ATTACHMENT A

OVERVIEW OF WESTERN RESEARCH INSTITUTE

Located in Laramie, WY, Western Research Institute (WRI) is a team of 83 scientists, engineers, technicians and management professionals working on both scientific research and applied RD&D to bring forth scientific knowledge, solutions and technologies in the fields of energy, environmental remediation and emission control, and longer lasting highway materials.

WRI's historical beginnings in Wyoming start in 1924 supporting high sulfur oil processing in Wyoming. WRI was established in 1983 when the U.S. Department of Energy (DOE) de-federalized the Laramie Energy Technology Center. The state of Wyoming via the University of Wyoming (UW) created and implemented a plan that retained the laboratory assets and jobs in Laramie by establishing the University of Wyoming Research Corporation d/b/a Western Research Institute as an independent nonprofit 501(c)3 cooperating entity with UW, though not UW or state employees. The resources saved by the state include a 22-acre research park in Albany County located just north of Laramie and the former DOE Laramie Energy Technology Center (LETC) building on the northwest corner of the UW campus. WRI retained ownership of the 22-acre park environmental issues and ownership of LETC building was transferred to UW. Presently, WRI leases space from UW its laboratories and office spaces within this building.

WRI's Mission Statement reflects the broad scope of topics, national and global based market sectors and beneficial contributions pursued.

WRI Mission Statement

- **Western Research Institute provides sustainable societal benefits by solving complex science and technology problems.**
- **We collaborate with partners to define the challenges, extend the body of knowledge and deliver innovative solutions in energy, environment and transportation technologies.**

Given the lengthy one to two decade timeframe to invent "Game-Changing" energy process plant technologies that achieve societal goals and then scale up that invention into commercial viable plants, it is vital to monitor megatrends in addition to the identified current day issues and needs. As researchers and technology developers within the energy sector it is vital that we target our early stage research problem and opportunity statements on the future challenges and opportunities requiring solutions 10 to 20 years from today. This strategy provides a research and technology pipeline with technologies nearing and ready for commercial deployment while preparing scientific knowledge and new inventions to address the problems and megatrend opportunities a few decades into the future.

Key highlights of WRI illustrated the agility and adaptability to adjust to changes in industry technology solution needs and regulations include the following:

1. WRI is a multifaceted organization with a highly diverse suite of expertise, staff experience, intellectual property and research and technology development equipment and facilities.
2. WRI's clients, research partners and stakeholders are very diverse with both local, national and international market interests and business operations.
3. WRI consists of three Business Units: *Energy Production and Generation* (EP&G), *Waste and Environmental Management* (WEM), and *Transportation Technologies* (TT).
4. WRI's business portfolio has evolved to follow the needs of the various market sectors served by WRI and consists of a majority of applied Research, Development and Demonstration (RD&D) with a strong basic scientific research component with TT and as needed scientific research within EP&G and WEM.
5. Strong collaborative with universities such as the University of Wyoming and junior colleges to assist in educating and developing the skilled workforce talent people to support quicken commercial deployment of successful research and technology developments.
6. Over the past three years, WRI has substantially diversified its client base to foster an increase in commercialization of our research and technologies. This diversification shift to commercial industry partner applied research achieved a 47% increase in FY2013 over FY2011. A further growth of approximately 50% in commercial business for FY2013 versus FY2012 has been continued this focus on industry commercial viable research and technologies.

ATTACHMENT B

CAT™ Process: A CO_2 Capture and Re-Use Technology for Fossil Fuel Plant Emissions

Coal utilization will continue to be a key factor in meeting the energy demand both domestically and internationally in the near future (Bauer, 2009). As shown in Table B-1, coal use and CO_2 emissions in the U.S. are expected to increase in the next few decades from 23 to 26 quadrillion Btu per year and 2.1 to 2.5 billion metric tons/yr, respectively. Additionally, CO_2 emissions from the transportation sector are predicted to be equal to that of emissions from coal by 2030. If emissions from one of these CO_2 sources could be reduced, then up to a 40% reduction in emitted CO_2 could occur. Without accelerated technology development to address CO_2 reduction, along with options for efficient and greener forms of energy supply from coal-based technologies, coal use and indirectly the economic progress of the country will be severely impacted. WRI's patent-pending CAT™ process could be used to capture, for example, coal-fired CO_2 emissions and produce biodiesel that replaces petroleum diesel, thus lowering the rate of CO_2 emission into the atmosphere.

Table B-1. Dominance of Coal in Energy Supply and CO_2 Emissions

Energy Source	Unit	Energy Use		Unit	CO_2 Emission	
		2006	2030		2006	2030
Coal	QBtu/yr	23	26	bmt/yr	2.1	2.5
Gas	QBtu/yr	22	24	bmt/yr	1.2	1.3
Nuclear	QBtu/yr	8	9			
Oil	QBtu/yr	41	38	bmt/yr	2.6	2.6
Renewables	QBtu/yr	6	14			
Total	QBtu/yr	100	111	bmt/yr	5.9	6.4
Change (Total)	%		11	%		8.0

Table from EIA, 2009.

The CAT™ Process. WRI's patent-pending CAT™ process is a novel biological carbon capture and re-use technology that can be added to stationary carbon dioxide emitters. This technology is not dependent on light, which affords it a number of advantages over current algal technologies. Current research and development efforts are concentrating on use of the CAT™ process for biodiesel production, but this process could be used for generation of other fuels and chemicals. Our models predict that biodiesel can be produced for approximately $3 to $5/gallon using the CAT™ process. This promising technology is currently at the research and development stage and is in need of funding opportunities to bridge the

"valley of death" in the funding landscape, which correlates to the technology development phase between early research and development and pilot scale technologies.

The CAT™ carbon capture and re-use process offers a safe and reliable alternative to geological storage, in addition to providing a low cost carbon capture technology to the emitter. WRI's CAT™ process competes with other cutting edge biological CO_2 capture technologies in terms of net efficiency, capital costs and plant availability. Deployment of the CAT™ technology would enhance the economic and energy security of the U.S. through the development of a technology that will (1) effectively capture CO_2 from stationary sources, (2) produce energy-dense, infrastructure compatible liquid fuels/bioproducts from CO_2, thereby reducing petroleum imports and CO_2 emissions (Figure B-1); and (3) minimize the efficiency reduction and financial expense of GHG emissions controlled facilities, such as industrial and manufacturing facilities and utilities.

