TITLE: Power Plants of the Future
21st Century Coal-Fired Steam Generator

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1.0 Introduction

The markets for new coal-fired steam generators will be driven by 21st century technologies that provide high-efficiency, low-pollutant emissions and low-cost-electricity. CastleLight Energy is a technology management firm that proposes a new **CCS Steam Generator™** (CCS SG) design incorporating the field-demonstrated **Clean Combustion System (CCS).** The CCS technology evolved from fundamental combustion research developed at Rockwell International for NASA's large moon-rocket engines.

The proposed CCS SG features a "compact furnace design with a "small foot print per $MW_{Thermal}$" and a "large MW per Ton of steel" steam capacity." These fundamental characteristics are found in the 1950's B&W cyclone wet-bottom EGU's; a low-cost steam generator design, that in its time captured a large U.S. EGU market. As important, the CCS SG uses equipment, steels, refractories and instrumentation in commercial use today on coal-fired EGU's and are very familiar to the plant operators.

2.0 Todays Coal-fired Electric Generating Unit

Figure 1 illustrates todays coal-fired EGU steam generator and the "back-end emissions control equipment" to meet EPA air quality regulations; i.e. SO_3 (Trona injection), NO_x (SCR + Ammonia), Mercury (Activated Carbon injection), Particulate (ESP or baghouse), SO_2 (Wet FGD + Limestone). This equipment comprises a significant fraction (~ 35%) of an EGU's cost, including a higher operating cost, a ~ 2% loss of efficiency (CO_2 increase) and reduced MWs of electricity delivered.

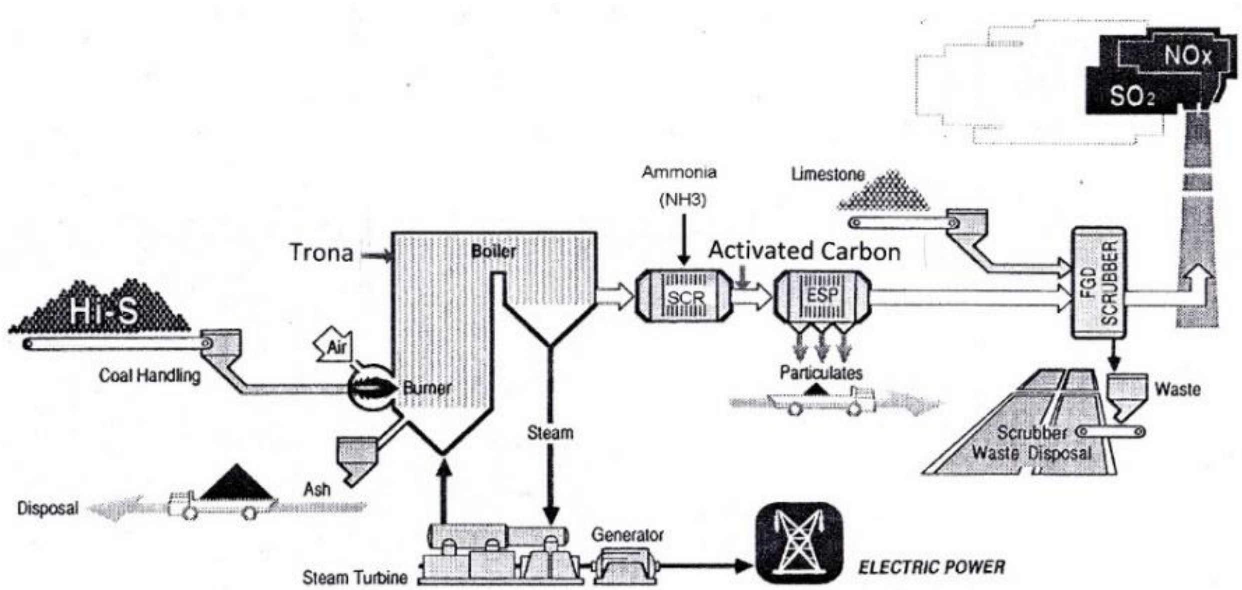

Figure 1. Today's Coal-fired Electric Generating Unit

Power Plants of the Future - 21st Century Coal-Fired Steam Generator

The U.S. EPA, through its management of the **1990 Clean Air Act Amendments (CAAA),** have set strict emissions performance limits for new coal-fired EGU's. Table 1 summarizes these emissions based on best available control technology (BACT).

