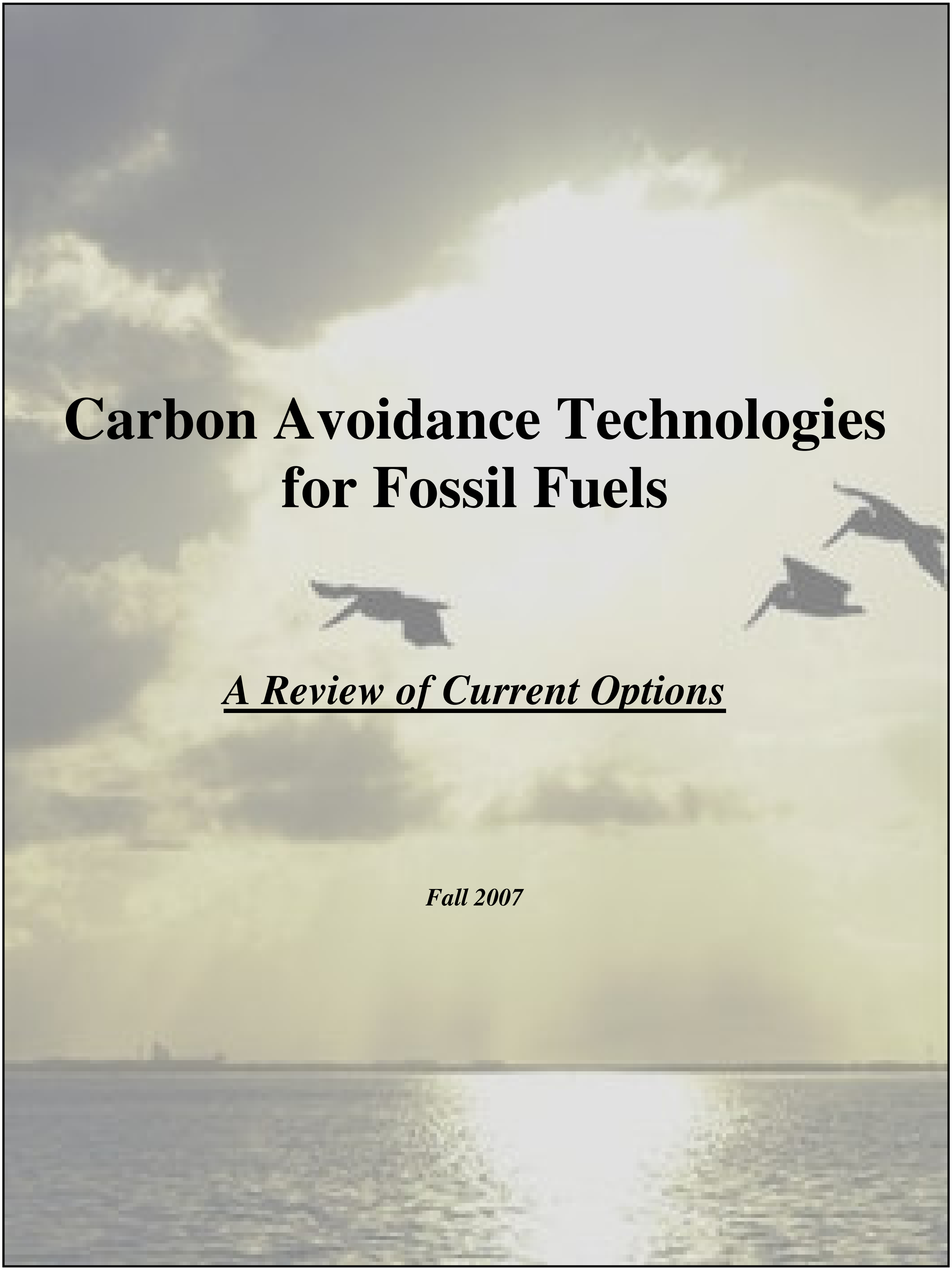

Carbon Avoidance Technologies for Fossil Fuels

A Review of Current Options

Fall 2007

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A Review of Current Options

EXECUTIVE SUMMARY

In this paper our objective is to review several options for carbon mitigation and avoidance. Advanced fossil fuel combustion technologies may be separated into two groups:

- Carbon Mitigation Technologies (CMT's), and
- Carbon Avoidance Technologies (CAT's).

Carbon mitigation technologies include the technologies for carbon-dioxide (CO_2) capture, storage, transport and sequestering. Alternatively, carbon avoidance technologies are a group of technologies which seek to avoid burning carbon, rather than mitigating the effects of CO_2 after the fact. CMT's and CAT's are fundamentally different philosophical and technological approaches to addressing the same question, i.e.

- What should we do with the carbon contained in fossil fuels?

Plasma Pyrolysis of Coals – A promising new carbon avoidance technology (CAT) is the high-temperature plasma pyrolysis of coals. The plasma pyrolysis process generates a unique, plasma-coal synthetic gas (PCS syngas) that is naturally low-carbon. CO_2 emissions resulting from the open-cycle burning of this PCS syngas are lower than those associated with conventional technologies, including current natural gas-fired power plant designs. It appears possible that this unique high-hydrogen, low-carbon PCS syngas may be used to generate electric power more economically, with a lower capital investment, with greater availability, and at higher efficiency, than is possible with other CO_2 management technologies.

The Bottom Line: This new plasma-based technology has the potential to produce a lower overall cost of electric power, while also dramatically reducing CO_2 production and CO_2 emissions for a low-carbon future.

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Carbon Avoidance Technologies for Fossil Fuels

A Review of Current Options

BACKGROUND

We will first divide all newer electric power generating technologies into two broad categories:

- advanced fossil fuel-related technologies, e.g., CCU, IGCC, SOFC, plasma technologies, and
- non-fossil and alternate technologies, e.g., hydro and nuclear, wind, solar, geothermal, DSM.

Within the advanced fossil fuel-related technologies we have identified two sub-groups:

- Carbon Mitigation Technologies (CMT's), and
- Carbon Avoidance Technologies (CAT's).

In this paper our objective is to review several options for carbon management, while highlighting a new carbon avoidance technology called plasma pyrolysis.

Carbon mitigation technologies or CMT's include the technologies for carbon-dioxide (CO_2) capture, storage, transport and sequestering.[1] Alternatively, carbon avoidance technologies or CAT's are a group of technologies which seek to *avoid* carbon, rather than mitigating the effects of CO_2. But why do we seek to manage carbon today?

Burning Fossil Fuels - Many believe that the burning of fossil fuels by humankind has contributed materially to global warming.[2] Life on Earth is part of the natural carbon cycle.[3] Plants have for millions of years combined chlorophyll, water and sunlight to convert atmospheric carbon-dioxide (CO_2) into hydrocarbons and, along with geologic processes, have sequestered carbon in carbon-bearing deposits, e.g., coal seams. The burning of these carbon-rich deposits by humankind has in effect reversed in only a few hundred years the natural sequestrating of billions of tons of carbon that had occurred over hundreds of millions of years, materially altering the natural carbon cycle and the global environment.

The re-release of large quantities of sequestered carbon, including its release from coal into the atmosphere as CO_2, has perturbed the global environment. This human intervention into the natural carbon cycle may be turning the Earth's environmental clock back to a time and to conditions that predate and could be hostile to the development of humankind.[4] CO_2 is one of a group of potent

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[1] Carbon Sequestering defined - See http://en.wikipedia.org/wiki/Carbon_sequestration

[2] Global warming defined – See http://en.wikipedia.org/wiki/Global_warming

[3] Carbon cycle defined – See http://en.wikipedia.org/wiki/Carbon_cycle

[4] U.S. DOE EIA, Carbon Coefficients and Assumptions, p. 4, Direct Global Warming Potential, p. 20 at http://www.eia.doe.gov/pub/oiaf/1605/cdrom/pdf/gg-app-tables.pdf

greenhouse gases.[5] Their release has contributed to recent changes - and is projected to cause future undesirable changes - in global temperature, weather and the carbon cycle; in other words the Greenhouse Effect.[6] To limit, and even reverse the effects of greenhouse gases on the planet, it is highly desirable for humankind to reduce, limit and perhaps even at some point eliminate future releases of CO_2. That is, to practice *carbon avoidance*.

That is why this paper seeks to promote carbon management, including methods for hydrogen extraction from hydrogen-bearing materials which minimize CO_2 release. These are technologies which minimize the release of carbon already sequestered in such fossil fuel deposits.

It is believed that carbon mitigation, i.e., the burning and post-burn capture, storage, transport and re-sequestering of CO_2, is less desirable. It is likely to be more risky and less economical when all the external environmental risks and consequences are considered. It may also prove to be technically, geologically, socially and/or politically infeasible for a wide range of applications.

Thusly, there exists the need for a source of readily available, environmentally friendly fuel, perhaps in the form of hydrogen, that both burns cleanly and minimizes the creation and release of CO_2 during its production cycle, and for apparatus and processes for the manufacture of such fuel from hydrogen-bearing carbonaceous and other feed materials.

The Cost of Carbon - The impact of CO_2 needs to be considered in any economic analysis, either:

- *as an indirect cost* - when the current unaccounted for environmental costs of CO_2 emissions are considered as externalities,[7] i.e., the Greenhouse Effect and its negative impact on the global economy, or

- *as a direct cost* - under a carbon tax, a carbon cap or alternatively when the cost of CO_2 capture, storage, transport and sequestering is considered.

Both of these considerations would appear to militate against the open-cycle burning of high-carbon fuels, such as coal and oil.

The Hydrogen Economy – By inference, if we are to avoid burning the carbon contained in fossil fuels, then we must burn what is left, the hydrogen. In recognition of the side affects of carbon release, President Bush has called for the development of a hydrogen economy.[8] The hydrogen economy envisioned is one in which energy is stored, transported and used as hydrogen gas (H_2). However, various hydrogen economy scenarios can be envisioned using hydrogen in a number of ways.

A common feature of these scenarios is using hydrogen as an energy *carrier*. That is, for the hydrogen economies envisioned, hydrogen acts as an energy storage medium, and is not a primary energy

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[5] Greenhouse gases defined – See http://en.wikipedia.org/wiki/Greenhouse_gas
[6] The Greenhouse Effect defined - See http://en.wikipedia.org/wiki/Greenhouse_effect
[7] Externalities defined – See http://en.wikipedia.org/wiki/Externality
[8] Hydrogen Economy defined – See http://en.wikipedia.org/wiki/Hydrogen%5Feconomy

source. Therefore, to achieve the vision of a hydrogen economy, there is a pressing need to find sources of hydrogen that do not also result in the release of carbon, CO or CO_2 into the environment.[9]

Proponents of a hydrogen economy suggest that hydrogen is an environmentally cleaner source of energy for end-users, particularly in transportation applications, without release of pollutants (such as greenhouse gasses) at the point of end-use. However, the potential advantages of the hydrogen economy could be lost to society and the environment unless hydrogen can be produced without (or at least with a minimum of) the systemic production and release of CO_2 or the need for CO_2 capture, storage, transport and sequestrating.

So, the use of hydrogen produced with energy derived from the burning of fossil fuels is problematic, unless and perhaps even if CO_2 capture, storage, transport and sequestering are utilized at the site of hydrogen production. To minimize the impact of the hydrogen economy on the environment, alternative safe, clean and environmentally acceptable primary sources of hydrogen, and processes for extracting that hydrogen from those resources, must be developed and employed.

DIFFERENT PHILOSOPHIES, DIFFERENT TECHNOLOGIES

CMT's vs. CAT's – CMT's and CAT's are fundamentally different philosophical and technological approaches to addressing the same question, i.e.,

- What should we do with the carbon contained in fossil fuels?

CMT's assume the continued burning of carbon and production of CO_2. CMT's then seek to mitigate the combustion process by attempting to isolate a portion of the CO_2 produced from the environment, e.g., through deep well sequestering. No CMT yet captures *all* CO_2 from the combustion stream, so some amount is still released into the environment. Current CMT's release the equivalent of about one-quarter of the CO_2 contained in combustion gases into the atmosphere, sequestering about three-quarters of the CO_2 relative to current open-cycle burners (when the effects of efficiency and availability are considered).[10] So, bottom line, CMT's attempt to re-engineer a way through the CO_2 emissions problem, rather than finding a way to avoid it.

Alternatively, CAT's attempt to redesign key process steps as a way *around* the CO_2 problem, rather than attempting remediate CO_2 after combustion. CAT's seek to substantially avoid the oxidation of carbon and the production of CO_2 in the first place. Current CAT's do not completely avoid the release

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[9] Nevertheless, controversy over the usefulness of a hydrogen economy has been confused by issues of energy sourcing, including fossil fuel use, greenhouse warming, and sustainable energy generation. These are separate issues, although the hydrogen economy impacts them all.

[10] "Analysis shows that capturing CO_2 from power plant flue gas and sequestering it in underground storage such as a gas field, oil field, or aquifer can reduce the GWP (global warming potential) of electricity production but the penalty is an increase in fossil energy consumption. First, capturing and compressing flue gas CO_2 results in a large decrease in the power plant efficiency. Secondly, maintaining a designated plant capacity means that additional electricity production must come from another source, most likely fossil. Therefore, although there is a substantial decrease in the GWP, sequestering 90% of the CO_2 from the power plant flue gas does not equal a 90% reduction in the GWP per kWh of electricity produced." See www.netl.doe.gov/publications/proceedings/01/carbon_seq/p4.pdf Capturing and Sequestering CO2 from a Coal-fired Power Plant – Assessing the Net Energy and Greenhouse Gas Emissions, Pamela L. Spath and Margaret K. Mann, National Renewable Energy Laboratory, 1617 Cole Boulevard, Golden, CO 80401.

of CO_2, but do limit it to one-quarter or less of the amount per kilowatt-hour (kWh) released by current coal-fired generation.