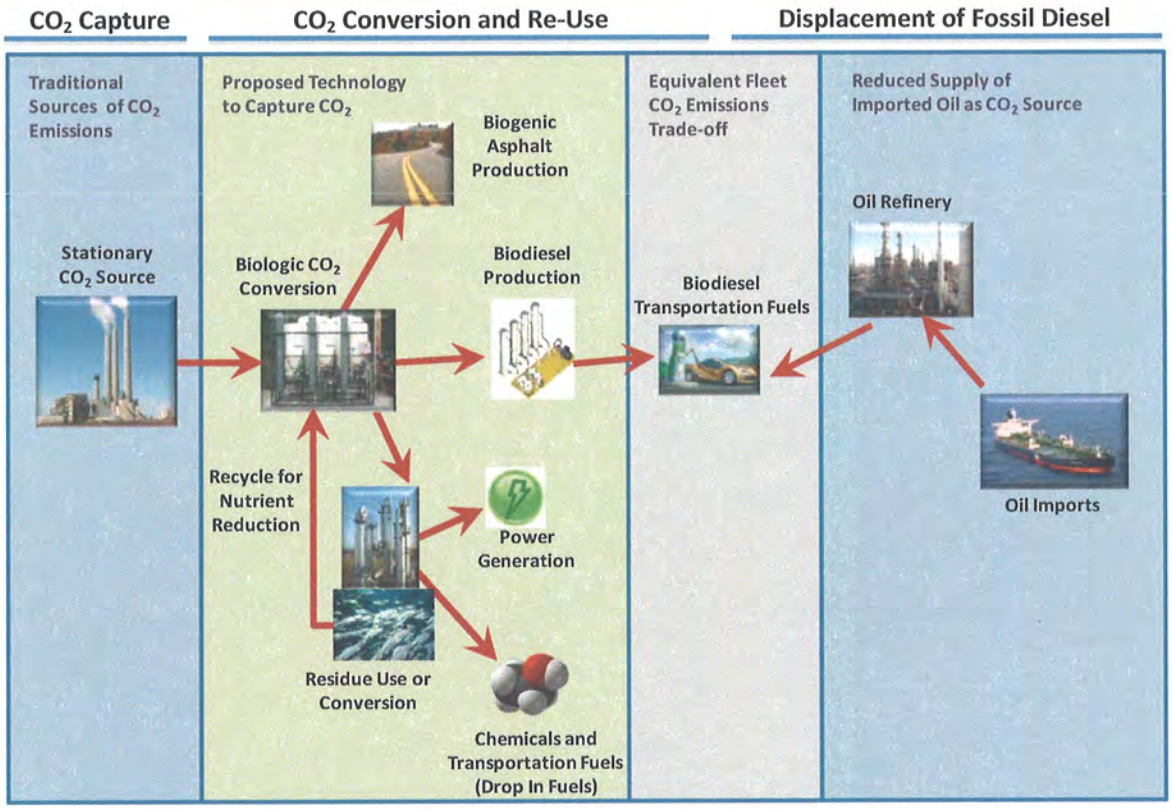


Figure B-1. CAT™ process schematic showing "Big Picture" global CO_2 reduction pathways.

The integrated societal energy system CO_2 reduction results when the synthetic diesel is used to displace conventional diesel consumption – achieving a second use of the carbon within coal prior to the eventual CO_2 emission from vehicle exhaust pipes. While the transportation sector CO_2 emissions are not directly reduced, the fact that the CAT biodiesel fuel prevented power plant CO_2 emission from entering the atmosphere we achieve an integrated societal system reduction in CO_2. A descriptive

formula comparison of Today (without CAT) and a Future (with CAT) illustrates the how an integrated societal energy system achieves lower net CO_2 emissions:

Today's Total CO_2 (without CAT) = Power Sector CO_2 + Transportation Sector CO_2 + Other CO_2 Emitters

Future Total CO_2 (with CAT) = Power Sector CO_2 <u>lowered by 80% to 90%</u> + Transportation Sector CO_2 + Other CO_2 Emitters

The CAT™ process uses chemoautotrophic bacteria (CAT bacteria) to capture and re-use carbon dioxide from flue gas, so these bacteria effectively recycle carbon that is likely from a fossil source for biodiesel production. To consume carbon dioxide from flue gas, the CAT bacteria get energy by oxidizing a reduced inorganic material. A synthetic symbiosis is then established to recycle the produced oxidized inorganic material, and this is accomplished by the use of reducing bacteria (RB). The RB consumes organic material while reducing the oxidized inorganic material. The organic material is derived from waste products from both the CAT™ process and other processes. A third type of bacteria is used to convert those waste products into organic material suitable for use by the RB (Figure B-2). RB and CAT bacteria will be harvested and further processed for biodiesel production.

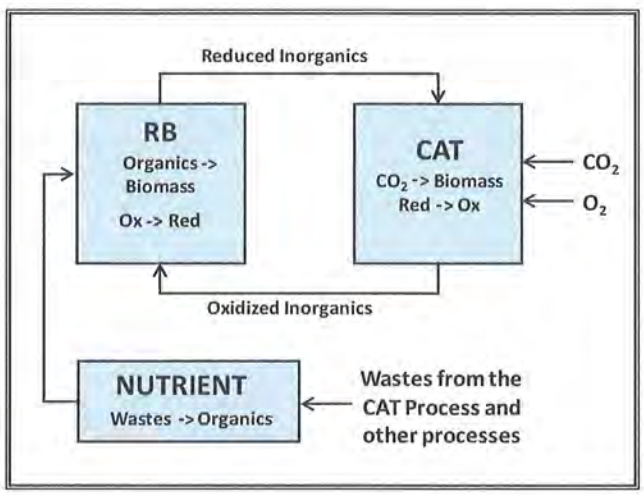


Figure B-2: Schematic of the CAT™ process.

Potential Applications. WRI has modeled the CAT™ process as an add-on to several existing technologies. The CAT™ process can be used to recycle CO_2 in various fuel emissions, such as those from coal, natural gas and biomass. This process is not limited to use with utilities but is applicable for a wide range of industrial CO_2 sources, such as cement and lime production, refineries, and others that use a fuel to produce heat and/or steam. Modeling results have shown the CAT™ process to produce approximately 53 gallons of biodiesel/ton of CO_2 captured. If the CAT™ process is used to capture carbon from a 100,000 ton of carbon dioxide per year emitter, we estimate that 5,329,930 gallons of biodiesel can be produced each year.

The CAT™ process can also be an economic driver for advanced coal-to-liquid technologies, such as gasification Fischer-Tropsch. Only 37% of the carbon entering the Fischer-Tropsch technology is converted to the liquid product, while 63% of that carbon is emitted as CO_2. If the CAT™ process is used to capture 75% of those carbon emissions for conversion to biodiesel, an additional 40% or more of the synthetic diesel could be produced. This completely changes the economics of the Fischer-Tropsch process to a more financially attractive investment.

Western Research Institute is investigating a wide range of applications for the CAT™ process in coal-based systems as well as non-coal applications.

Economics. Economic analysis performed at WRI was performed with an assumed biodiesel price of $3/gallon. Preliminary assessments of costs and revenue of a CAT™ process facility that captures 90,000 tons of carbon dioxide per year are listed in Table B-2. The calculated costs and revenues do not include potential income earned by selling carbon credits.

Table B-2. Predicted economics of the CAT™ process when deployed at a 100,000 ton of carbon dioxide per year emitter.

	Cost
Capital	$40.85M
Operation and Management	$7.6M/year
Revenue	$24.35M/year

Benefits. The CAT™ process has significant advantages over carbon capture and re-use technologies that rely on light, including many algal technologies. Table B-3 below summarizes these advantages. The independence from light of the CAT™ technology allows bacteria to be grown in deep, cylindrical reactors that can be partially buried. These reactors require significantly less capital than custom photobioreactors used by algae. In addition, the CAT™ technology uses 95-97% less land than open ponds of algae to produce the same amount of biodiesel. Since the reactors are in a closed system, unlike open ponds of algae, evaporative water losses are not an issue, which makes this technology more attractive in regions with limited water. We believe that these advantages would make this system an attractive carbon capture and re-use technology for existing stationary carbon dioxide emitters, especially power utilities and cement plants. Introduction of this biodiesel into the market would displace some of the petroleum diesel used, which in turn would slow the rate of carbon dioxide release into the atmosphere in an integrated national accounting approach.

Table B-3: Summary of benefits of the CAT™ process compared to algal technologies, particularly open ponds of algae.

	CAT™ Process	Algae
Productivities	On par with algae	On par with CAT
Reactor Type	Closed reactors, commercially available	Open raceway ponds, high surface area photobioreactors
Climatic Requirements	No particular requirements. Reactors may be insulated or buried to maintain temperature	Reduced performance in climatic extremes or locations with reduced sunlight. Reactors may require heating
Land Requirements	Relatively small footprint due to deep cylindrical reactors. A 95-98% reduction is estimated for larger CO_2 sources.	Large foot print, productivity maximized when reactors are no greater than 10-15 cm deep
Water Use	No evaporative losses	High evaporative losses

Next Steps. The CAT™ process is in the early research and development phase and has entered into the "valley of death" of the funding landscape. This technology is not brand new and thus is not eligible for many federal grants. However, since the technology is not yet at a pilot scale, industry is not as likely to be willing to invest in this stage of technology. While the Department of Energy ARPA-E program can provide funding opportunities for research and development activities through scale-up, these opportunities appear to only be available to technologies that were funded by ARPA-E at an early stage and focused on photobioconversion technologies. A funding mechanism for technologies, such as the CAT™ process, that are in this "valley of death" would accelerate the movement of promising technologies to the market.

References.

Bauer, C. *Energy Production and CO_2 Emissions: Protecting our Air Quality*. in *Air Quality VII, International Conference*. 2009. Arlington, VA.

EIA. 2009; Available from: www.eia.gov.