Stack Emissions	SO_2	SO_3	NO_x	Particulates	HAPS (Hg)
Lb. / MW-h	1.13	< 1	0.6	0.11	~ 9 E-6
Lb. / MMBtu	0.13	< 1	0.07	0.013	~ 0.6 E-3
Parts / Million	~ 60	< 1	~ 50		

Table 1. EGU Pollution Emission Performance Targets

The U.S. EPA's recent **Affordable Clean Energy Plan** also proposes to limit carbon dioxide (CO_2) emissions from new EGU's. Table 2. summarizes the proposed efficiency targets, corresponding CO_2 emissions and unit heat rate equivalents.

Coal-Fired Generation	Units	EPA CO_2 Target	EPA CO_2 Target
MW Rating	MW	< 350	>350
Efficiency Target	%	42.1	44.6
MW-h of Electricity	Lb. / MW-hr	2,000	1,900
Heat Rate Equivalent	Btu/kWh	8,100	7,650

Table 2. EPA Proposed EGU CO_2 Emission Targets

2.1 Proposed CCS SG EGU

Figure 2 illustrates a coal-fired EGU with the CCS-SG; a coal-drying step coupled with a hybrid of coal-gasification providing SO_2 and NO_x control to meet EPA air quality regulations. Limestone is added to the coal to provide the calcium necessary for sulfur capture. Particulate control is furnished with an ESP or baghouse. The CCS-SG reports improved combustion efficiency (~ 6+%) and delivers ~10% more electricity for the same coal fired, at one-third the cost of conventional FGD + SCR systems.