Carbon as a By-Product - It is an objective of this paper to discuss advanced technologies which produce "green hydrogen" and electricity from "black carbon" fossil fuel resources. The perspective of this paper is that the carbon in any fuel is an unwanted *by-product*. The negative impact of CO_2 on the environment renders it a by-product.

Plasma Pyrolysis – In the plasma pyrolysis process envisioned here carbon, substantially contained in the process by-products, will be re-sequestered in *unburned* solid form to minimize CO_2 production and release to the environment. For example, this may be accomplished by returning much of the processed unburned carbon in coal to the underground seam from whence it came, perhaps in a vitreous slag form.[11] (Some processes are *non-pyrolytic* and err by introducing oxygen, air and/or water to covert all the carbon into CO and CO_2, and then require its removal from the syngas and/or combustion stream.[12])

Open-Cycle vs. Closed-Cycle – All open-cycle fossil-fueled generator designs emit CO_2. The combustion gases are released to the environment untreated for CO_2. Most fossil-fired power plants operating today are of the open-cycle design. They simply dump the raw combustion gases and the contained CO_2 into the surrounding atmosphere where it contributes to the Greenhouse Effect. A closed-cycle design seeks to process the combustion gases for CO_2 and thereby attempts to remove a significant fraction of that CO_2. The remainder of the CO_2 is discharged into the atmosphere as it would be discharged in an open-cycle design. The term closed-cycle is perhaps a little misleading, as current closed-cycle designs only trap the equivalent of about three-quarters of the CO_2, allowing the substantial remainder to be emitted to the atmosphere as in an open-cycle design.

We will next review several examples of each and discuss some of their pros and cons.

Example CMT's

Closed-Cycle Conventional Steam – CO_2 capture, storage, transport and sequestering technologies may be appended to the current designs for coal-fired steam generating power plants. Unfortunately, these CMT's dramatically increase the capital and operating cost and reduce the operating efficiency and reliability of all current power plant designs.

Closed-Cycle IGCC – One technology which seeks to replace the current open-cycle coal burning conventional steam power plant is the close-cycle integrated-gasification combined-cycle (IGCC) with CO_2 capture, storage, transport and sequestering. These technologies will be discussed further below.

Much of the information on the open- and close-cycle conventional and IGCC technologies contained here was taken from two recent papers, including:

- a presentation by Jared P. Ciferno, National Energy Technology Laboratory (NETL), entitled "CO_2 Capture: Comparison of Cost & Performance of Gasification and Combustion-based

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[11] Vitreous defined – See http://en.wikipedia.org/wiki/Vitreous
[12] See hydrogen.energy.gov/pdfs/review06/pdp_10_lynch.pdf

Plants," presented to the *Workshop on Gasification Technologies*, Denver, Colorado, March 14, 2007,[13] and

- a NETL update entitled, "Cost and Performance Baseline for Fossil Energy Plants," DOE/NETL-2007/1281, Volume 1: Bituminous Coal and Natural Gas to Electricity, Final Report, Revision 1, August 2007.[14]

Hereinafter, we will refer to these two substantial documents collectively as "the NETL papers."

Example CAT's

Natural Gas

The Methane Advantage - Natural gas is largely composed of methane. Methane is made up of a single central carbon atom surrounded by four hydrogen atoms each connected to it by a single bond. Its chemical formula is CH_4. Methane has a naturally high hydrogen-to-carbon ratio, i.e., 4:1, and so could perhaps be an eligible candidate for open-cycle carbon avoidance (fuel cost aside for the moment), given that there are fewer moles of carbon burned per mole of hydrogen burned than in any other naturally occurring fossil fuel.

Two Methane CAT's – Two natural-gas based carbon avoidance technologies, both involving the separation of hydrogen from methane, have been identified by our literature search. The production of hydrogen in a cost-effective manner while minimizing environmental impacts is a major challenge. One possibility involves the extraction of hydrogen by the thermal decomposition of natural gas, with carbon co-produced as a by-product.

1. **Plasma Pyrolysis of Methane to Hydrogen and Carbon Black -** The plasma-driven thermal decomposition of methane, yielding hydrogen and solid-phase carbon, has been suggested as an environmentally friendly alternative to conventional methods of producing hydrogen from natural gas. The advantage of the process is that hydrogen is obtained directly from methane without producing CO_2 as a byproduct.[15]

2. **Using a Concentrating Solar Reactor to Produce Hydrogen and Carbon Black via Thermal Decomposition of Natural Gas -** A system using a solar reactor to produce hydrogen on-site for fueling stations has been examined for its technical and economic feasibility. Integrated energy and material balance calculations were made to determine the amount of hydrogen that could be produced from a given reactor size and heliostat field area.[16] This technology might also be useful for power generation.

While these CAT's are relatively simple technologies, they must work within the context of the relatively high cost of natural gas as a feedstock for hydrogen production. They are provided here for contrast and comparison with the process for the plasma pyrolysis of coal.[17]

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[13] See www.gasification.org/Docs/Workshops/2007/Denver/02%20Ciferno.pdf
[14] See http://www.netl.doe.gov/energy-analyses/baseline_studies.html
[15] See http://pubs.acs.org/cgi-bin/abstract.cgi/iecred/2002/41/i06/abs/ie010722e.html
[16] See http://scitation.aip.org/getabs/servlet/GetabsServlet?prog=normal&id=JSEEDO000125000002000159000001&idtype=cvips&gifs=yes
[17] No substantial CAT's relating to oil came to light in our literature search.

Coal

Plasma Pyrolysis of Coal – One of the few carbon avoidance technologies (CAT's) which might be referred to as a near-clean coal technology is the plasma pyrolysis of coal. Briefly, powdered coal is introduced into a high-temperature reactor and exposed to a neutral, oxygen-free plasma. This plasma pyrolysis technology does *not* introduce air, water or oxygen into the reactor, as an IGCC would. All thermal and chemical reactions within the plasma reactor occur without introduced oxygen. The high temperature plasma first volatizes the oils and tars in the powdered coal and then thermally decomposes them into their constituents, liberating substantial hydrogen into the gas process stream. A unique, high-hydrogen, low-carbon manufactured gas, sometimes referred to as a plasma-coal synthetic fuel gas or PCS syngas, is thereby formed.

The resulting PCS syngas is substantially composed of hydrogen, but may also contain small amounts of carbon-monoxide (CO). The molar hydrogen-to-carbon ratio is typically more than 10:1. Open cycle burning of this low-carbon PCS syngas, say in a combustion turbine associated with a CCU, releases less CO_2 per kilowatt-hour generated than the open-cycle burning of natural gas or using an IGCC design. It is as effective at reducing CO_2 emissions as many of the CO_2 management systems in operation or available today, but without the high cost of processing the syngas or combustion gases for CO_2 capture, storage, transport and sequestering.

Coal as a Source for Hydrogen

Purity – By mass percent, coal consists substantially of carbon, but this is usually mixed with various other chemicals and impurities, including hydrocarbons (oils and tars), water and mineral matter, such as sand and clay. The relative amount of these latter impurities affects the usefulness of the coal as a fuel in an open-cycle furnace. Traditionally, the quality of coal used for open-cycle burning has been determined by its rank and grade. Coal purity has been ranked in an ascending order of its carbon content (going from lowest to highest):

Lignite → sub-bituminous coal → bituminous coal → anthracite.

Chemical Composition – The chemical composition of coal is defined in terms of its proximate and ultimate (elemental) analyses. The parameters of proximate analysis are moisture, volatile matter, ash, and fixed carbon. Elemental or ultimate analysis encompasses the quantitative determination of carbon, hydrogen, nitrogen, sulfur and oxygen within the coal.

Hereinafter, we will use the same example coal referenced in the NETL papers[18] employing that particular coal for our purposes here. However, for the plasma pyrolysis CAT's, we will assume a well-dried version of this example pulverized coal.[19] This provides us with an underlying elemental consistency in the fuel costs portrayed with the different technologies reviewed here.

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[18] See www.gasification.org/Docs/Workshops/2007/Denver/02%20Ciferno.pdf and http://www.netl.doe.gov/energy-analyses/baseline_studies.html

[19] Dried example coal elemental analysis (in mass %):

Dried Illinois #6

Analysis of example coal	wt. %
Carbon (C)	70.9%
Hydrogen (H)	5.0%
Nitrogen (N)	1.4%
Sulfur (S)	2.8%
Oxygen (O)	7.7%
Ash	11.1%
Moisture (H2O)	1.1%
Total	100.0%

Dulong Formula - The total calorific value Q_T of a coal is the total heat liberated by its *complete* combustion with oxygen. Q_T is a complex function of the elemental composition of the coal. Q_T can be determined experimentally using calorimeters.

However, Dulong suggests using the following formula for Q_T -- when oxygen in the coal is less than 10%, as measured by mass percent:[20]

$$Q_T = 337C + 1{,}442(H - O/8) + 93S$$

where C is the mass percent of carbon, H is the mass percent of hydrogen, O is the mass percent of oxygen, and S is the mass percent of sulfur in the coal.

Plasma Pyrolysis of Coals

Hydrogen from Dry Coal - Modifying Dulong's formula to remove the calorific contribution of carbon, oxygen and sulfur, we get the following approximate hydrogen-only calorific content (Q_H):[21]

$$Q_H \sim 1{,}442 \bullet H$$

Taking the ratio of Q_H to Q_T yields the approximate percentage of total available energy in dry coal that may be derived from burning extracted hydrogen.

$$\boxed{\begin{aligned} Q_H / Q_T &\sim 1{,}442 \bullet H \,/\, [337C + 1{,}442(H - O/8) + 93S] \\ &\sim \frac{73}{303} \\ &\sim \mathbf{24\%} \quad \text{or} \quad \sim \mathbf{3{,}150} \text{ Btu/lb.} \end{aligned}}$$

So, Q_H is on the order of 24% • Q_T. However, in all fairness to Dulong, this result is of course only an approximation of the value for hydrogen energy derived from any coal using plasma pyrolysis.

Hydrogen plus a Little Carbon – All coal contains some bound-up oxygen, e.g., 7.7% by mass percent. So, no process involving coal can be completely oxygen free. We recognize that heat from the plasma will liberate oxygen and drive a small fraction of the carbon (C^*) in the example coal to react with that oxygen.[22] It will first form carbon-monoxide (CO) in the syngas, and then later CO_2 when that syngas is burned. So, we may now rewrite the calorific content of this high hydrogen, low carbon syngas (Q_{H+C^*}) as:

$$Q_{H+C^*} \sim 337 \bullet C^* + 1{,}442 \bullet (H - O/8)$$

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[20] A useful formula to check the measurement of specific energy is the Dulong formula, which calculates specific energy from the ultimate analysis. The calculated values are usually within about 2% of measured values for the rank of bituminous coal and above. With these constants, Q is given in kilojoules per kilogram. See http://en.wikipedia.org/wiki/Energy_value_of_coal .

[21] The disaggregation of Dulong's formula is used here as a teaching tool and for sake of simplicity. It provides approximate values for hydrogen energy production. However, a more rigorous study would perform a molar enthalpy analysis of using high temperature plasma pyrolysis of feed coal to make manufactured syngas. See appendices.

[22] The C-O bond and reaction is preferred to the S-O and O-H bonds and reactions, so for our purposes here and to simplify the analysis we assume that all the contained oxygen in the coal reacts with carbon, but not with the hydrogen or sulfur. At this point in the paper, we also assume dry coal with no entrained water and air.

where C^* represents the mass percent associated with reacting a small amount of carbon with all the oxygen (O) bound up in the coal to form carbon-monoxide (CO). Because each carbon bond is more energetic than an oxygen-hydrogen (O-H) bond, formation of CO is preferred to the formation of water, and there is a small net energy gain associated with reacting this small amount of carbon (C^*) with the contained oxygen. Under plasma pyrolysis, we know that the only oxygen available to react is that which was originally bound up in and is now liberated from the coal, e.g., from breaking O-H bonds. So, the moles of carbon that are converted to CO equal the moles of oxygen liberated.[23]

Then Dulong's equation may be re-written as an approximation for Q_{H+C^*} as follows:

Calorific contribution of H+C^* in a low-carbon syngas:

$$Q_T = 337C + 1{,}442(H - O/8) + 93S$$

$$Q_{H+C^*} \sim 337 \bullet C^* + 1{,}442 \bullet (H - O/8)$$

$$Q_{H+C^*} \sim 337 \bullet \text{Awt}_\text{C} / \text{Awt}_\text{O} \bullet O + 1{,}442 \bullet (H - O/8)$$

$$\text{Awt}_C / \text{Awt}_O = \quad 0.75$$

$$\text{and } 337 \bullet \text{Awt}_C/\text{Awt}_O = 253$$

$$Q_{H+C^*} \sim 253 \bullet O + 1{,}442 \bullet H - 180.25 \bullet O$$

$$Q_{H+C^*} \sim 73 \bullet O + 1{,}442 \bullet H$$

We have estimated this adjustment for an example coal containing 7.7% bound oxygen by mass percent. The adjustment recognizes the reaction of this contained oxygen with a small amount of carbon (C^*) first to carbon-monoxide (CO) and then later to CO_2. The CO reaction is predominant under plasma pyrolysis at temperatures above 800°C.[24] The formation of CO_2 is assumed to occur later when this high-hydrogen, low-carbon synthetic gas (or syngas) substantially composed of hydrogen is reacted with oxygen contained in air, perhaps in a combustion turbine, a reciprocating internal combustion engine or a solid oxide fuel cell (SOFC).

