



A Technical Assessment of Coal Utilization and Research Trends

GCEP Energy Assessment Analysis
Fall 2006

Abstract

Coal is an abundant fossil fuel resource that is highly polluting when converted to energy or chemicals. Used predominantly for electricity generation, coal contributes to approximately 25% of the world's primary energy but imparts 40% of the world's CO₂ emissions¹. The resource is estimated to be between 220 to 280x10²¹J which is larger than the oil and gas resource combined². Unlike concentrated oil and gas resources, coal deposits are widely dispersed across continents, making it accessible to both developing and industrialized countries. Traditional growth in coal utilization will be from increasing electricity demand, while additional growth will be from increasing demand for liquid fuels. Growing concern over the impact of CO₂ on the environment has led to research and development on coal utilization strategies and technologies that mitigate CO₂ released to the atmosphere. Research trends include increasing thermal efficiency, understanding solid to liquid separations, developing advanced materials, and integrating systems for CO₂ capture and separation technologies to reduce emissions. Advanced coal utilization without carbon storage requires ideas and insight on alternative end states for CO₂. This assessment discusses the current status and market of coal resources, common conversion and transformation methods, and the forefront of research strategy and needs. In order to reach the Kyoto Protocol targets for carbon dioxide (550ppm or 5% below 1990 levels), we will need all the options for increasing coal conversion efficiency, carbon capture and long-term storage, while reducing overall coal consumption.

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Foreword

This report is one of a series of assessments on various areas of the energy landscape prepared by GCEP staff. The assessments are intended to provide an introduction to the energy area as well as context for future fundamental research activity towards reducing greenhouse gas emissions. By examining the goals and potential of the energy transformations in question as well as the current progress and research towards these ends, the assessments take a step toward elucidating the most promising areas for future research. This report, produced by GCEP Energy Analysis staff, was written by Emilie hung with contributions from Wes Hermann, Paolo Bosshard, Rebecca Hunt, and AJ Simon. Please address all correspondence to gcep@stanford.edu.

Introduction

Worldwide, coal contributes approximately 25% of the world's primary energy but imparts 40% of the world's CO₂ emissions¹. While the coal resource is widely available, abundant, and inexpensive, coal conversion and utilization releases more pollutants and greenhouse gases than any other fossil fuel. Most of the coal consumed generates electricity, but there is rising demand for coal-derived liquid fuels and chemicals such as dyes, perfumes, plastics, solvents, fertilizers, resins, and preservatives³. Additionally, coal markets are less volatile than oil and natural gas markets and thus maintain price stability. If the world continues its addiction to coal as an energy source and cannot reduce coal consumption by developing low CO₂ emitting alternatives, long term research is needed for CO₂ abatement options other than geologic storage. Short term strategies for advanced coal technology increase efficiency by understanding fundamental conversion processes, evolving advanced materials and mitigating CO₂ release by integrating CO₂ capture and separation systems for underground storage. This paper discusses the current status and market of coal resources, common conversion and transformation methods, and associated research needs.

Coal Resource

Coal is a fossil fuel resource formed from peat and decayed vegetative matter from prehistoric swamps. Coal formation occurs over several hundreds of millions of years as the swamp humus degrades and is buried under layers of sediment. Increases in pressure and temperature compress the humus, reduce the moisture content and other organics, and create coal seams. Ultimately, coal is sedimentary rock comprised primarily of carbon, hydrogen, oxygen, sulfur, and nitrogen. Yet coal is not uniform, trace quantities of 76 of the 92 elements in the periodic table have been found in coal³. This heterogeneity is attributed to different chemical bonds and molecular structures formed under a range of pressures, temperatures, and elements.

The exergy, or theoretical work potential, of the coal occurrences is estimated between 220 to 280x10²¹J, and coal utilization occurs at a rate of 3.6TW^{2,4}. Even if the utilization rate doubles, the coal resource will last several thousands of years. Moreover, coal resources are broadly dispersed across geographical locations with appreciable reserves on every continent except Antarctica. By comparison, oil and gas resources are centered in the Middle East, and the total exergy potential of the oil and gas resources combined is less than that of coal^{2,4}. In 2004, global recoverable coal reserves were estimated over 900 billion metric tons with major reserves in United States, China, India, Russia, and Australia^{5,6}. Figure 1 shows a breakdown of estimated recoverable coal by region.

