air or oxygen under high temperatures and pressures. The heat and pressure cause chemical reactions with the steam and oxygen to form a gaseous mixture. This mixture is called a synthesis gas (or syngas), and is made up primarily of carbon monoxide and hydrogen. The syngas is then combusted in a gas turbine to generate electricity.

In gasification-based systems, impurities can be separated from the gaseous stream before combustion. As much as 99% of sulfur and other pollutants can be removed and processed into commercial products such as chemicals and fertilizers.

Combined cycle system

If the syngas is burned to produce electricity, it typically serves as a fuel in an Integrated Coal Gasification Combined Cycle (IGCC) system. The IGCC system has two basic components. A high efficiency gas turbine burns the clean syngas to produce electricity, and exhaust heat from the gas turbine is recovered to produce steam for traditional high-efficiency steam turbines.

IGCC power generating systems are being developed and operated in Europe and the United States. These systems raise efficiency by taking the heat from the gas to produce steam to drive a steam turbine. Existing commercial systems can achieve a thermal efficiency greater than 40%. With further advances in gas turbine technologies, these systems are capable of reaching above 50% efficiency. IGCC systems can be designed to produce little solid waste and low emissions of SOx and NOx. In addition, over 99% of the sulfur present in the coal can be recovered.

Furthermore, carbon monoxide in the synthesis gas can be reacted with steam to make hydrogen and carbon dioxide. This creates the potential to separate a relatively pure stream of carbon dioxide for "sequestration," thus avoiding its emission into the atmosphere. The resulting hydrogen can be burned in a gas turbine for electricity generation, or as a fuel in other applications, such as hydrogen-powered vehicles. Instead of burning it to generate electricity, the syngas can be processed...
Coal may be converted into liquid fuels by several different processes. with commercially available technologies to produce a wide range of fuels, chemicals, fertilizer, and industrial gases. (For more details, visit http://www.fossil.energy.gov/programs/powersystems/gasification/index.html.)

Coal liquefaction

Coal may be converted into liquid fuels by several different processes, such as Bergius, Fischer-Tropsch, Schroeder, and Low-Temperature Carbonization.

- **Bergius:** Hydrogen at 700 atm pressure is injected into a heavy paste of crushed coal at a temperature of 400°C (750°C) with an iron/molybdenum-oxide catalyst. The process requires about 7000 cubic feet of hydrogen per barrel of oil it produces.

- **Fischer-Tropsch:** This process involves first treating white-hot hard coal or coke with a blast of steam, producing carbon monoxide and hydrogen. This is followed by a catalyzed chemical reaction in which carbon monoxide and hydrogen are converted into liquid hydrocarbons of various forms. Typical catalysts are based on iron and cobalt.

- **Low-Temperature Carbonization:** LTC is a pyrolysis process that involves heating coal, shale, or lignite to about 425°C (800°F) in the absence of oxygen. Oil is thus distilled from the material, rather than burned as it would if oxygen were present. Also known as the Karrick process, a ton of coal yields up to a barrel of oil, 3000 cubic feet of rich fuel gas, and 1500 pounds of solid smokeless char (semi-coke).

- **Schroeder:** The coal is pulverized and dried, and then saturated with methanol. The methanol-saturated coal is slurred in benzene, and the slurry is exposed to microwave energy of a frequency and for a period of time sufficient to cause hydrogenation of the coal. The principal product is benzene. Unreacted coal and char may be recycled or subjected to gasification with steam and oxygen to produce synthesis gas that can be converted to methanol.

All of these liquid fuel production methods release carbon dioxide (CO₂), far more than is released in the extraction and refinement of liquid fuel production from petroleum. Therefore, carbon dioxide sequestration is needed to avoid releasing it into the atmosphere.

Hybrid generators

Linking a coal gasifier and a fluidized-bed combustor arranged in a “topping cycle” could be an ideal combination of lower-cost capital equipment, high-performance fuel combustion, and improved environmental performance for future power plants (Fig. 2). The combination may be particularly suited for smaller power stations, those in the 200 to 300 megawatt range.