The approximate fraction of total energy (Q_T) recovered from plasma pyrolysis of coal into this high-hydrogen, low-carbon syngas may then be expressed as:

Energy release from plasma pyrolysis of coal:

$$Q_{H+C^*} \sim 73 \bullet O + 1{,}442 \bullet H$$

$$Q_{H+C^*} \sim \quad 79$$

$$Q_{H+C^*} / Q_T \sim \quad 79 \quad / \quad 303 \quad = \quad \mathbf{26\%}$$

$$Q_T \quad = \quad 13{,}126 \text{ Btu/lb.}$$

$$Q_{H+C^*} \quad = \quad \mathbf{3{,}402} \text{ Btu/lb.}$$

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[23] However, a mole of oxygen and a mole of carbon are not of equal atomic weight (Awt) or molar mass, so an adjustment is needed to accommodate the mass percents used in Dulong's equation. We can make this adjustment by using the ratio of the two different atomic weights, thereby adjusting the oxygen mass percent used for Dulong's equation to compute the mass percent of carbon reacted with contained oxygen to form CO. This requires we multiply the oxygen mass percent by the relative atomic weight ratio of carbon to oxygen to infer C^*. That is, we may calculate C^* as the product of $\text{Awt}_C/\text{Awt}_O \bullet O$, i.e., by multiplying O by the ratio of Awt_C (12.011) divided by Awt_O (15.9994).

[24] "Above 800 °C, CO is the predominant product" see http://en.wikipedia.org/wiki/Carbon_monoxide

However, it is important to note that the chemical composition of this unique syngas -- formed from the plasma pyrolysis of coal -- differs materially from the syngas derived from other processes. Those other processes are designed to gasify *all* the carbon in the feed coal. Their syngas is much higher in carbon-monoxide. So, these other processes cannot be referred to as carbon avoidance technologies.

We have seen that a plasma process operating under pyrolysis will convert only a fraction (e.g., up to 9%) of the carbon in the feed coal to carbon-monoxide. Hydrogen predominates in this unique manufactured syngas and supplies most of the energy extracted from the coal in this way.[25]

The following table shows the hydrogen-to-carbon ratio for this high-hydrogen, low-carbon coal-based syngas and the energy released by its open-cycle burning, relative to Q_T.

Relative calorific contributions in low-carbon plasma syngas:

Calorific Quant.	~% / Q_T	Btu/lb.	Hydrogen-to-carbon ratio
For open cycle burning of coal:			
Q_T =	100%	13,126	1 : 1 mol_H/mol_C
For Plasma Pyrolysis Reacting of Coal:			
Q_H ~	24%	3,150	
Q_{C*} ~	2%	252	
Q_{H+C*} / Q_T ~	26%	3,402	12:1 mol_H/mol_C

Taking the ratio of Q_{H+C*} to Q_T yields the approximate percentage of total energy that may be derived from the example coal by extracting this high-hydrogen, low-carbon manufactured gas. In this case, approximately 26% out of the 13,126 Btu/lb.[26] or about 3,402 Btu/lb., would be captured by this high-temperature plasma pyrolysis process.[27] Also note that the hydrogen-to-carbon ratio[28] of this high-hydrogen, low-carbon syngas is on the order of 12:1. This is 3-times better than the hydrogen-carbon ratio achievable from the open-cycle burning of natural gas (4:1). For this example coal and the resulting syngas, about 93% of the syngas energy comes from hydrogen and 7% from carbon-monoxide. As a point of reference, we note that during the open-cycle burning of natural gas (the cleanest naturally occurring fossil fuel) about 59% of the energy released comes from hydrogen, while the remaining 41% comes from burning carbon and producing CO_2.

Example Wet Coal – The preceding example assumed thoroughly dried powdered coal, with no entrained air or water. However, more often than not there is water and air trapped in the feed coal. Modifying this dry coal assumption to account for contained moisture has an impact on the resulting manufactured gas or syngas, its calorific content and hydrogen-to-carbon ratio. Both water and air can contribute oxygen to the process and produce additional CO in the resulting syngas. CO adds carbon

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[25] The presence of entrained water and air in the feed coal would change the results somewhat depending upon the amounts entrained. Both water and air would release additional oxygen into the plasma which would also react with small additional amounts of carbon, and in the case of entrained water, would add some hydrogen. It is likely that the presence of water *and* air in the feed coal would increase the gross calorific content of the resulting manufactured gas and increase the energy percentage to about 30% and the per unit toward 4,000 Btu/lb, before adjusting for plasma energy inputs.

[26] Available from the open-cycle burning of this example coal.

[27] This analysis does not yet account for plasma electrical energy inputs or any energy recovered from the high temperature plasma mix in the combined cycle unit.

[28] i.e., the ratio of the moles of hydrogen to the moles of carbon reacted or mol_H/mol_C.

and energy potential to the syngas, but also increases the amount of CO_2 generated when this syngas is burned.

Let us assume that the dried powdered feed coal still contains 1.1% residual water by mass percent (and for our present purposes no air). Then the calorific content of the syngas would be as follows:

Energy released from low-carbon plasma reacting of coal:
Q_{H+C*} ~ 73 • O + 1,442 • H
Q_{H+C*} ~ 80
Q_{H+C*} / Q_T ~ 80 / 300 = **27%**
Q_T = 13,126 Btu/lb.
Q_{H+C*} = **3,512** Btu/lb.

The Btu/lb. energy value increases about 3% from the additional carbon reacted with oxygen contained in the entrained water. Further, the energy contribution from hydrogen contained in the syngas increases (i.e., through the water shift reaction) and the hydrogen-to-carbon ratio increases, since water (H_2O) contains 2 hydrogen atoms for each oxygen atom reacted with carbon. However, overall CO_2 emissions would also increase for this wetter example coal. [29]

Relative calorific contributions in low-carbon plasma syngas:

Calorific Quant.	~% / Q_T	Btu/lb.	Hydrogen-to-carbon ratio
For open cycle burning of coal:			
Q_T =	100%	13,126	1 : 1 mol_H/mol_C
For Plasma Pyrolysis Reacting of Coal:			
Q_H ~	25%	3,282	
Q_{C*} ~	2%	231	
Q_{H+C*} / Q_T ~	27%	3,512	12.2:1 mol_H/mol_C

In either case, the manufactured gas produced by plasma pyrolysis of coal is a unique, high hydrogen, low-carbon synthetic gas or syngas substantially composed of hydrogen, but with a small amount of CO from reacting carbon with any bound and entrained oxygen.

A more detailed molar-energy analysis is contained in the attached appendices.

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[29] This calculation does not yet account for the plasma input energy required to volatize the feed coal and this amount of entrained water. That would normally affect the overall plant efficiency by somewhat reducing net electrical output. However, also note that any energy used to dissociate the moisture is partially recovered from the syngas when it is burned and the constituents are returned to water vapor and converted to CO_2. So, this plasma input heat (needed to dissociate the moisture in the coal) is recycled as the heat associated with formation of water vapor and CO_2 in the combined cycle unit combustion products, and this heat energy is converted back to electricity, recycling a portion of this starting plasma energy, subject of course to the thermodynamic efficiency of the system.

HYDROGEN AND CARBON DIOXIDE

CMT's & CAT's - A Process Comparison

Two CMT's

Closed-Cycle Pulverized Coal Subcritical Steam – Attaching CO_2 capture, storage, transport and sequestering infrastructure to existing power plants or designs is one way to limit CO_2 emissions. However, the added capital cost of these appendages and the estimated efficiency and availability loss of 8-12% cries out for some form of compensating, offsetting efficiency gain. Combined cycle technology might be an answer.

Closed-Cycle IGCC – One CMT -- which is somewhat more efficient and seeks to replace the current generation of open-cycle coal burning power plants -- is the close-cycle integrated-gasification combined-cycle (IGCC) design, with CO_2 capture, storage, transport and sequestering. Briefly, this technology first gasifies the coal to produce substantial quantities of carbon monoxide (CO) and a lesser quantity of hydrogen gas (H_2). It may use a water-shift reaction to convert CO to CO_2. The CO_2 is then scrubbed from the syngas. The processed syngas is then higher in hydrogen and lower in CO and CO_2. However, substantial CO_2 is produced from the syngas as a by-product, which must then be compressed, transported by pipeline and sequestered. The IGCC burns the processed synthetic gas in a combustion turbine (CT) and then employs a steam turbine (ST) bottoming cycle as part of its combined-cycle unit (CCU) design.

This IGCC technology enjoys several advantages, and yet suffers from several key disadvantages. The CCU portion can achieve efficiencies well above the 37% or so achievable with the current generation of conventional open-cycle coal-fired steam generators. However, in order to gasify the coal and sequester CO_2, this closed-cycle IGCC approach must add a gasifier and append two chemical factories to the CCU power plant foot print. These two expensive appendages are:

- an oxygen plant appended to the front-end -- to eliminate atmospheric nitrogen from the synthetic gas and thereby facilitate CO_2 capture (by reducing the total volume of gas to be treated, compressed, transported and sequestered), and

- CO_2 management infrastructure -- for CO_2 capture, storage, transportation and sequestering to dispose of a portion of the CO_2 contained in the syngas or gaseous combustion by-products.

Unfortunately, both of these appendages add substantially to the complexity and capital cost, and reduce the operating efficiency (e.g., by 8-12%) and availability (e.g., 10%) for any power plant design. Note that the gasifier/reactor is a component the ICGG design shares with the plasma pyrolysis designs mentioned below.

Cost of Sequestering – Others have examined the cost of sequestering CO_2 and a possible carbon tax, commenting:

- "Using present technology, estimates of sequestration costs are in the range of \$100 to \$300/ton of carbon …"[30]

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[30] See http://www.fossil.energy.gov/sequestration/overview.html

- "We found that a typical shadow price on carbon (a carbon fee or tax, for example) to prevent the concentrations of CO_2 from more than doubling was around $200 per ton Carbon emitted."[31]

From these statements and the results of our literature search we conclude two things:

1. CO_2 capture, storage, transport and sequestering are young, still expensive technologies, which will require some number of years to fully mature, and

2. the cost of emitting carbon could increase in the not too distant future, impacting the relative economic advantages and disadvantages of the various CMT's and CAT's as technological solutions to the CO_2 problem.

Both of these learnings will be incorporated into the analyses presented hereinafter. We have selected a lower range base case carbon tax assumption for carbon emitted in CO_2. We will also assume proxy costs for pipeline transport and deep well sequestering. The sensitivity of the results to changes in these assumptions will be tested later in this paper.

Two CAT's

Plasma Pyrolysis of Methane to Hydrogen and Carbon Black - The plasma-driven high temperature thermal decomposition of methane produces a higher ratio of hydrogen per unit of feed material mass than most other processes.

The plasma pyrolysis of natural gas takes advantage of two key factors:

- the higher naturally-occurring hydrogen-to-carbon ratio of natural gas, and
- the inherent carbon-avoidance capabilities of oxygen-free plasma pyrolysis.

The resulting products are hydrogen gas liberated from the CH_4 and solid carbon black, a by-product. The fuel-related variable cost of hydrogen produced using this carbon-avoidance technology or CAT approach, is about $11.39 per million British Thermal Units (MMBtu's) of hydrogen burned. For discussion purposes here we have assumed a base case cost of $6.75 /MCF for natural gas delivered to the plasma pyrolysis reactor. See the summary table below.

Natural Gas	Chemical Formula …………………..		predominant species = CH_4	
	Molar Weights	Formula	Enthalpy	
	g/mol		*kJ/mol*	*kJ/g*
Carbon	12.011	C	(394)	(33)
Hydrogen	1.008	H	(143)	(142)
CH_4	16.043	CH_4	(966)	(60)
Fraction of Enthalpy released by burning contained ………..			hydrogen	59%
			carbon	41%
Delivered Cost of Natual Gas ……….	$6.75	/MCF	1.000	MMBtu/MCF
Cost of Hydrogen from Natural Gas ..	**$ 11.39**	/$MMBtu_{H2}$	0.592	MMBtu/MCF

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[31] See Statement of Stephen Schneider, Ph.D., Professor, Department of Biological Sciences, Stanford University, Stanford, California, Testimony Before the House Committee on Ways and Means, February 28, 2007 at http://waysandmeans.house.gov/hearings.asp?formmode=view&id=5564

Plasma Pyrolysis of Coal – The hydrogen locked up in the tars and oils in coal is another potential source of clean-burning hydrogen. The same plasma-driven high temperature thermal decomposition of coal into its constituents also produces substantial hydrogen gas.

However, hydrogen represents only about 1/4th of the energy contained in a ton of coal. Yet, as an offset, coal is relatively inexpensive and its price is less volatile when compared to the price behavior of natural gas.

The resulting fuel-related variable cost of energy for the hydrogen liberated from this plasma-based carbon avoidance technology, is about $6.80 per MMBtu's, some 101% of the cost of natural gas, and only 60% of the cost of natural gas-derived hydrogen calculated above. See the summary table below.[32]

An Example Dried (no moisture) Coal

	wt. %	g/mole	Enthalpy *kJ/mol*
Carbon (C)	71.7%	12.011	(394)
Hydrogen (H)	5.1%	1.0079	(143)

	Coal	Hydrogen	
Energy Content ………………………………	26.3	6.8	MMBtu/ton
	13,126	3,088	Btu/lb.
		~ 26%	

Cost of Coal …. $ 42.11 per ton = 2.1 ¢/lb.