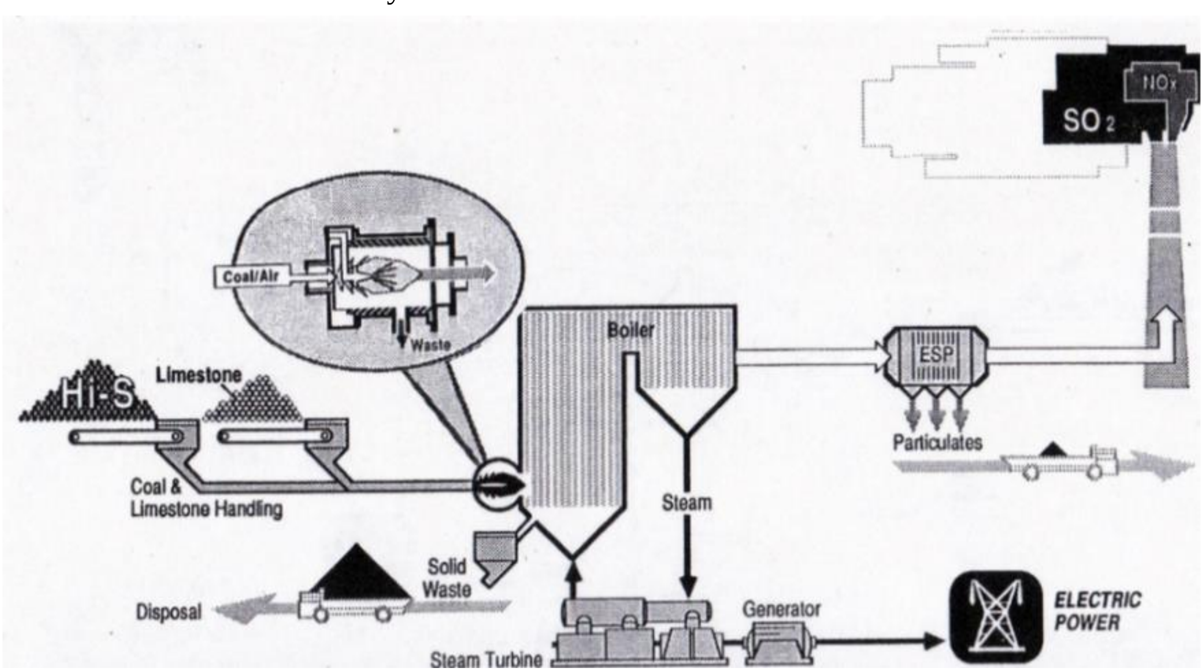

Figure 2. Electric Generating Unit with CCS SG

2.3 Coal-fired Steam Generator with Integral SO_2 and NO_x Control

The Figure 3. CCS Schematic illustrates the CCS process for SO_2 and NO_x control; a rather simple "hybrid of coal-gasification" (replacing conventional coal-burners) and in-furnace air-staged combustion. The Gasification Chamber(s) are fabricated as studded, refractory lined water-walls mounted on the boiler furnace. The water-cooled refractory surfaces become coated with coal slag to provide a reliable, renewable protective surface from the coal gasification products.

A number of CCS Burners (as required for the unit) fire pulverized coal (and powdered limestone) with very little hot combustion air into the Gasification Chamber(s), creating a hot very-fuel-rich gas as required for the CCS sulfur capture and NO_x destruction processes as described below. The high gasification temperatures melt the coal-ash, that then drains from the GC as a slag product. The hot fuel-rich gases of N_2, CO, and H_2 then exit the gasification chamber into the furnace. A clear, bright-orange gas fills the furnace to generate steam. The furnace walls remain clean, free of slagging, fouling and corrosive sulfur deposits.

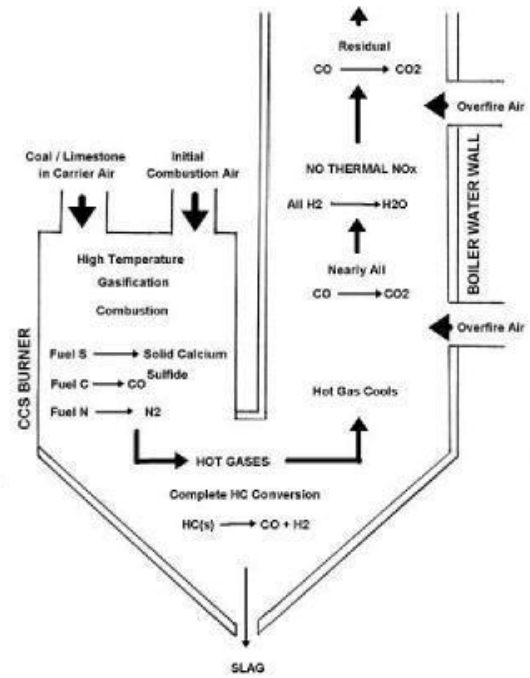

Figure 3. CCS Schematic

As the gasses cool in the furnace (> 2300 F to avoid any "thermal NO_x" formation), over-fire-air (OFA) is staged through a multiple of ports to complete the combustion of CO to CO_2 and H_2 to water (H_2O) The gasses then exit the furnace into the boiler's back pass super heater section. Figure 4 shows a CCS Gasification Chamber being installed on a 30 MW_T industrial stoker boiler.

2.4 Sulfur Capture in Combustion:

Engineers are aware that the sulfur in the coal can be captured right in the initial combustion step. For example, commercial fluidized bed furnaces (FBC), burns coal in a bed of sand and limestone (at ~1600 F), fluidized with hot combustion air. The FBC combustion process is fairly slow, (several seconds) and requires high horse-power, high pressure air blowers to circulate the fluid bed.

By comparison, the CCS combustion process is fast (fractions-of-a-second). As the carbon is oxidized, the sulfur is released from the coal into the hot gasses. The calcium (from limestone) reacts with the sulfur to form calcium sulfide (CaS), a solid particle at these temperatures.

