State Clean Energy-Environment Technical Forum
Integrated Gasification Combined Cycle (IGCC)
Background and Technical Issues
June 19, 2006
3:30 – 5:00 p.m.

I. PREFACE

The State Clean Energy-Environment Technical Forum was created by EPA to present analytical questions and key issues on state clean energy efforts to state agency officials. The Technical Forum is organized as a monthly discussion (via phone) among state energy, environmental and public utility commission officials, and features discussion, expert presentations, and targeted technical assistance. This background paper on Integrated Gasification Combined Cycle (IGCC) technology was prepared for the June 19, 2006 Technical Forum. It is solely a product of EPA staff and does not reflect the input of other members of the technical forum.

This purpose of this paper is to present information about IGCC technology. Information concerning policy-related issues and incentives available to encourage the use of IGCC will be covered in another Technical Forum call. IGCC is a dynamic and rapidly evolving technology. The information provided in this paper provides a snapshot of available information and conditions in a changing industry. This paper does not establish, prescribe, or change any EPA policy or legal interpretation with respect to the regulation and permitting of IGCC or pulverized coal facilities. Emissions limitations and permit conditions for such facilities should be determined by permitting authorities on the basis of applicable EPA and state regulations and the record in each permitting proceeding. EPA retains the discretion to promulgate or amend regulations and policy concerning the control of emissions from such sources on the basis of additional information or public comment in the record of an Agency action.

II. OVERVIEW

Expanding worldwide energy demand, significant increases in natural gas and petroleum fuel costs, and continued concerns regarding the environmental impacts of fossil fuel conversion have refocused attention on coal-based power generation technologies. Prominent among these is IGCC technology, which has been under development for the past 25 years. Four commercial demonstration plants have been in operation for the past 12 years. As of June 2006, there are 24 proposed coal-fired power plants using gasification technology.[1]

IGCC is an innovative energy conversion system that "integrates" a *gasification process* with *gas turbine and steam* power generation technologies that operate in tandem as a combined power cycle. The gasification process converts coal (and other carbon-based feedstock) into a synthetic gas (syngas) to fuel the combined cycle. High efficiency, low pollutant emissions, design modularity (e.g. IGCC technology is designed so that individual functional units can be added to the system), and feedstock and product flexibility are important attributes.

Another IGCC attribute, as compared with conventional combustion-based power generation, is cost-effective carbon capture capability. Gasification processes that operate at elevated pressure and use high-purity oxygen can be configured to yield syngas consisting primarily of hydrogen (H_2) and carbon dioxide (CO_2). Separation of these constituents, using either commercial or advanced capture equipment, yields H_2 and a pure stream of CO_2 that can be sequestered in different geologic formations, such as saline formations and depleted oil formations. This process of CO_2 removal and geological sequestration is known as carbon capture and storage (CCS).

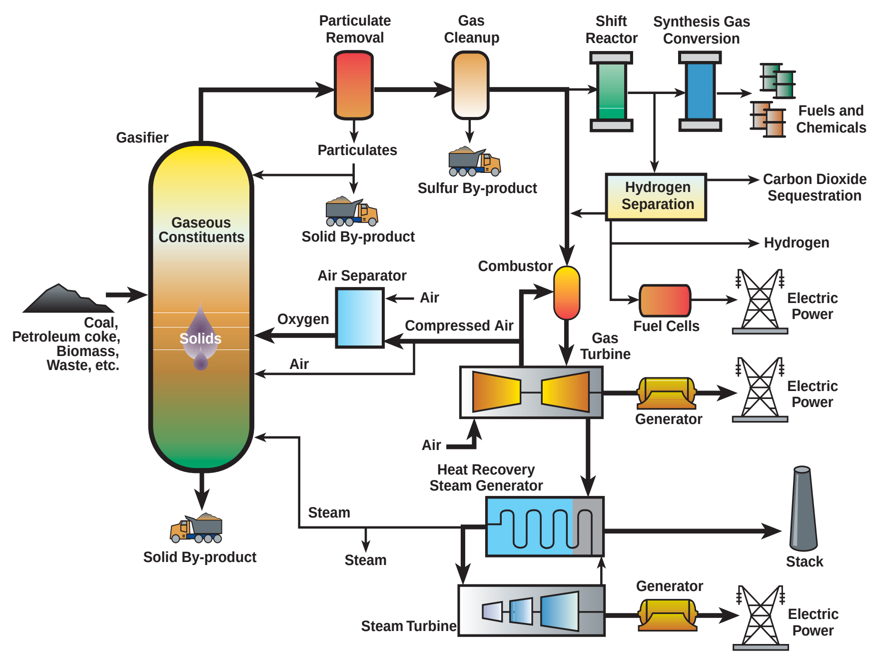
III. BACKGROUND

A. Technology

Figure 1 provides a simplified illustration of alternative IGCC design options. Various gasification technologies can be used to convert coal (or other carbon-based feedstocks) and an oxidant (i.e., oxygen or air) to a raw gas. Environmental cleanup technologies are then used to further process the gas into a usable syngas, which is converted into marketable products such as *electricity, fuels, chemicals, steam, and hydrogen*. The heart of any gasification-based system is the gasifier, which can process a wide variety of feedstocks, including *coal, biomass, petroleum coke, refinery residues, and other wastes.*

The combustion technology used in conventional pulverized coal (PC) power plants uses air in excess of the amount theoretically required to completely convert all fuel carbon to CO_2. In contrast, *gasification* generally uses one-fifth to one-third of the theoretical oxygen to only *partially oxidize* the combustible constituents of coal. The heat generated by the partial oxidation provides most of the energy required to break chemical bonds in the coal, increase the products to reaction temperature, and drive heat-absorbing gasification reactions.[2]

Figure 1: Schematic of a Generic IGCC Power Plant



Source: Ratafia-Brown, J., L. Manfredo, J. Hoffmann, and M. Ramezan, "Major Environmental Aspects of Gasification-Based Power Generation Technologies," prepared for DOE/NETL. December 2002.

The major components of syngas are carbon monoxide (CO) and hydrogen (H_2), with a small fraction of the carbon completely oxidized to yield some CO_2. A small amount of methane (CH_4) may also be present (see Figure 2). Minerals in the feedstock separate and primarily leave the bottom of the gasifier as an inert slag (or as bottom ash), a potentially marketable solid product. In addition, a fraction of the ash is entrained with the raw syngas (referred to as fly ash) and requires removal downstream in particulate control equipment, such as filtration and water scrubbers. The minor and trace components of coal are also transformed in the gasification reactor and require removal from the raw syngas using environmental control equipment. Most of the coal's sulfur converts to hydrogen sulfide (H_2S), and some carbonyl sulfide (COS). Nitrogen bound with the coal generally converts to gaseous nitrogen (N_2), with some ammonia (NH_3) and a small amount of hydrogen cyanide (HCN) also being formed. Trace elements, such as mercury and arsenic, are also released during gasification and are contained in the fly ash, bottom ash, slag, and syngas.[3] In general, all of these pollutants are removed with greater efficiency in gasification-based plants than in conventional power plants because cleanup occurs while the syngas volume is relatively small, as compared to the larger volume of flue gas emitted from a combustion-based power plant.

Figure 2: Typical Syngas Composition (% by Volume)

CO	**30 - 60**
H_2	**25 - 30**
CO_2	**5 - 15**
H_2O	**2 - 30**
CH_4	**0 - 5**
H_2S	**0.2 - 1**
COS	**0 - 0.1**
N_2	**0.5 - 4**
Ar	**0.2 - 1**
NH_3 + HCN	**0 - 0.3**

Although there are various coal gasification reactors, with different design and operating characteristics, all are based on one of three generic reactor types: *moving-bed*, *fluidized-bed*, and *entrained-flow*. Entrained flow gasifiers have been selected for nearly all the coal- and oil-based IGCCs currently in operation or under construction. Gasifiers use either air (i.e., *air-blown designs*) or high-purity oxygen (i.e., *O_2-blown designs)* as the gasification oxidant. Air-blown designs have an advantage in that they save the capital cost and operating expense of the *air separation unit* (ASU) that generates the oxygen; however, the extra inert nitrogen (N_2) volume going through the plant increases vessel sizes significantly and increases the cost of downstream equipment. Additionally, the dilution of the combustion products with nitrogen makes the separation of CO_2, in particular, more expensive. Oxygen-blown designs make use of an ASU to separate O_2 and N_2 prior to use. They do not introduce the additional nitrogen into the gasifier, which minimizes downstream syngas volume and vessel sizes. The O_2-blown design also allows CO_2 to be more easily and cheaply separated, which makes O_2-blown designs the most likely choice for future IGCC/CCS plants.[4]

After it is cleaned, the syngas can be used in the following ways:

- Be combusted in a gas turbine, with the waste heat used to generate steam in a combined cycle mode (i.e., the IGCC configuration). The gas turbine typically produces 55 to 65% of the net power output.
- Provide H_2, through a separation process, for refinery applications or as a fuel for highly efficient fuel cells. The waste heat from this process can be used to generate steam in a combined cycle mode.
- Be converted using various processes to produce a broad range of chemicals and fuels.