Fuel-related Cost of Hydrogen from coal …………… **$6.80 /MMBtu**$_H$

Relative fuel cost of Hydrogen ………….. 101% of natural gas
60% of natural gas-sourced H

CO$_2$ Avoidance is Best! - The advantage of plasma-generated hydrogen gas in both cases is that it largely avoids the burning of carbon and minimizes the production, emission and/or capturing, storage, transport and sequestering of CO$_2$. The lower cost of manufactured hydrogen derived from coal makes this plasma pyrolysis process a more attractive option when compared with hydrogen from natural gas, while still achieving our low carbon objectives.

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[32] Note that the molar energy analysis above calculates a somewhat different hydrogen-only energy per unit of mass, i.e., 3,088 vs. 3,150 Btu/lb., for the same coal as compared with using the approximate values from Dulong's formula presented above. This is why we believe that use of Dulong's formula should be viewed as an approximate representation of the hydrogen-only energy available from plasma pyrolysis of coals used to produce a high-hydrogen, low-carbon syngas.

GENERATING ELECTRICITY

We will now examine in somewhat greater detail the relative cost of these various technologies, including the use of the plasma pyrolysis derived, high-hydrogen, low-carbon ($H+C^*$) PCS syngas to generate electricity. The cost of electricity is the sum of its fixed and variable components. Our assumptions and both components are examined below.

Current and Advanced Technologies Compared

The current open-cycle and advanced closed- and open-cycle fossil fuel technologies reviewed here include:

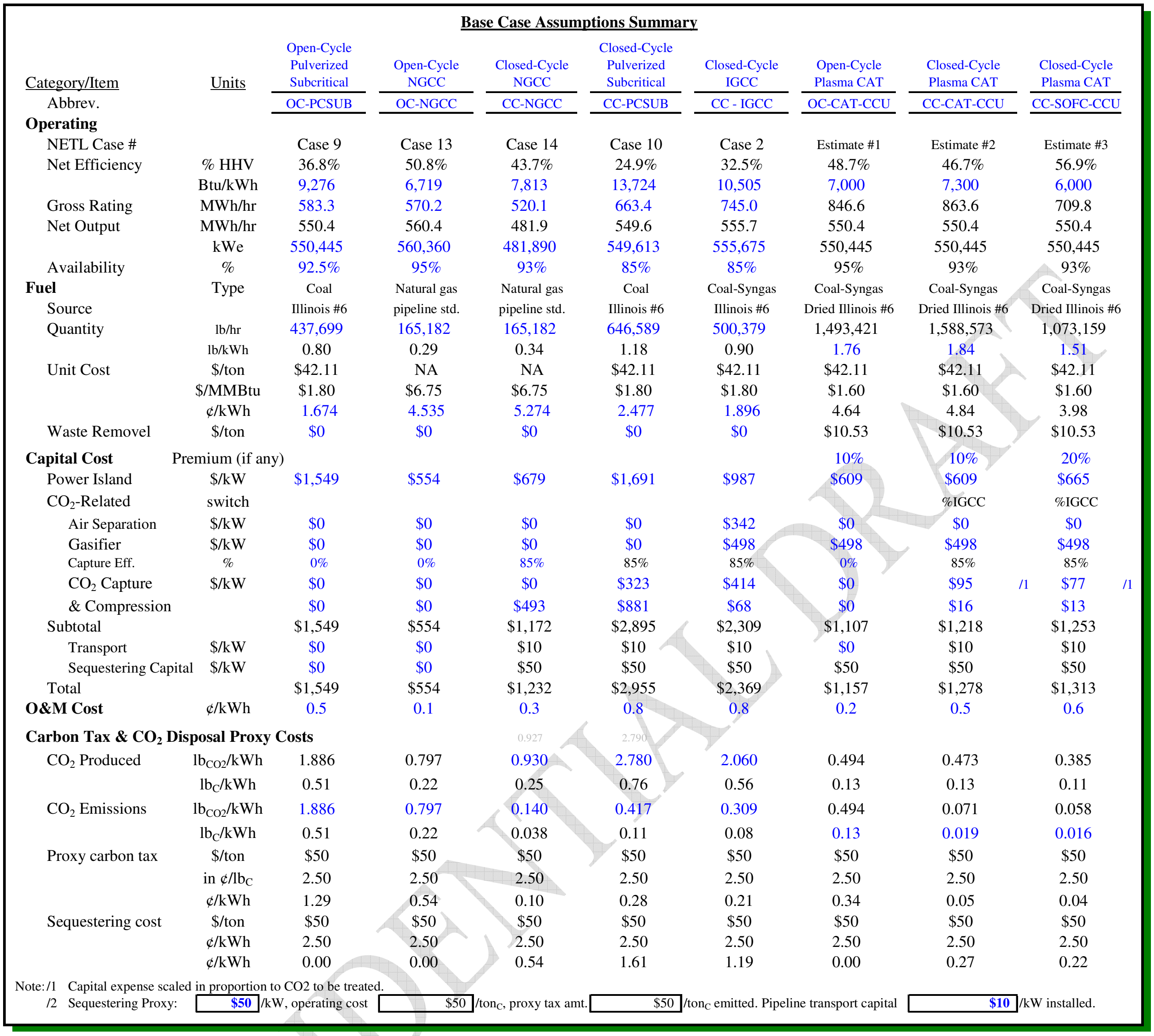
- A conventional open-cycle pulverized coal subcritical steam generator design (OC-PCSUB),
- A standard open-cycle natural gas-fueled combined cycle (OC-NGCC) design,
- A closed-cycle natural gas-fueled combined cycle (CC-NGCC) design,
- A closed-cycle pulverized coal subcritical (CC-PCSUB) steam generator with CO_2 capture,
- A closed-cycle coal-fueled integrated gasification combined cycle (CC - IGCC) with CO_2 capture,
- An open-cycle combined cycle unit burning the PCS syngas (the OC-CAT-CCU),
- A closed-cycle combined cycle unit burning the PCS syngas (the CC-CAT-CCU), and
- A closed-cycle combined cycle unit with solid oxide fuel cells (SOFC's) burning the PSC syngas (the CC-SOFC-CCU).

Assumptions

The assumptions used here and the resulting economics reflect to a considerable degree the uneven state of development and of our incomplete collective understanding of the various aspects of these newer technologies. Some of these newer technologies are nearing their pre-commercial state. A number are still in the RD&D (research, development and demonstration) phase of their product life-cycle. Most have yet to fully enter their mainstream commercial phase, or at best have relatively limited commercial scale experience.

For example, large scale capture and deep well sequestering of CO_2 from power plants is only now in the pre- and initial commercial-scale testing phase, even though the oil industry has had years of experience injecting CO_2 into oil and natural gas fields. At the other end of the spectrum, the use of SOFC's with a CCU design has only recently been suggested, and this technology awaits further research, development and demonstration testing in the laboratory.

Further, many costs are highly site dependent. Fuel transportation, construction costs and CO_2 pipeline transport are only a few of these site dependent costs. Finally, some costs fall into the "pending" category. The carbon tax is one such uncertain cost, as CO_2 is neither regulated nor taxed in the U.S. today at the federal level. A proxy carbon tax has been adopted until the issue is better resolved.



Base Case Assumptions Summary

Category/Item	Units	Open-Cycle Pulverized Subcritical	Open-Cycle NGCC	Closed-Cycle NGCC	Closed-Cycle Pulverized Subcritical	Closed-Cycle IGCC	Open-Cycle Plasma CAT	Closed-Cycle Plasma CAT	Closed-Cycle Plasma CAT
Abbrev.		OC-PCSUB	OC-NGCC	CC-NGCC	CC-PCSUB	CC - IGCC	OC-CAT-CCU	CC-CAT-CCU	CC-SOFC-CCU
Operating									
NETL Case #		Case 9	Case 13	Case 14	Case 10	Case 2	Estimate #1	Estimate #2	Estimate #3
Net Efficiency	% HHV	36.8%	50.8%	43.7%	24.9%	32.5%	48.7%	46.7%	56.9%
	Btu/kWh	9,276	6,719	7,813	13,724	10,505	7,000	7,300	6,000
Gross Rating	MWh/hr	583.3	570.2	520.1	663.4	745.0	846.6	863.6	709.8
Net Output	MWh/hr	550.4	560.4	481.9	549.6	555.7	550.4	550.4	550.4
	kWe	550,445	560,360	481,890	549,613	555,675	550,445	550,445	550,445
Availability	%	92.5%	95%	93%	85%	85%	95%	93%	93%
Fuel	Type	Coal	Natural gas	Natural gas	Coal	Coal-Syngas	Coal-Syngas	Coal-Syngas	Coal-Syngas
Source		Illinois #6	pipeline std.	pipeline std.	Illinois #6	Illinois #6	Dried Illinois #6	Dried Illinois #6	Dried Illinois #6
Quantity	lb/hr	437,699	165,182	165,182	646,589	500,379	1,493,421	1,588,573	1,073,159
	lb/kWh	0.80	0.29	0.34	1.18	0.90	1.76	1.84	1.51
Unit Cost	$/ton	$42.11	NA	NA	$42.11	$42.11	$42.11	$42.11	$42.11
	$/MMBtu	$1.80	$6.75	$6.75	$1.80	$1.80	$1.60	$1.60	$1.60
	¢/kWh	1.674	4.535	5.274	2.477	1.896	4.64	4.84	3.98
Waste Removel	$/ton	$0	$0	$0	$0	$0	$10.53	$10.53	$10.53
Capital Cost	Premium (if any)						10%	10%	20%
Power Island	$/kW	$1,549	$554	$679	$1,691	$987	$609	$609	$665
CO_2-Related	switch							%IGCC	%IGCC
Air Separation	$/kW	$0	$0	$0	$0	$342	$0	$0	$0
Gasifier	$/kW	$0	$0	$0	$0	$498	$498	$498	$498
Capture Eff.	%	0%	0%	85%	85%	85%	0%	85%	85%
CO_2 Capture	$/kW	$0	$0	$0	$323	$414	$0	$95 /1	$77 /1
& Compression		$0	$0	$493	$881	$68	$0	$16	$13
Subtotal		$1,549	$554	$1,172	$2,895	$2,309	$1,107	$1,218	$1,253
Transport	$/kW	$0	$0	$10	$10	$10	$0	$10	$10
Sequestering Capital	$/kW	$0	$0	$50	$50	$50	$50	$50	$50
Total		$1,549	$554	$1,232	$2,955	$2,369	$1,157	$1,278	$1,313
O&M Cost	¢/kWh	0.5	0.1	0.3	0.8	0.8	0.2	0.5	0.6
Carbon Tax & CO_2 Disposal Proxy Costs				0.927	2.790				
CO_2 Produced	lb_{CO2}/kWh	1.886	0.797	0.930	2.780	2.060	0.494	0.473	0.385
	lb_C/kWh	0.51	0.22	0.25	0.76	0.56	0.13	0.13	0.11
CO_2 Emissions	lb_{CO2}/kWh	1.886	0.797	0.140	0.417	0.309	0.494	0.071	0.058
	lb_C/kWh	0.51	0.22	0.038	0.11	0.08	0.13	0.019	0.016
Proxy carbon tax	$/ton	$50	$50	$50	$50	$50	$50	$50	$50
	in ¢/lb_C	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50
	¢/kWh	1.29	0.54	0.10	0.28	0.21	0.34	0.05	0.04
Sequestering cost	$/ton	$50	$50	$50	$50	$50	$50	$50	$50
	¢/kWh	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50
	¢/kWh	0.00	0.00	0.54	1.61	1.19	0.00	0.27	0.22

Note: /1 Capital expense scaled in proportion to CO2 to be treated.
/2 Sequestering Proxy: **$50** /kW, operating cost $50 /$ton_C$, proxy tax amt. $50 /$ton_C$ emitted. Pipeline transport capital **$10** /kW installed.

Differences from the NETL Papers – We have chosen to use somewhat different assumptions from those contained in the NETL papers in a couple of areas. A CO_2 capture efficiency ratio of 85% was adopted as being somewhat more typical of recent operating experience. A carbon tax proxy and separate added costs for pipeline and deep well sequestering field infrastructure and operations were assumed. We have also assumed dried powdered coal for CAT applications. Otherwise, where possible, the same fuel, cost, operating, efficiency and availability assumptions have been adopted here.

CAT Assumptions – The CAT assumptions have borrowed heavily from the NETL papers, as well. The CAT operating, efficiency and availability assumptions used are similar to the NETL values used for the NGCC. The CAT gasifier capital cost equals that used for the CC - IGCC. The CO_2 capture costs were based on the NETL papers, but were prorated downward linearly from CC - IGCC values, based on the relative amount of CO_2 to be processed. As noted, these are estimates, not final values. Finally, we have included a 25% CAT waste handling charge for transporting and re-sequestering the unburned by-product carbon-slag resulting from the plasma pyrolysis process.

Variable Power Cost

The variable costs are largely fuel and CO_2-related. Here we compare the variable cost of electricity produced using

- The NETL assumptions for the carbon mitigation technology (CMT) designs and costs[33] and
- Estimates for the cost of the plasma pyrolysis carbon avoidance technology (CAT) producing a high-hydrogen, low-carbon (*H+C**) PCS syngas.

Cost of Fuel – The cost of fuel is relatively straight forward, as compared with pricing the complexity of plant capital costs and the cost of CO_2 mitigation and emissions. Further, the cost of fuel is a major factor in determining the overall economics of electric power generation. The relatively low cost of coal as a fuel gives it economic advantages which may be used to offset some or most of its environmental disadvantages. Representative base case prices for natural gas and coal have been selected from the NETL papers, but other relative inter-fuel price levels were also examined to test the robustness of the results presented here.