Figure 4. CCS Gasification Chamber

The gasification temperatures are sufficiently hot to melt the coal ash (silica - SiO_2, and alumina - Al_2O_3) along with the CaS creating a liquid glass / slag product. Recall that bottle glass is a melt of silica, alumina and calcium oxide (CaO). However, since CaS has replaced CaO, the sulfur is now encapsulated and bound in the slag; it cannot leach out in water. About half of the melted coal-ash contacts the walls of the gasification chamber and drains into a water quench tank as bottom ash for disposal. The remaining fine ash droplets that carry into the furnace section solidify as fly ash particulate (~10 micron) as the gasses cool to make steam.

2.5 NO_x Formation and Destruction:

The nitrogen in the coal (~ 1%) is the major source of NO_x (~85%) from coal combustion. "Thermal NO_x", formed from oxidation of nitrogen at high temperatures (>2300 F) in the furnace comprise the balance of NO_x emissions.

In the late 1970's, combustion research by Dr. A. E. Axworthy, Principal Scientist at Rocketdyne confirmed that the nitrogen in the coal forms NO_x, or the precursors of NO_x - such as ammonia (NH_3), and cyanide (HCN), at the same time and place as the carbon is oxidized. Further, he demonstrated that this fuel-NO_x formation process cannot be avoided when firing coal; as compared thermal NO_x formation when firing natural gas.

A theory evolved to look for a process to reduce (destroy) NO_x to nitrogen (N_2). A lab furnace was set up and it was determined that calcium sulfide (CaS) compound was a gang buster NO_x destruct catalysis, especially under the fuel-rich, high-temperature conditions, such as found in the CCS. This was a remarkable discovery! Rockwell's new burner concept provided sulfur capture and synergistic NO_x destruction all within the combustion step. An SCR catalysis and ammonia (NH_3) are not needed for NO_x control. As important, follow-on CCS programs have demonstrated the CCS NO_x control process operates reliably from initial start-up to full load operation, generally reporting about 50 ppm, to meet a strict < 0.07 Lb. NO_x /MMBtu emission rate.

Figure 5. LNS Pilot-Demonstrated Emissions illustrates the field-demonstrated emissions performance of this hybrid gasification scheme firing Western low-sulfur PRB type coals:

- SO_2 < 0.2 lb./MMBtu (~ 100 ppm),
- NO_x <0.15 lb./MMBtu (~ 110 ppm)
- High efficiency (LOI <0.1 %) and near-zero (SO_3).

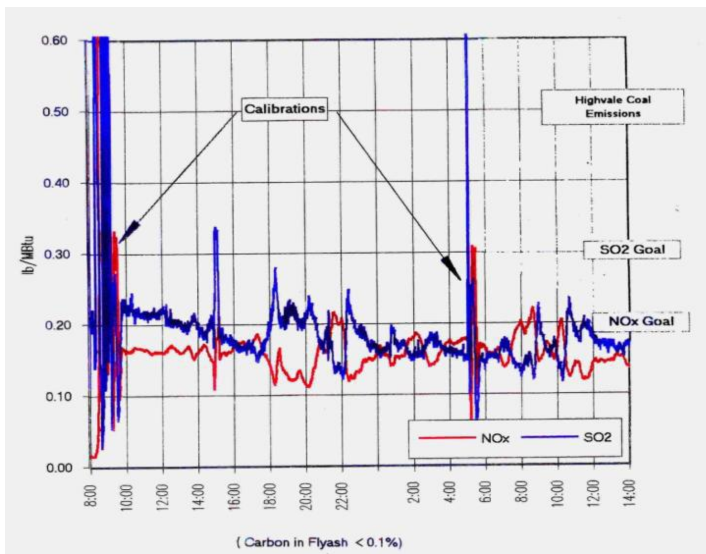

Figure 5. LNS Pilot-Demonstrated Emissions

2.6 Coal Drying to Improve EGU Efficiency

Raw-PRB coal quality is ~8,560 Btu / Lb. and includes ~30% water. This moisture carred through the furnace results in a significant "latent heat of water" energy loss. With a simple coal drying step, PRB quality is improved ~+25% to ~10,700 Btu / Lb.; i.e. resulting in ~ 3% higher combustion efficiency, reduced coal consumption, lower operating cost and lower CO_2 emissions.