<u>IGCC Efficiency</u>

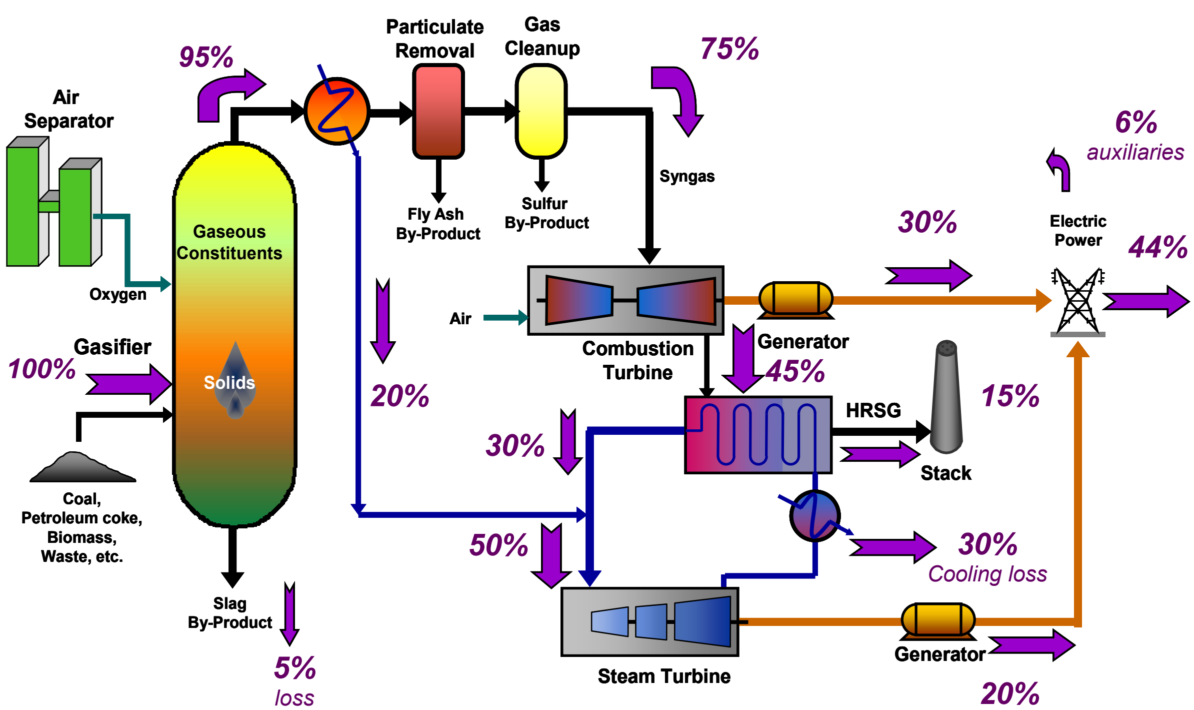
IGCC plants operate at efficiencies of about 40% but have the potential to be as high as 45% (or higher if fuel cells are used). By comparison, combustion-based power plants have efficiencies that range from about 18% to 43%. The average power plant efficiency for plants firing "black coal" (primarily bituminous and subbituminous coals) in 2004 was about 34.6%.[5] Fleet-wide statistics for domestic, coal-fired, subcritical power plants indicate an average efficiency of

30.9% with a range of 17.6% to 37.8%. The efficiency of coal-fired PC boilers installed in these power plants since 1991 ranges from 33% (subbituminous coal) to 36.7% (bituminous coal).[6]

Fleet-wide statistics for domestic, coal-fired, supercritical power plants indicate an average efficiency of 34.3% with a range of 29.5% to 38.6%. One study identifies the upper end of supercritical pulverized coal (SCPC) performance as 38.3% and the upper end of ultrasupercritical (USCPC) performance as 42% to 43% for bituminous and subbituminous coals.[7]

Figure 3 shows the energy flows in a generic IGCC plant with an assumed efficiency of 44% (7,757 Btu/kWh heat rate), which is at the high-end of current design capability. While the major energy flows are identified, there are minor losses in the acid gas recovery (AGR) unit and other ancillary devices that are not shown in the figure. The distribution of energy flows vary depending on the type of IGCC technology and individual plant configuration. The two domestic IGCC plants, Wabash River Generating Station and Polk Power Station, have demonstrated heat rates of 8,600 and 9,100 Btu/kWh, respectively.[8,9] These heat rates correspond to efficiencies of 39.7 and 37.5%. The heat rates for the two international coal-based IGCC plants, Buggenum and Puertollano, have been reported as 8,240 (41.4%) and 8,230 (41.5%) Btu/kWh, respectively.[10] Future integrated gasification fuel cell plants (IGFC), combined with other technology improvements, project efficiencies of nearly 60% (HHV-basis) and will have near-zero emissions. Cycles have been identified by NETL and the National Fuel Cell Research Center that are capable of achieving this efficiency goal for advanced power systems like FutureGen.[11]

Figure 3: Generic Energy Flow Diagram For An IGCC System



Source: Ratafia-Brown, J., L. Manfredo, J. Hoffmann, and M. Ramezan, "Major Environmental Aspects of Gasification-Based Power Generation Technologies," prepared for DOE/NET, December 2002.

Key design factors that influence the IGCC efficiency are:[12]

- ***Coal type.*** Coals of high rank (e.g., bituminous and some sub-bituminous coals) can be gasified more efficiently than coals of low rank (e.g., lignite). The higher moisture and ash content of low rank coals require a higher degree of oxidation (more oxygen) to achieve slagging temperatures because of the energy needed to vaporize the moisture and melt the ash. Most recent studies have focused on high rank coals.
- ***Gasification technology.*** Gasifiers with a dry feed are more efficient than gasifiers with a slurry feed because less water must be vaporized. Gasifier technologies that include syngas coolers for heat recovery of the thermal energy of the hot gas, are more efficient than those with a water quench.
- ***Degree of air separation unit (ASU) integration.*** Integration of the ASU with the gas turbine increases the electrical efficiency but can also result in operational difficulties. In cases where integration is practical, supplying all or part of the ASU air from the gas turbine reduces the auxiliary power requirement of the ASU main air compressor. In order to avoid operational problems, most new designs compromise at 25% to 50% of ASU air supply extracted from the gas turbine compressor (the optimum percentage is determined by the specific gas turbine compressor characteristics), with the remaining air provided by the ASU's dedicated compressor.
- ***Technology level.*** Gas turbine technology and turbine inlet temperature, together with the choice of steam cycle, have the most significant impact on electrical efficiency.

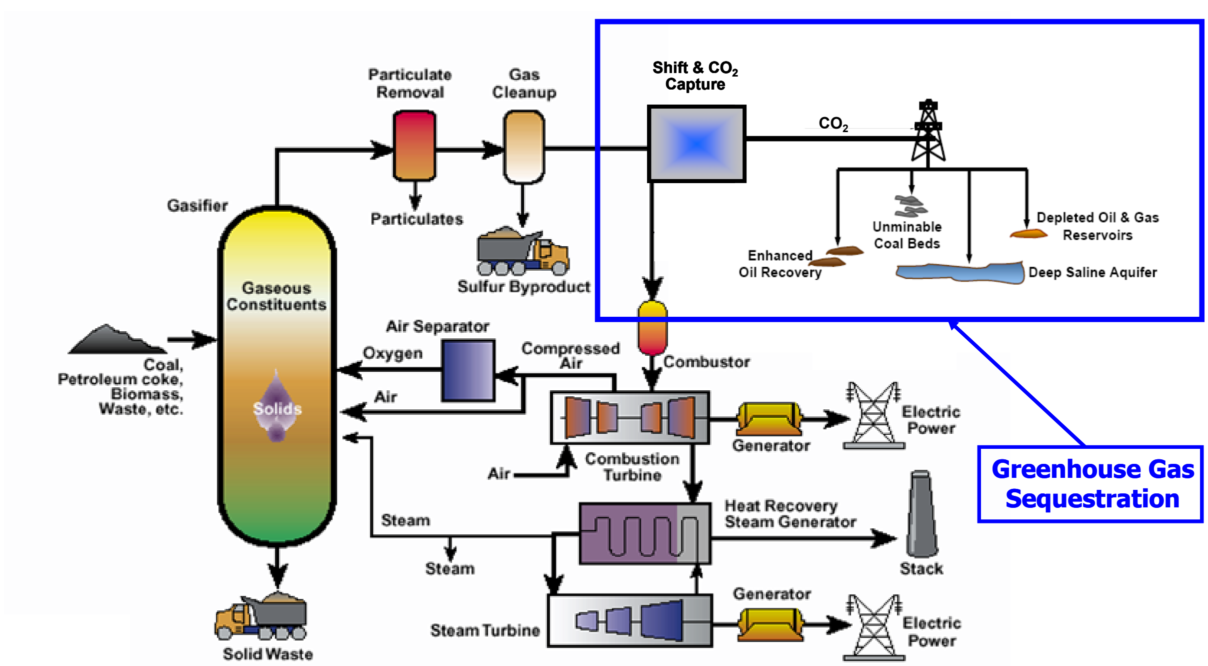
<u>Opportunity for Carbon Capture and Storage</u>

Carbon sequestration is the removal and retention of CO_2 in terrestrial, oceanic, and geologic environments. *Geologic* sequestration – also known as carbon capture and storage (CCS) – is the underground emplacement of anthropogenic CO_2 captured from industrial facilities such as cement manufacturers and power plants. Instead of releasing the captured CO_2 to the atmosphere, CCS operations compress the gas to a "supercritical" liquid and send it via a pipe (or pipeline) to an injection well, where it is pumped underground to depths generally greater than 800 meters to maintain critical pressures and temperatures. Once underground, the CO_2 occupies pore spaces in the surrounding rock like water in a dry sponge. Suitable geologic storage sites have a caprock, or an overlying impermeable layer, that prevents CO_2 from escaping back towards the surface.

