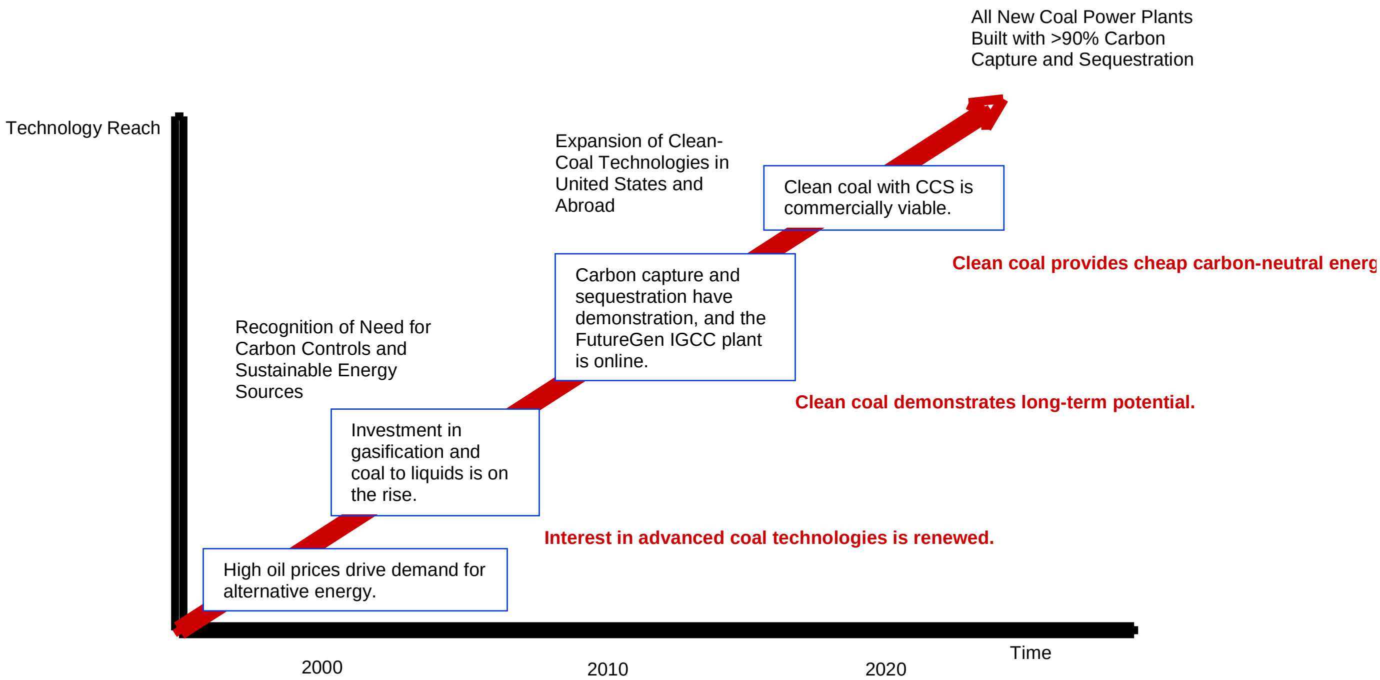
APPENDIX D: CLEAN COAL TECHNOLOGIES (BACKGROUND)

The Technology

Figure 9[1]
TECHNOLOGY ROADMAP: CLEAN COAL TECHNOLOGIES



Source: SRI Consulting Business Intelligence

Clean Coal Technologies

Clean coal is a marketing term often used by the coal industry and coal advocates to describe a group of technologies and industry practices that increase coal-derived energy-generation efficiency (including coal gasification), significantly reduce coal–power-plant emissions (including CO_2 through carbon capture and sequestration [CCS]), or convert coal to chemical feedstock or transportation fuels to offset oil demand (for example, by coal to liquids [CTL]). Use of direct-carbon fuel cells is another method to obtain clean energy for coal but for now is largely confined to the laboratory because commercialization is too expensive and power output too low (~1 kW) at this stage of development. From an environmental perspective, coal derived energy is only truly *clean* with CCS. Variants of some modern coal energy technologies have existed for much of the twentieth century, but the low price and relative availability of oil has precluded their

[1] The Technology Roadmap highlights the timing, features, and applications of significant technology milestones that would be necessary for developers of this technology to achieve if successful (equivalent to commercial) application—and possible disruption—is to occur by 2025.

widespread adoption. Successfully developed *clean* coal (with CCS) would allow the United States (or any coal-rich nation) to rely safely on an abundant domestic energy resource. However, according to a report from the Massachusetts Institute of Technology, CCS is not yet guaranteed to work on the scale necessary to contain 90% of the emissions from a major power plant (a DOE goal).