ATTACHMENT C

Megatrend and Overarching Market and Economic Considerations

The following Megatrend, Market and Economic Conditions are used to focus WRI research on the challenges and opportunities.

Global economy will grow lead by emerging country economies and economic trading zones. It is reasonable to expect the economy in the Organisation for Economic Co-operation and Development (OECD) countries to experience modest real growth over the next three decades, including riding well through recessionary down periods. Energy consumption is often used as a measure of economic activity. The chart from the U.S. Department of Energy, Energy Information Administration (EIA) 2013 Energy Outlook Quick Look report shown in Figure C-1 illustrates the sharp decline in U.S. energy consumption associated with the economic decline following the 2008 Financial Crisis and the resulting Great Recession. The low gradual energy growth through 2040 reflects energy efficiency gains and relatively low U.S. growth forecast for the EIA Reference Case. The forecast is flat to negative for low economic condition scenarios.

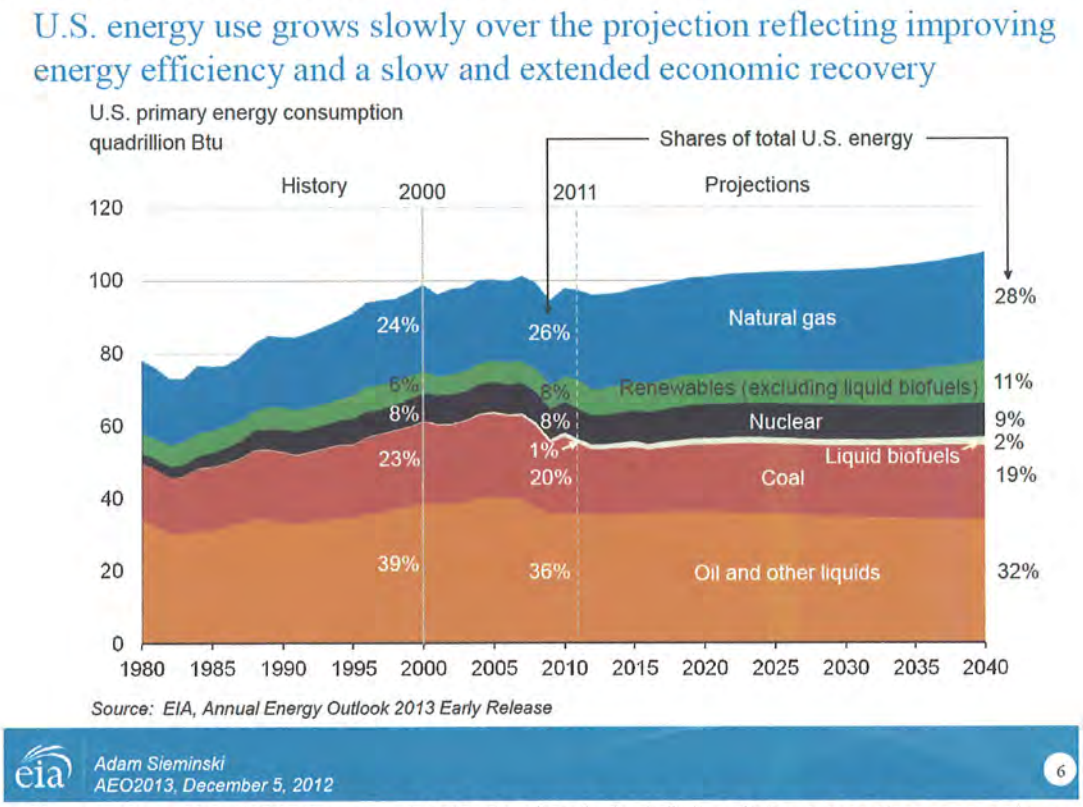


Figure C-1. U.S. DOE Energy 2013 Outlook Quick Look Energy Consumption

Figure C-2 from the U.S. EIA and Figures C-3 and C-4 from the International Energy Agency (IEA) forecasts greater energy consumption increases for emerging economies compared to the OECD countries.