The Impact of Carbon – Consider that an IGCC coal gasifier forms a high-carbon (CO+H) syngas to generate electricity. As a result, in its open-cycle form it also releases substantial CO_2 to the environment. In the closed-cycle form the IGCC requires an expensive pre-burn oxygen plant and costly infrastructure for CO_2 capture, storage, transport and sequestrating. However, whether these carbon-related costs are monetized in closed-cycle form or are incurred indirectly by the open-cycle variant (in the form of environmental damage and impacts on future generations), they are viewed here as material. These CO_2 impacts do exist and they are widely believed to be real and material, so they are priced out here. We will assume that carbon emissions are taxed (rather than capped and traded) and may incur the added costs for CO_2 capture, storage, transport and sequestering.

A Carbon Tax - Views on a carbon tax range all over the map from a low of \$5/ton[34] to \$37/ton for a "starter tax"[35] to a higher shadow price of \$200/ton [36] (or more) of carbon emitted to the environment *in* CO_2 or to \$340/ton [37] of emitted CO_2. Regardless, it appears likely that some kind of carbon regulations will apply at some time during the economic life of any new power plant contemplated and built today. So, for the base case, we will use a lower range proxy carbon tax of \$50 per ton of carbon emitted in CO_2. We will also adopt a "best technology" CO_2 management requirement. This avoids the untenable situation where plant operators simply choose to pay the carbon tax, rather than building the infrastructure needed to reduce CO_2 emissions.

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[33] The NGCC and CMT figures used here were in large part based the NETL papers.

[34] See The Lincoln Plan at http://www.climateark.org/lincoln_plan/

[35] "The \$37 per ton of carbon "starter tax" mentioned earlier, equating to around 10 cents a gallon of gasoline, fits the lower end of that range." See Carbon Tax Center at http://www.carbontax.org/faq/

[36] "We found that a typical shadow price on carbon (a carbon fee or tax, for example) to prevent the concentrations of CO_2 from more than doubling was around \$200 per ton Carbon emitted." See Statement of Stephen Schneider, Ph.D., Professor, Department of Biological Sciences, Stanford University, Stanford, California, Testimony Before the House Committee on Ways and Means, February 28, 2007 at http://waysandmeans.house.gov/hearings.asp?formmode=view&id=5564

[37] "Most luxury homes in Aspen, Colorado contain energy-guzzling amenities such as heated driveways and outdoor pools. In response, Pitkin County has implemented the world's stiffest tax on carbon emissions, rated at \$340 per ton of carbon dioxide, as part of a plan to finance green projects in the region." (*Christian Science Monitor*) See http://www.globalpolicy.org/socecon/glotax/carbon/2003/0109aspen.htm

Carbon Sequestering - Disposing of carbon by sequestrating CO_2 can be expensive. Further, finding acceptable long-term permanent injection sites can be highly problematical. Finally, the cost of sequestering CO_2 is highly site dependent and difficult to estimate.

The life-cycle costs of deep well sequestering are estimated by others to be in the range from $100 to $300/ton of carbon using present technology.[38] This range is large and uncertain, and sequestering costs were not addressed in detail in the NETL papers. So, for the sake of discussion here, we have selected a base case sequestering cost of $50 per ton of carbon ($\$/\text{ton}_C$) for the infrastructure and operating costs of sequestering CO_2. This lower value is assumed in the hope that future improvements will result in sequestering costs below the range sited above.

Open-Cycle Conventional - Current technology for conventional open-cycle pulverized coal-fired subcritical (OC-PCSUB) steam and natural gas-fired combined cycle (OC-NGCC) generation are listed for reference and comparison against the newer CMT and CAT technologies. The open-cycle burning of coal in an OC-PCSUB steam generator has a lower direct (fuel) cost, but also emits the largest quantities of carbon as CO_2. The open-cycle burning of natural gas results in lower CO_2 emissions, but also higher fuel cost and volatility, relative to coal.

Closed-Cycle CMT's - The carbon mitigation technologies (CMT's) reviewed here include the closed-cycle NGCC (CC-NGCC), closed-cycle pulverized coal-fired subcritical (CC-PCSUB) and closed-cycle IGCC (CC - IGCC), all included in the NETL papers. Each seeks to capture, store, transport, and sequester CO_2. According to the available literature, the overall thermal efficiency and availability losses associated with closed-cycle CO_2 remediation in coal-based plants are on the order of 8-12%, and are, therefore, considerable. Also note that the coal-based CMT technologies still emit substantial CO_2. No CMT carbon capture process recovers 100% of the CO_2 contained in the exhausted combustion gases. The question is, "Do CMT's achieve a sufficient reduction in CO_2 emissions at an affordable price?" We believe that the answer for the coal-based CMT's reviewed here is at best "not yet". Further, it appears that both the CC-NGCC and the closed-cycle plasma pyrolysis of coal (e.g., the CC-CAT-CCU) hold the potential for achieving very low CO_2 emissions.

Open-Cycle CAT's – In its open-cycle form, the plasma pyrolysis carbon avoidance technologies (CAT's) discussed here may achieve reductions in carbon emissions similar to those of the coal-based CMT's, while largely avoiding the capital cost, efficiency and availability downside of these coal-based CMT's. This is simply because the open-cycle CAT designs use a plasma pyrolysis process that is naturally low-carbon.

Close-Cycle CAT's - The primary combustion by-products from burning the unique plasma-coal derived high-hydrogen, low-carbon ($H+C^*$) PCS syngas are hot water vapor and a small amount of CO_2. Should the already low carbon emissions associated with this PCS syngas require further mitigation to achieve ultra-low, near-zero CO_2 emissions, then a CO_2 capture process somewhat similar in purpose to that used with the CMT's could be appended to the PCS syngas process. This suggests that extremely low CO_2 emissions could thereby be achieved.[39]

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[38] See http://www.fossil.energy.gov/sequestration/overview.html

[39] The added cost of this add-on CO_2 capture process will be addressed later in this paper.

Close-Cycle Carbon Avoidance Technologies:	CC-CAT-CCU	CC-SOFC-CCU	
Pre-treatment Carbon in CO_2 ……………………………………	0.13	0.11	lb_C /kWh
CO_2 capture efficiency assumed	85%		
Post-treatment Carbon in CO_2 emissions	0.019	0.016	lb_C /kWh
Percent of CC - IGCC post-treatment emissions …..	23.0%	18.7%	
Percent of OC-PCSUB emissions …………………	3.8%	3.1%	

It is noteworthy, that the combustion by-products - from the high-hydrogen, low-carbon PCS syngas - are materially different from those produced by the typical CMT processes. The open-cycle CMT gasifier produces a fuel gas which is high in carbon monoxide (CO) and may be described as a high-carbon, low-hydrogen syngas. Without CO_2 capture, its combustion by-products are far higher in CO_2 and much lower in water vapor than is the seen for the PCS syngas. The volume and mass of CO_2 that must be remediated in the PCS syngas reviewed here is a small fraction of the amounts which must be processed by the CMT CO_2 capture, storage, transport and sequestering infrastructure.

CO_2 Management - A typical Closed-Cycle IGCC plant would process about 0.56 lb_C/kWh, while capturing up to 0.48 lb_C/kWh (~85%) and emitting about 0.08 lb_C/kWh (~ of an open-cycle coal plant). Emissions may only be further reduced by burning a different, lower-carbon fuel, such natural gas, or by improving the CO_2 capture process.

In contrast, the CC-CAT-CCU begins with 0.13 lb_C/kWh, about 1/5th of the amount produced by the CC - IGCC gasifier, and then emissions are reduced to only about 0.019 lb_C/kWh. So, for a CAT, which is already a low-carbon process, further processing of the PCS syngas or combustion by-products would reduce CO_2 emissions nearly to zero.

A simple cooling process would condense the hot water vapor in the PCS combustion by-products to liquid water, leaving a relatively small amount of CO_2 behind for mitigation. Assuming an 85% CO_2 capture efficiency, treatment of the PCS syngas or combustion gases would further reduce CO_2 emissions to the level of only a few percent of the typical open-cycle coal-fired power plant design. For the example coal, CO_2 emissions would be reduced to the range of 0.016 to 0.019 lb_C/kWh, or 3.1% to 3.8% of the CO_2 released from the typical open-cycle coal-fired power plant. This very low CO_2 emissions level is also about 1/5th of that achievable using the CC - IGCC CO_2 capture process.

So, these closed-cycle CAT technologies appear to offer the best opportunity for attaining ultra-low, *near zero* CO_2 emissions from coal and other fossil fuels.

Scaling CO_2 Management Impacts – It is expected that the cost of CO_2 capture, storage, transport and sequestering for these close-cycle CAT designs will be considerably lower than that required for the coal-based close-cycle CMT's. This is simply because the CAT's involve natural carbon avoidance which results in much lower CO_2 volumes.

We have recognized this and scaled the CO_2-management costs, availability impacts and efficiency losses assumed in proportion to the lower CO_2 volumes processed. We believe, subject to further study, that the costs, availability and efficiency losses may all scale linearly downward. This could leave these close-cycle CAT designs with both a lower overall cost *and* ultra-low CO_2 emissions. Whether economic and environmental considerations warrant investing in such a "two-pass" approach to CO_2 management, or not (i.e., first avoidance and then residual CO_2 remediation), remains to be seen.

Disclaimer - While we believe the tabulations presented here are instructive, serving as order-of-magnitude comparisons, identifying general trends, and providing relative costs, they are only suggestive, and are by no means absolute or final. Some costs, such as the carbon tax proxy, should be viewed as placeholders, waiting for future developments to unfold.

Variable Costs Compared

So, now despite the many uncertainties and unknowns, we will now presume much and venture to present a comparison of a set of not-yet-fully-developed technologies in terms of not-yet-final assumptions and costs, and with the expectation that these comparisons will likely need to be updated, recalculated and revised in the future and perhaps for every power plant site where these technologies may be considered.

Fuel-CO2 Technology - Variable Cost Matrix

The variable cost of electricity in open- and closed-cycle generators with different CO2 technologies:

Technology		Open-Cycle Pulverized Subcritical	Open-Cycle NGCC	Closed-Cycle NGCC	Closed-Cycle Pulverized Subcritical	Closed-Cycle IGCC	Open-Cycle Plasma CAT	Closed-Cycle Plasma CAT	Closed-Cycle Plasma CAT
Abbreviation		OC-PCSUB	OC-NGCC	CC-NGCC	CC-PCSUB	CC - IGCC	OC-CAT-CCU	CC-CAT-CCU	CC-SOFC-CCU
Fuel		Coal	Natural gas	Natural gas	Coal	Coal-Syngas	Coal-Syngas	Coal-Syngas	Coal-Syngas
Net Thermal Efficiency		37%	51%	44%	25%	32%	49%	47%	57%
Carbon Produced	lb_C/kWh	0.51	0.22	0.25	0.76	0.56	0.13	0.13	0.11
CO_2 Capture Efficiency		0%	0%	85%	85%	85%	0%	85%	85%
CO2 Avoided vs OC-PCSUB (%)		0%	58%	93%	78%	84%	74%	96.2%	96.9%
Carbon Emitted	lb_C/kWh	**0.51**	**0.22**	**0.04**	**0.11**	**0.08**	**0.13**	**0.019**	**0.016**
Relative to OC-PCSUB	(%)	100%	42%	7.4%	22%	16%	26%	3.8%	3.1%
Net Btu/kWh		9,300	6,700	7,800	13,700	10,500	7,000	7,300	6,000
Coal Required	lb/kWh	0.8	-NA-	-NA-	1.2	0.9	1.8	1.8	1.5
Variable cost of									
Fuel	¢/kWh	1.3	5.3	5.3	2.5	1.9	4.6	4.8	4.0
Carbon Tax		1.3	0.5	0.1	0.3	0.2	0.3	0.05	0.04
CO_2 Sequestering		0.0	0.0	0.5	1.6	1.2	0.0	0.3	0.2
Subtotal	¢/kWh	**2.6**	**5.8**	**5.9**	**4.4**	**3.3**	**5.0**	**5.2**	**4.2**

Assumptions:	$/MMBtu	¢/kWh			Underlying Coal			Underlying Coal	
Natural Gas	$6.75	5.3			Illinois #6			Dried Illinois #6	
	$/ton-coal	¢/lb-coal	Disposal Cost		Btu/lb.	%C in Coal	%C in Coal	Btu/lb.	Btu/lb.
Coal Price	$ 42.11	2.1	(as % of coal)		11,666	63.8%	70.9%	13,126	3,968
Slag disposal cost	$10.53	0.53	25%		*in total*			*in total*	*for syngas*
	CO_2 Tax Proxy		CO_2 Sequestering Proxy		$/MMBtu		Plasma Energy	$/MMBtu	%Recovered
CO_2 tax and	$/ton $_C$	in ¢/lb$_C$	$/ton $_C$	in ¢/lb$_C$	$1.80		10%	$1.60	30%
Sequestering Proxies	$50	2.5	$50	2.5					

Note that the amount of CO_2 emitted from the *open-cycle* plasma pyrolysis CAT (the OC-CAT-CCU) is between that achieved by the OC-NGCC and the coal-based closed-cycle CMT's. This is simply because plasma pyrolysis is a naturally low-carbon process. The CO_2 emitted is just over one-half of that achieved by a typical OC-NGCC. The CAT fuel cost line is higher than that calculated for other coal-burning technologies. Further, these CAT's also avoid substantial CO_2 management-related capital and operating costs, and avoid the inevitable CMT operating availability and efficiency penalties. This makes a considerable difference in total cost, which we will consider next.

We will also note that the following Total Cost table uses first-year capital costs, not the 20-year levelized costs that were employed in the NETL papers. Otherwise, the capacity costs (expressed in $/kW) and remaining assumptions are generally consistent with those contained in the NETL papers.