IGCC syngas has a relatively high CO_2 concentration (up to 15%), but this percentage can be increased via a "water-gas shift reaction," which converts H_2O and CO to CO_2 and H_2, prior to combustion. The addition of water-gas shift-conversion reactors to an IGCC system yields a syngas primarily composed of H_2 and CO_2, with CO_2 concentration of about 40%. This compares with CO_2 concentration in the flue gas discharged from a conventional PC plant (about 75% nitrogen) of about 12%. IGCC's high pressure operation and high CO_2 concentration yields a high CO_2 partial pressure that permits use of physical absorption (e.g. the Selexol process) rather than the more energy-intensive chemical absorption required at lower partial pressures; reduction in the energy required to regenerate the solvent results in lower auxiliary power requirements than would be the case for combustion-based removal. Acid gas partial pressure is the key driving force for the Selexol process. Typical feed conditions range between 300 and 2000 psia with acid gas composition (CO_2 + H_2S) from 5% to more than 60% by volume. High pressure operation also results in more compact process equipment for IGCC syngas applications versus that applied to flue gas. In general, IGCC design and operating characteristics yield more CO_2 control options and improved cost and performance. Figure 4 depicts this process.

The high percentage of CO_2 captured when using the water-gas shift reactor, combined with the high operating pressure of commercial gasifiers (~400 psig)[13], makes it easier to recover CO_2 from syngas in IGCC power plants than from flue gas in conventional coal power plants. Key issues related to adding CO_2 capture capabilities to the IGCC plant are: 1) energy is expended to capture and further compress CO_2, which decreases plant efficiency; 2) hydrogen-rich fuel changes gas turbine design and performance, thus more fuel is required to avoid a turbine power reduction; 3) there is increased energy loss from the syngas; 4) some gasifier designs (e.g., those without a water quench) require extraction steam from the steam turbine, which further reduces power output; and 5) carbon in the form of methane is not removed. Overall, IGCC system studies indicate that inclusion of a CCS component reduces plant efficiency by about 15% for IGCC as compared to about 25% for natural gas combined cycle (NGCC) and 38% for ultra-supercritical pulverized coal (PC) power generation.[14]

Figure 4: Schematic Design for an IGCC/CCS System



Source: Ratafia-Brown, J., L. Manfredo, J. Hoffmann, and M. Ramezan, "Major Environmental Aspects of Gasification-Based Power Generation Technologies," prepared for DOE/NETL, December 2002.

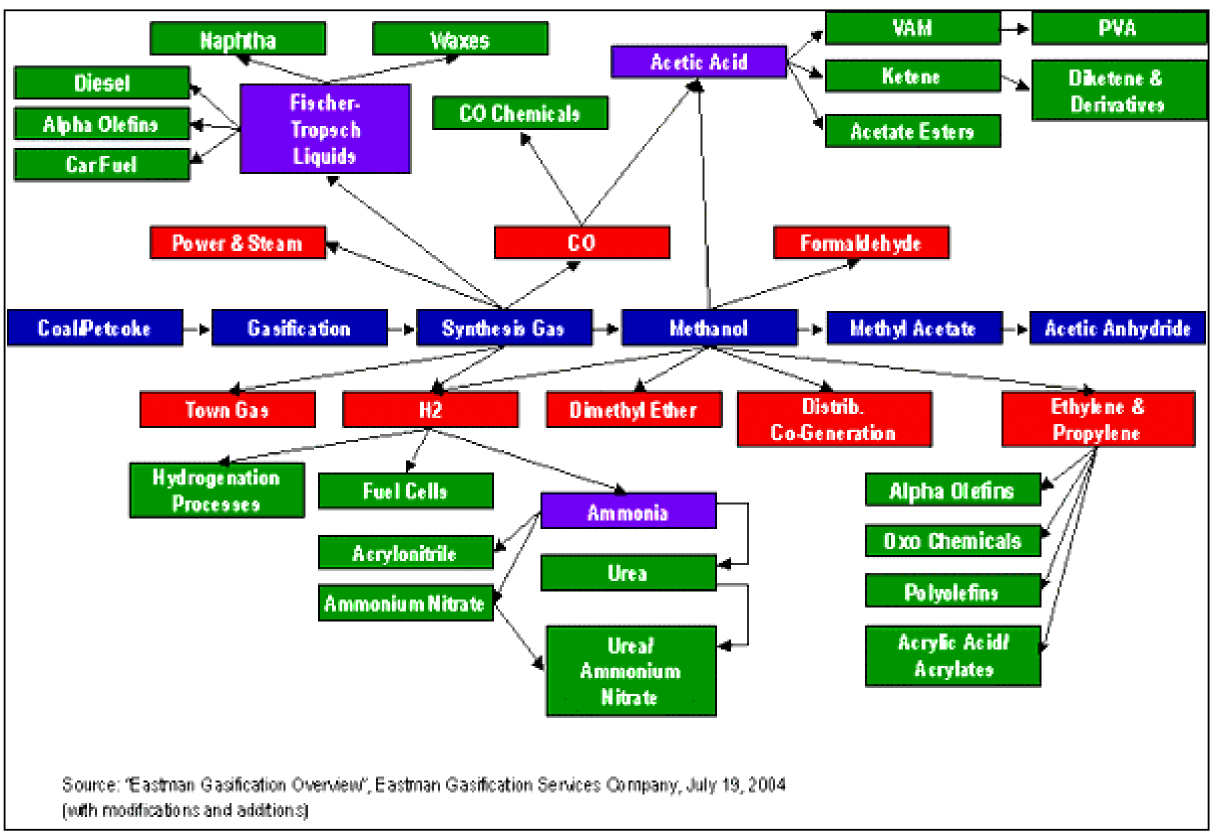
Co-Production Capabilities

The syngas produced by gasification plants can be used for the "polygeneration" of a variety of valuable products and materials for industrial consumption, including: power, liquid and gaseous fuels, hydrogen, sulfur and/or sulfuric acid, ash/slag, pure CO_2, and process heat. Other derivative chemicals can also be produced, as shown in Figure 5.

The flexibility to co-produce a range of high-value commodities is an important advantage of gasification technologies as compared to combustion technologies; markets can be served, and economics improved, by fully utilizing all outlet streams of the process. The sale of value-added byproducts from waste streams and the associated minimization of waste disposal can also substantially improve the economics of gasification processes.

Specific plant locations can influence the economic options for IGCC based on fuel availability (e.g., petcoke and coal) and product demand. For example, Texas can use its ample lignite fuel resource to co-produce electric power, H_2 or substitute natural gas (SNG), and CO_2. The electric power can be sold to the grid, the H_2 sent by pipeline to the Gulf Coast petroleum refineries, the SNG sold as a natural gas supplement, and the CO_2 sent via pipeline to the West Texas oil fields for enhanced oil recovery (EOR). EOR provides an economically attractive option for partially

Figure 5: Polygeneration Potential of Gasification



Additional Source: Schlosser, L. Gasification Incentives. Workshop on Gasification Technologies. DoubleTree Westshore, Tampa, Florida, March 2-3, 2006.

sequestering CO_2, and thus reducing greenhouse gas emissions from the Texas lignite conversion.

<u>Advanced IGCC Research & Development (R&D)</u>

Gasification R&D, which is primarily funded by DOE's Office of Fossil Energy, focuses on a variety of areas to further improve IGCC technology. Some of the most promising programs are described below.

- ***Advanced Gasification Technology.*** Advances in gasifier technology to enhance feedstock conversion efficiency, reliability, feedstock flexibility, conversion economics, and production of H_2 and concentrated CO_2 are proceeding to meet system goals in the *DOE Clean Coal Technology Roadmap*. Research is being conducted on innovative technologies, such as the *transport gasifier* and *rocket engine-based gasifier*.[15] Transport gasifiers are more cost-effective when handling low rank coal, and coals that are high in moisture and ash. They are also expected to have lower capital and operating costs than other gasifier designs.
- ***Advanced Gasification Materials.*** A low-chrome/chrome-free refractory material is being developed that can last at least three years in a slagging gasifier, as compared with the current 18-month lifetime. [16]
- ***Air Separation Technology.*** When used for IGCC, cryogenic (i.e., low temperature) separation typically represents 12 to 15% of the capital cost of a plant and consumes approximately 10% of the gross power output.[17] R&D is focusing on an advanced air separation technology called ion transport membranes (ITM). Based on the development of a prototype ITM facility at Eastman Chemical Company's "Chemicals from Coal" facility in Tennessee, the ITM technology is expected to be commercially ready in the 2006 to 2008 timeframe. The economic benefits of ITM oxygen for the IGCC application include a 7% reduction in overall plant installed capital cost, 7% improvement in power output, 35% savings in the installed specific cost of the ASU (as compared to cryogenic separation), 37% improvement in the power requirement of the ASU, and 2.2% improvement in the overall power plant efficiency.[18]
- ***Hydrogen/Carbon Dioxide Separation.*** Significant cost and performance opportunities for improving current separation techniques can result from the use of advanced membrane technologies; much R&D involves developing membranes to be consistent with the temperature and pressure requirements of IGCC applications and with required product specifications. Development of a high-pressure, non-membrane CO_2 separation technology, including production of CO_2 hydrates and dry scrubbing processes with regenerable sorbents, is also being supported. Improved gas separations involving H_2 and CO_2 can lead to reduced capital and operating costs, as well as improvements in thermal efficiency and environmental performance. One study estimates that advanced membrane technology can reduce the cost of H_2 production from coal by 25%. Co-production of H_2 and electricity can further reduce the cost of H_2 production by 32%.[19]

B. Barriers to Deployment

Each major IGCC subsystem has been broadly used and tested in industrial and power generation applications, yet the *integration* of a gasifer using coal with a combined cycle to produce commercial electricity has been demonstrated for a relatively short period at only four plants worldwide. Thus, while IGCC technology holds great promise for major benefits in the areas of environmental protection, technology advancement, economic growth, and national security, there are still considerable challenges to large-scale deployment. Key deployment challenges, as reported in several DOE studies on future IGCC market penetration, are identified in Table 1.[20,21]