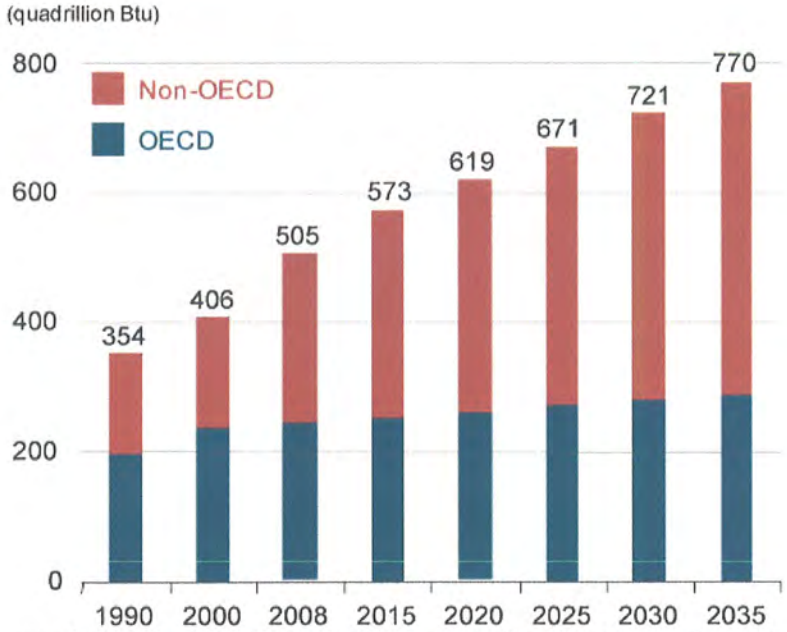


Figure C-2. U.S. DOE EIA World Energy Consumption Forecast

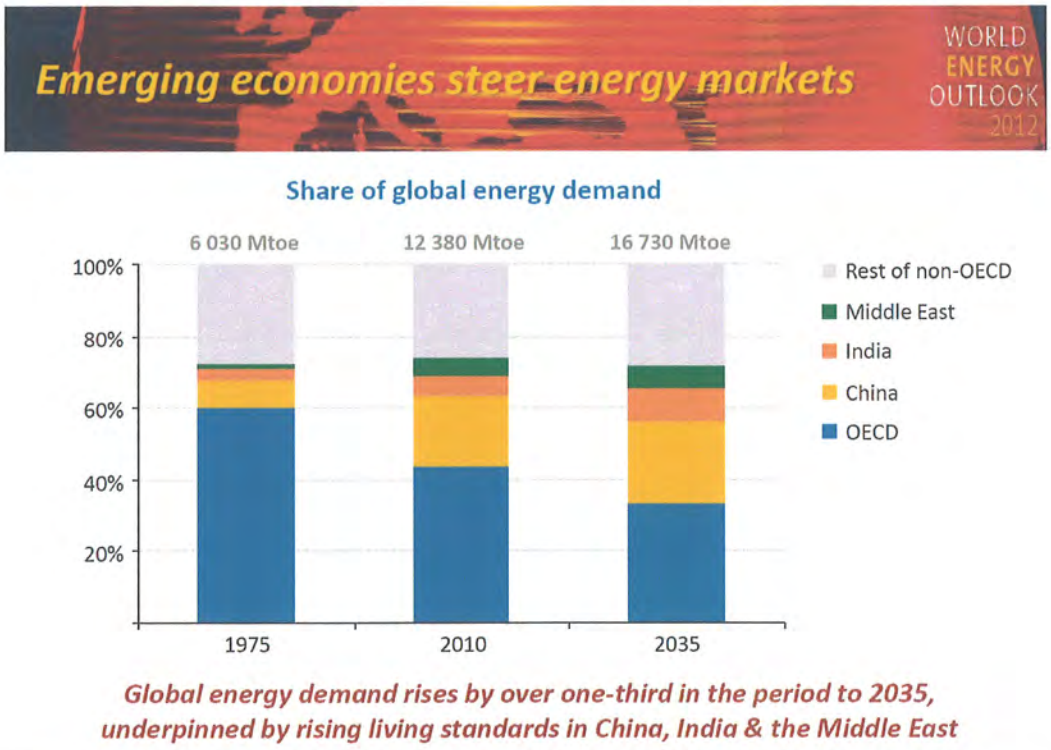


Figure C-3. International Energy Agency Global Energy Consumption Forecast

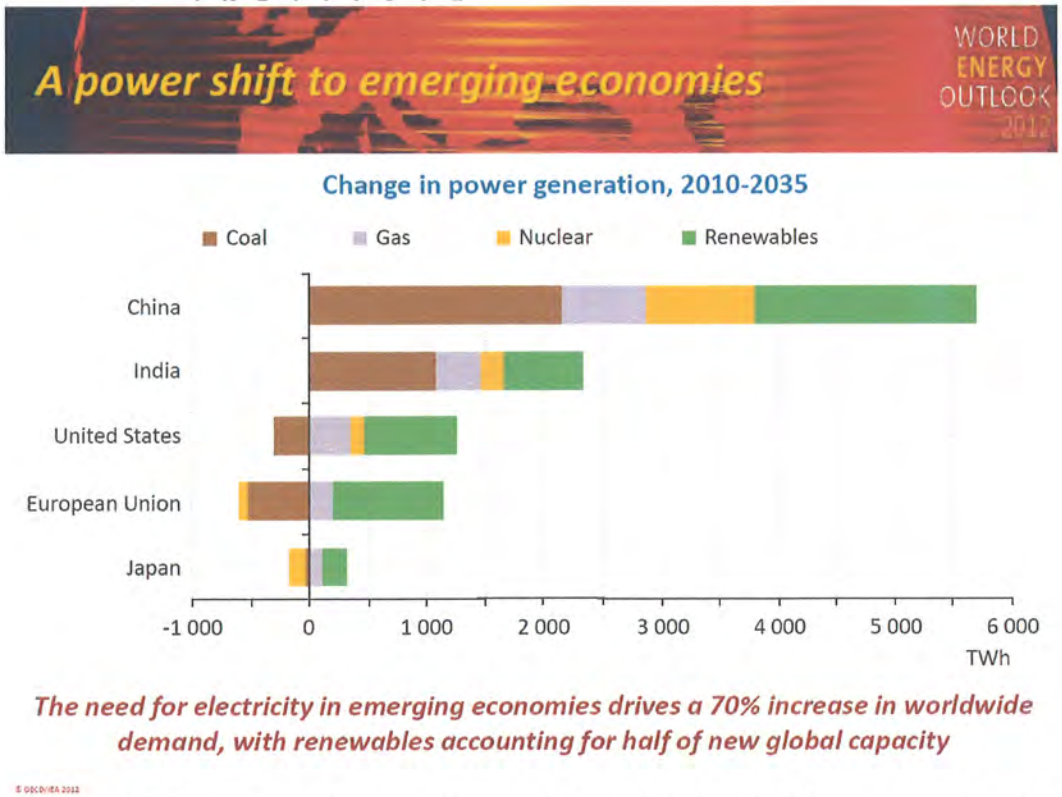
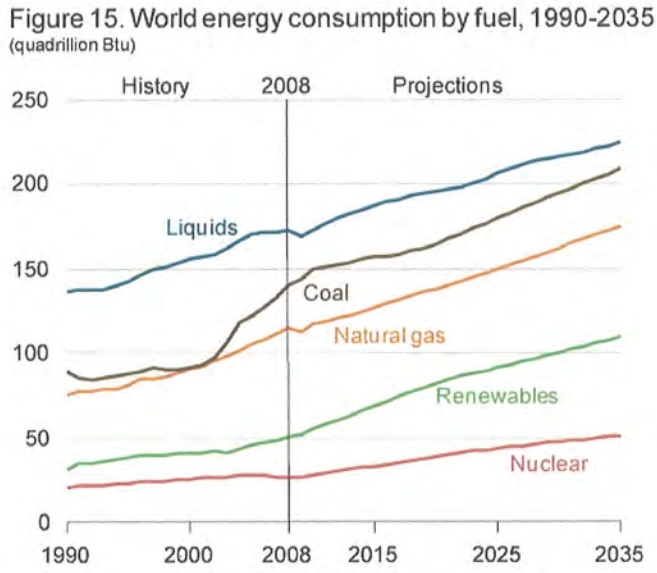


Figure C-4. International Energy Agency Global Electricity Generation Forecast

The U.S. DOE EIA global energy consumption forecast by various energy types illustrated in Figure C-5 highlights the megatrend demand for liquid energy fuels. This projection provides a clear picture and motivation to focus on recycle energy resource through multiple uses of carbon containing molecules in both fossil and biomass energy natural resources.



ATTACHMENT D

WRITECoal™ Technology – An advanced Coal-based Technology to Enhance Coal Quality, Reduce Air and Water Emissions, Increase Plant Efficiency and Reduce Cost of Electricity

Western Research Institute (WRI) with the support of the U.S. Department of Energy, National Energy Technology Laboratory (USDOE, NETL), the states of Wyoming and the North Dakota and a wide range of utilities and industry organizations[2] have been developing a novel patented and patent-pending coal treatment/upgrading and multi-pollutant emissions control technology that increases efficiency and reduces the cost of electricity (COE) for both the existing fleet of coal-fired electricity generation units (EGUs) and new coal-fired EGUs, such as Integrated Gasification Combined Cycle (IGCC) and supercritical air-fired and oxy-fired plants.

The integration of the WRITECoal™ technology into an existing nominal 600MWe subcritical low-rank coal-fired power plant or new construction plant results several benefits. A previously untapped benefit is the ability to utilize the water delivered with low-rank coals to lower power plant consumption water from community water supplies. For example, subbituminous coal may supply 720 gallons of water per 1,000 tons of coal. This amounts to approximately 300,000,000 gallons for water in Wyoming coal production that has been untapped each year.

- Recovery of the water in low-rank (high water) coals evolved from the WRITECoal™ process for use at the power plant, requiring particulate removal only[3] - an untapped water-rich resource,
- The use of plant waste heat for drying increases energy efficiency,
- Increased plant power offsets parasitic power (important with future retrofit for carbon capture options),
- Reduction of emissions, such as mercury, NOx, SO_2, and CO_2 emissions on lbs/MWh basis, as well as on a percentage removal basis,
- Elimination of the need for a combustion or partial oxidation facility at an offsite or minemouth and associated cleanup of process streams, both gas and water,
- Elimination of the spontaneous combustion or dust/fines issues associated with transporting and storing thermodynamically unstable partially dried fuel, and
- Purchase coal from a variety of producers, not from a limited number of suppliers of a low-moisture, low-mercury processed coal at a higher price.

The following provides several examples of the retrofit integration of the WRITECoal™ process with subcritical air-fired and oxy-fired plants. In addition, the performance of integrating the WRITECoal™ process into a gasification/IGCC plant application is presented. There are other coal-fired applications, such as supercritical oxy-fired EGUs and new gasification Fischer Tropsch coal to liquids plants that are applicable, but not presented herein.

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[2] Includes State of Wyoming, State of North Dakota, North Dakota Industrial Commission/Lignite Research Council, Electric Power Research Institute, Basin Electric Power Cooperative, Detroit Edison, Montana-Dakota Utilities, Alliant Energy, Southern Company and SaskPower.

[3] Since the water recovered is free of regulated trace metals and organics and with conventional suspended solids removal, it can be used in the plant without further treatment.

WRITECoal™ Process and Performance

The WRITECoal™ process is a patented and patent-pending two-step thermal coal upgrading and multi-pollutant emissions control methodology. In the first step, raw coal is heated to a temperature not exceeding 300 °F wherein the free water and most of the more tightly bound water is evaporated and removed. No evolution of mercury and other volatile metals (e.g., arsenic and selenium) occurs in this step allowing for water recovery without treatment for metal species removal. In the next step, the completely dried coal is heated to a temperature of 500-600 °F, wherein mercury in coal is volatilized and removed by an inert sweep gas. High temperature (500-600 ºF) sorbents, capable of capturing volatile metals, such as mercury and arsenic, have been developed to avoid the thermal energy efficiency loss resulting from cooling the sweep gas to 275 °F to enable conventional activated carbon sorbents to effectively capture the volatile metals. A relatively small sweep gas stream compared to plant exhaust stack gas flow is enabled by the WRITECoal™ process. This smaller volume of sweep gas creates higher volatile metals concentration that allows the sorbents to perform more efficiently compared to post-combustion emission capture in the large more dilute plant exhaust stack gas stream.