Total Power Cost

The cost differences between the alternative conventional, CMT and CAT technologies are further magnified when we consider the total cost of power. The conventional designs emit more CO_2 and incur higher carbon taxes. CMT's tend to require higher capital investments (and suffer from lower overall operating efficiencies and availabilities). CAT's incur higher fuel costs, as a proportion of total cost. So, the CMT's and CAT's introduce a "fixed capital vs. variable cost trade-off" dimension into these numerical analyses, as well.[40] See the table below.

Fuel-CO_2 Technology - Total Cost Matrix

Fixed & variable cost of open- & closed-cycle generators using different CO2 technologies:

Technology >		Open-Cycle Pulverized Subcritical	Open-Cycle NGCC	Closed-Cycle NGCC	Closed-Cycle Pulverized Subcritical	Closed-Cycle IGCC	Open-Cycle Plasma CAT	Closed-Cycle Plasma CAT	Closed-Cycle Plasma CAT
		OC-PCSUB	OC-NGCC	CC-NGCC	CC-PCSUB	CC - IGCC	OC-CAT-CCU	CC-CAT-CCU	CC-SOFC-CCU
Fuel		Coal	Natural gas	Natural gas	Coal	Coal-Syngas	Coal-Syngas	Coal-Syngas	Coal-Syngas
Net Thermal Efficiency		37%	51%	44%	25%	32%	49%	47%	57%
Plant size (in net MWs)		550	560	482	550	556	550	550	550
Availability (%)		92.5%	95.0%	93.0%	85.0%	85.0%	95.0%	93.0%	93.0%
Net Generation (GWh/yr)		4,460	4,663	3,926	4,092	4,138	4,581	4,484	4,484
Net Emissions	lb_C/kWh	**0.51**	**0.22**	**0.04**	**0.11**	**0.08**	**0.13**	**0.019**	**0.016**
Fixed Capital Cost (in $/kW-installed)									
Power Island		$1,549	$554	$679	$1,691	$987	$609	$609	$665
Air Separation		$0	$0	$0	$0	$342	$0	$0	$0
Gasifier		$0	$0	$0	$0	$498	$498	$498	$498
CO2 Capture		$0	$0	$0	$323	$414	$0	$95	$77
& Compression		$0	$0	$493	$881	$68	$0	$16	$13
Transport		$0	$0	$10	$10	$10	$0	$10	$10
Sequestering Capital		$0	$0	$50	$50	$50	$50	$50	$50
Total Capital	$/kW	$1,549	$554	$1,232	$2,955	$2,369	$1,157	$1,278	$1,313
Plant Cost (in billions)		$0.9	$0.3	$0.6	$1.6	$1.3	$0.6	$0.7	$0.7
Annual SL (in millions)		$42.6	$15.5	$29.7	$81.2	$65.8	$31.9	$35.2	$36.1
Return on Capital (1st-yr)		$106.6	$38.8	$74.2	$203.0	$164.5	$79.6	$87.9	$90.3
1st Yr. Total		$149.2	$54.3	$103.9	$284.2	$230.4	$111.5	$123.1	$126.5
Capital Cost (CC	¢/kWh	3.3	1.2	2.6	6.9	5.6	2.4	2.7	2.8
CC% of TC		*52%*	*16%*	*30%*	*57%*	*58%*	*32%*	*32%*	*37%*
O&M Cost Est.	¢/kWh	0.5	0.1	0.3	0.8	0.8	0.2	0.5	0.6
Variable Costs (excl. Capture)									
Fuel	¢/kWh	1.3	5.3	5.3	2.5	1.9	4.6	4.8	4.0
Carbon Tax		1.3	0.5	0.1	0.3	0.2	0.3	0.0	0.0
CO_2 Sequestering		0.0	0.0	0.5	1.6	1.2	0.0	0.3	0.2
VC Subtotal		2.6	5.8	5.9	4.4	3.3	5.0	5.2	4.2
VC% of TC		*40%*	*82%*	*67%*	*36%*	*34%*	*65%*	*61%*	*56%*
Total Cost (TC)	¢/kWh	**6.5**	**7.1**	**8.8**	**12.1**	**9.7**	**7.7**	**8.5**	**7.6**
% of OC-PCSUB		*100%*	*110%*	*136%*	*187%*	*150%*	*118%*	*131%*	*118%*

For the base case assumptions, we see that the conventional technologies are still lowest cost, but emit far more CO_2 (thus the "best technology" requirement noted previously). The CAT's avoid the coal-based CMT's substantial CO_2 management-related capital and operating cost penalties, while still substantially avoiding carbon, reducing CO_2 production and CO_2 emissions. The large efficiency and availability losses associated with the coal-based CMT's CO_2 management is avoided, allowing the

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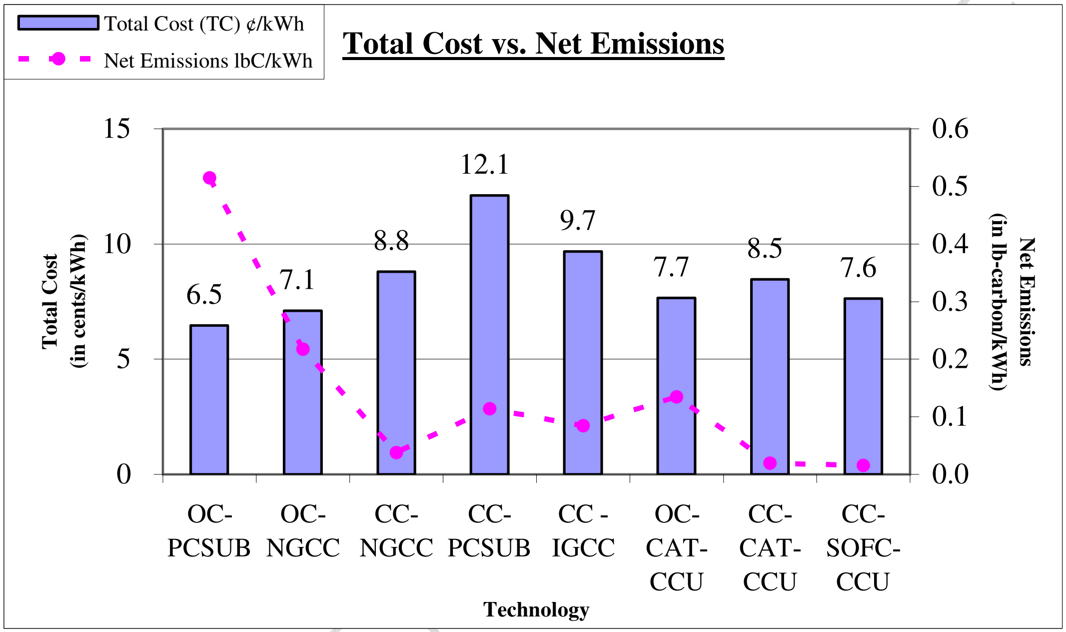
[40] Another example of this fixed vs. variable cost trade-off today is open-cycle super-critical coal (SCC) vs. open-cycle natural gas combined cycle (NGCC). SCC is capital intensive, but less fuel intensive. The NGCC is more fuel intensive, but requires a lower capital investment.

conventional designs and CAT's to achieve higher overall operating efficiencies, which in turn reduces the cost of power and CO_2 emissions. This higher efficiency is in part offset by the substantial power requirements of the plasma generators. These are power-intensive plasma arcs using considerable electric power to super heat the carrier gas in order to vaporize and dissociate the oils and tars contained in coal. However, a significant portion of this energy may be recycled by recapturing heat contained in the PCS syngas, the by-product carbon-slag and the resulting combustion gases.

Comparisons

The following graph compares the base case total costs and net emissions for the various conventional, CMT and CAT technologies reviewed here.



Lower Capital, Higher Fuel Costs - Where lower CO_2 emissions is important, but using less complex technology with lower capital costs is a determining factor, the combined cycle unit (CCU) design may fit the requirements best. Both the standard open-cycle natural gas-fired CCU (OC-NGCC) and the open-cycle plasma-coal OC-CAT-CCU show similar performance and fixed vs. variable cost profiles; e.g., lower carbon emissions, with lower capital costs, but higher fuel costs. An added advantage of the OC-CAT-CCU is a lower fuel cost level and lower volatility -- given that historically coal prices have been less variable than natural gas prices. Note that considerably, i.e., ~38%, lower CO_2 emissions per kWh than the typical OC-NGCC design may also be achieved using the plasma pyrolysis carbon avoidance technology with a CCU power plant design.

Costs expressed in ¢/kWh	Open-Cycle NGCC OC-NGCC		Open-Cycle Plasma CAT OC-CAT-CCU	
	Natural gas	*%TC*	Coal-Syngas	*%TC*
Net Thermal Efficiency	51%		49%	
Emissions (in lb_C/kWh)	0.22		0.13	
Capital Cost	1.2	16%	2.4	32%
O&M Cost Est.	0.1	2%	0.2	3%
Variable Cost	5.8	82%	5.0	65%
Total Cost (TC)	7.1		7.7	

If a “best technology” criterion exists, the OC-CAT-CCU is a low-carbon choice. Otherwise, simply paying the base case carbon tax is more economical than making CO_2 management investments.

Higher Capital vs. Higher Fuel Costs – Next we compare a more capital intensive CMT (the CC - IGCC) with a more fuel intensive CAT technology (the OC-CAT-CCU) in a “fixed vs. variable cost” shoot out. Both indicate lower CO_2 emissions per kWh than natural gas in an OC-NGCC design.

	Closed-Cycle		Open-Cycle Plasma CAT	
Costs expressed in ¢/kWh	CC - IGCC		OC-CAT-CCU	
	Coal-Syngas	*%TC*	Coal-Syngas	*%TC*
Net Thermal Efficiency	32%		49%	
Emissions (in lbC/kWh)	0.08		0.13	
Capital Cost	5.6	58%	2.4	32%
O&M Cost Est.	0.8	8%	0.2	3%
Variable Cost	3.3	34%	5.0	65%
Total Cost (TC)	9.7		7.7	

Lower Fuel, Higher Capital Costs - If lower carbon emissions *and* lower fuel cost and volatility are objectives, yet more complex technology and higher capital costs are not a barrier, then one of the more complex, higher fixed cost CMT or CAT technologies may be pursued. Note that the plasma-coal carbon avoidance technologies reviewed here hold the promise of higher operating efficiencies, in part offsetting their higher fuel costs. Lower CO_2 emissions per kWh may also be achievable using the plasma pyrolysis carbon avoidance technologies in CC-SOFC-CCU design.[41]

	Closed-Cycle		Closed-Cycle	
Costs expressed in ¢/kWh	CC - IGCC		CC-SOFC-CCU	
	Coal-Syngas	*%TC*	Coal-Syngas	*%TC*
Net Thermal Efficiency	32%		57%	
Emissions (in lb_C/kWh)	0.08		0.02	
Capital Cost	5.6	58%	2.8	37%
O&M Cost Est.	0.8	8%	0.6	7%
Variable Cost	3.3	34%	4.2	56%
Total Cost (TC)	9.7		7.6	

Ultra-Low CO_2 Emissions - We should also reiterate that ultra-low CO_2 emissions are possible with this combination of CAT and CMT technologies. CC-CAT-CCU and CC-SOFC-CCU CO_2 emissions levels of 3.1% to 3.8% of the typical open-cycle coal-fired power plant appear achievable. This CO_2 emissions level is also about 1/5th of that achieved by the CC - IGCC CO_2 capture process.

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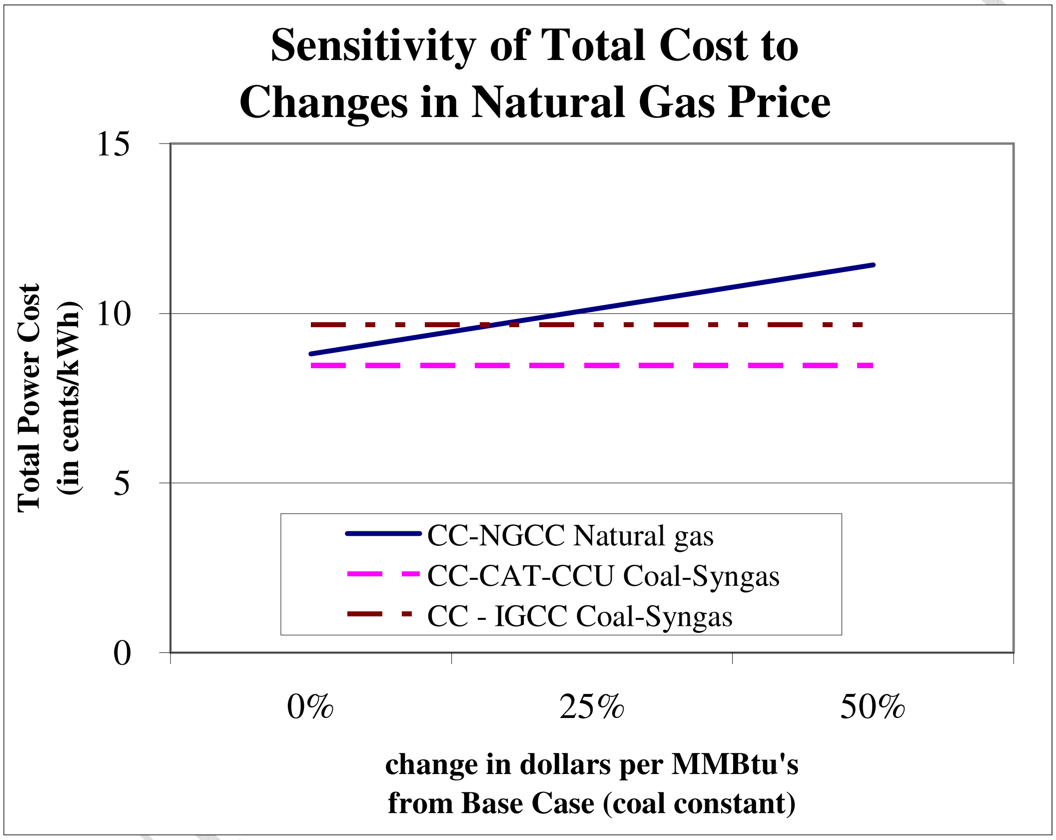
[41] The SOFC-CCU: Owing to its unique nature, the solid oxide fuel cell or SOFC is not limited by the “second-law” thermodynamic restrictions which limit conventional thermal plant designs. The SOFC portion of a power plant design may in theory exceed gross efficiencies of 75% on hydrogen, while the CCU balance-of-plant achieves gross efficiencies of around 50%. The overall gross efficiency could in theory equal 65% for certain open-cycle designs. We have used 65% as representative of a gross efficiency objective for a SOFC-CCU design, although higher levels may also be achievable. The resulting net efficiency after plasma loads and CO2 management is estimated at about 57%. Further, the use of SOFC’s in combination with CCU’s has only recently been suggested and more research and development (R&D) is undoubtedly required to prove out the durability of this design for electric power generation.