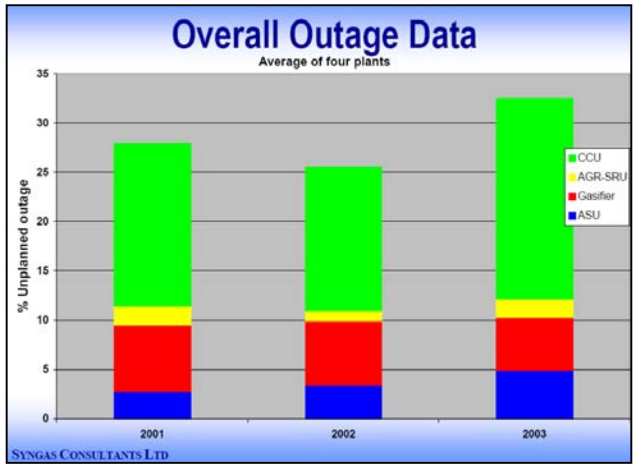
Table 1: Barriers to Deploying IGCC

Deployment Category	IGCC Deployment Barriers[a]
Technological Fitness and Readiness Issues	• **Low plant availability[b]** • General lack of operating experience • Experience with commercial facilities
Technology Acceptance and Project Siting Issues	• Plant operators' lack of familiarity with IGCC • **Power Industry Culture: IGCC is more like a chemical plant than a typical power plant and power utilities understand combustion, not chemical units** • Lack of appreciation for fuel diversity (e.g., IGCC fuel flexibility); • Poor perception of coal by the general public • Lack of appreciation for social benefits
Project Economic and Financial Issues	• **Higher capital costs than other fossil power plants, particularly PC plants** • Doubts about plant financial viability without subsidies • **Concerns with the ability to obtain viable performance guarantees and warranties** • **IGCC performance** • Increased risks associated with up-front development costs • **Availability of turnkey IGCC vendors** • History of construction and startup problems • **Long construction lead times**
Market Competition	• Competition includes SCPC/USCPC, nuclear, distributed generation (e.g., microturbines), renewables, and fuel/technology options with LNG • **Application of carbon constraints favors greater adoption of gas-based technology, nuclear, and renewables** • LNG is viewed as both a competitor and substitute.

[a] Key barriers are marked in bold font.

[b] Availability refers to the percentage of time that a plant is available to operate when required.

Figure 6: Overall Outage Data



Source: O'Brien, J., "An Analysis Of The Institutional Challenges To Commercialization And Deployment Of IGCC Technology in the U.S. Electric Industry: Recommended Policy, Regulatory, Executive and Legislative Initiatives," Prepared for NETL and National Association of Regulatory Utility Commissioners, March 2004.

Upfront IGCC project *capital cost*, projected plant *availability*, performance *guarantees*, and long construction *lead times* are perhaps the most significant concerns expressed by stakeholders in DOE-sponsored surveys and workshops.

Cost and construction lead time issues can be addressed through standardized designs, greater design experience and optimization, and subsystem R&D. Availability is defined as the percentage of time that a plant is available to operate, when required. IGCC availability is a major concern because some of the early demonstration projects achieved lower than 80% availability (most conventional base load power plants achieve 90% availability). For example, the 253 MW coal IGCC Buggenum project in the Netherlands had only a 72.5% availability in 2003 (the plant commenced operations in 2000). On the other hand, the two commercial-size projects in the U.S. have continued to increase their availability. The Wabash plant has had a significant increase, from an average of 62.4% in its demonstration phase to 82.4% in 2003[22] and the Tampa Electric Polk Power Station has achieved up to 80% availability. Higher levels of availability may be achievable as future plants are designed with spare gasifier trains (current plants only have a single gasifier train).[23] EPRI found that including a spare gasifier could increase availability to 90%[24] -- at Eastman Chemical Company's coal gasification syngas plant for chemical manufacture, spare gasifiers enabled the plant to be operating 98.1% of the time for the three-year period from November 2001 to November 2004.[25] However, IGCC availability is associated with other IGCC components in addition to gasifiers, as shown in Figure 6, which aggregates outage data for key subsystems at the Polk, Wabash, Buggenum and Puertollano IGCC plants.[26]

In general, IGCC should be able to further enhance its market position by reducing investment costs, increasing reliability, taking advantage of overcapacity from bankrupt NGCC facilities, and repowering older coal-fed PC plants that can't meet environmental regulations. IGCC's polygeneration capability also can yield product diversification and a flexible operating structure. An IGCC polygeneration site would produce power and other products that conceivably could be varied depending on the market price and plant turndown ratio. In addition, polygeneration could provide energy storage potential as plants produce electricity during peak demand and store synthetic fuel or other products during off-peak periods.

C. Potential Benefits

IGCC offers certain technological, environmental, and economic benefits, which are described below.

Technology Benefits

The benefits of IGCC technology are summarized as follows:

- ***High Thermodynamic Conversion Efficiency.*** Electricity-only IGCC plants have demonstrated efficiencies of 35% to 42% (based on fuel higher heating value [HHV]), and have the potential to improve to more than 45%. Future integrated gasification fuel cell plants, combined with other technology improvements, have projected efficiencies of nearly 60%.[27]
- ***Flexible Application.*** IGCC can be used for new power generation applications, as well as for repowering older coal-fired plants, significantly improving their environmental performance. Repowering improves cost-effectiveness through the use of existing infrastructure related to fuel delivery and storage, water delivery and discharge, steam turbine-generator, waste disposal, and electricity distribution.
- ***Flexible Feedstock Utilization.*** Depending on the type of gasifier used, IGCC is capable of processing a variety of low-cost, widely available, carbonaceous feedstock, including coal, biomass, petroleum coke, refinery residues, and other wastes. This permits plant siting flexibility that takes advantage of unique feedstock availability, as well as purchasing flexibility to minimize operating cost.
- ***Flexible Product Conversion.*** Depending upon plant design and modular add-on processes, IGCC is capable of co-producing a suite of marketable products, such as electricity, steam, Fischer Tropsch liquid fuels, gaseous fuels, fertilizers, chemicals, and hydrogen.
- ***Flexible Plant Operation.*** Co-production of power and alternative conversion products provides the potential to alter product mix based on cyclical market demand and times of local and national emergency. This includes energy storage for electrical demand peak shaving, clean fuel for domestic use or export, and chemical and fuel sales.

Environmental Benefits

Based on the experience of currently operating plants and future projections, IGCC technology offers environmental advantages over conventional coal-fired technologies.[28] Commercial IGCC plants have achieved lower levels of criteria pollutant air emissions (i.e., NO_x, SO_x, CO, and PM_{10}) than other types of coal-fueled power plants. Emissions of trace inorganic and organic hazardous air pollutants (HAPs) are extremely low, comparable with those from coal combustion-based plants that use advanced emission control technologies. If mercury is regulated, commercial mercury control equipment is already available for IGCC. The ash (slag or bottom ash) and sulfur (or sulfuric acid) generated by operating IGCC plants have been tested to be environmentally benign and can be sold as valuable by-products. Discharge of solid by-products and wastewater is reduced by roughly 30% to 50%, compared with combustion-based plants, varying with design and gasifier type. Another significant environmental benefit is a reduction of CO_2 discharge, by at least 10%, for an equivalent net production of electricity. This is due to higher operating efficiency as compared to an existing subcritical PC power generation technology. If more significant CO_2 reduction is required in the future, the IGCC/CCS technology incorporates unique design and operating features (i.e., lower energy intensity of capture)that can be exploited to capture CO_2 more efficiently than is currently possible with combustion technology.

Based on National Energy Technology Laboratory (NETL) R&D program successes to-date,[29] long-term carbon storage in geologic reservoirs appears feasible and can be made cost-effective. All parts of this technology (including carbon capture and compression, transport, and injection) are already in commercial practice today, but at substantially smaller scales than would be necessary for widespread application. Determining the viability of carbon capture and storage requires substantial research, including attaining commercial experience through the development of several large-scale demonstration projects over the next 10 to 15 years.[30]

Detailed environmental benefits of IGCC technology are summarized as follows.

Air Emissions. IGCC results in very low pollution levels, and all air emissions levels are lower with IGCC than with most coal combustion technology. Actual performance data for the Polk, Wabash, Buggenum, and Puertollano plants are provided in Table 2. This performance data is provided only for informational purposes and its inclusion in this paper does not establish these levels as emissions limitations for any source. Emissions limitations and permit conditions are determined by permitting authorities on a case-by-case basis considering applicable EPA and state regulations and the record in each permitting proceeding.

Table 2: Existing IGCC Plants: Design and Operating Features and Emissions Levels

	Polk Power Station (Florida)	Wabash River Generating Station (Indiana)	NUON/Demkolec (Buggenum, The Netherlands)	ELCOGAS (Puertollano, Spain)
DESIGN AND OPERATING FEATURES				
Gas turbine, MWe	192	192	155	182
Steam turbine, MWe	121	104	128	135
Auxiliary power, MWe	63	34	31	35
Net Power Output MWe	250	262	253	298
Efficiency, % (HHV basis)	37.5	39.7	41.4	41.5
Efficiency, Btu/kWh (HHV basis)	9,100	8,600	8,240	8,230
Coal Usage (tons/day)	2,500	2,544	2,200	2,400
EMISSIONS				
SO_2 (lb/MWh)	<1.35[c]	1.08[e]	0.44[i]	0.15[j]
NO_x (lb/MWh)	0.52[d]	1.09[e]	0.7[i]	0.88[j]
Particulates (lb/MWh)	<0.04[c]	<0.10[e]	0.01[i]	0.044[j]
Sulfur Removal, %	> 98	> 98	>99	99.9
NO_x, ppmvd (@ 15% O_2)	15[k]	25[l]	< 10[n]	< 10[n]

Table 2: Existing IGCC Plants: Design and Operating Features and Emissions Levels				
	Polk Power Station (Florida)	**Wabash River Generating Station (Indiana)**	**NUON/Demkolec (Buggenum, The Netherlands)**	**ELCOGAS (Puertollano, Spain)**
a Year 8 operation, ending September 2004 b Year 8 operation in 2003 **c** Reported SO_2 emissions in 2000, 98% SO_2 Removal reported in 2005, PM emissions from 2003 DOE Fact Sheet **d** Estimate based on average of 14 months of CEMS data prior to 2003 and post-2003 NO_x reduction from 25 to 15 ppm. **e** Average Emissions in 2001[31] **f** EPA ICR Results in 2000 **g** August 2003 to May 2004[32] **h** August 2003 to May 2004[33] **i** Average emissions reported for 2001[34] **j** Average emissions reported for 2001[35] **k** Reference for 2005 [36] **l** Reference for 2004[37] **m** Reference [38] **n** Reference [39] Note: Emission rates are not provided by EPA.				