The Enabling Building Blocks

Power plants equipped with CCS can pressurize and pump CO_2 emissions into deep saline reservoirs and depleted oil and gas reservoirs for long-term storage. Pumping CO_2 into oil reservoirs is an established method to enhance oil recovery over the conventional pumping of water and has been under development for that purpose for some time. The Weyburn Enhanced Oil Recovery Project in North Dakota and Canada has used CO_2 from an area coal-gasification plant to enhance oil extraction since 2000. Long-term sequestration methods may evolve from these methods but, according to a report from the Massachusetts Institute of Technology, CCS is not yet guaranteed to work on the scale necessary to contain 90% of the emissions from a major power plant (a DOE goal).

Adding CCS remediation to a coal power plant at present consumes about 40% of the power that the plant produces and increases the cost of the energy it produces by 2.7¢ per kilowatt hour, and can not operate on the scale necessary to collect a majority of the GHG. The largest CCS project in operation today (the Sleipner gas field in the North Sea) sequesters 1 million tons of carbon dioxide per year, which is a small fraction of that generated by a coal-fired power plant. CCS development has a long way to go before it can reach the DOE’s carbon-capture goal.

Integrated gasification combined cycle (IGCC) provides improved energy recovery from coal versus burning the coal to drive an electricity-generating turbine with pressurized steam. By heating the coal under an oxygen and water atmosphere (no nitrogen), the gasification process generates selected combinations of product, including heat energy, carbon monoxide, hydrogen, methane, and carbon dioxide. The carbon monoxide or methane can serve as a chemical feedstock or burn completely to carbon dioxide. Similarly, an IGCC plant can collect hydrogen as an added fuel product or power an additional gas-driven generator to produce electricity. Remaining solids can find use in a conventional coal-burning furnace as a low-grade fuel. The leftover mineral components are often recovered as useful industrial materials much like flyash is recovered from coal-burning plants for use in concrete (the process is *beneficiation*). Elimination of the nitrogen (normally, 80% of air) means that the CO_2 produced by the plant is fairly pure and is prime for sequestration. Besides increasing emission cleanliness and useful recoverable materials, IGCC plants can also generate power about 20% more efficiently than coal-burning plants.

Room exists also for improved efficiency of operation in conventional coal-burning plants. Pulverized-coal– (PC-) burning power plants can sustain energy-efficiency improvements through increased temperature of operation. Some new boiler designs also include fluidized-bed operation in which the coal is suspended with a flow of pressurized gas (making it seem somewhat like quicksand). Increased surface contact between coal and oxidizing gases increases furnace temperature, and the fluidized bed allows for noncombustible materials to settle as a slag for potential beneficiation. These attributes increase efficiency and ease elimination of various pollutants from plant emissions (including sulfur).

Coal-to-liquids technology was widely developed by Germany under the fuel embargo leading up to World War II, and apartheid South Africa followed similar embargos lasting much of the second half of the twentieth century. Today, South Africa's Sasol (South African Coal and Oil) operates one of the few profitable coal-to-liquids operations in the world, providing fuel and chemical feedstock to South African industry and for export. Although coal-to-liquids technologies do not reduce greenhouse-gas emissions relative to petroleum (in fact, credible studies show that CTL may increase GHG emissions), they do provide opportunity for coal producers to diversify their product's utility and for coal-rich nations to depend less on petroleum and chemical products that derive from oil, diluting the geopolitical strength of oil-producing nations.