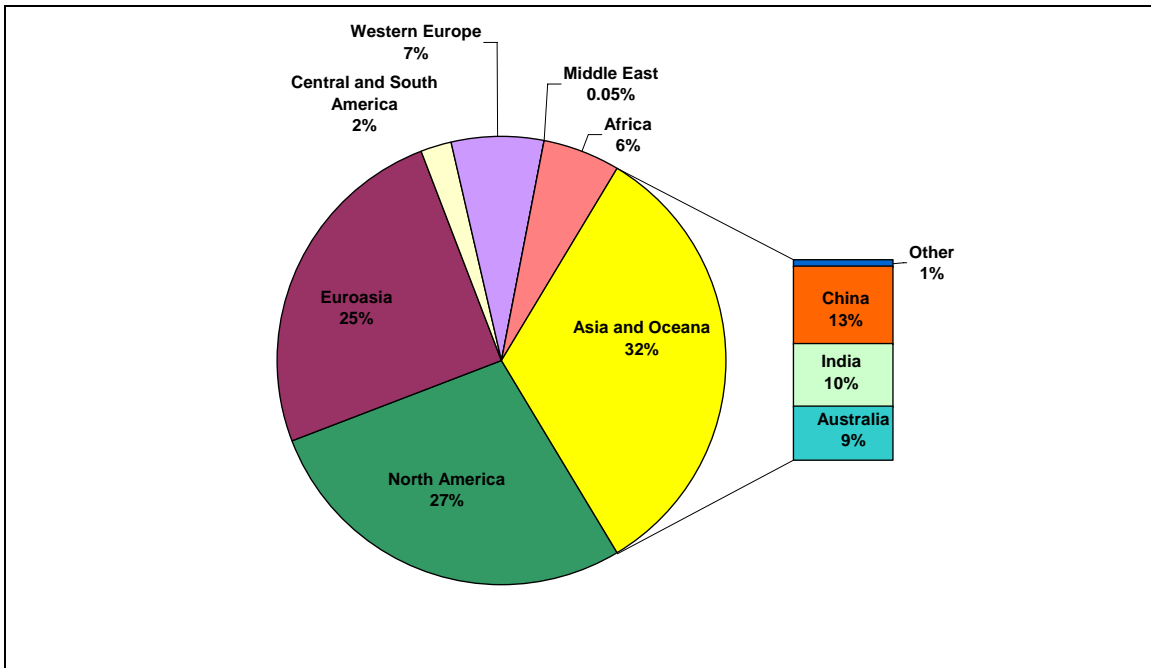


Figure 1: Allocation of Proven Reserves

Coal seams are characterized by the coal type (rank), the presence of organic and inorganic matter, thickness and layering (banding), and fractures (cleats). In the US, the American Society of Testing and Materials (ASTM) standardizes methods to analyze coal for chemical and physical characteristics pertinent to industry use and coal bed science. An ASTM procedure to classify coal by rank (low to high) approximates the heating value, fixed carbon, moisture content and volatile matter in coal. Given the various characteristics and origins of coal, knowing the coal rank provides insight into coal behavior during extraction and conversion. Lignite and sub-bituminous are considered low rank coals, characterized by light brown or dull black color, high moisture content, and a low heating value. By comparison, bituminous coal and anthracite are high rank coals, black and reflective in appearance with less moisture and a higher heating value from more fixed carbon. Sub-bituminous and bituminous coals are the most plentiful types of reserves worldwide⁷. Table 1 and Figure 2 provides a general summary of coal ranks and the corresponding parameters^{3,8,9}.

Table 1: Classification characteristics by coal rank

| Coal Rank | Volatile Matter (wt %) | Fixed Carbon (wt %) | Heating Value (MJ/kg) |
|----------------|------------------------|---------------------|-----------------------|
| Lignite | 27 - 35 | 65 - 73 | 26 - 28 |
| Sub-bituminous | 22 - 27 | 73 - 78 | 28 - 32 |
| Bituminous | 8 - 22 | 78 - 92 | 32 - 36 |
| Anthracite | < 8 | > 92 | 36 - 37 |

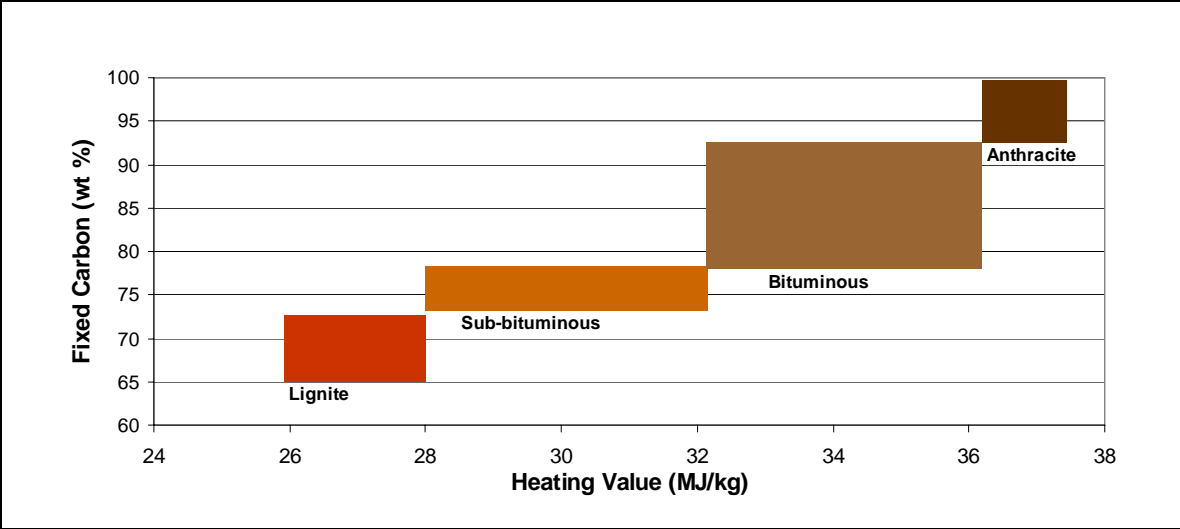


Figure 2: Proximate Analysis of Coal Rank

Coal Consumption and Production

Coal contributes 40% of the world’s electricity generation, over twice that of other resources such as gas, oil, nuclear or hydro as seen in Figure 3¹, and most of the mined coal supports electricity demands, Figure 4. The prevalent use of coal is due to broad availability, accessibility, transportability, and ease of storage. Coal can be mined quickly and transported across numerous supply routes without specialized infrastructure such as pipelines or pressurized systems. These resource advantages substantially lower fuel cost below oil or gas. While the capital cost for coal-fired power plants is more than oil or gas-fired plants, the overall cost of electricity from coal plants is economically competitive because coal is inexpensive¹³.

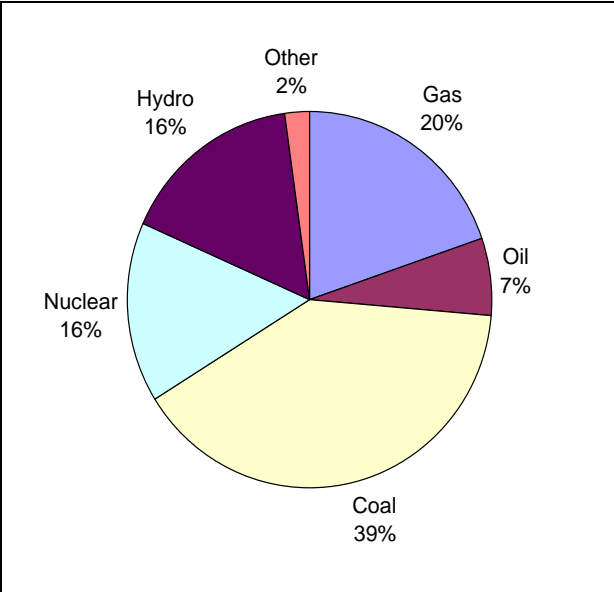


Figure 3: Global Electricity Generation by Fuel

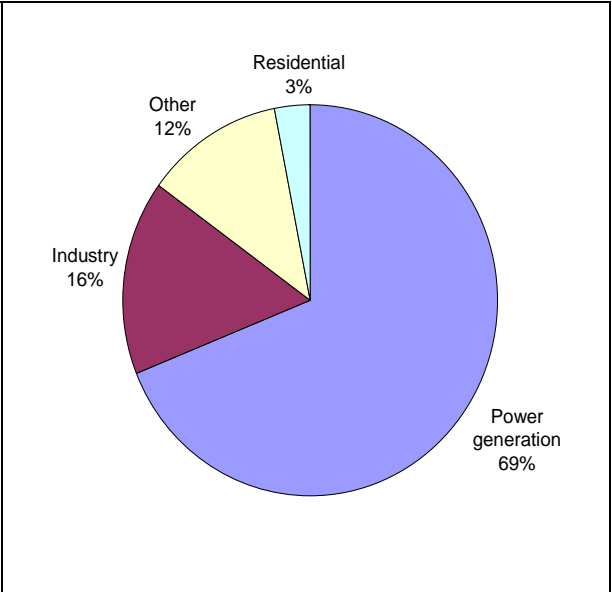


Figure 4: Global Coal Consumption by Sector (2002)