Waste Discharge and Solid Byproducts. Benefits related to waste discharge and solid byproducts are described below.

- **Less Volume.** IGCC yields about half the solid wastes of conventional coal-fired power plants. This is due to the higher efficiency of IGCC and the production of marketable byproducts. Table 3 presents the results of a DOE study that compared solid waste output from an IGCC plant with two supercritical PC power plants.
- **Better Form.** Since most prominent coal gasification processes incorporated into IGCC, such as GE and Conoco-Phillips E-Gas processes, are slagging systems, ash is primarily in the form of an inert vitreous (glass-like) slag that has generally been determined to be a non-leachable, non-hazardous material. Compared with combustion fly ash, slag is less difficult to handle, use, and dispose of than fine ash material. Slag's hardness also makes it suitable as an abrasive or roadbed material, as well as an aggregate in concrete formulations.

Marketable Byproducts. The largest solid waste/by-product stream produced by IGCC is coal ash in the form of fly ash, bottom ash, or slag. The specific form is a function of gasifier type and the quantity is a direct function of the ash content of the feed fuel. A 300-MWe IGCC power plant using 2,500 tons of 10% ash coal per day may generate 250 tons/day of slag or bottom ash, the disposal of which represents a significant operating cost. Commercial application of coal gasification technologies can be greatly enhanced if the solid byproduct can be used, rather than disposed of in a landfill. It should be noted that solid wastes generated by PC plants can also be sold as industrial by-products. A second potential large-volume solid stream is sulfur or sulfuric acid. The sulfuric acid produced is generally about 98% pure and the sulfur by-product is typically greater than 99.99% pure. Both are highly marketable by-products.

Table 3: Comparison of Water Use and Solid Waste from IGCC and PC Plants

Parameter	IGCC Plant[a]	Supercritical PC Plant[b]	Supercritical PC Plant[c]
Cooling Tower Makeup (gal/MWh)	608	1099	984
Total Makeup Water (gal/MWh)	678	1169	1042
Solid Output (lb/MWh)	92	193	155

a ConocoPhillips E-Gas gasification system, 526 MWe, 8717 Btu/kWh (HHV), Pgh #8 Bituminous Coal, Solid output includes slag and sulfur.

b 2400 psig/1000°F/1050°F single reheat configuration, 521 MWe, 9641 Btu/kWh (HHV), Pgh #8 Bituminous Coal, Solid output includes ash, flyash, and gypsum.

c 3500 psig/1050°F/1050°F single reheat configuration, 518 MWe, 8564 Btu/kWh (HHV), Pgh #8 Bituminous Coal, Solid output includes ash, flyash, and gypsum.

Source: Rutkowski, M.D., et al., "Power Plant Water Usage and Loss Study," Prepared for U.S. DOE National Energy Technology Laboratory, August, 2005, Tucson.

Water Consumption and Discharge. Environmental benefits associated with water consumption and discharge are described below.

- **Less Water Usage.** IGCC units use less water than conventional coal plants and can use dry cooling to minimize water use. Table 3 presents the results of a DOE study that compared water use from an IGCC plant with two supercritical PC power plants. For these plants, the IGCC plant water usage is 35% to 45% less than the PC plants' water usage. In general, losses in the closed loop cooling cycle for IGCC represent about 90% of the total water losses, with about one-third of this amount leaving the power plant as a blowdown water flow. IGCC process wastewater amounts to less than one-tenth of the cooling water blowdown. Lower water consumption is a significant advantage over PC combustion power generation.
- **Less Water Loss.** IGCC process water loss, cooling water blowdown and cooling tower evaporation are typically 30% to 50% less than a comparably sized PC plant.

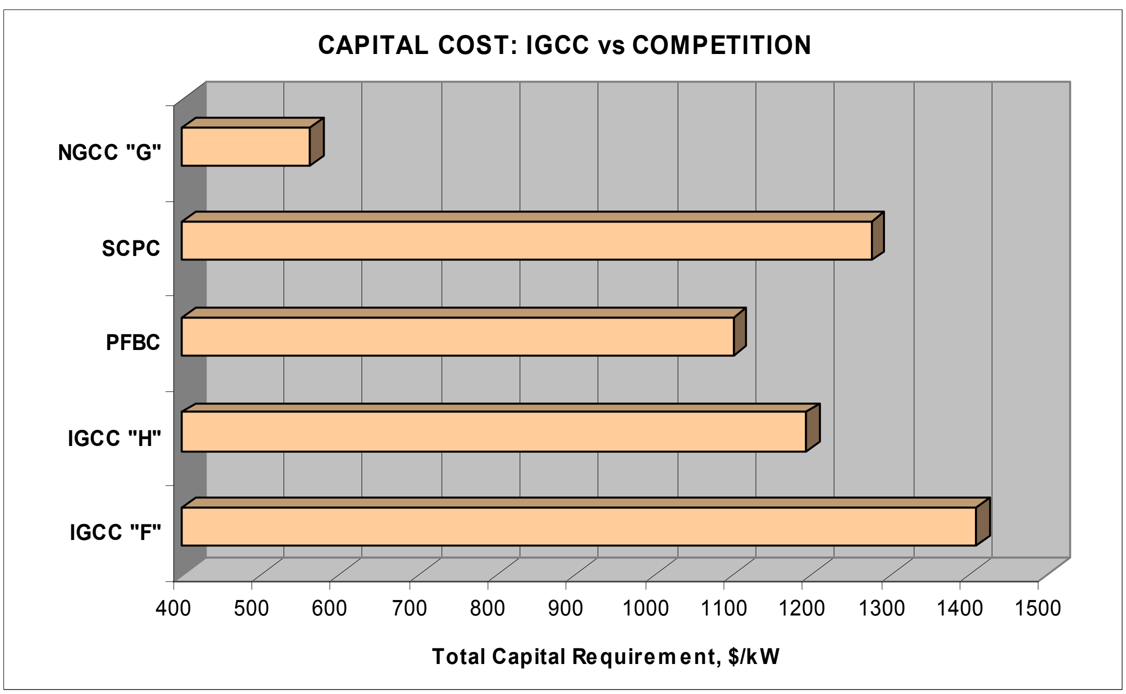
Reduced Global Climate Change Impact . IGCC has two operating advantages that permit more efficient CO_2 capture (i.e., energy intensity of capture) than is possible with combustion technology. Syngas has a high CO_2 concentration, which can be increased via the water gas shift reaction to convert CO to CO_2 prior to combustion (while simultaneously producing more hydrogen). Also, IGCC gasifiers typically operate under relatively high pressure (~400 psig at the Wabash River plant). Both of these conditions make recovery of the CO_2 from the syngas easier than capture from flue gas.[40]

Economic Benefits

The economic benefits of IGCC are described below.

- ***IGCC Cost.*** IGCC's elevated capital cost and cost of electricity (COE) are critical challenges to deployment. However, increased engineering, procurement, and construction (EPC) experience; vendor turnkey services; improved reliability; and R&D advances are continuing to improve IGCC economics relative to competing technologies. DOE projects cost-competitive IGCC plants by 2010 based on $1000/kW capital cost, efficiency approaching 50%, availability of advanced ITM air separation, 85% availability, and 98% carbon conversion. Figures 7 and 8 present comparisons of capital costs and the cost of electricity for IGCC versus natural gas combined cycle (NGCC), supercritical pulverized coal (SCPC), and pressurized fluidized bed combustion (PFBC) plants. Results also identify the class of gas turbine used, F, G, and H (H is the most efficient). The IGCC and NGCC are based on the ConocoPhillips E-Gas technology.

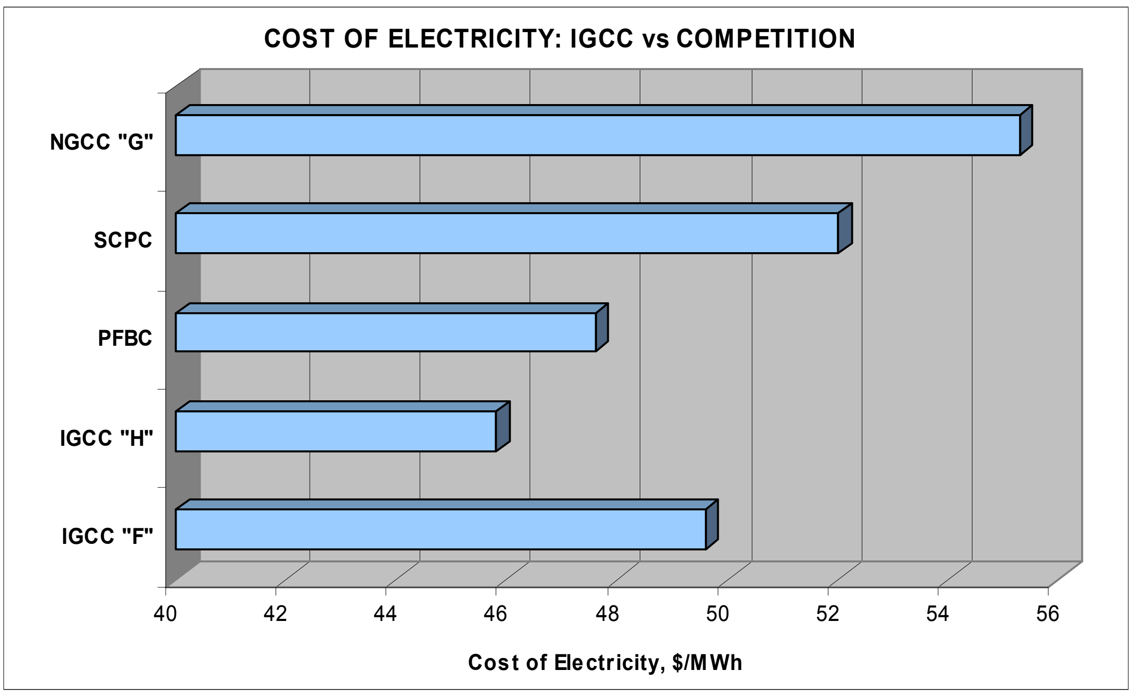
Figure 7: Capital Cost of IGCC vs other Technologies: Total Capital Requirement ($/kW)



Source: NETL, "Process Engineering Division," PED-IGCC-1998, Revised June 2000. Fuel price data updated in 2005.