Implications of Advancement in Various Technological Capabilities

The United States has the world's largest known coal reserves, and analysts project that coal will remain the backbone of the U.S. electricity supply through 2050. Some sort of GHG emission regulations are certain to take shape over the next decade, and improved energy- and cost-efficiency and CCS are all necessary to sustain coal as a practicable option in a carbon-constrained regulatory environment. The key technology to enable clean coal will be carbon capture and sequestration, but as Figure 9 (the Technology Roadmap) indicates, we are unlikely to see commercially viable CCS until 2020. However, such a timeline does not detract from the possible disruptive implication of increasingly effective clean coal technology, because of the likely ongoing trend toward a carbon-constrained energy environment. Consider the drivers of today and the future: Global energy demand will continue to increase well into the twenty-first century, and the scientific community has established that carbon dioxide (and certain other gases) generated by human industrial activity will have lasting effects on the global climate. Substantive changes in local ecosystems (rainfall, average temperature, temperature extremes, soil conditions) and eventually extreme economic damage (flooding, dry spells, hurricanes) will most likely follow. In an effort to avert these outcomes, policy to create a carbon constrained energy environment is all but inevitable but must reconcile with the energy demands of a growing population and economy.

Synergistic Technologies

Certain complementary or synergistic technologies will enhance the probability of success of clean coal as an economically and environmentally viable option to meet U.S. energy needs in a regulatory environment that constrains carbon emissions.

- *Corrosion-resistant nickel alloys.* Increasing the temperature of operation readily improves the thermodynamic efficiency of a coal-burning power plant. Unfortunately, increasing the temperature leads to the accelerated corrosion and breakdown of materials constituting the plant machinery. Advanced or ultrasupercritical coal-fired boilers require metals to withstand temperatures greater than 1400°F and are resistant to the corrosive effects of flyash at such high temperatures.
- *Advanced turbine design.* The U.S. National Energy Technology Laboratory (NETL) operates an advanced turbine research program for coal-fired power plants. The goal is

to promote the design of turbines that increase power-plant efficiency and are driven by either hydrogen or syngas produced from coal gasification.

- *CO_2 membrane separation.* Separation membranes serve as selective filters that can pass CO_2 while containing other gases. Effective membranes are still under development but could serve in lieu of amine scrubbers that dissolve CO_2 gas in an ammonia-like liquid for collection, with potentially higher efficiency and lower cost. Absorption membranes allow passage of CO_2 from a gaseous environment on one side to a liquid contained on the other in which the CO_2 dissolves. Absorption membranes also improve efficiency of CO_2 collection.
- *Fuel cells.* Hydrogen and hydrocarbon-based fuel cells have grown in popularity as potential energy generators in the transportation and home energy markets. Hydrogen-powered automobiles may even reach the market within the next five to ten years and would boost demand for hydrogen that derives from coal gasification. Direct-carbon fuel cells, although far from commercially viable, may one day represent a coal-consuming energy generator.

Applications

Key Uses and Instantiations of Clean Coal Technologies

- The FutureGen Initiative for electricity generation with CCS is under way and will select one of four locations in Indiana or Texas to build a $1.5 billion experimental IGCC plant by 2012.
- The Wabash River Coal Gasification Repowering Project in West Terre Haute, Indiana, and the Polk Power Station near Mulberry, Florida, are the first two full-size commercial gasification-combined cycle plants in the United States. The plants generate 292 MW and 313 MW of electricity, respectively, most of which is supplied to the grid. The plants have operated since 1995 and 1997, respectively.
- The Sleipner gas field is a natural-gas field in the North Sea operated by the Norwegian state-owned oil company Statoil ASA. The facility includes the largest CCS operation, separating CO_2 from the mined methane and sequestering it in the field’s deep saline formations.
- The Great Plains Synfuels Plant enjoyed its first dividend in 2007. The Synfuels plant generates methane gas from low-grade lignite coal and supplies CO_2 for enhanced oil recovery in southern Sascatchewan. The DOE helped build the $2.1 billion plant in 1984 in response to the energy crisis of the late 1970s and later sold it to Basin’s subsidiary—Dakota Gasification—for $85 million in 1988. What people once considered a waste of taxpayer dollars is now a model for the future of clean coal.
- Sasol generates 150 000 barrels of synthetic oil a day at its coal-to-liquids facility at Secunda (Mpumalanga, South Africa) and develops methods for producing fuels and petrochemicals at its CTL research reactor in Sasolburg.