Global coal production and consumption is expected to increase on average at 1% to 2% annually until 2030^{6,7}. China, India and the United States consume most of the world's coal. These countries, along with Australia and South Africa, are also the top coal producing countries. Demand for coal is likely to accelerate in India and China above the average rate due to economic growth. In China, coal-fired power plants contribute over 70% of the electricity generated and forecasted growth rates range from 2 to 4% annually until 2030^{6,10}. Developing countries will consume more coal not only for coal-fired power plants, but also as an input for manufacturing construction materials (steel, cement) and transportation fuels. Figure 4 shows that global coal consumption is expected to almost double between 2003 to 2030⁶.

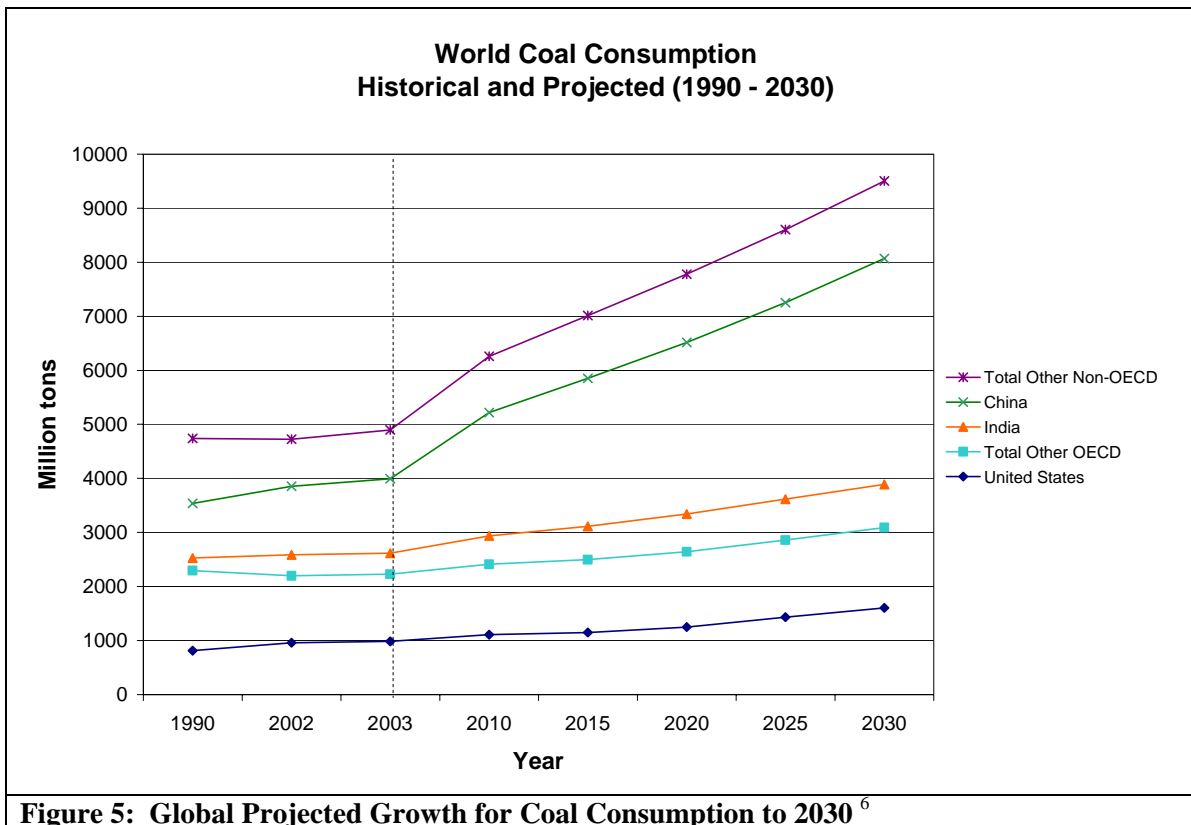


Figure 5: Global Projected Growth for Coal Consumption to 2030⁶

Environmental Implications and Impact

Although coal is economically affordable, coal mining and conversion pollutes the environment more than other fossil fuels. When utilized, coal is removed from its existing environment and converted to heat, gases and particulate emissions. An array of pollutants such as dioxins, mercury, particulates, and greenhouse gases are released with coal conversion impacting the environment and atmosphere. Mining and preparation also immediately effects the local physical environment. Coal is mined from the surface (opencut) or underground depending on the depth of a coal seam. While surface mining is safer than underground mining, the scale of current surface mine operations alters the landscape, effecting soil and nutrient dynamics, animal and plant habitats as well as

watersheds. Surface mining accounts for about 40% of world production⁷. In Australia and the US, surface mining attributes to the majority of their coal produced, 80% and 67% respectively⁷.

Besides the local impact from coal mining, a global effect of coal conversion occurs from the release of toxins and greenhouse gases to the atmosphere. Mercury, methane, particulates, sulfur and nitric oxides are produced from coal combustion, but it is the concentrations of CO₂ released are the most substantial. Figure 5 shows how the coal combustion process emits more CO₂ than other electricity generating, fossil fuel combustion technologies¹¹. Large simple and combined-cycle turbines operate with natural gas and are more efficient and releases less CO₂. But they are pinned to volatile natural gas prices.