This very low level of CO_2 emissions is probably about as close to a "zero emissions" design as we are likely to see with current technology and processes.

SENSITIVITY TO CHANGING ASSUMPTIONS

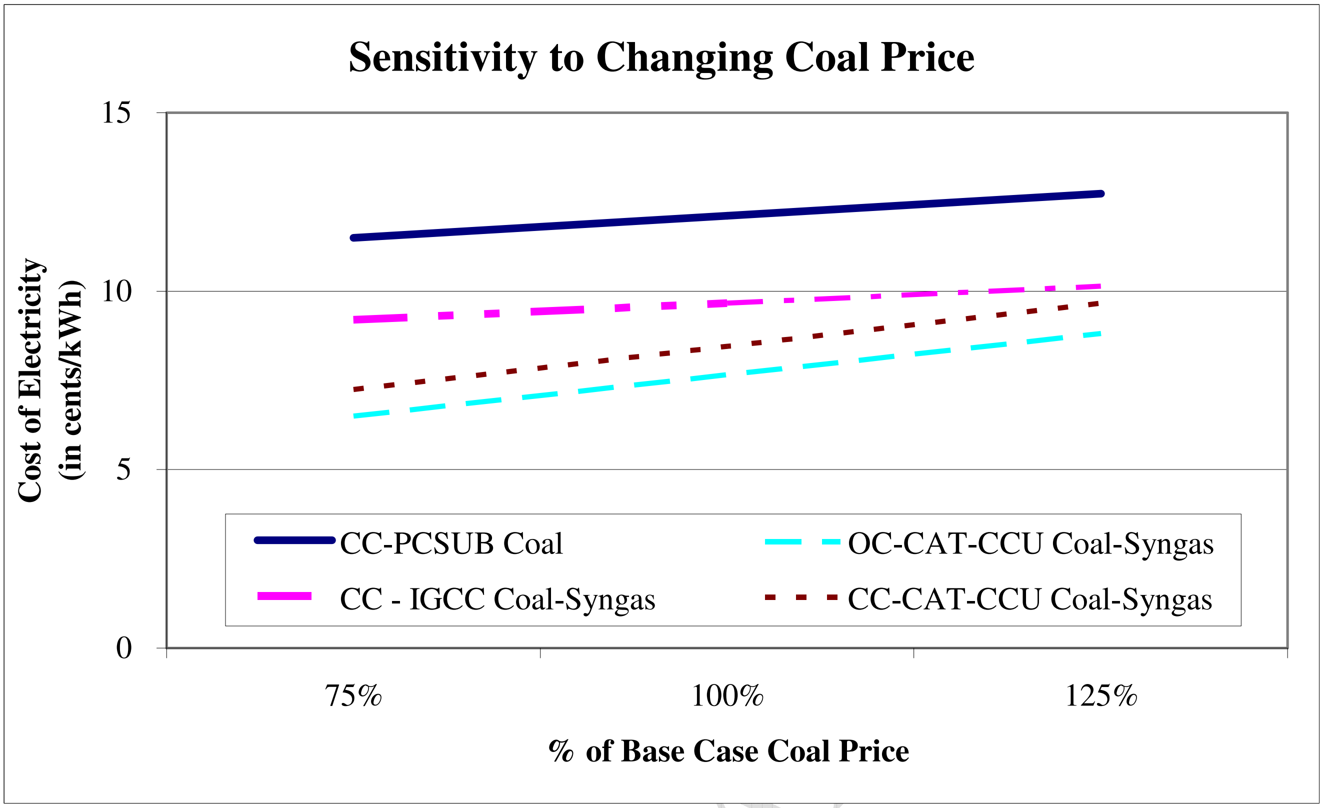
Fuel Prices

The base case analyses were predicated upon a particular set of assumptions. One assumption is the relative price ratio between the alternative fuel sources natural gas and coal. To study fuel price sensitivity the natural gas-to-coal price ratio was adjusted by changing the cost of natural gas while holding the cost of coal constant (see graph below). Obviously, coal-based technologies look better when the ratio is higher and natural gas looks better when the natural gas-to-coal price ratio is lower.



Technology & Capital Employed

The relative outcome is also dependent on the technology and capital intensity involved. Certain technologies are more or less sensitive to changes in the various assumptions. As expected, the power costs of higher fuel-use technologies tend to be more sensitive to changing fuel price assumptions than other technologies. Conversely, the power costs of the more capital intensive technologies tend to be less sensitive to fuel price changes. The following graph shows how the more capital intensive CMT and CAT technologies react less to changing coal prices (i.e., the slope of the curve) than the more fuel intensive technologies. Again, we note that the CAT CO_2 emissions tend to be lower than those of other technologies.



Robust Solutions

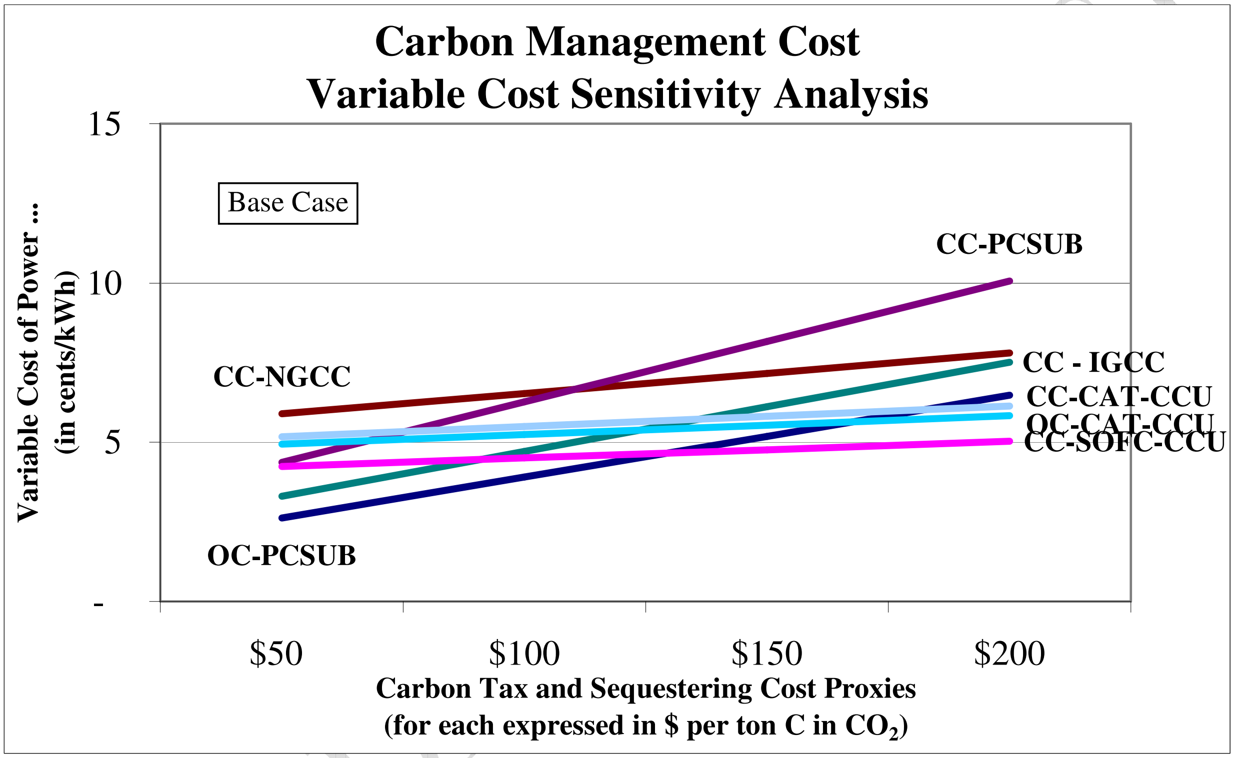
In looking for low CO_2 emissions and "best-in-class" economics, we generally seek outcomes where the order of preference does not change with changing input assumptions. For example, changes in the price of coal assumed do not modify the relative ranking of the various CMT and CAT designs. The CAT's remain lower in emissions and lower in cost than the coal-based CMT's over the range of fuel prices examined.

IGCC vs. CAT-CCU - As the assumed price of coal is increased, it is expected that the relative ranking of the more capital-intensive IGCC would eventually switch places with the more fuel-intensive CAT-CCU technologies. However, these two technologies appear not to arrive at parity in overall generating costs until a coal price somewhat over 125% of the $42 /ton base case cost is reached, e.g., above $53 /ton. The CAT-CCU remains the technology of choice for the above range of coal prices.

CC-NGCC vs. CC - IGCC - The CC - IGCC is a higher cost carbon mitigation technology until a natural gas-to-coal price cross-over point. At that point, natural gas is equally expensive when compared with coal for these CMT assumptions. Above that point, the CC-NGCC design is more expensive.

Sensitivity to CO_2 Management Costs

Next, we examine the sensitivity of variable cost to changes in the carbon tax and sequestering cost assumed. We have collectively referred to these as carbon management costs below. No national tax exists today. However, we have chosen a base case proxy carbon tax of \$50 /ton_C emitted in CO_2. Sequestering costs are likely to be site-specific and are relatively uncertain. We have a chosen base case value of \$50 /ton_C for sequestered CO_2. Then we have ratcheted these costs upward in uniform increments to test the sensitivity of the outcomes to changes in the level of these two assumptions. The graph below shows the results of that sensitivity analysis.



At the low end of the range are the base case results.[42] The CC-NGCC has a higher variable cost unless the assumed costs of carbon management are very high. As the assumed cost of carbon management is increased, the variable cost of subcritical coal (OC-PCSUB and CC-PCSUB) technologies rise more rapidly, eventually exceeding the variable cost of other technologies at high carbon management cost levels. Further, as the assumed cost of carbon management is increased, the variable cost of the CAT's fall below those of other designs (at base case fuel prices). The higher efficiency CAT's (OC-CAT-CCU, CC-CAT-CCU and CC-SOFC-CCU) fall below the cost of the closed-cycle CC-PCSUB design in the vicinity of the base case assumptions.

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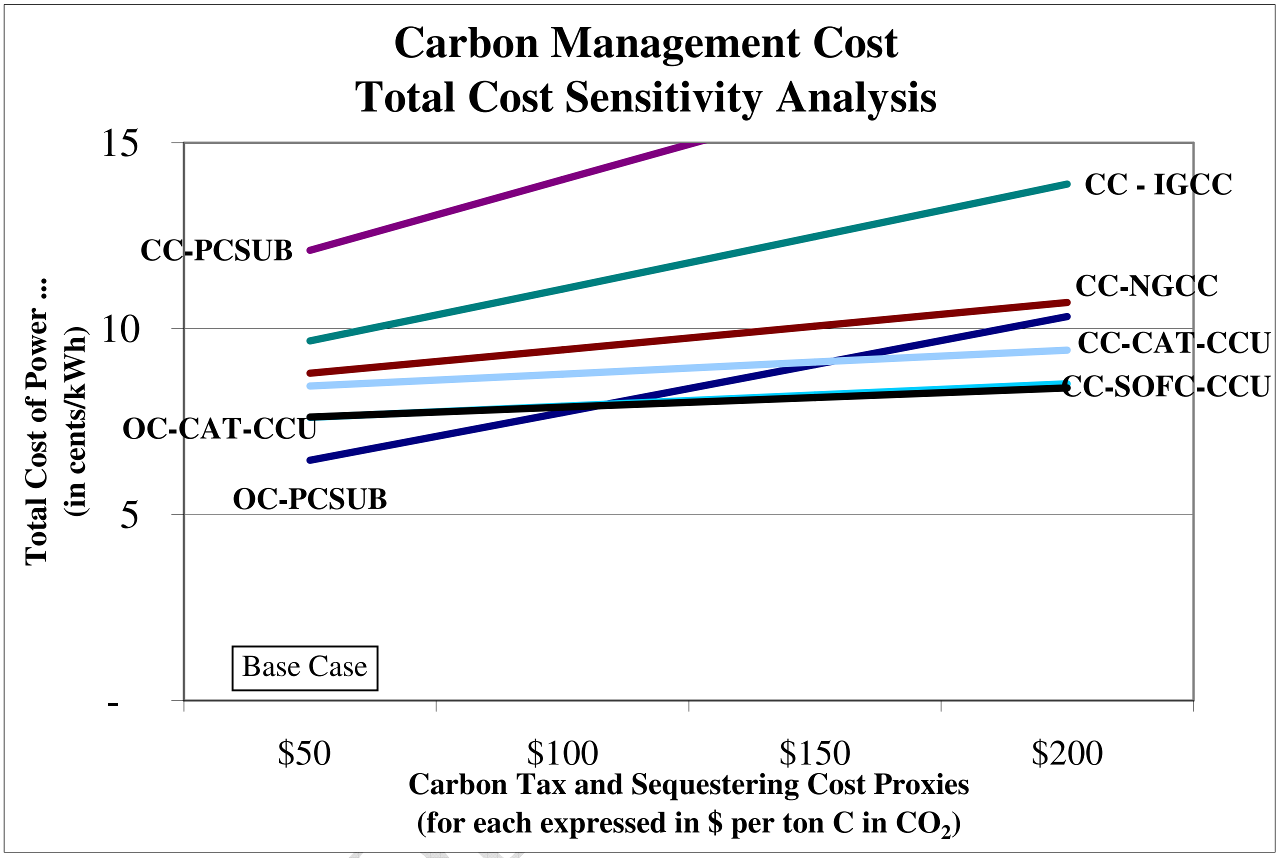
[42] We note that today there is no variable cost penalty associated with CO_2 emissions. Unfettered by any cost burdens associated with the environmental impacts of CO_2, the open-cycle burning of coal is the lowest cost approach for the generator, i.e., if only direct variable fuel costs are considered, but is not necessarily lower cost for society as a whole.