Current Affected Products

In 2004, coal accounted for 26% of global energy consumption and is likely to increase to 28% by 2030. Coal power provides about half of the electricity in use in the United

States. Advanced coal-power technology will continue to develop in coal-rich areas of the world with a growing thirst for inexpensive energy. The United States is one of the largest energy consumers (when including noncoal sources) and possesses the largest known coal reserves in the world. With the world's third-largest reserves, China produces the most coal in the world (twice as much as the United States) and given its rapidly developing economy, constantly needs new power supplies. India, possessing the fourth-largest known coal reserves, is also growing rapidly and likely to increase production dramatically in the next 20 years. The DOE's projections (which assume that the current regulatory environment stays in place) indicate that China's coal use for electricity will increase from 22.7 quadrillion Btu in 2004 to 55.9 quadrillion Btu in 2030, in comparison with the U.S. growth of 1.7% annually from 20.3 quadrillion Btu to 31.1 quadrillion Btu in the same period. Russia possesses the second-largest known coal reserves but does not produce nearly as much coal as do other coal-rich nations because it is also rich in oil and natural gas. Australia and New Zealand together represent the next-largest producers of coal.

New Capabilities Created by Clean Coal Technologies

Improvements in efficiency of operation provide a natural incentive of economic benefit to coal–power-plant operators. Coal gasification can also generate natural gas, hydrogen, and liquid fuels for sale as a clean-burning home or transportation fuel source. However CCS represents the real breakthrough to make coal a clean-energy alternative. Although seemingly not a new capability, providing electricity from an abundant natural resource without contributing to the growing problem of global warming will become a more important—if not an essential—characteristic of energy supplies as policy makers work to constrain greenhouse-gas generation.

Timeline

New technologies for coal gasification and coal to liquids are just crossing the threshold of cost-effectiveness thanks largely to high natural gas and crude oil prices. Investment in alternative energy supplies will continue as long as those prices remain high, and interest in clean, renewable sources is sustained by concerns about global warming. Gasification, CTL, and CCS technologies will continue to advance toward cost-effectiveness and meeting evolving environmental standards in the next 10 to 20 years.

Issues Determining the Development of Clean Coal Technologies

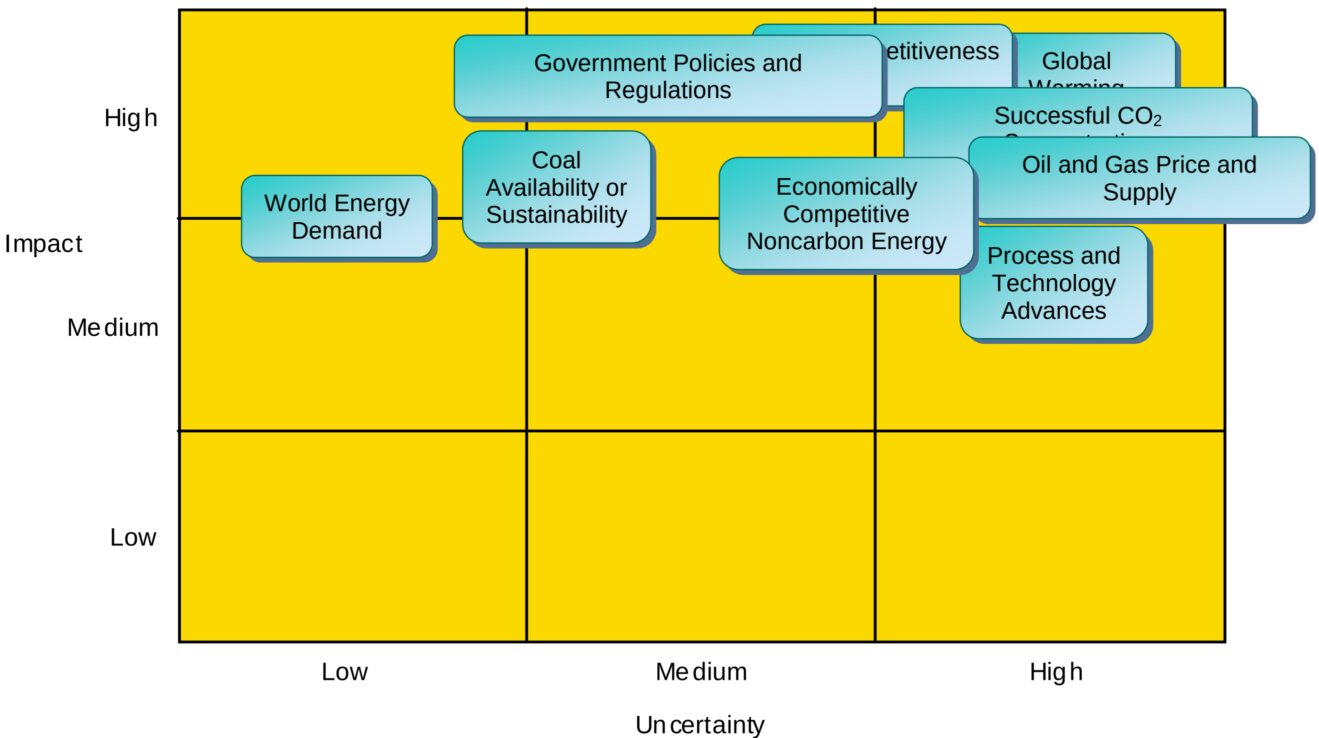
The most influential factors and issues that will determine the timing and direction of developments of these potentially highly disruptive technologies will be political, regulatory, and economic:

- Coal gasification and CTL plants are extremely expensive to build and operate and CCS is not proved to work on the necessary scale for offsetting the CO_2 produced by coal to meet the energy needs of a developed nation. Coal gasification requires high temperatures and advanced (expensive) turbines to run off of the very high-temperature gases present in such a plant. The turbines also have a tendency to break down more often than conventional operators and more downtime means more lost revenue. IGCC adds about 50% to the cost per kWh of coal electricity, and CCS adds about another 50%, bringing the cost of coal from about 4¢ per kWh to ~8¢ per kWh (requiring ~$2 billion in initial investment).

- Coal-to-liquids plants are similarly expensive to operate and are cost-effective only when oil prices are high (above $50 per barrel). The other problem is that several years and billions of dollars are necessary to take a CTL plant online, which means that investors must believe that high oil prices (like the $50 to $70 per barrel prices we have today) will continue for the foreseeable future.
- Global energy demand will continue to increase well into the 21st century, and the scientific community has established that carbon dioxide (and certain other gases) generated by human industrial activity will have lasting effects on the global climate. Substantive changes in local ecosystems (rainfall, average temperature, temperature extremes, soil conditions) and eventually extreme economic damage (flooding, dry spells, hurricanes) will most likely follow. In an effort to avert these outcomes, policy to create a carbon constrained energy environment is all but inevitable, but must reconcile with the energy demands of a growing population and economy. Many world powers are working to address this problem and reduce GHG emissions. The United States has not taken a leadership role in this area. Some people attribute this lack to the political influence of major GHG-emitting companies that represent the bulk of the U.S. economy and the fact that the science debate proceeded in a manner that confused the issue.
- At present, no financial incentive exists for a coal plant (IGCC or otherwise) to sequester its CO_2 emissions beyond what is useful for enhanced oil recovery. Because it costs nothing to emit CO_2, no market forces are driving sequestration. In fact, the situation is quite the opposite. But public attention toward climate change from anthropogenic greenhouse gases (CO_2) is leading policymakers toward substantive policy changes that would require reductions in CO_2 emissions. Common proposals to achieve this end include a carbon tax or (perhaps more likely) cap and trade that puts a market price on carbon emissions. Increased plant efficiency means less coal in use to generate the same amount of energy, thus reducing CO_2 emissions per unit energy, but the end result more often has been increased power generation, not decreased emissions. Whatever the GHG-emission–reduction goal is, it will materialize only through regulation.

Items to Watch

Figure 10[2]
CLEAN COAL TECHNOLOGIES: ISSUES AND UNCERTAINTIES



Source: SRI Consulting Business Intelligence

From Figure 10, the key areas of uncertainty to monitor and better understand are:

- *World energy demand.* The world's appetite for energy will increase in the coming years, but economic growth has no guarantee. Continue to look to the United States, China, and India as increasing consumers of coal.
- *Government policies and regulations.* U.S. public interest in stemming GHG emissions will force policy makers to act at the federal level, as some states and regional groups have already done. The uncertainty is whether these actions will represent substantive sweeping change in GHG emission-control policy or will be a symbolic compromise that does not force industrial players with substantial political clout to act against their own economic interests.
- *Oil and gas price and supply.* Public interest in alternative energy stems from concern about the environment, geopolitical instability, and high energy cost. If oil prices drop

[2] Figure 10 illustrates major issues and events that will have an impact on the rate or direction of a technology's development and thereby application. The impact of these issues and events is plotted against a measure of uncertainty, where uncertainty implies insufficient knowledge of how (and usually just when) the issue or event will be resolved or be sufficient to drive or hold back development of the technologies. An organization that is able to accurately predict or (better) influence or dictate the outcome (thereby moving the issue/event to the left of the figure), will have a distinct advantage over organizations that are still in the dark or just passively following developments.

significantly, then interest (and investment) in alternative technologies will drop as well. For example, CTL transportation fuel is cost competitive with oil-based diesel when oil is about $50 per barrel.