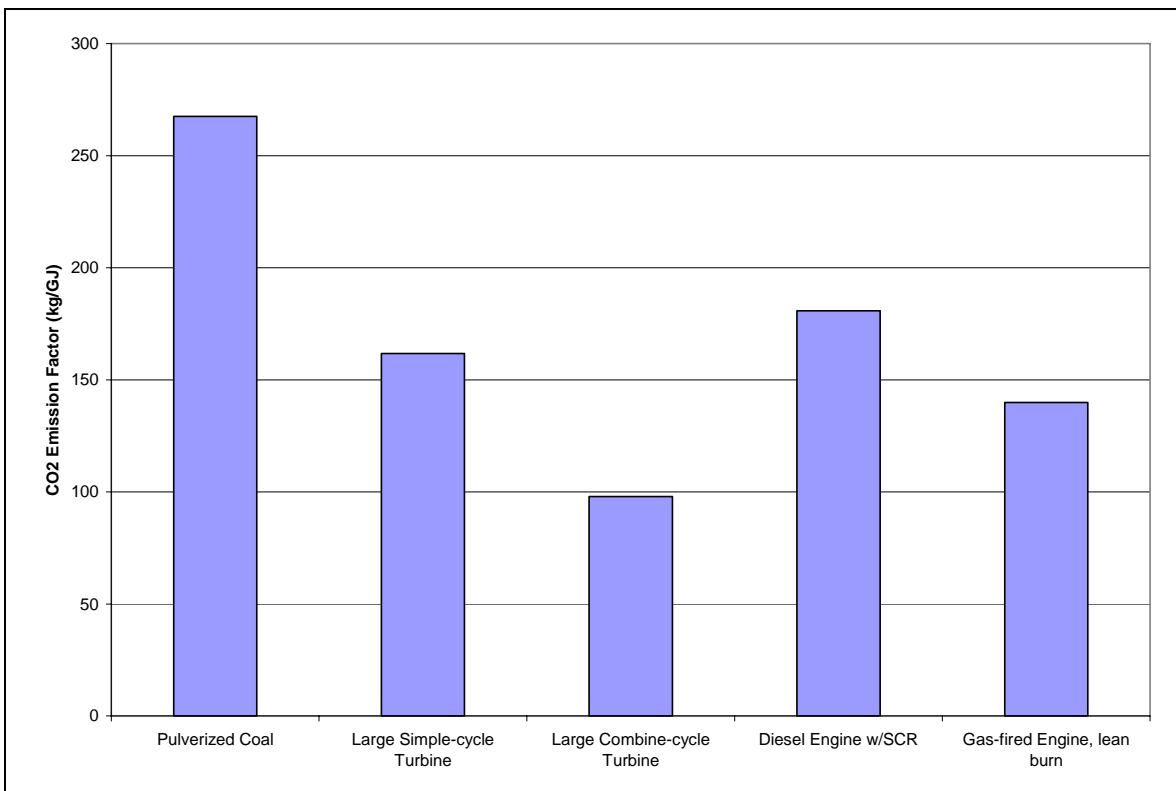


Figure 6: CO₂ Emissions from Different Forms of Electricity Generation¹¹

Annually, global electricity generation releases over 7700 million metric tons of CO₂ into the atmosphere of which 85% is due to coal-fired power plants^{12,13}. The International Energy Agency estimates that by 2030, the CO₂ released from coal power and heat plants (11334 million metric tons) will be twice as much as that emitted in 2002 and will surpass the current release from all fuel types for electricity generation¹⁰. The numbers are staggering. Carbon dioxide abatement and mitigation strategies must address the issues of greenhouse gas emission from coal utilization. Specific materials and technologies for carbon capture and separation are beyond the scope of this report and are discussed in the GCEP Technical Assessment Report on Carbon Capture. Instead, this

assessment will explore the methods, effects, and needs of coal utilization strategies directed towards CO₂ abatement.

Coal Transformation and Utilization Processes

A combination of the thermal, mechanical, chemical, and biological processes can transform coal to heat, liquids, and gases. Direct combustion, pyrolysis, gasification, liquefaction and bioprocessing are the predominant conversion methods, with the major reactions depicted in Table 2^{9,14}.

Table 2: Reactions for coal utilization

| Reaction | Heat of Reaction (370°C, kJ/C-atom) | Eqn |
|--|--|-----|
| Combustion | | |
| $C + \frac{1}{2} O_2 \Rightarrow CO$ | -110 | (1) |
| $C + O_2 \Rightarrow CO_2$ | -394 | (2) |
| Pyrolysis | | |
| $C_xH_y \Rightarrow (x-y/4)C + y/4 CH_4$ | | (3) |
| Gasification | | |
| $C + H_2O \Rightarrow CO + H_2$ | 135 | (4) |
| $C + 2 H_2O \Rightarrow CO_2 + 2 H_2$ | 96 | (5) |
| $C + CO_2 \Rightarrow 2 CO$ | 173 | (6) |
| Water-Gas Shift | | |
| $CO + H_2O \Rightarrow CO_2 + H_2$ | -38 | (7) |
| Methane Formation | | |
| $C + 2/3 H_2O = 1/3 CH_4 + 2/3 CO$ | 62 | (8) |
| $C + H_2O = 1/2 CH_4 + 1/2 CO_2$ | 6 | (9) |

Combustion

Solid coal combustion, the most common conversion method, produces heat and gas. Combustion reactions (Table 2, Eqn 1 & 2) are highly exothermic, and coal power technologies utilize heat released from the carbon bonds to make steam for electric power generation. A new conventional steam plant using the Rankine cycle can achieve approximately 45% efficiency (where the theoretical maximum based on the Carnot equation is 63%)⁸. By comparison, advanced combined cycle systems that fire gas in a turbine (Brayton cycle) and recover heat to generate steam (Rankine cycle) can achieve around 58% efficiency (with a Carnot efficiency is 82%)⁸. If the fuel gas is generated from coal, the overall process efficiency will be lower because the conversion efficiency from coal to gas must be incorporated.

Pyrolysis

Pyrolysis is an endothermic process where coal is heated in an oxygen-constrained environment, altering the coal structure and producing residual char, volatiles, and minerals. The products of pyrolysis such as coke, liquids (oils, tars, light liquids) and gases, can be directly combusted or upgraded depending on chemical needs. Pyrolysis processes are categorized by temperature ranging from low to high. During pyrolysis, covalent bonds cleave at temperatures between 375 to 450°C¹⁵. As the temperature

approaches approximately 600°C, the coal softens, plasticizes, and repolymerizes while continuing to release volatile matter and around 1000°C the process completes with hardened coke¹⁴. Pyrolysis behavior and yield are affected by coal rank (high sensitivity), pressure and heat¹⁶. Depending on the coal type and pyrolysis conditions, the weight of the coal will decrease anywhere from 75% to 30%¹⁴.