Typical large (500 MW) coal-fired EGU's consume about 10,000 T/day of coal. Coal drying programs such as "Dry-Finning" require time (~30 minutes) to dry the coal, resulting very large equipment investments necessary to supply sufficient coal. Further dried PRB coal cannot be stored; it is a very reactive fuel and for safety must be consumed immediately.

Conventional "direct-fired" EGUs use coal-mills to grind the coal to a talcum like powder using hot (~ 600 F) "primary air" from the air pre-heater - as a sweep-gas to convey the powdered coal from the mill to the coal-burner(s) on the furnace.

As noted, the CCS gasification process uses very little combustion air as compared to typical coal burners, so an “indirect coal-fired system” is used, directing the coal from the mill to a small baghouse to remove the sweep gas and collect the powdered coal in a hopper.

Rather than use hot primary air for the sweep gas, the CCS uses hot (~600 F) inert flue-gas (O_2 < 10%) drawn from the EGUs exhaust – recall that the CCS exhaust gasses have near-zero SO_3. As the coal is pulverized, the hot sweep gas evaporates the coal’s surface moisture (from~30% to ~7%), safely drying the coal particles in about one second; see Figure 6. Coal Drying Scheme.

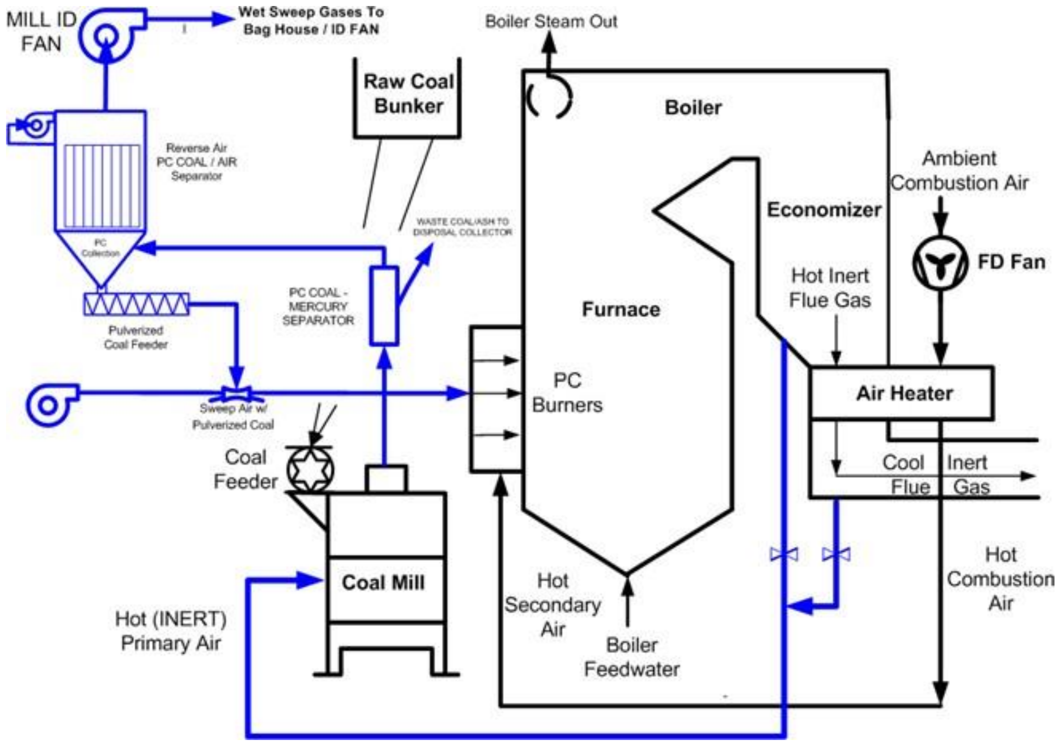

Figure 6. CCS Coal Drying Scheme

The sweep-gas conveys the pulverized coal and limestone from the mill to a small bag house (See Figure 7. Coal-Sweep Air Separator) added to each coal mill where the powdered coal is separated from the wet sweep gas. The dry powdered coal is then collected in the bag house hopper and directly metered and conveyed to the CCS burners as required to meet EGU firing loads. The now cool and wet sweep gas from the bag house is rerouted around the furnace to the EGU’s exhaust.