Coal Upgrading. For subbituminous coals, such as from the Powder River Basin (PRB), the WRITECoal™ process produces a coal that is low in moisture (<1.0%), low-sulfur (<0.6%), high heating value (11,000-11,500 Btu/lb), low in mercury and other volatile trace metals, such as arsenic and selenium (e.g., <0.03 ppmd mercury) and maintains a high volatile matter content and a high O_2 content compared to bituminous coal – important in integration of the process with oxy-combustion and gasification/IGCC systems.

Emission Reduction. When coupled with native capture with the fly ash and an oxidizer additive, the WRITECoal™ integrated retrofit process is estimated to achieve 87-92% mercury removal without the need for large volume post-combustion activated carbon injection (ACI)-based Hg control; and with pre-combustion physical separation technologies, such as air jig, mercury removal efficiency to consistently exceed 91%.

In addition, the WRITECoal™ product reduces NOx emissions by a dramatic 13% to 40% reduction in the flue gas. The impact of NOx emissions reduction on integration of the WRITECoal™ technology is significant from both a regulatory compliance and NOx credit perspective.

Table D-1. Characteristics of Typical Raw and WRITECoal™ Treated Low-Rank Coal.

Parameter	Wyoming PRB Coal		ND Lignite	
Proximate Analysis (wt%, as received)	Raw	WRITECoal™ Product	Raw	WRITECoal™ Product
Total Moisture	28.4	<1.0	36.55	<1.0
Ash	4.82	6.14	6.62	10.20
Volatile Matter	32.64	43.93	31.26	43.20
Fixed Carbon	34.14	48.93	25.57	45.60
Higher Heating Value (Btu/lb)	8,716	11,188	6,864	10,877
Mercury (ppmd)	0.126	0.025	0.184	0.083
Arsenic (ppmd)	4.2	1.4	10.4	6.5

Water Recovery. Another important benefit of the WRITECoal process is that it is possible to recover the water associated with the coal, typically 28-30% for PRB coals and 38-40+% for lignites found in states such a North Dakota and Texas. As mentioned the two-step WRITECoal™ process first removes water without volatile metals and other organic species, while the second step releases and captures the volatile metals from a relative low volume, dry sweep gas. The recovered water is clean with only suspended solids requiring filtration before being used within the plant. The water can supply the 50% to 60% of the boiler feed water makeup, or a portion of scrubber water or even a small fraction of the cooling water makeup water, thereby using less local water supply.

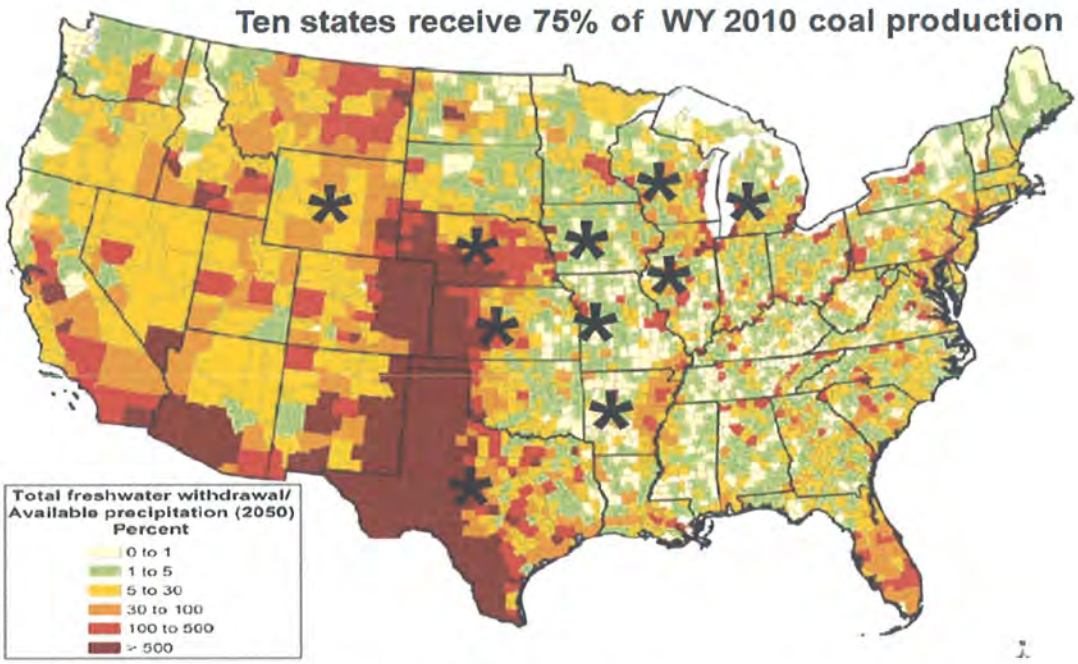

Figure D-1. National Resources Defense Council Map of US Showing the Areas of Drought Distress with Major Markets for PRB Coal Overlaid

Retrofitting Subcritical PC Coal Fleet with WRITECoal™ Technology

Retrofit Existing Fleet without Carbon Capture.

Efficiency. ASPEN Plus® modeling of the integrated WRITECoal™ retrofit based on a base case of 577MWe (net) PRB coal-fired plant and a 570MWe (net) lignite-fired plant with and without the WRITECoal™ process resulted in increased power output due to efficiency gains and the capacity to increase coal-firing. For example, it is possible to generate 34MWe (5.9%) of additional power by increasing coal feed by 4.4% for the PRB coal-fired plant and 30MWe (5.2%) additional power for a lignite plant with only a 2.2% increase in coal firing. The results showed a 3.4 to 3.6% increase in boiler efficiency gain up to 88.4% for the lignite and PRB cases with WRITECoal™ integration, translating to a 0.5 to 1.0 percentage increase in net plant efficiency. For example, a 1% increase in absolute net plant efficiency fleet-wide in coal-fired plants would result in about 60 million tons/year reduction in CO_2 emissions in the U.S.

Economics. Economic analysis (Jan 2009$) indicate that the Present Worth Revenue Requirements (PWRR) advantage for a WRITECoal™ retrofitted lignite plant was 26.3% and 11.7% compared with the same plant with activated carbon injection (ACI) and TOXECON, respectively for the lignite case and 8.2% for the PRB case compared to ACI deployed plant. The capital cost for a new subcritical 600MWe ND lignite-fired plant and PRB coal-fired plants without CO_2 capture and storage is estimated at $3,040/kWe and $2,870/kWe respectively. WRITECoal™ process total installed capital costs for the lignite-fired and PRB coal-fired subcritical plant translates into a cost of electricity (COE) advantage of 1.1 cents/kWh for the WRITECoal™ process compared to a new sub-critical lignite coal-fired plant COE of 6.7 cents/kWh.

Retrofit to Carbon Capture.

A second retrofit option is the conversion of an existing coal plant into an oxy-combustion plant with carbon capture. The conversion of the existing fleet to carbon capture results in a large increase in auxiliary power (parasitic) power and increases the cost of electricity by up to 80% with some carbon capture technologies. This results in a de-rating of the existing plant due to the fact that the plant does not have the capacity to simply increase coal throughput. As a result only options are to (1) take a major de-rating of the existing plant, (2) purchase power from a carbon capture plant to offset the parasitic power, or (3) install additional facilities like natural gas combined cycle plant to offset the parasitic power. Pilot-scale testing at 1 MWth-scale, modeling studies and costs and LCOE of an oxy-fired subcritical plant was conducted. Figure D-2 shows the mobile 1-2 MWth WRITECoal™ pilot plant integrated with a 1 MWth oxy-combustion pilot plant at Southern Research Institute.

Figure D-2. Mobile WRITECoal™ 1-2 MW_{th}-scale pilot plant at WRI that can be integrated into pilot combustion system

Efficiency and Levelized Cost of Electricity (LCOE). Efficiency modeling and LCOE of such as oxy-combustion retrofit are shown in Table D-3 and indicate that the purchasing of power does not increase efficiency and increases the COE from 6.8 cents/kWh for the raw coal case. However, the installation of high-efficiency Natural Gas Combined Cycle (NGCC) to cover the parasitic power associated with carbon capture increase efficiency by 4.85% and reduces the LCOE to 5.8cents/kWh from the base of 6.8 cents/kWh. This is a major increase in efficiency and more importantly a major reduction in the cost of electricity when deploying carbon capture to the existing fleet of coal-fired subcritical plants.