Gasification

Gasification converts coal to light gases, condensable liquids and solid products in the presence of reactive gases such as steam, oxygen or air. This process differs slightly from pyrolysis, which occurs in a less reactive inert-gas atmosphere. There are two distinct stages to coal gasification: devolatilization and then gasification (Table 2, Eqn 3-6). Devolatilization releases gases, tars, char, condensable liquids, and then sequentially the char is gasified to produce synthesis gas which can be a mixture of CO₂, CO, H₂, CH₄ and H₂O. Char gasification is partial oxidation or combustion with insufficient oxygen to turn all the carbon into carbon dioxide and all the hydrogen into water (Table 2, Eqn 1-2)¹⁷. Two criteria to evaluate the effectiveness of gasification are cold gas efficiency and carbon conversion efficiency as seen in the equations below. The conversion efficiency of gasifiers is approximately 80%⁸. Cold gas efficiency must be approximately 78% for the overall gasification process to be more practical than combustion⁸.

Cold gas efficiency (%) = (Heating value of product gas / Heating value of feedstock) x 100

Carbon Conversion (%) = (1- Residual Carbon/Feedstock Carbon) x 100

Coal to Electricity

Mature coal power technologies employ many of the same processes developed in the late 19th and early 20th century. These processes have been refined to optimize cost and efficiency. Newer technologies and concepts that integrate emission controls are not widely adopted because of lower capacities, higher costs and performance uncertainties. Nonetheless, technological advancement must eliminate the CO₂ emitted from electricity generation in coal plants. The generation technologies listed below discuss the common and advanced principles for converting coal to electricity.

Pulverized Coal Combustion

Pulverized coal (PC) combustion is the most mature technology used to generate heat for steam electric power, and plant capacities reach several thousand megawatts. Coal is dried and ground into fine particles to increase the surface area and improve reactivity. The particles are blown and burned in the boiler where heat is transferred from the radiating burning particles to water in the boiler tubes, which turns into steam. The steam then powers a turbine generating electricity. Figure 7 shows a schematic of a typical pulverized coal system⁷.

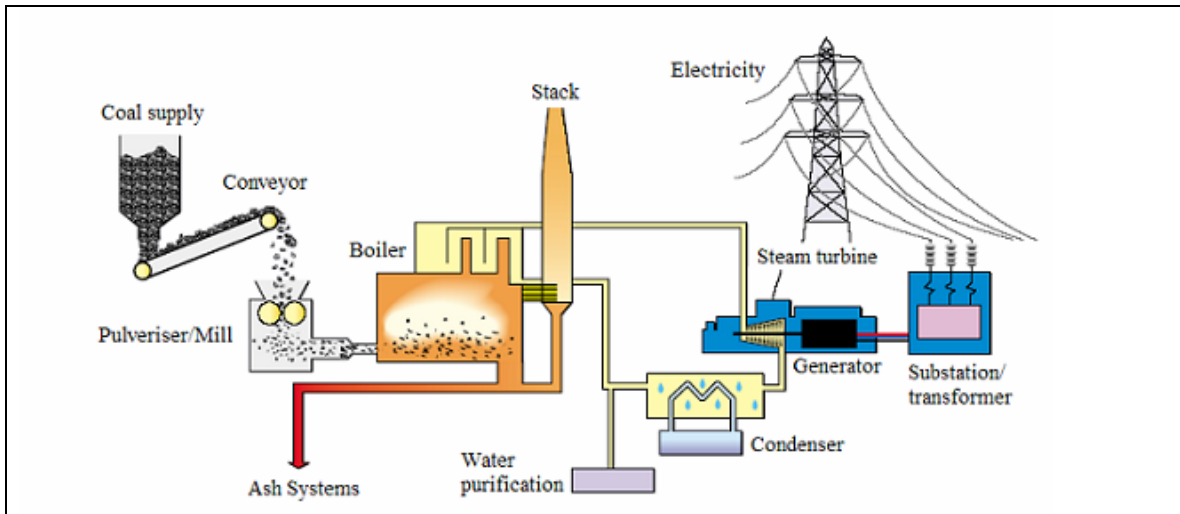


Figure 7: Pulverized Coal System Schematic⁷

Mixing and spraying pulverized coal must be properly dispersed to sustain a stable flame and desirable temperature profile in the boiler. Burners and reactor designs must provide sufficient residence time for particles to complete combustion and also maintain temperatures (1300-1700°C) where residual minerals and inorganic matter can be removed as ash or slag. When the temperature in the combustor is below the melting point of ash, fly ash is removed from the flue gas. If temperatures in a reactor approach the melting point of ash, deposits build up on heat exchanger surfaces which reduces heat transfer¹⁸. Some combustors designs operate at higher temperatures where ash will become slag and is collected from the bottom of the combustion chamber. Old pulverized combustion plants average 35% efficiency because of non-ideal operating conditions and material limitations, whereas new, state-of-the art plants achieve 45% efficiency²⁴.

Fluidized Bed Combustion

Fluidized bed (FBC) combustion technology modifies pulverized combustion to improve performance and offer wider fuel flexibility. Coal particles are blown in a rapid stream of gas or steam and heated particles (such as sand and sorbents for emission control). At high velocities, the mixture of particles and reactants behave like a fluid which promotes rapid mixing and effective heat transfer. The fluidizing action promotes complete coal combustion at relatively low temperatures, and provides a means to transfer combustion heat efficiently from the bed to the steam tubes. Fluidization occurs when coal particles are at a velocity where the weight of the particle is balanced by the frictional force between the particles and the flowing fluid⁹. The fluidized flow can be bubbling or circulating and the reactor can be at atmospheric pressure or above. Circulating systems have a cyclone/separator unit where entrained materials cycle from the flue gas back into the furnace, whereas bubbling systems remove the material as fly ash. This feature allows circulating systems to have smaller furnaces, operating with more complete coal combustion (burnout). Unlike atmospheric systems, pressurized systems introduce excess air and pressurize the coal feedstock so that additional electricity is generated through a combined cycle system by expanding hot flue gas through a gas turbine. The

total energy output is split between 80% from the steam turbine and 20% from the gas turbine¹⁹.