Figure 7. Coal-Sweep Air Separator

3.0 CCS Steam Generator©

It is generally accepted by the Utility industry that the “best Rankine Cycle heat rates” (Btu/kW-hr.) for EGUs will require super-critical high-temperature, high-pressure steam boilers. These units operate best at full loads; are limited in turn-down and require exotic (expensive) steels to survive the high temperatures. Also, today’s electric grid require EGUs be capable of rapid response to match loads that meet load variation from “renewable solar and wind” generation.

For these reasons, the proposed CCS SG is a sub-critical boiler design featuring super-critical heat rate performance (42+% efficiency, < 8100 Btu/kW-h). This design can provide wide load following; from low-load over-night operation at ~25% MCR with the ability to ramp up at ~ 4% MCR per minute to 100% MCR operation.

The sub-critical CCS SG is sized for ~ 350 MWe and operates at 2,400 psig or 2,520 psig, or as close to these pressures as can be done safely. The CCS SG will include one or two reheat steam cycles to the turbine and an efficient feed-water heater system; for example, a total of 8 feed-water heaters, one being the De-Aerator. Natural-gas, supplemented with coal co-firing will be used for start-up and warm-up duty in about 5 hours.

A 3D-view of the CCS Steam Generator configuration is shown in Figure 8. 3D-View. The CCS SG is a compact “heat-recovery furnace / steam generation section (*blue)*. that includes multiple stages of over-fire-air (OFA). There are six 50T/hr coal pulverizers (*green)* and coal-drying systems (*turquoise)*; one for each GC and its CCS Burners. Near the furnace bottom are six (6) CCS Gasification Chambers (three located on each side of the furnace - *gold*), each GC directs its hot gases into the furnace section. Each GC has four (4) down-fired entrained-flow CCS Burners, for a total of 24 CCS Burners. Each CCS Burner is sized for ~150 MMBtu/hr.