The 5.8 cents/kWh for the WRITECoal oxy-combustion with high-efficiency NGCC has equivalent LCOE of a new subcritical plant without carbon capture.

Table D-3. Summary of the Efficiency and Costs for Retrofit of Existing Subcritical Coal-fired Unit to Oxy-combustion with Carbon Capture.

	PRB Oxy-Fired with CO_2 Capture Retrofit		
Costs Jan. 2012 $	**Case 1 Base Raw**	**Case 3 W-Coal w/ Purchase Power**	**Case 4 W-Coal w/ NGCC**
Performance			
CO_2 Capture, %	90	90*	83*
Gross Power-Coal, MWe	590.0	590.0	641.5
Gross Power-NG, MWe		191.2	149.3
Net Power, MWe	401.0	401.0	592.0
Efficiency Gains over Base %	0.0	0.0	4.85
Costs			
TCR [1], 1000$** **$/kW	1,110 2,800	1,110 2,800	1,420 2,400
Fixed O&M, 1000$	24.80	24.80	32.20
Var. O&M, 1000$[4]	69.70	125.30	86.53
Total O&M, 1000$	94.50	150.10	118.80
PWRR, 1000$	1,870	2,560	2,360
LCOE, cents/kWh	**6.8**	**9.3**	**5.8**

*Assumes purchased power is from 90% CO_2 capture EGU.

WRITECoal™ Gasification/IGCC Technology New Plant Application

WRITECoal™ Gasification /IGCC. The WRITECoal™ process can also provide the industry with an economical method of environmental compliance for new plants such as IGCC using low-rank lignite and subbituminous coals, termed WRI's **"WRITECoal™ Gasification/IGCC"** technology. This patent-pending integrated technology not only improves gasifier efficiency, but also features CO_2 recycle to generate additional CO feed to the water-gas-shift reactor thereby producing additional H_2 for power generation and/or chemical production.

The WRITECoal™ gasification/IGCC technology is based on three advantages/benefits of the integrated system; (1) the reduction of moisture (to near zero percentage by weight) in the WRITECoal™ product to the gasifier results in

lower gasifier size (capital costs); (2) control of the oxidation of carbon to CO results in enhanced volume of hydrogen in syngas to the gas turbines, allowing reduced fuel feed for the same gas/steam turbine output; and (3) the WRITECoal™ process uses as much waste heat as possible and maximizes gas turbine power. The net result of these three features is a reduction in gasifier capital from a reduction in size and parasitic load from the Air Separation Unit (ASU) and increased power output from the integrated system per unit of coal feed.

The WRITECoal™ integrated gasification/IGCC generates a higher $CO+H_2$ syngas of >82% and a lower CO_2 content (~5.1%) especially advantageous for chemical production, such as H_2 production. Cold gas efficiency, a measure of the efficiency of the gasifier, is increased by 5% with the addition of WRITECoal™. The high CO and low CO_2 reflect the higher efficiency of gasification with the treated coal and the lower consumption of oxygen (Bland et al., 2012). The WRITECoal™ gasification/IGCC process can be deployed with nearly all of the commercially available gasification systems and positively impact the efficiency and ultimately the COE which varies with gasifier and IGCC subsystem selection.

Efficiency and LCOE. A summary of the performance and Levelized Cost of Electricity (LCOE) of WRITECoal™/IGCC for power production using three different gasifiers is presented in Table D-4. The data establishes that 3.28 to 4.81% efficiency increases with the three gasifiers as a result of the integration of the WRITECoal™ gasification, including moisture removal/coal upgrading and the recycle of CO_2 to the gasifier compared to the raw coal case without CO_2 recycle.

Table D-4. Summary of the Efficiency and Cost of Electricity of WRITECoal™ Gasification Scenarios

Parameter	High Temperature Gasifier			Transport Gasifier			Fluidized Bed Gasifier		
	Raw PRB	Partially Dry 6%	W-Coal™	Raw PRB	Partially Dry 18%	W-Coal™	Raw PRB	Partially Dry 20%	W-Coal™
Operating Performance									
Fuel Moisture Content, %	28.35	6.00	0.00	28.35	18.00	0.00	28.35	20.00	0.00
CO_2 Recycle to Gasifier	No	No	Yes	No	No	Yes	No	No	Yes
TOTAL POWER, MWe	589.8	585.7	607.9	645.8	610.1	639.4	605.3	590.4	610.8
Net Power, MWe	371.1	386.8	411.1	468.4	442.6	502.4	430.0	125.1	452.5
Efficiency Increase, %	0.00	2.26	**4.33**	0.00	0.0	**4.81**	0.0	0.10	**3.28**
Costs									
TCR, $/kW	5,900	5,700	5,300	4,100	4,200	3,500	4,400	4,400	4,100
Capital Costs, mills/kWh	115.00	104.49	**97.58**	41.17	42.10	**35.92**	50.07	49.91	**46.17**
Fixed O&M, mills/kWh	36.35	32.61	30.58	33.49	34.76	29.65	48.19	47.01	49.57
Variable O&M, mills/kWh	20.70	18.93	17.62	17.56	17.55	15.29	19.92	19.76	17.73
Total LCOE, cents/kWh	**17.2**	**15.3**	**14.2**	**9.2**	**9.4**	**8.1**	**11.5**	**11.7**	**11.4**

LCOE – Levelized Cost of Electricity

This corresponds to a lowering of LCOE from 17.2 to 14.2 cents/kWh for the high temperature gasifier, to 11.5 to 11.4 cents/kWh for a fluidized bed gasifier and from 9.2 cents/kWh to 8.1 cents/kWh for the transport gasifier. Part of the difference between the transport gasifier and the fluidized bed gasifier is a result of the higher operating pressure for the transport gasifier.

Conclusions and Next Steps

It has been demonstrated that the benefits of the WRITECoal™ process on retrofit and new EGUs are:

- Applicable to all low-ranks coals: Powder River Basin subbituminous and Gulf Coast and North Dakota lignites.
- In combustion systems, the WRITECoal™ upgrading technology results a 3-5 % increase in boiler efficiency and a 1-3% increase in net efficiency. A 1% increase in efficiency fleet wide in the U.S. results in 60 million tons of CO_2 emission reduction per year.
- In gasification systems, the integrated WRITECoal™ technology results in 3-5% increase in IGCC cycle efficiency.
- The WRITECoal™ multi-pollutant technology when integrated into an existing subcritical plant results in gaseous emissions reductions (e.g., NOx reductions of up to 40%) and volatile metals reductions (e.g., mercury reductions of 87-92%, arsenic of ~40%-60%, and selenium of ~25%),
- The water in the coal can be recovered and used in the plant, thereby reducing freshwater consumption[4],
- The WRITECoal™ process deployed at the power plant uses waste heat to a large degree, lowering WRITECoal™ energy costs, and
- In both retrofit of the existing fleet and construction of new coal-fired EGUs, the WRITECoal™ integration results in a lower levelized cost of electricity (LCOE), especially when 80-90% carbon capture is required.

As such, the WRITECoal™ process represents one of several important advancements/improvements in gasification for both power generation and chemical production and should be considered as one of the potential enabling technologies that will allow the industry to continue to provide the ratepayers with low-cost, low-greenhouse gas emissions coal-based electrical power. A significant component/process step is that it improves efficiency and costs of retrofitted subcritical air-fired and oxy-fired pulverized coal plants, as well as new IGCC plants each of which may be required to deploy carbon capture in the near future.

As such, WRI has demonstrated that the application pathways for the WRITECoal™- exist for both environmental and COE benefits for existing and new coal-fired plants to the benefit of the industry and the rate payers. The hereto successful research and demonstration results still requires additional support from federal and state governments and industry partners for accelerated large-scale demonstration and deployment of the technology.