Sensitivity of Total Cost

Finally, we will examine the sensitivity of the total costs to changes in the cost assumed for carbon management. Fixed costs are by their nature independent of the changes in variable costs like a CO_2 taxes. So, we would expect to see a similar shape for the total cost curves, as they are in large part driven by changes in the variable cost of carbon management assumed.



Using base case assumptions without a “best technology” requirement, it appears that the open-cycle technologies are somewhat less expensive. However, at higher carbon tax levels, they are no longer lowest-cost. Without a “best technology” requirement this creates an untenable situation where plant operators could simply choose to pay the carbon tax (if any), rather than building the infrastructure needed to reduce CO_2 emissions.

Presuming a “best technology” requirement, the lines representing both the lowest carbon emissions and lowest cost technologies are the following CAT’s:

- the OC-CAT-CCU,
- the CC-CAT-CCU, and
- the CC-SOFC-CCU.

The CC-NGCC is a CMT and is a somewhat higher cost, low-carbon technology, and would come next. The CC-PCSUB design is far out of the running. Curiously, the CC - IGCC also appears relatively expensive, when the added costs of sequestering and residual CO_2 emissions are considered.

CONCLUSIONS

CAT-CCU Compares Favorably to NGCC

The plasma pyrolysis of coal may be used to produce a unique high-hydrogen, low-carbon PCS syngas. This PCS syngas may be burned in a combined-cycle unit (CCU) to create a carbon-avoidance/CCU generating technology, the CAT-CCU. The open- and closed-cycle CAT-CCU designs both appear to be naturally low-carbon and economic, relative to either of the natural gas-burning CCU designs (on the low-cost side of the inter-fuel price cross-over). Finally, lower CO_2 emissions, coupled with lower, more stable fuel costs make the CAT-CCU a better choice for a low carbon future, when compared with the NGCC.

SOFC-CCU is an Advanced Design

The plasma pyrolysis of coal and use in the SOFC-CCU is an advanced generating technology. It is less well developed and is likely to be more capital intensive than the NGCC or other CAT-CCU designs, as well as being more fuel-intensive than the subcritical coal designs. However, it is likely to be less capital intensive than the other closed-cycle coal mitigation technologies, such as variants of the closed-cycle IGCC technology with CO_2 capture, storage, transport and sequestering. Finally, the SOFC-CCU design is likely to be only slightly more fuel intensive than the close-cycle IGCC design, while possessing higher overall operating efficiency and availability rates, as well as lower CO_2 emissions.

CAT's offer Higher Efficiency, Lower Capital Cost, Lower CO_2 Emissions

The new plasma pyrolysis-based CAT's reviewed here allow for higher overall efficiency, availability and lower capital investment, while being somewhat more fuel intensive than the CMT's. Plasma pyrolysis provides important environmental benefits given its natural carbon avoidance capabilities, while offering the potential to achieve ultra-low emissions levels at somewhat higher cost.

Closed-Cycle CAT's are Ultra-Low CO_2 Emitters

The combination of plasma pyrolysis carbon avoidance technology with CO_2 mitigation is possible. This "two-pass" doubling up of both CAT and CMT carbon management technologies minimize CO_2 emissions and holds the potential for achieving ultra-low emissions, i.e., below 3.8% of current open-cycle coal-fired generators, and at a lower overall cost, when the impacts of CO_2 management are considered.

CAT's are a Low-Carbon "Win-Win" for the Future

In our view, plasma pyrolysis of coal, when combined with conventional CCU technology (and/or advanced, high efficiency SOFC's), is a "win-win" combination for the hydrogen economy and a low-carbon future.

Appendices

Molar Analysis

For a better estimate of the energy which may be extracted using plasma pyrolysis, it is necessary to do a full molar-energy analysis. This is what we will do next.

Starting Chemical Analysis

The following table lists the major constituents of the example feed coal. It also lists the reaction products resulting from combustion of the high-hydrogen, low-carbon syngas formed by the plasma pyrolysis process. The constituents of primary interest are the hydrogen, oxygen and moisture content of the example feed coal. From these constituents we may determine the resulting hydrogen and carbon monoxide (CO) gaseous products of the plasma pyrolysis process, and the energy available from burning the high-hydrogen, low-carbon syngas produced.

Coal Analysis - Chemical Data			Awt$_x$	Molar wt.	
Example Coal Molar Weights		wt. %	*g/mol*	*g/mol-coal*	lb$_x$/lb$_{coal}$
• Carbon (C)		70.9%	12.0110	8.52	0.709
• Hydrogen (H)		5.0%	1.0079	0.05	0.050
• Nitrogen (N)		1.4%	14.0067	0.19	0.014
• Sulfur (S)		2.8%	32.0600	0.90	0.028
• Oxygen (O)		7.7%	15.9994	1.22	0.077
• Ash		11.1%	54.0456	6.01	0.111
• Moisture (H_2O)		1.1%	18.0152	0.20	0.011
Total		100.0%	17.0885	17.09	1.000
Reaction Molar Weights					
• Carbon Reacted (C*)	75%	6.5%	12.0110	0.78	0.065
• Total Oxygen (O_T)					
> bound in coal		7.7%		1.22	0.077
> bound in water	89%	1.0%		0.16	0.010
Oxygen subtotal		8.6%	15.9994	1.38	0.086
• Total Hydrogen (H_T)					
> bound in coal		5.0%		0.05	0.050
> bound in water	11%	0.1%		0.00	0.001
Hydrogen Subtotal		5.1%	1.0079	0.05	0.051
• Carbon Monoxide (CO)			28.0104		
• Carbon Dioxide (CO_2)			44.0098		

The use of a molar-energy approach to analyze this high-hydrogen, low-carbon syngas would be expected to produce results close to those estimated from use of Dulong's equation, and, so each serves as a good cross-check of the other.

Moles Reacted

Next we will tabulate the reaction products of the plasma pyrolysis process, primarily hydrogen gas and carbon monoxide.[43] The hydrogen is liberated from contained tars and oils (and water) in the coal. In the absence of introduced air or oxygen (i.e., pyrolysis), the only oxygen available to the reaction is

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[43] Formation and processing of nitrogen and sulfur gases will not be dealt with here for the sake of simplicity.

that formerly bound up or entrained in the coal. Bound oxygen is liberated by the plasma heat. Entrained oxygen is contained in water and is liberated (along with hydrogen) from the dissociation of water entrained in the example coal.

Chemical and Thermodynamic Reactions Type of Coal: Dried Illinois #6

Results of Plasma Pyrolysis Treatment *Transformation of Chemical Species*

BEFORE				**AFTER**			
wt. %		moles_x		wt. %		g_x/lb_{coal}	moles_x
70.9%	C (solid)	26.8	→	64.4%	C (solid)	292.2	24.3
				6.5%	C* (in CO)	29.4	2.4
5.0%	H (bound)	22.5	→	5.0%	H from coal (gas)	22.7	22.5
7.7%	O (bound)	2.2	→	15.1%	CO (gas)	68.6	2.4
1.4%	Nitrogen (N)	0.5	→	1.4%	Nitrogen (N)	6.3	0.5
2.8%	Sulfur (S)	0.4	→	2.8%	Sulfur (S)	12.7	0.4
11.1%	Ash (solid)	#N/A	→	11.1%	Ash (solid)	50.4	#N/A
1.1%	H_2O	0.3	→	0.1%	H from water (gas)	0.6	0.6
			→	1.0%	O (in CO from dissociated water)	4.5	0.3
100.0%				100.0%		453.5	
5.0%	H (bound)		=	5.0%		22.7	22.5
0.124%	Hydrogen in H_2O		=	0.1%		0.6	0.6
	Total Hydrogen (H_T)		=	5.1%		23.3	23.1
7.7%	O (bound)		=	7.7%	O (in CO from coal)	34.7	2.2
0.99%	Oxygen in H_2O		=	1.0%	O (in CO from dissociated water)	4.5	0.3
	Total Oxygen (O_T)		=	8.6%		39.2	2.4

For the example coal used here and at these high plasma temperatures, the resulting high-hydrogen, low-carbon syngas contains substantial hydrogen in a monatomic gaseous form and some carbon monoxide (CO) gas. The following table lists the moles of each produced for this coal.

Molar Balances - *for Plasma formed high-hydrogen, low-carbon syngas*

Input (moles_x)					Reaction Product (moles_x)	
0.3	H_2O + Energy			→	0.6	Hydrogen (gas)
				+	0.3	Oxygen (gas)
22.5	H (bound in coal) + Energy			→	22.5	Hydrogen (gas)
26.8	C (solid) +	2.4	Oxygen	→	2.4	Carbon Monoxide (gas)
				+	24.3	C (solid)

Molar Balances - *when the syngas is burned in a CCU*

2.4	CO +	2.4	$\frac{1}{2}O_2$ from air	→	2.4	CO_2
23.1	H +	11.5	$\frac{1}{2}O_2$ from air	→	11.5	H_2O

Broad Process Steps - The following broad process steps result in the plasma pyrolysis production of a high-hydrogen, low-carbon PCS syngas. This high-hydrogen, low-carbon syngas is assumed to be burned in a combined cycle unit generating plant at relatively high efficiency. For this molar analysis, the combustion gases are then assumed to be released into the atmosphere (without using any CO_2 capture, storage, transport and sequestering technology). These broad steps follow:

Step 1a	plasma dissociates moisture into free hydrogen and oxygen radicals, and
Step 1b	plasma liberates hydrogen and oxygen bound-up in the tars and oils in the coal
Step 2	liberated oxygen reacts with a small portion of the carbon in the coal to form carbon monoxide in the syngas
Step 3	this high-hydrogen, low-carbon syngas is burned in a power plant

Note that high temperature water vapor is the predominant molecular species in the by-products released from combustion of this high-hydrogen, low-carbon syngas.

Energy Analysis

Step 1a above involves the dissociation of water into its constituents, hydrogen and oxygen, and takes energy. This endothermic dissociation reaction takes heat energy away from the high-temperature plasma gas (and the exoergic CO-forming reaction step). In step 1b, the high temperature plasma breaks hydrogen-carbon bonds in the oils and tars contained in the coal, liberating hydrogen as a gas and carbon as a solid. The reactions dissociating water and liberating hydrogen from the coal are both endoergic, requiring net plasma energy to drive the reactions to completion (see below). In step 2, the oxygen liberated from the coal and from any entrained water reacts with a small portion of the carbon in the coal to form carbon monoxide (CO), releasing some additional energy. In Step 3 the syngas is burned releasing its chemical energy.

Steps	Enthaply Balances	Products	Enthalpy	Quantities	Energy
	Chemical Reactions:		*kJ/mol*	*moles*	*Btu/lb-coal*
1a	$H_2O + E \rightarrow 2H + O$ (ions)	Dissociation of water	285.8	0.3	(76)
1b	Coal + E[†] → H (ions) + C (solid)	Dissociation of coal			
2	$C + O \rightarrow CO$ (gas) + E	Carbon Monoxide	(110.5)	2.4	257
3	$2H + O \rightarrow H_2O$ (vapor) + E	Water Vapor	(285.8)	11.5	3,130
	$CO + \frac{1}{2}O_2 \rightarrow CO_2$ (gas) + E	Carbon Dioxide	(283.0)	2.4	658
		Gross energy available in syngas formed ……			3,968
		Plasma energy inputs [†] ………………………			(474)
Note: † Assuming 125 kWh per ton of coal.		Net energy available from plasma process …..			3,494

Results Summary

The above molar-energy analysis estimates the gross energy content of this unique high hydrogen, low-carbon (*H+C**) PCS syngas at about 4,000 Btu/lb. for the example coal. After deducting the plasma energy inputs required to dissociate the coal and water, the net energy available is 3,494 Btu/lb.

The quantity of plasma energy required to accomplish the full dissociation reaction is estimated at 474 Btu/lb. for the example coal, based on experimental results achieved by others.[44] The resulting net energy available from this syngas (after deducting plasma inputs) is within 0.5% of the 3,512 Btu/lb. value estimated using the modified Dulong equations presented above. This conclusion suggests that using Dulong's equation provides fairly reasonable results which are both close and perhaps slightly conservative estimates of the amount of energy available from this unique high hydrogen, low-carbon syngas -- produced from the plasma pyrolysis of coals.

-THE END-

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[44] See http://www.westinghouse-plasma.com/gasif.htm