Fluidized bed systems have a longer series of reactions than pulverized combustion involving 1) heating and devolatilization of coal particles, 2) combining volatiles and oxidant, 3) combustion of the volatiles, 4) mixing of the char, 5) char particle attrition, and 6) char combustion⁹. Despite this additional complexity, fluidized bed technology improves upon conventional combustion systems through the following⁹:

- a lower combustion temperature (800-900°C) inhibits NO_x formation which begins around 1200°C,
- removal of sulfur dioxide during the combustion process (instead of scrubbing flue gas) by adding a sorbent such as limestone,
- uniform temperature from the complete mixing of solids increases heat transfer capability to the water/steam tubes (improvements are two to four times greater than conventional boilers),
- ability to burn a range of fuels without the necessity of derating the boiler because the system is essentially independent of ash characteristics.

Scalability of fluidized systems is a challenge due to the number of coal injection feedpoints needed for uniform distribution of coal particles¹⁸. Generating capacities have been limited to a few hundred megawatts. The technology has been substantially proven but it has not been implemented for large, utility-scale capacities.

Integrated Gasification Combined Cycle and Integrated Power Systems

An integrated gasification combined cycle (IGCC) system gasifies coal with oxygen, air, or steam to create a synthesis gas (syngas) mixture of CO₂, CO, H₂, CH₄ and H₂O. IGCC systems generate electricity using steam and gas turbines and are approximately 45% efficient. Figure 8 shows a schematic diagram of an IGCC system⁷. Gasifier technologies are named after methods of solids movement (fixed bed, fluidized bed, entrained flow), ash removal (dry, slagging), and operating pressure^{9,17}. Large-scale, fully integrated IGCC power systems with carbon capture are in the demonstration phase. IGCC systems operate at higher pressures favorable for CO₂ capture and separation. Injecting compressed feedstock and operating the gasifier at higher pressures saves more compression energy than operating at atmospheric pressure and compressing the syngas⁸.

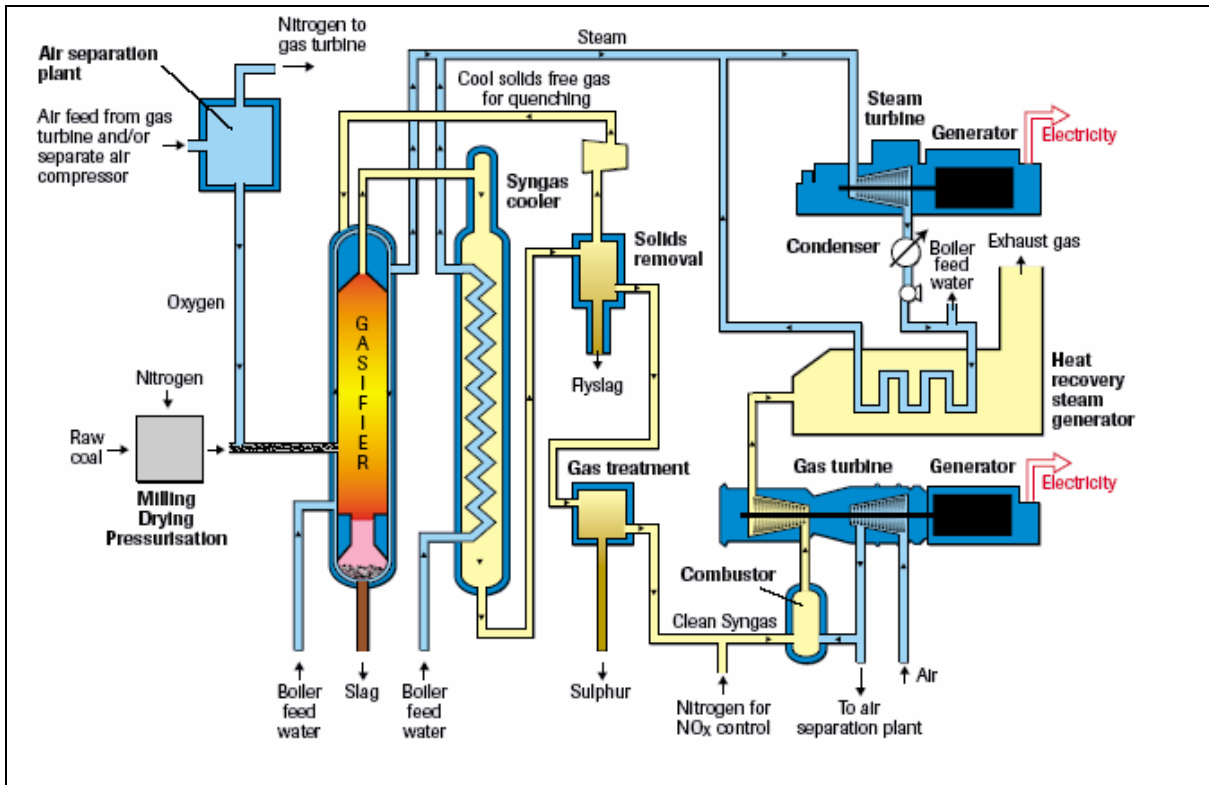


Figure 8: Integrated Gasification Combined Cycle Schematic⁷

IGCC systems are complex, capital intensive and have several disadvantages:

- Air separation is needed for input O₂. Oxygen is preferred as an oxidant instead of air, because the nitrogen content in air lowers the cold gas efficiency from 82% to 61%⁸. Oxygen obtained by air separation can be up to 15% of the plant cost and require 5% to 7% of gross generator output⁸.
- Efficient gas turbines are temperature sensitive and require high purity gas streams. Hot gas cleanup can reduce the efficiency by 10% due to temperature swings for emission control which do not take advantage of heat from combustion and energy required for compression²⁰.
- Redundant and stand-by gasifiers are necessary to prevent unscheduled outages because of plant complexity, as well as unpredictable gasifier performance.

Alternative or hybrid power concepts aimed at higher power generation efficiency (50-60%) incorporate gasifier products with fuel cells or magnetohydrodynamics (MHD) instead of a gas turbine. MHD generators produce electric power by expanding a high-velocity, electrically conductive fluid through a strong magnetic field. For a coal-fired MHD system, a conductive alkaline metal compound such as potassium carbonate must be added to high temperature, gasified coal products to provide adequate electrical conductivity⁹. Heat recovery systems in MHD systems generate additional electricity using steam turbines. Integrated fuel cell systems use H₂ and CO in the gas stream with molten carbonate or solid oxide fuel cell technology to generate electricity and water. Alternative power concepts are still being developed and face with many similar issues as IGCC such as O₂ input, hot gas cleanup, scale, and corrosion resistant materials.