Expanding on WRI's WRITECoal™ technology for application as a retrofit to existing plants, a larger-scale utility slipstream demonstration using coal-fired flue gas heating media should be pursued with PRB coal-fired utilities and cogeneration facilities. Specifically, the following recommendations are made.

- A 5 MW_{th} demonstration of the WRITECoal™ gasification/IGCC technology, such as at GTI's U-GAS Flex Fuel facility, is needed to further define and validate the commercial deployment opportunities and cost benefits, or alternatively a5 MW_{th} slipstream unit can be designed and operated at a commercial coal-fired utility site. This scale needs the financial support of the Federal government, State government and coal industry organizations as well as individual utilities.
- And lastly, it is imperative that for advanced coal technologies, such as WRI's WRITECoal™ technology, to be deployed that such deployment not result in New Source Review.

[4] Since the water recovered is free of regulated trace metals and organics and with conventional suspended solids removal, it can be used in the plant without further treatment.

ATTACHMENT E

In-situ Enhanced Biogenic Methane Production for Increased Coal-Based Gas Production Efficiency

WRI has developed an advanced system for in-situ enhanced biogenic methane production from coal using naturally occurring microorganisms that normally live in coal. This technology extends the life of current coal bed methane wells and allows the revitalization of abandoned, unproductive wells. Additionally, this technology can be used to produce methane from low-rank coal deposits and deposits beyond the reach of financially viable mining. Overall, the enhanced biogenic methane industry is involved in pilot demonstrations internationally but struggling within the United States due to a lack of clear regulations for this industry. Research regarding the environmental impacts, including affects on environmental quality and quality of produced methane, of this technology needs to be completed so appropriate regulations and monitoring practices can be established.

Coal Treatment. The activity of the naturally occurring, methane-producing microbes present in coal can be enhanced in multiple ways. First, coal can be treated to make it a more accessible food source for the microbes, and thus the microbes will produce methane at a faster rate than without the treatment. WRI has data (Figure E-1) showing that this treatment affects the structure of the coal and breaks large carbon compounds into smaller, more easily accessible carbon for the microbes to consume. The smaller compounds, circled in panel B of Figure E-1, are clearly present only after the treatment of coal. It is worth noting that once coal is treated, the treatment does not "spread" beyond the treatment zone. If additional enhanced biogenic methane production is desired, then the in-situ coal conversion zone must be treated again. At this time, it is unknown how the treatment of coal affects metals, such as mercury, that can be trapped within the structure of the coal. Research to understand the effects of coal treatment on potential reduction/avoidance of environmental hazards, such as mercury, arsenic, and other metals, is an essential research area for the establishment of regulations for the enhanced biogenic methane industry.

Nutrient Addition. Nutrients can also be added to stimulate the naturally occurring microbes to consume more coal thereby producing more methane. These nutrients could be found in common food products. WRI has found that addition of nutrients to the naturally occurring microbes in coal can stimulate methane production, but it is a combination of the treatment of coal and addition of nutrients that provides the greatest stimulation of methane production (Figure E-2). When coal is treated and nutrients are added, approximately 20 times more methane was produced in the same amount of time as compared to untreated coal with no added nutrients. Work done by WRI and others has shown that coal can be treated and nutrients added multiple times, and methane production is enhanced with each round of treatment and nutrient addition. The public may be concerned over the release of nutrients into the environment and potentially the water supply. Research regarding the effect of these nutrients on the environment needs to be conducted to understand if then what appropriate level of environmental control and monitoring should be applied.

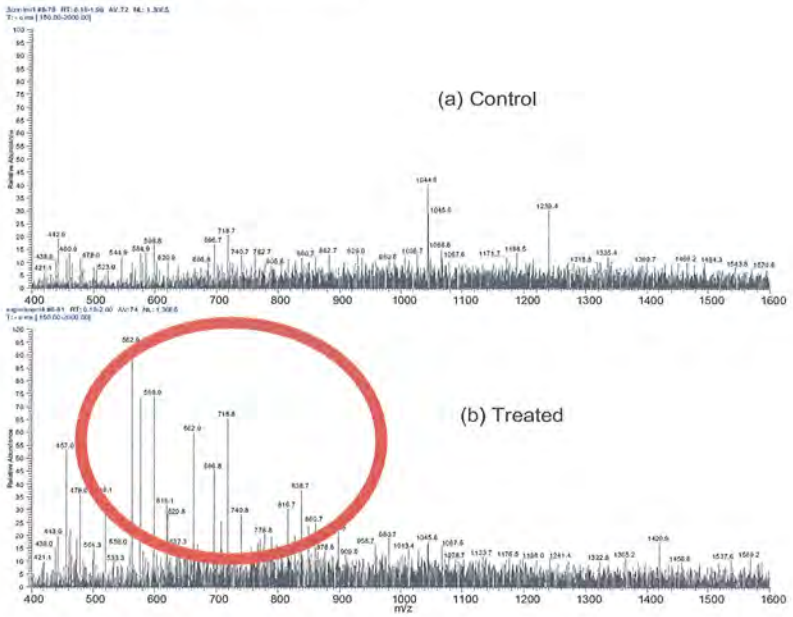

Figure E-1: Negative Ion Electrospray Ionization Mass Spectra of (a) Control and (b) Treated Water-Soluble Fraction in Coal Samples

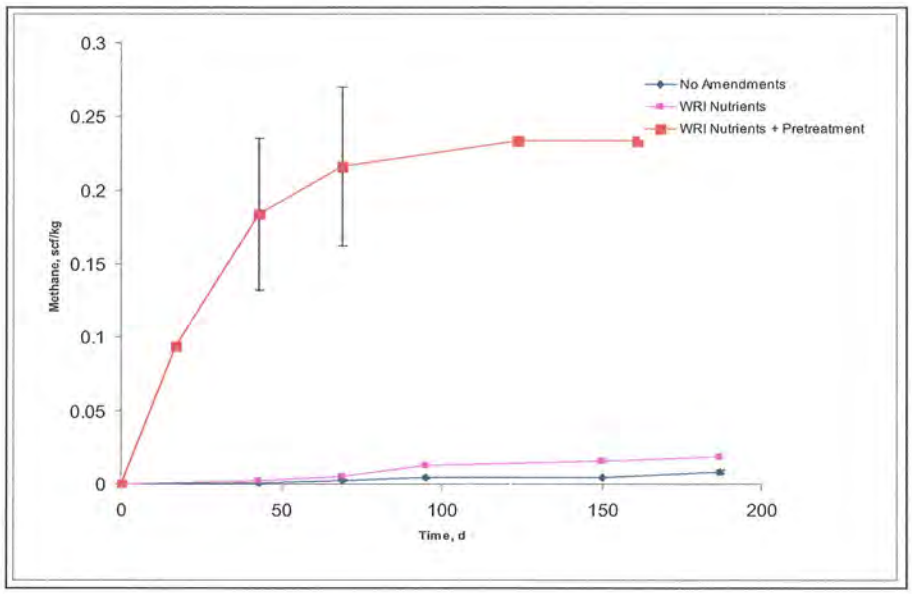

Figure E-2: Methane production was compared from untreated coal, untreated coal with added nutrients, and treated coal with added nutrients. Treatment with nutrients approximately doubled the amount of methane produced when compared to untreated coal with no nutrients. When coal was treated and nutrients were provided, the amount of methane produced was approximately 10 times greater than the amount produced when coal was only treated with nutrients.

Test Sites. United States-based enhanced biogenic methane companies are performing pilot demonstrations of this technology in other countries. A summary of enhanced biogenic methane projects are below, organized by company:

Western Research Institute (WRI). WRI, located in Laramie, Wyoming, partnered with Regal Resources Ltd. of Australia to operate at a pilot scale WRI's enhanced biogenic methane technology [1] . Pictured below in Figure E-3 is WRI's technology deployed at a pilot scale in Australia.

Figure E-3: WRI's pilot scale enhanced biogenic methane technology in Australia.

Ciris Energy. Ciris Energy of Centennial, Colorado has a 160 acre test site and other leases in Wyoming [2]. Ciris Energy has also partnered with Regal Resources Ltd. of Australia for enhanced biogenic methane production in Australia [3]. Recently Ciris Energy announced that it received approximately $25 million from an undisclosed Hong Kong investor for international expansion [3], presumably in Asia.