- *Economically competitive noncarbon energy.* Nuclear, solar, wind, and tidal power are growing in popularity and investment. Substantive R&D efforts are under way to cut the cost of these and other technologies to compete on a level playing field with fossil fuels, and if any of these efforts result in a truly cost-competitive alternative, it could actively decrease interest in coal and other fossil fuels.
- *Successful CO_2 sequestration.* A recent report from the Massachusetts Institute of Technology underscored the fact that CO_2 sequestration on the scale necessary to contain a single coal power plant's output has not had successful demonstration. The report also points out that known "reserves" of porous rock capable of containing CO_2 may be of insufficient supply for long-term expansion of GHG-free use of fossil fuels.
- *Coal availability or sustainability*. Even though the United States has the largest known coal reserves in the world that are likely to last approximately 200 years, signs indicate that much of the coal is in difficult-to-recover locations. As mining becomes more challenging, miner safety issues and coal prices may become a bigger concern.
- *Global warming.* The main uncertainty is the speed and extent to which government policies will push the development of low-carbon energy technologies. As the extent of the dangers of global warming become increasingly clear in the coming years, the impact of global warming on the drive for clean-coal technology will continue to evolve.
- *Process and technology advances*. Clean-coal process technologies require significant improvements in their efficiency, cost, and ability to achieve widespread deployment. Advances in materials science will be a key factor.
- *Cost competitiveness.* The cost competitiveness of clean-coal energy is a major determinant of its success in the marketplace. Consumers will be drawn to clean-coal energy sources when costs are close to—or below—competing alternatives (clean or otherwise).

Directional Signposts

Identifying the major issues that will determine how clean coal technology will develop and understanding the uncertainty of items important to watch help us to understand better the potential dynamics of development and application that we might see in the future. That heightened sense of awareness is necessary because the United States will want to formulate a policy and act before unambiguous evidence on the drivers and barriers to, and direction of advancement of clean coal technology is available. Preparation for a watch-and-respond system is essential to identify signposts that would indicate whether the advancement of clean coal technology is proceeding rapidly or not. The following developments are likely to occur near the suggested years, and their outcomes will strongly influence the status of clean coal technology. Their occurrence would indicate that the above issues and uncertainties were being resolved in the direction of positive development and application of clean coal technologies.

- 2008—The U.S. Department of Energy (DOE), National Energy Technology Laboratory, enters the "Deployment Phase" of the Carbon Sequestration "Regional Partnerships Initiative" and begins large-scale demonstrations of CCS technologies.
- 2010—Shenhua Coal Liquification Corporation (China) is producing 100 000 barrels of liquid fuel from coal.
- 2012—The 275-MW FutureGen demonstration IGCC plant is online with 1 million to 2.5 million tons per year CO_2 capture and storage in deep saline formations.
- 2015—Rising natural-gas prices tilt economic decisions about new power-plant construction toward coal.
- 2020—CCS capable of supporting new coal plants capturing 90% of CO_2 emissions becomes commercially viable.

Within the timeline in which these developments are likely to occur, some specific signposts will be important to watch for and monitor to understand the direction in which and the pace with which the field is advancing and to assess the potential threats to and opportunities for U.S. interests. Key signposts, which, if positive, would indicate progress toward clean coal include:

- Global demand for energy
- Development of other carbon- and non-carbon-based alternative energy sources and their economic viability (for example: bio-fuels, solar energy, wind,)
- The price of oil in comparison with that of alternative energy
- U.S. government policy regulating the emission of greenhouse gases, increasing energy efficiency, and investing in and subsidizing alternative and renewable energy sources
- Successful sequestration of CO_2 through energetically and economically viable means.

Abbreviations

The following abbreviations are used in this disruptive technology profile:

CCS	carbon capture and sequestration
CTG	coal to gas
CTL	coal to liquids
DOE	Department of Energy (U.S.)
GHG	greenhouse-gas
IGCC	integrated gasification combined cycle
NETL	National Energy Technology Laboratory (U.S.)
PC	pulverized-coal
R&D	research and development