Combustion and Gasification Research Trends and Directions

Research into coal combustion technologies are driving increased thermal efficiency and systems integration for CO₂ capture and separation. Years of research has been dedicated to studying coal's complex combustion behavior such as devolatilization, char reactivity, flame stability, chemistry and kinetics in the formation of pollutants^{21,22,23,26}. Computer models and lab-scale tests continue to explore the physics and fundamentals in the coal conversion and transformation processes. Below is a list of well-recognized issues and research needs for combustion and gasification technologies²⁰.

- Development of corrosion resistant materials (alloys, ceramics, or membranes) for extreme temperature and pressure conditions. Advanced materials are needed throughout the conversion process in turbines blades, boiler tubes, and hot flue gas streams.
- Quantitative understanding of carbon kinetics for proper reactivity expressions, taking into account catalytic and physical interaction with ash and graphitization of carbon as the oxidation process proceeds. The interaction between pyrolysis, carbon oxidation, and emissions is not fully understood.
- Hot gas cleanup systems that reduce contaminant levels. Inorganic membranes with high separation efficiencies and long-term resistance to high temperature corrosive environments.
- For low temperature gasification processes where high carbon conversion is needed, catalysis of carbon gasification by ash constituents such as calcium or by adding catalysts.
- Improving the efficiency of air separation units for oxygen-fired pulverized coal combustion and IGCC systems.

Due to recent advancements in high temperature materials for turbines and reheaters, supercritical steam pulverized coal plants can perform at efficiencies commensurate with IGCC systems. In supercritical steam applications, the temperatures and pressures are above the critical point of water (374°C, 22.1 MPa) where there is no phase boundary between liquid and gas. Supercritical steam behaves like an organic solvent which can lower pollutant emissions and reduce gas-cleanup. The thermal efficiency in supercritical steam pulverized coal plants can be 43% to 50%, and Figure 6 shows the schemes to improve efficiency such as reducing excess air and stack temperature, increasing steam and reheat conditions^{12,18}. Long-term prospects to achieve efficiencies greater than 50% increase steam conditions to ultrasupercritical temperatures of 700°C²⁴. But the reactions are highly corrosive and advanced materials are required to withstand both the chemical attack and extreme pressures and temperatures.

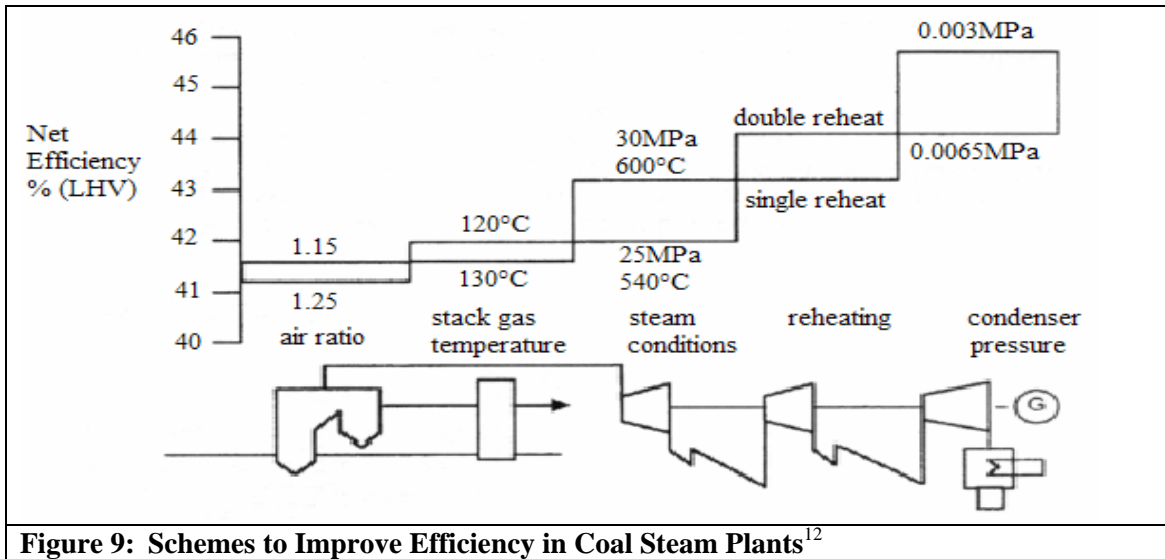


Figure 9: Schemes to Improve Efficiency in Coal Steam Plants¹²

A growing awareness of the atmospheric effects of CO₂ has driven the development of combustion and gasification options that reduce or eliminate CO₂ emissions to the atmosphere. Advanced coal utilization without geologic sequestration necessitates alternative end-states for CO₂. Advanced coal utilization with geologic storage allows carbon capture and separation strategies prior to or after combustion (pre- or post-combustion), coal combustion in an oxygen-rich atmosphere, and separating CO₂ in fuel cells that operate with fossil fuel-derived gases²⁵. Pre-combustion capture applies to IGCC or other gasification systems where fuel gas (H₂ or CH₄) is intermixed with CO and CO₂. Several separation technologies exist for pre-combustion capture and are discussed in the GCEP Carbon Capture and Separation Area Assessment. Often the CO is shifted to CO₂ (Table 2, Eqn 7) to increase the concentration of CO₂ and depends on the CO₂ separation technology used. By comparison, post-combustion capture removes CO₂ from flue gases after the fuel is burned and is used most often with pulverized coal steam plants. Large volumes of the flue gas stream must be handled because the concentration of CO₂ is only 14% which results in handling large volumes¹³. Post-combustion systems typically use an amine-based, chemical sorbent capable of capturing 90% of the CO₂ in the flue gas²⁵.

One strategy for pulverized combustion systems is O₂/CO₂ recycle combustion where coal is burned in a mixture of oxygen and recycled flue gas. Cycling the flue gas maintains the low flame temperature and can result in 98% CO₂ rich flue gas^{26,27,28}. This method can be cheaper and smaller than existing, post-combustion, amine scrubbing methods which are stressed by the volume flow.