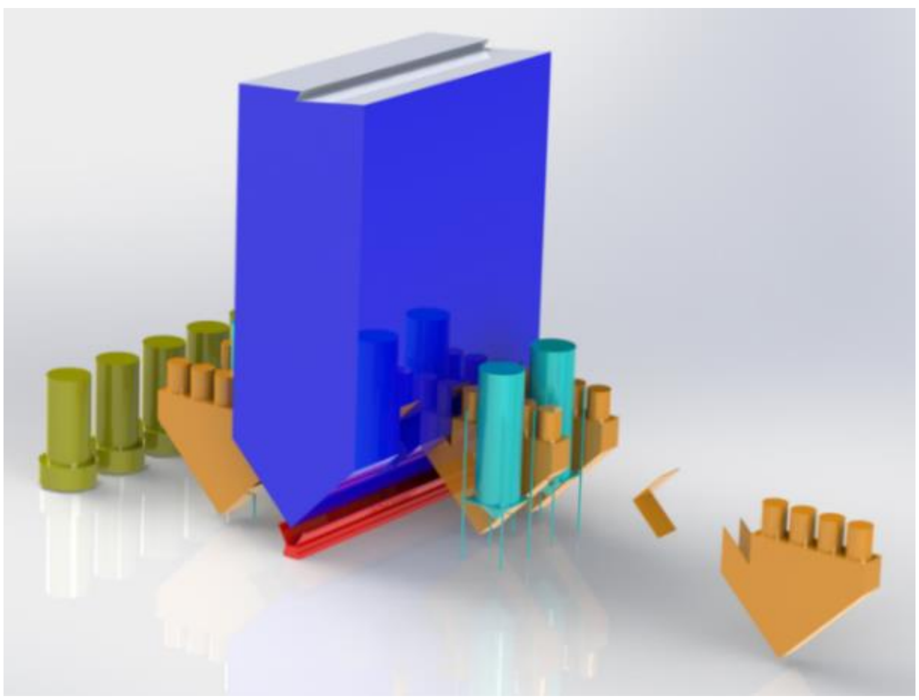

Figure 8. 3D-View of CCS SG

The hot gases from the GC must make a 180 degree turn to enter the furnace. Each GC includes water-cooled slag screens that remove half of the liquid ash, which then drains into a water quench tank under the GC. A wet-drag-link system conveys the ash/slag into a dumpster for disposal. This slag product has commercial values of ~ $3/T; for roof grit, etc. and is suitable for grit blasting metal as it doesn’t cause silicosis.

The CCS SG will fire PRB Sub bituminous and Lignite - low sodium coals to meet the strict EPA air quality regulations for a new coal-fired EGU; i.e. SO_2 emissions (<0.13 Lb. SO_2 / MMBtu, ~ 66 ppm), NO_x emissions (< 0.07 Lb. NO_x/ MMBtu, ~ 50 ppm). A bag house is required for fly-ash particulate control (< 0.13 Lb./MMBtu).

4.0 EGU Steam-Turbine-Generator and other Rotating Machinery:

To optimize the EGU efficiency objectives, the Steam Turbine-Generator and other large rotating equipment will be designed for high efficiency service. CastleLight recommends the design criteria presented in the report by Dr. Melvin Giberson – President, **TRI Transmission & Bearing Corp**: "Program for Coal-fired Electrical Generation Units to Maximize these Objectives: - Boiler Efficiency - Electrical Generation (kW) for a Given Fuel Rate (Btu/hr), - Reliability and Availability, as well as Operability."

5.0 CCS SG Commercialization Path

As mentioned, the cost for a coal-fired EGU includes FGD and SCR pollution emissions control. As the 21st century CCS SG does not require this equipment, it is expected to save an EGU about ~35%, compared to conventional boiler technology.

For commercialization, CastleLight recommends forming an investor group to acquire a PRB coal-fired power plant (100 to 200 MW with its Title V permit current). This organization can then re-engineer the plant with the CCS technology. As an emissions reduction program, the CAAA provides construction permits with waivers of New Source Prevention Standards (NSPS) and Prevention of Significant Deterioration (PSD) with no New Source Review (NSR) trigger. Table 3 shows such a CCS Re-engineering project can make a coal-fired EGU competitive with that of a new NG-fired Gas Turbine (NG @ $3.00/MMBtu).

Table 3. 400 MW - CCS Re-engineered SG vs NG GTCC

Technology @ 80% CF (Est.)	CAPx ($/kW)	Fuel ($MW-h)	Fixed + Variable O&M ($/MW-h)	LCOE ($/MW-hr.)
CCS Re-Engineered w/Efficiency Mods (412 MW Net)	620	19.81	2.47	33.40
New NG Fired GTCC Plant @ 60% eff. (400 MW Net)	1525	16.61	0.68	37.70

With commissioning, testing and tuning for optimum performance, and a few years of operation, the first CCS Steam Generator EGU may then be sold to recover the investment. Thus, proving CSS Steam Generator™ a commercial system for use world-wide.

Keith Moore

CEO – Castle Light Energy Corp.

Business Development &Technology Management

Mr. Moore focuses on strategies to mitigate / control pollution emissions from coal-fired electric generating plants to meet U.S. EPA's stringent air quality regulations.

Mr. Moore has 30 years of technical, business development and management of advanced environmental control technologies;

Dry Flue Gas Desulfurization Systems (Dry FGD scrubber), including development and commercialization

The Clean Combustion System (CCS): a field-demonstrated hybrid of coal-gasification and combustion for control of SO_2 and NO_x emissions with improved efficiency,

Coal Beneficiation Processes – Remove water, ash and recover oil values from coal,

He holds patents for Sulfur Capture and Coal Beneficiation.

B.S., Electrical Engineering, Virginia Polytechnic Institute
General Contractor - "B" License, State of California
Pilot – Commercial / Instrument, IGI; SEL, Glider

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