- ***Fuel Cost.*** Historically, coal prices have been much more stable than other fossil fuels. In addition, in terms of a $/Btu basis, coal is much cheaper than either natural gas or oil, although coal does somewhat track price escalation of the others during price surges. EIA projects relatively flat coal prices over the next 20 years. Natural gas is the primary alternative fuel choice to coal, but its prices have historically been much more volatile than coal prices and it is quite likely that supplies will remain tight and prices high for the foreseeable future.

Figure 8: Cost of Electricity for IGCC and Other Technologies ($/MWh)[a]



[a] Figure 8 includes the following fuel cost assumptions: Natural gas: $5.40/mmBtu, Central Appalachian compliance coal (PC and PFBC): $65/ton and Northern Appalachian coal (IGCC): $55/ton.

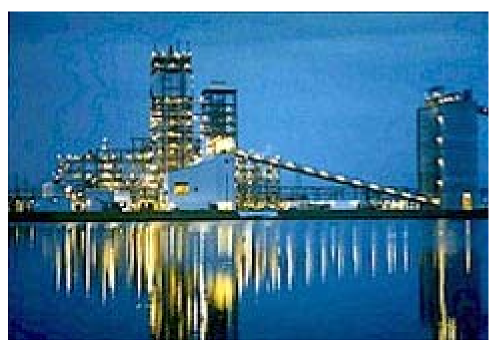
Source: NETL, "Process Engineering Division," PED-IGCC-1998, Revised June 2000. Fuel price data updated in 2005.

- ***IGCC Markets.*** IGCC technology provides an opportunity to cost-effectively repower older, conventional fossil plants, and address a number of environmental problems. This would involve a substantially lower cost than piecemeal, incremental retrofits.[41] By 2020, over 200 GW of current capacity is expected to be repowered or life-extended. Also, high natural gas prices have caused gas power generation to be much less profitable than expected, which has led to gas-fired power plants being put up for sale or in some cases, being repossessed by lenders. One option that can utilize this stranded capacity and add to U.S. energy security is to convert these existing NGCC plants to coal-based IGCC, thus burning a domestic energy source in the cleanest way possible. The large and likely growing number of NGCC plants and warehoused turbines that are for sale provides an opportunity to further develop IGCC technology at reduced costs. There are 194 NGCC plants with a capacity greater than 250 MW, representing a total gross generation capacity of approximately 114 GW that is most suitable for future conversion to IGCC.[42] Such a use of IGCC technology would reduce reliance on natural gas for electricity generation, and free up natural gas for essential uses such as industrial processes and residential heating.

- ***Foreign Trade.*** The rapid commercialization and deployment of IGCC power plant technology in the U.S. could also lead to valuable foreign trade opportunities. This would bolster U.S. exports and contribute to growth in domestic employment. The potential for IGCC power plant exports is vast given the rapid growth in electricity demand and abundant coal reserves in countries such as China and India.
- ***Energy Security.*** The timely commercialization and deployment of IGCC power plants can help decrease reliance on imported fuels from unstable regions that are currently hostile to U.S. interests. Using coal rather than natural gas or oil to generate electricity can be done without fear of shortages or international disruptions. Additionally, IGCC power plants can produce diesel fuels that could displace a significant amount of domestic transportation fuel consumption and thereby reduce oil imports. Also, the coal supply chain is much less vulnerable to sabotage than oil or natural gas infrastructures.
- ***Opportunities for CCS***. IGCC technology also provides inherent capability to integrate carbon capture components into the syngas processing section of a plant. Combining IGCC and CCS is a less expensive and more efficient method (relative to current generation conventional power plants) for reducing CO_2 emissions. When using bituminous coal, the cost of avoiding emissions of CO_2 is projected to be $89/tC using current generation IGCC technology, $186/tC with ultra-supercritical steam technology, and $194/tC with supercritical steam technology. The technology cost differential may or may not be as large when a comparison is based on use of subbituminous or lignite coals, since relative efficiencies and capital costs are altered with these fuels.[43]

IV. INITIATIVES

A. Tampa Electric Polk Power Station (Florida)



In December 1989, DOE's Clean Coal Technology (CCT) Demonstration Program selected the Tampa Electric Integrated Gasification Combined-Cycle Project at the Polk Power Station as a project under Program Round III. Construction was started in October 1994 and operation began in September 1996. This plant has successfully demonstrated advanced IGCC technology using an entrained-flow gasifier, integrated with a combined-cycle turbine system for power generation. Net power production meets the target goal of 250 MWe[44] at high stream factor and plant availability. Carbon conversion exceeds 95% (i.e., the gasifier converts 95% of the coal's carbon content to syngas, with the remaining 5% lost with the slag or bottom ash), and emissions of SO_2, NO_x, and particulates are below the original regulatory limits set for the Polk plant site. This plant is currently the lowest-cost producer within the TECO grid and the first to be dispatched.[45]

B. Wabash River Plant (Indiana)

In December 1991, DOE's Clean Coal Technology (CCT) Demonstration Program selected the Wabash River Coal Gasification Repowering Project at the Wabash River Generating Station as a project under Program Round IV. Construction was started in July 1993 and operation began in November 1995. This plant has successfully demonstrated advanced IGCC technology using an entrained-flow gasifier, integrated with a combined-cycle turbine system for power generation. Repowering for this project involved refurbishing the steam turbine to both extend its life and withstand the increased steam flows and pressures associated with combined-cycle operation. The repowered steam turbine produces 104 MWe, which combined with the combustion turbine generator's 192 MWe and the systems auxiliary load of approximately 34 MWe, adds 262 MWe (net) to the Cinergy grid. Gasifier carbon burnout exceeds 95%, and emissions of SO_2, NO_x, and particulates are below the original regulatory limits set for the Wabash River plant site. The Wabash plant is currently testing a 2 MW fuel cell in cooperation with DOE.

C. Other Coal Gasification Plants

<u>Great Plains Synfuels (North Dakota)</u>

The Dakota Gasification Company's (DGC) Great Plains Synfuels Plant (GPSP) in Beulah, North Dakota has operated successfully for 20 years as the only commercial coal-to-natural gas facility in the United States. While not an IGCC plant, the GPSP provides significant information on the design, construction, and operation of coal gasification facilities, and CO_2 capture technology, and sequestration experience. Figure 9 presents GPSP plant characteristics. Dakota Gasification Company's Beulah plant produces about 170 million scf/day of synthetic natural gas (SNG) from lignite coal; the SNG has heating value of about 972 Btu/scf. In addition, it has expanded operations to co-produce anhydrous ammonia, ammonium sulfate, krypton, xenon, dephenolized cresylic acid, liquid nitrogen, naphtha, and phenol. In 2000, the plant also began exporting CO_2 for use in EOR operations in Canada. Currently, about 95 million scf/day of CO_2 produced at the plant is transported via a 205

Figure 9: Great Plains Synfuels Plant Characteristics

By-products	Formula	Production
Ammonium Sulfate	$(NH_4)_2SO_4$	~110,000 tons/year
Anhydrous Ammonia	NH_3	~400,000 tons/year
Carbon Dioxide	CO_2	~40 billion scf/year (1.56 million tons/year)
Dephenolized Cresylic Acid	71% C_7H_8O 12% $C_8H_{10}O$ 8% $C_8H_{10}O$	~33 million pounds/year
Krypton and Xenon Gases	89% Kr 8% Xe	~3.1 million liters/year
Liquid Nitrogen	N_2	~200,000 gallons/year
Naphtha	43% C_6H6 18% C_7H_8 4% C8H_{10}	~7 million gallons/year
Phenol	C_6H_6O	~33 million pounds/year

Source: U.S. DOE Office of Fossil Energy, "Practical Experience Gained During the First Twenty Years of Operation of the Great Plains Gasification Plant and Implications for Future Projects," April 2006.

miles long pipeline to EnCana Corporation's Weyburn oil field in southern Saskatchewan.[a] CO_2 emissions from the GPSP, factoring in flaring at the oil fields, the energy consumption of the CO_2 compressors, and makeup boiler fuels, are down 30 percent since 2000. Through the end of 2005, over 5 million tons of CO_2 had been sequestered.[46]

Eastman Chemical

Eastman Chemical Company has operated a "chemicals from coal" gasification facility in Kingsport, Tennessee since 1983. This is the first commercial-scale coal gasification plant in the U.S. The facility converts about 1,250 tons/day of high-sulfur, Appalachian coal to methanol and acetyl chemicals. Since the products produced at this facility eventually wind up in consumer products, Eastman has incorporated high-efficiency mercury control in the gasification facility since start-up. The mercury control technology is a fixed bed of sulfur-impregnated activated carbon, operated at low temperature (86^{o} F) and high pressure (900 psi), which routinely achieves 90 to 95% removal with a bed life of 18 to 24 months.[47]