Once CO₂ is separated, it is compressed for transportability, but compression energy requirements reduce efficiency by 3% to 5%²⁴. Overall, retrofitting existing plants with current CO₂ mitigating technologies is expensive and reduces system efficiency up to 13%¹³. Table 3 compares the cost and energy penalties for CO₂ emission control between two current state-of-the-art coal power systems: IGCC and supercritical pulverized combustion plants²⁹. The efficiency penalty for CO₂ capture is lower in an

IGCC plant than a supercritical steam plant because less energy is needed for the regeneration of the solvent used for capture^{28,30}.

Table 3: Cost and penalties for CO₂ emission control²⁹

| Process | Efficiency % LHV | CO ₂ Emission (g/kWh) | Cost of Electricity (¢/kWh) |
|---|---------------------|--|-----------------------------------|
| Supercritical PC (no CO ₂ capture) | 46 | 722 | 3.7 |
| Supercritical PC w/CO ₂ capture | 33 | 148 | 6.4 |
| IGCC (no CO ₂ capture) | 46 | 710 | 4.8 |
| IGCC w/CO ₂ capture | 38 | 134 | 6.9 |
| IGCC O ₂ /CO ₂ recycle combustion | 37 | 28 | 6.8 |

Note: Capture in PC plant is by amine solvent scrubbing, capture in IGCC is by physical solvent scrubbing, and in O₂/CO₂ case, capture is by condensation of water.

Coal for Liquid Fuels

Liquid fuels can be produced from coal and used as transportation fuel or chemical feedstock. Liquefaction processes are capital intensive, and the CO₂ emissions per Joule are at least twice as much as crude oil refining³¹. Although liquefaction research efforts declined after the 1970's, renewed interest in coal liquefaction for transportation fuels is growing in China and India. Transportation fuels developed from coal will still release CO₂ in the exhaust, therefore GCEP research interests are solely in conversion processes that are radically different and do not create CO₂ in the first place.

For transportation fuels, a higher concentration of hydrogen and lower concentration of oxygen is desirable, thus coal to liquid fuel conversions break the carbon bonds, remove oxygen, sulfur and nitrogen, and add hydrogen. The comparison of hydrogen to carbon mole ratios for several fossil fuels in Figure 7 reveal that lower rank coals have a higher H:C ratio and are preferred for liquid fuel conversion processes³². Depending on the coal rank, either direct or indirect processes can be used to liquefy coal. In direct liquefaction, coal is converted directly from a solid to a liquid by thermal treatment. Comparatively, indirect liquefaction is a two stage process where solid coal is gasified and then the gas is reformed to a liquid.

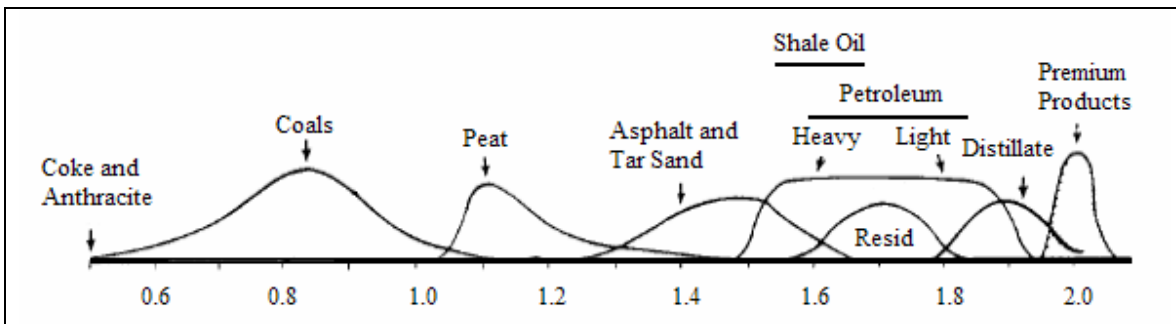


Figure 10: Hydrogen to Carbon Mole Ratios³²

For biotreatment and bioconversion, high surface area, porosity, and surface oxidation aid microbial effectiveness, because organisms work on the exterior of the coal substrate³⁵. Low rank coals such as lignite (that are less suitable for combustion processes where moisture diminishes the energy content) are well suited for bioprocessing because of their higher reactivity, volatility and oxygen content. Major barriers of bioprocessing and bioconversion of coal include the need for solvents, high contact areas, long conversion times, and hospitable conditions for the organisms. Microorganisms are sensitive to temperature, pH, and concentrations of toxins or nutrients. Bioprocesses are better suited for high quality products because of conversion timescales and quantities of converted products required for large-scale use.

Bioliqefaction

Bacteria and fungi are capable of breaking down coal that has been degraded to organic compounds. Research has focused on organisms that attack the original coal matrix. Weathering or pretreatment oxidizes coal and improves reactivity. Products from bioliqefaction typically are a mix of moderate- to high-molecular weight aromatic substances that are water soluble³⁶. Research has focused on fungi and bacteria that can degrade lignin or lignocellulose in woody plants which forms the basis of lignite. The products of bioliqefaction often need further upgrading and processing before they can be used.

Biogasification

Biogasification typically converts coal to methane employing a three-stage process. A liquid solvent or chemical treatment lowers the molecular weight of the coal. For example, alkaline compounds and hydrogen peroxide breakdown lignite into single ring-aromatic compounds⁹. Then a microorganism is introduced to ferment the slurry into acetate and CO₂. Finally, another organism ferments the acetate into methane. The organisms to ferment the slurry under anaerobic conditions are akin to municipal waste systems that generate methane. The drawback of biogasification is the need to add and remove different organisms at the second and third stages.

Conclusions

Coal prevails as an energy source because it is abundant, and the industry has developed mature conversion technologies. However coal conversion and utilization for electricity generation pollutes the atmosphere with higher concentrations of CO₂ than any other fossil fuel used in the power sector. New methods of coal utilization must curb CO₂ emission through innovative conversion processes and integrated systems, with regard to the overall system efficiency and capital costs. The research and development in coal technologies has a long history in catalysts, coal behavior, reactors and materials development. Opportunities exist in those areas, but must be considered in a new way and opportunities may exist in broader system integration with air or carbon separation, solid oxide fuel cells, magnetohydrodynamics, chemical cycling, multi-fuel generation or co-firing with biomass. In order to reach the Kyoto Protocol targets for carbon dioxide (550ppm or 5% below 1990 levels), we will need all the options for increasing coal conversion efficiency, carbon capture and long-term storage, while reducing overall coal consumption.

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