Luca Technologies. Wyoming was a primary target location for Luca Technologies, located in Golden, Colorado, but the company is now pursuing other locations for their pilot demonstrations after permitting problems in Wyoming.

Next Fuel, Inc. Next Fuel, Inc. located in Sheridan, WY has announced that they are "working on strategic partnership with Australian energy companies to commercialize" their enhanced biogenic methane technology, that they have a pilot scale demonstration in China, and that they have initiated field projects in Indonesia [4]. Next Fuel, Inc. also announced that they "are discussing with a few Canadian resource owners about establishing partnership to commercialize" their enhanced biogenic methane technogy [4]. In 2013, Next Fuel, Inc. announced that it had signed an agreement to conduct a pilot scale project with Vistat Oil-tech Private Ltd. in Gujarat, India [5].

Next Steps: Regulatory issues related to enhanced biogenic methane production in the United States need to be resolved to allow for industry growth and energy production using this technology. To

develop meaningful regulations, reliable answers from research are needed. Some research needs to be addressed when developing regulations for this industry include:

- Demonstrations are needed to verify the environmental impacts of this technology are needed to develop reasonable regulations for the enhanced biogenic methane technology. This includes monitoring of water quality, determination of the needed amount and location of monitoring wells, and monitoring of the surrounding coal to verify that this technology does not degrade the quality of that coal for mining.
- The regulatory agency that regulates the enhanced biogenic methane industry needs to be determined, since it is currently unclear whether it should be regulated with coal and natural gas or if it should be regulated by an environmental agency.
- The United States should examine regulations for enhanced biogenic methane production in countries that are using this technology.
- The owner of the mineral rights to methane produced from coal needs to be established. It is currently unclear if the person/entity that owns the mineral rights for the coal also owns the right for the in-situ methane produced from that coal or if it is a different mineral right since the resource being collected is methane.

References:

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3. Herndon, A. *Hong Kong Investor Backs Ciris's Microbial Coal-to-Gas Process*. 2013 [cited 2013 July 16]; Available from: http://www.businessweek.com/news/2013-02-28/hong-kong-investor-backs-ciris-s-microbial-coal-to-gas-process.
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Western Research
INSTITUTE

ATTACHMENT F

Coal Dryer Energy Enhancer: Delivering Cleaner, Higher Energy, Lower Emission Low-Rank Coal

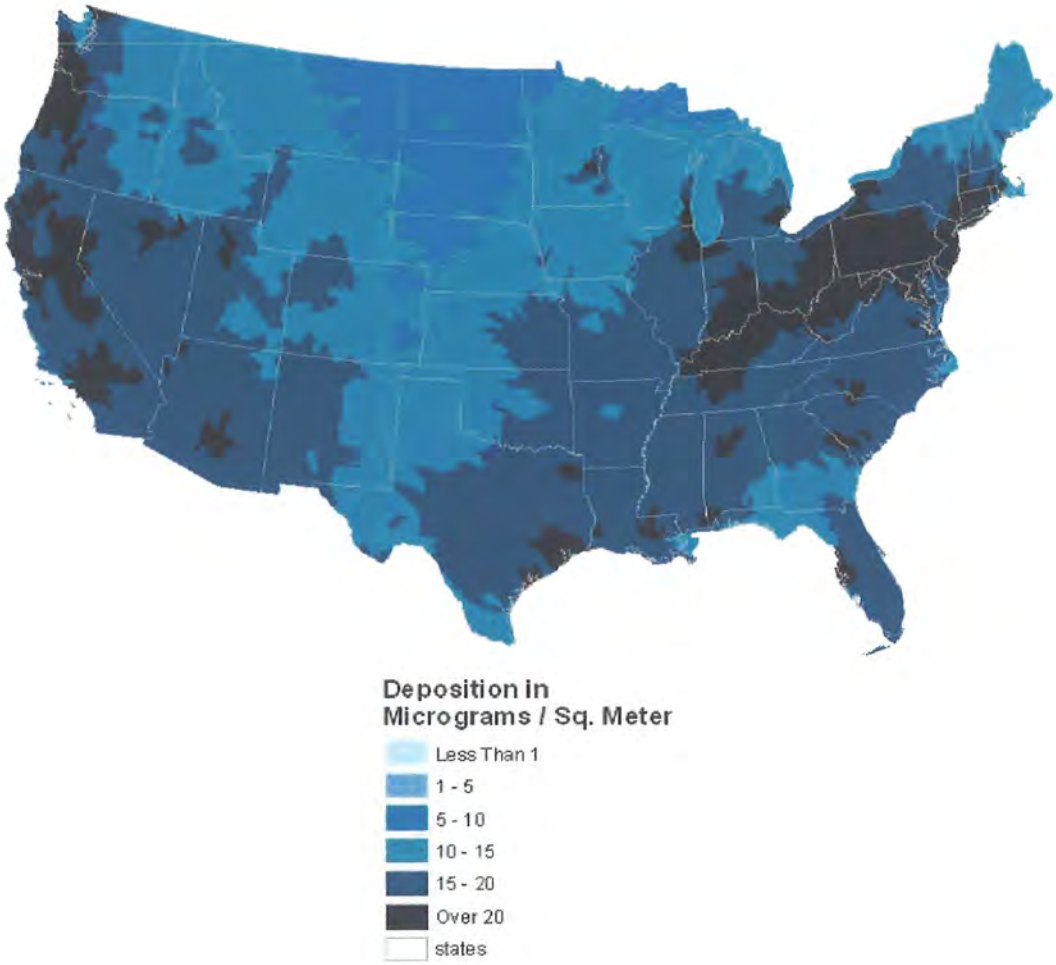
Benefits:

- ✓ Upgrades PRB coal energy value from 8,000 to 10,500-11,000 Btu/lb
- ✓ Removes ~85% of mercury and 40-60% of arsenic and selenium delivering a cleaner coal
- ✓ Low mercury coal lessens mercury capture retrofit and operational expense
- ✓ Clean Wyoming coal export lowers emissions in other countries that don't install emission controls. **Note**: More mercury lands in the U.S. each year from foreign country sources.
- ✓ Export sale enables achieving U.S. domestic mercury reduction policy goals.
- ✓ Inherently stable against spontaneous combustion without need for coating
- ✓ Increases sale price of low-rank coal ($9-11/ton) comparable to eastern coals: $30 - 50/ton
- ✓ Energy-Water Nexus: Produced water is non-toxic and is usable for Clean Air Act dust suppression at mine sites

Summary:

- WRI successfully developed a coal upgrading technology which increases marketability and environmental performance of low rank coals.
- The technology increases heating value, reduces moisture content, and reduces mercury, arsenic and sulfur constituents to allow for large scale use by coal consumers.
- Successfully designed and operated a patented process for coal upgrading, at a scale of ~100 tons/day, delivering a value-enhanced cleaner coal for power and heat generation.
- Reduces carbon footprint and other emissions while increasing energy efficiencies.
- Technology addresses energy-water nexus as the water discharge is clean and usable as-is for dust management to meet Clean Air Act dust management requirements.

Next Steps: Plans are under development to deploy the technology in Gillette, Campbell County, Wyoming. This first commercial plant for upgrading the energy (Btu) value of low rank

coal will remove 85% of the mercury from PRB coal will deliver the cleanest coal available in the world. The project is expected to create 20 jobs during the construction phase and 30 jobs during operations of the first plant. The project is expected to bring up to $50 million to the State of Wyoming during construction and job wages of $2.3 million per year during operations.

The figure below illustrates the high mercury areas within the U.S. High levels exist in the west coast states. The source for the figure is from the U.S. EPA 2005 Community Multiscale Air Quality Model. Presently, a large percentage of mercury depositing in the west coast states is attributable to coal burning power plants in China. The amount of mercury depositing in these states is expected to increase over the next few decades due in large part to predicted large growth in coal burning plants in China. The Wyoming technology described above provides a means to remove nearly all mercury from Wyoming coal that is exported to Asian markets, including China. This provides an U.S. developed technological solution to protect western states from growth in future mercury deposits while dealing with the practical reality of environmental policies in China and other Asian countries – a win for Wyoming and a win for California.