D. Other IGCC and IGCC/CCS Initiatives

Clean Coal Power Initiative (CCPI)

The Clean Coal Power Initiative (CCPI) was initiated in 2002 by President Bush and is an innovative technology demonstration program that fosters more efficient clean coal technologies for use in new and existing electric power generating facilities in the US. In the first round of solicitations, one of the projects, the *Gilberton Coal-to-Clean Fuels and Power Project*, will demonstrate gasification to convert coal waste into clean transportation fuels. Two coal gasification projects were selected in the second round of solicitations: the 285 MW *Transport Gasifier Project* at Orlando, Florida with Southern Company and the *Mesaba Energy Project* with Excelsior Energy in Minnesota. The Gilberton project will gasify anthracite culm using commercially available Shell gasification technology and will convert the synthesis gas produced in the Fisher-Tropsch technology to diesel fuel and naptha with the generation of power. The Southern Company project will use an air-blown, coal-based transport gasifier that offers the potential for higher efficiency and lower capital and operating costs along with the ability to use low-rank coals, such as sub-bituminous coal, and these capabilities will be demonstrated. Excelsior's Mesaba project will use an improved version of ConocoPhillips' E-Gas with the Wabash IGCC plant as a base design. It is expected that this coal-fired power plant will achieve lower emissions, 15 to 29 percent lower CO_2 emissions, 15 percent higher availability, and improved thermal efficiency all at lower installed unit costs.

EPRI CoalFleet for Tomorrow Initiative

In late 2004, a number of leading coal-fired power generators and the Electric Power Research Institute (EPRI) announced a new initiative, "CoalFleet for Tomorrow," to accelerate the deployment of clean, efficient, advanced coal technology and to develop options for managing the CO_2 emitted from power plants.[48] The initiative is developing standardized plant design guidelines for IGCC advanced coal technologies. An expert working group will direct the effort and work with early deployers of advanced coal plants to produce an advanced coal technologies

---

[a] The Weyburn field is the subject of a long-term monitoring program to assess the final deposition of the CO_2 being injected in this project.

knowledge base, user design basis specifications, and generic design specifications to form the platform for standardized plant designs.

U.S. DOE Office of Fossil Energy (FE) Carbon Sequestration R&D Program

R&D focuses on developing new sequestration technologies and approaches to the point of pre-commercial deployment. FE's carbon sequestration R&D program is scheduled to deliver commercially deployable solutions by 2015. This accounts for initiation of large-scale demonstrations by 2008 for value-added (enhanced oil recovery, enhanced coalbed methane recovery, enhanced gas recovery) and non-value added (depleted oil/gas reservoirs and saline formations) methods. By 2010 the program intends to develop instrumentation and protocols to accurately measure, monitor, and verify both carbon storage and the protection of human and ecosystem health. By 2015, the program hopes to enable deployment of "direct capture technologies and sequestration of GHG and criteria pollutant emissions from fossil fuel conversion processes that result in near-zero emissions and approach a no net cost increase for energy services, net of any value-added benefits."[49]

V. FEDERAL AGENCIES THAT ARE FACILITATING R&D AND IMPLEMENTING IGCC

U.S. Environmental Protection Agency (EPA)

In 1994 EPA established the Environmental Technology Council (ETC) to coordinate and focus the Agency's technology programs. The ETC strives to facilitate innovative technology solutions to environmental challenges, particularly those with multi-media implications. The Council has membership from all EPA technology programs, offices, and regions and meets on a regular basis to discuss technology solutions, technology needs and program synergies. One of the technologies identified as a promising option to address the production of energy from coal in an environmentally sustainable way is IGCC. Under the ETC, EPA established a cross-Agency action team to address technical, environmental and other issues related to IGCC. The ETC also established a similar action team to address technical, environmental and other issues related to waste-to-energy gasification technologies.

U.S. Department of Energy

- ***Office of Fossil Energy (FE)/National Energy Technology Laboratory (NETL)*****:** FE supports the most directly applicable R&D programs to advance IGCC technology in numerous areas. Applicable programs include Gasification Technology, FutureGen, Advanced Research, Advanced Turbines, Hydrogen and Other Clean Fuels, Fuel Cells, and Carbon Sequestration.

- ***Office of Science and Engineering Research (OSER):*** The OSER performs basic and applied research and development in fossil energy and environmental science. Areas include development of gas separation membranes; chemical processing of the syngas to produce a fuel; and advanced materials for gasification refractory (*Albany Research Center*).

- ***Energy Efficiency and Renewable Energy (EERE):*** The FE gasification program and EERE programs are complementary. EERE is primarily interested in several areas of gasification that do not involve fossil fuels, such as the gasification of biomass and the black liquor that is produced in paper making. Other programs at EERE include programs to develop gasification technology for industrial use and hydrogen infrastructure.

- ***Energy Information Administration (EIA)*:** The EIA has the primary responsibility for gathering, analyzing and disseminating information related to the nation's energy supply. The National Energy Modeling System (NEMS) is used to model every energy sector of the U.S. economy, including the electricity supply sector. In cooperation with FE, the model forecasts market penetration, impacts, and benefits of FE technologies, including IGCC and IGCC with sequestration, as they compete against all other similar technologies.

VI. FEDERAL AGENCIES THAT ARE FACILITATING R&D AND IMPLEMENTING CCS

U.S. Environmental Protection Agency (EPA)

EPA's goal is to ensure the safe and effective implementation of CCS technologies in order to facilitate development of CCS as a viable climate change mitigation technology with respect to long-term storage integrity and minimization of adverse health and environmental effects. EPA's Office of Air and Radiation and Office of Water currently co-chair an agency working group on geologic sequestration. EPA convened this working group to stay abreast of technology and policy developments, identify research needs, and conduct risk assessment. Participants include representatives from EPA regional offices, laboratories, program and policy offices, and general counsel. The members bring a range of technical and policy expertise to the working group. Working group efforts include researching the potential risks of CCS, organizing and facilitating technical workshops and conferences, and developing guidance on permitting CO_2 injection wells under the Safe Drinking Water Act. EPA is working closely with state regulatory agencies through a memorandum of agreement with the Interstate Oil and Gas Compact Commission and ongoing collaboration with the Ground Water Protection Council, which represents state oil and gas and environmental protection agencies.

U.S. Department of Energy

- ***National Energy Technology Laboratory (NETL):*** In its "Core R&D" efforts, NETL focuses on developing new sequestration technologies and approaches to the point of pre-commercial deployment. Primary objectives are (1) lowering the cost and energy penalty associated with CO_2 capture from large point sources, and (2) improving understanding of factors affecting CO_2 storage permanence, capacity, and safety in geologic formations and terrestrial ecosystems. Funded research activities address: CO_2 capture; carbon storage; monitoring, mitigation, and verification. The NETL portfolio also includes breakthrough R&D that furthers revolutionary and transformational sequestration concepts with potential for low cost, permanence, and large global capacity. Also, NETL manages seven regional carbon sequestration partnerships. These partnerships engage state agencies, universities, and private companies to create a nationwide network that will help determine the best approaches for capturing and permanently storing greenhouse gases. Work accomplished through regional carbon sequestration partnerships helps determine the most suitable technologies, regulations, and infrastructure needs for carbon capture, storage, and sequestration.[50]

- ***Office of Science – Biological and Environmental Research:*** Established CSiTE, a research consortium, to perform fundamental research that will lead to acceptable methods to enhance carbon sequestration in terrestrial ecosystems as one component of a carbon management strategy.

- ***Oak Ridge, Pacific Northwest, and Argonne National Laboratories:*** Operate CsiTE
- ***Berkeley Lab & Lawrence Livermore National Laboratory*****:** These national labs jointly operate the Center for Research on Ocean Carbon Sequestration to study the capture and storage of atmospheric carbon dioxide in the ocean.

VII. RESOURCES

Advanced Clean Coal Workshop. July 29, 2004.
http://www.climatevision.gov/events_coal.html

American Electric Power, "IGCC Technology," March 16, 2006.
http://www.aep.com/about/igcc/technology.htm

Amick, P., "ConocoPhillips and Gasification's New World – An Overview," Gasification Technologies Conference 2005, October 11, 2005.
http://www.gasification.org/Presentations/2005.htm

Herzog, Howard. The Future of Coal: Addressing Carbon and Other Environmental Concerns. 2006 EIA Energy Outlook and Modeling Conference. MIT. March 27, 2006.
http://www.eia.doe.gov/oiaf/aeo/conf/pdf/herzog.pdf

IPCC Special Report on Carbon Dioxide Capture and Storage.
http://arch.rivm.nl/env/int/ipcc/pages_media/SRCCS-final/IPCCSpecialReportonCarbondioxideCaptureandStorage.htm

Jenkins, S., "Real-World Experience with IGCC – Lessons Learned in Design, Permitting, Operations and Maintenance," URS Corporation Presentation, August 2005.
http://www.energy.ca.gov/2005_energypolicy/documents/2005-08-17+18_workshop/presentations-081705/Jenkins_URS_IGCC_corrected.pdf

Nexant, Inc.,"Environmental Footprints and Costs of Coal-Based-Integrated Gasification

Combined Cycle and Pulverized Coal Technologies," Final Report, prepared for the U.S. EPA July 2006. http://www.epa.gov/airmarkets/articles/control.html

Maurstad, O., "An Overview of Coal based Integrated Gasification Combined Cycle (IGCC) Technology," MIT LFEE 2005-002 WP, September 2005
http://lfee.mit.edu/metadot/index.pl?id=2235