In this hybrid system, coal is partially gasified in a pressurized gasifier. This produces a fuel gas that can be combusted in a gas turbine, the “top” of the cycle, hence the name. Left behind in the gasifier is a combustible char that can be burned in a fluidized bed combustor or advanced high-
temperature furnace that produces steam to drive a steam-turbine power cycle and to heat combustion air for the gas turbine. Heat from the gas turbine exhaust also can be recovered to produce steam for the steam turbine.

This highly integrated system of gasifiers, combustors, gas, and steam turbines results in a high overall fuel-to-electricity efficiency, exceeding 55% in many advanced concepts. (The average efficiency of today’s coal-burning power plant typically is around 33 to 35%).

Hybrid systems may also lead to less expensive power plants. Because it is not required to break down coal completely into synthetic gas, a partial coal gasifier can be a relatively simple, compact, and low-cost component. The char combustion system likewise can be a relatively low cost module, and unlike many older coal combustors, which are designed to fire a specific type of coal, fluidized bed combustors can accept a wide range of fuels and would have no trouble burning chars produced from a variety of different coals. (This information is from http://www.fossil.energy.gov/programs/powersystems/combustion/index.html.)

The challenge

Coal produces solid waste (ash) when burned, and coal from the eastern United States contains sulfur, which produces sulfuric acid, the genesis of “acid rain.” However, it is neither the ash nor the sulfur that is the major environmental concern regarding coal as fuel for electrical power generation: The biggest challenge is the carbon dioxide that is produced by burning coal.

The combustion of carbon produces carbon dioxide, the most important of the “greenhouse” gases. Coal derives all of its energy from the combustion of carbon, producing significantly greater quantities of carbon dioxide than does the combustion of natural gas for a given amount of energy. Therefore, if coal is to become a truly viable solution, the carbon dioxide will have to be “sequestered.”

Sequestration is a process by which carbon dioxide is stored in underground sites such as porous rock beds, for a 25% premium. It is estimated that new electric power plants can sequester 80 to 95% of the carbon dioxide emissions. However, the cost of the addition and maintenance of sequestration equipment to a current generating facility results in a 60% premium over current costs. (For more details on sequestration, visit http://www.fossil.energy.gov/programs/sequestration/overview.html.)

We will be able to get as much coal as we need in the near to intermediate future, but the cost of processing to remove contaminants will go up as more is burned. Coal liquefaction and gasification are methods to explore as means of cleaning before burning, and methods of disposing of the ash after burning. It is estimated that coal gasification, which leads to cleaner burning and is ash-free, can be achieved at a premium of about 20 to 25% over current coal costs.

FutureGen

FutureGen is an initiative to build the world’s first integrated sequestration and hydrogen production research power plant. The $1 billion dollar project is intended to create the world’s first zero-emissions fossil fuel plant. When operational, the prototype will be the cleanest fossil fuel fired power plant in the world. The prototype plant will establish the technical and economic feasibility of producing electricity and hydrogen from coal, while capturing and sequestering the carbon dioxide generated in the process. Sponsored by the Dept. of Energy, the initiative will be a government/industry partnership to pursue an innovative “showcase” project focused on the design, construction and operation of a technically cutting-edge power plant that is intended to eliminate environmental concerns associated with coal utilization. This will be a living prototype with future technology innovations incorporated into the design as needed.

Coal gasification technology will be integrated with combined cycle electricity generation and the sequestration of carbon dioxide emissions. The project will be supported by the ongoing coal research program, which will also be the principal source of technology for the prototype. The project will require ten years to complete and will be led by the FutureGen Industrial Alliance Inc., a nonprofit industrial consortium representing the coal and power industries, with the project results being shared among all participants, and industry as a whole.

Because coal accounts for over 50% of the electricity generated in the United States today, a significant increase in the cost of coal-generated energy would be felt throughout the economy. For example, an environmentally acceptable conversion to all-coal electrical generation would likely result in about an 80% increase in the price per kilowatt-hour in the near term. However, the premium would fall as new technologies supplant those to which the carbon-trapping equipment is added after construction.

In sum, coal can provide large reserves of energy. However, coal must be cleaned before it is burned, and the products of coal combustion must likewise be cleaned. Whether the cost of environmentally benign electricity is too high or not is a question that people concerned with local, national, and global economics and environmental issues will have to answer.

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