O'Brien, J., "An Analysis Of The Institutional Challenges To Commercialization And Deployment Of IGCC Technology in the U.S. Electric Industry: Recommended Policy, Regulatory, Executive and Legislative Initiatives," Prepared for NETL and National Association of Regulatory Utility Commissioners, March 2004.
http://www.netl.doe.gov/technologies/coalpower/gasification/pubs/reports.html

Princeton Environmental Institute Carbon Mitigation Initiative.

http://www.princeton.edu/~cmi/

Ratafia-Brown, J., et.al, "Major Environmental Aspects of Gasification-Based Power Generation Technologies," National Energy Technology Laboratory, December 2002.
http://www.netl.doe.gov/technologies/coalpower/gasification/pubs/prev-reports.html

10 Things You Should Know About Gasification – Eastman Gasification Services Company. http://www.gasification.org/Docs/Knoxville%20Pres/The%20Top%2010%20Things%20You%20Should%20Know%20About%20Gasification.pdf

U.S. DOE Office of Fossil Energy, "Gasification World Survey Results," September 2005. http://www.netl.doe.gov/technologies/coalpower/gasification/pubs/brochures.html

U.S. DOE, "Practical Experience Gained During the First Twenty Years of Operation of the Great Plains Gasification Plant and Implications for Future Projects," April 2006. http://www.fossil.energy.gov/programs/powersystems/publications/Brochures/dg_knowledge_gained.pdf

Western Business Roundtable. The Path to Clean Coal for America. March 17, 2006. http://www.westernroundtable.com/energy/what_is_clean_coal.pdf#search='igcc%20altitude%20performance'

VIII. END NOTES

[1] National Energy Technology Laboratory, "Tracking New Coal-Fired Power Plants: Coal's Resurgence in Electric Power Generation," June 21, 2006, http://www.netl.doe.gov/coal/refshelf/ncp.pdf.

[2] Simbeck, D.R., et al., "Coal Gasification Guidebook: Status, Applications, and Technologies," TR-102034, Final Report, Prepared for Electric Power Research Institute, December 1993.

[3] U.S. DOE, "2005 Assessment of Advanced Integrated Gasification Combined Cycle (IGCC) Power Plants," Draft report, Section 8, January 2006.

[4] ibid.

[5] Utility Data Institute and Platts, UDI Data & Databases, "Comprehensive Energy Industry Intelligence from Platts," http://www.platts.com/Analytic%20Solutions/UDI%20Data%20&%20Directories/.

[6] NETL Coal Plant Database, Phase 1 and 2 Coal Plants, 2003 Data; EPA Clean Air Markets database. See NEEDS (National Electric Energy System) database at http://www.epa.gov/airmarkets/epa-ipm/#documentation2004 (Documentation Report - Standalone Version (2004 Update), "Standalone Documentation for EPA Base Case 2004 (V.2.1.9) Using the Integrated Planning Model," September 2005) and http://www.epa.gov/airmarkets/epa-ipm/needs_2004.xls.

[7] Nexant, Inc. , "Environmental Footprints and Costs of Coal-Based-Integrated Gasification Combined Cycle and Pulverized Coal Technologies," Final Report, prepared for the U.S. EPA. July 2006, http://www.epa.gov/airmarkets/articles/control.html.

[8] "Wabash River Coal Gasification Repowering Project: Final Technical Report," Cooperative Agreement No. DE-FC21-92MC29310, August 2000.

[9] "Tampa Electric Polk Power Station Integrated Gasification Combined Cycle Project: Final Technical Report," Cooperative Agreement No. DE-FC21-91MC27363, August 2002.

[10] Ratafia-Brown, J., L. Manfredo, J. Hoffmann, and M. Ramezan, "Major Environmental Aspects of Gasification-Based Power Generation Technologies," Prepared for DOE/NETL, December 2002.

[11] Gray, D., S. Salerno, and G. Tomlinson, "Current and Future IGCC Technologies: Bituminous Coal to Power," Mitretek Technical Report MTR-2004-05, August 2004.

[12] Maurstad, O., "An Overview of Coal based Integrated Gasification Combined Cycle (IGCC) Technology," MIT LFEE 2005-002 WP, September 2005.

[13] "PSIG" is defined as pressure in units of pounds per square inch gauge. Atmospheric pressure equals 14.7 psig. Therefore, 400 psig is equivalent to 27 times atmospheric pressure. This pressure is required to increase the speed of the gasification chemical reactions.

14 Parsons Infrastructure and Technology Group, "Updated Cost and Performance Estimates for Fossil Fuel Power Plants with CO_2 Removal," Interim report prepared for EPRI and U.S. DOE, December 2002.

15 U.S. DOE, op. cit.

16 U.S. DOE, op. cit.

17 Parsons Infrastructure and Technology Group, op. cit.

18 Winkler, P., "Oxygen Technology for Combustion or Gasification Applications," Air Products presentation at Evolution of Combustion Technology to Support National Energy Needs, January 15, 2002.

19 Hydrogen from Coal, Mitretek Technical Paper MTR 2002-31. July 2002.

20 O'Brien, J., "An Analysis Of The Institutional Challenges To Commercialization And Deployment Of IGCC Technology in the U.S. Electric Industry: Recommended Policy, Regulatory, Executive and Legislative Initiatives," Prepared for NETL and National Association of Regulatory Utility Commissioners, March 2004.

21 Aiken, R., et.al, "Coal-Based Integrated Gasification Combined Cycle: Market Penetration Strategies and Recommendations, Prepared For and Supported By: Department of Energy (DOE) - National Energy Technology Laboratory (NETL) and Gasification Technologies Council (GTC).

22 Williams, R.H., "IGCC: Next Steps on Path to Gasification-Based Energy From Coal,", Princeton Environmental Institute, Princeton University, November 2004.

23 Integrated Gasification Combined Cycle and Pulverized Coal Power Plants, Working Draft, Nexant, August 17, 2005.

24 EPRI, Economic Evaluation of Existing Plants, 2004.

25 Trapp, W. and N. Moock, "Coal Gasification: What Are You Afraid Of?" PowerGen International Conference, Orlando, Florida.

26 Higman, C., "Reliability of IGCC Power Plants," Gasification Technologies Conference, San Francisco, October 2005.

27 Gray, David, Salerno, Salvatore, and Tomlinson, Glen, "Current and Future IGCC Technologies: Bituminous Coal to Power," Mitretek Technical Report, August 2004.

28 Nexant, Inc. , "Environmental Footprints and Costs of Coal-Based-Integrated Gasification Combined Cycle and Pulverized Coal Technologies," Final Report, prepared for the U.S. EPA. July 2006, http://www.epa.gov/airmarkets/articles/control.html.

29 NETL Carbon Sequestration Newsletter, Jan – March 2005, http://www.netl.doe.gov/sequestration.

30 National Energy Technology Laboratory - Carbon Sequestration Program Vision and Goals, http://www.netl.doe.gov/ coal/Carbon%20Sequestration/index.html.

31 Keeler, C., "Operating Experience at the Wabash River Repowering Project – 2001 Project Update," Presentation at the 2001 Gasification Technologies Conference, San Francisco, CA, October 2001.

32 Holt, N., "Coal-based IGCC Plants – Recent Operating Experience and Lessons Learned," Presentation to Gasification technologies Conference, October 2004.

33 ibid.

34 Smeers, Y., "Coal Options - Evaluation of Coal-Based Power Generation in an Uncertain Context," OSTC - Global Change and Sustainable Development 1996-2000 Sub-Programme 2 "Scientific Support for Belgian Policy on Climate Change," Contracts CG/DD/231 and CG/DD/232, September 2001.

35 Carnot Online, Case study: "Conversion of Solid-Fuels, Puertollano IGCC Power Plant," http://enpov.aeat.com/carnot/case_studies/pdf/Puertollano.pdf, ia.

36 Jenkins, S., "Real-World Experience with IGCC –Lessons Learned in Design, Permitting, Operations and Maintenance," URS Corporation Presentation, August 2005.

[37] Holt, N., op. cit.

[38] Wolters, C., "Operating Experience at the Willem-Alexander Centrale," NUON technical presentation, http://www.gasification.org/Docs/2003_Papers/19WOLT.pdf, October 2003.

[39] Hanneman, F., U. Schiffers, and J. Karg, "V.92 Buggenum Experience and Improved Concepts for Syngas Applications," Presentation to Gasification Technologies Conference, http://www.gasification.org/Docs/2002_Papers/GTC02013.pdf, October 2002.

[40] Ratafia-Brown, J., et.al, op. cit.

[41] Clayton, S., G. Stiegel, and J. Wimer, "Gasification Markets and Technologies – Present and Future, An Industry Perspective," U.S. Department of Energy, Gasification Technologies Product Team, July 2002.

[42] Ramezan, M., et al., "Potential for NGCC Plant Conversion to a Coal-Based IGCC Plant – A Preliminary Study," SAIC report prepared for NETL Gasification Technologies Program, May 2004.

[43] Williams, R.H., op. cit.

[44] "MWe" is the abbreviation for Megawatt (electric) and is used as the unit of electrical power produced by a generator.

[45] "Clean Coal Technology – Tampa Electric Integrated Gasification Combined-Cycle Project – An Update", DOE Topical Report Number 19, July 2000.

[46] U.S. DOE Office of Fossil Energy, "Practical Experience Gained During the First Twenty Years of Operation of the Great Plains Gasification Plant and Implications for Future Projects," April 2006.

[47] Parsons Technology and Infrastructure Group for U.S. DOE, "The Cost of Mercury Removal in an IGCC Plant," September 2002.

[48] Parkes, J., "CoalFleet for Tomorrow – An Industry Initiative to Deploy Advanced Coal Power Plants," Gasification Technologies Conference 2005, October 11, 2005.

[49] NETL Sequestration Web site; http://www.netl.doe.gov/coal/Carbon%20Sequestration/index.html

[50] ibid.