**Presented at the Fourth International Conference on Greenhouse Gas Control Technologies, Interlaken, Switzerland, 1998**

# A Power Plant Concept Which Minimizes The Cost Of Carbon Dioxide Sequestration And Eliminates The Emission Of Atmospheric Pollutants

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## ABSTRACT

This paper describes an electric power generating plant that minimizes the cost of isolating and sequestering carbon dioxide. The steam power plant operates on fossil fuels in which the atmospheric pollutants associated with the burning of fossil fuels are eliminated. A working fluid, composed by volume of 90% steam and 10% carbon dioxide in the case of the stoichiometric combustion of methane and oxygen at design conditions, is created in a steam generator.

The key elements in the process are: 1) a process to separate oxygen from air; 2) a method to introduce the oxygen and the gaseous fuel into a combustion chamber of a steam generator; 3) a method to control combustion temperature by the rate of cooling as a result of water injection; 4) a steam turbine and electric generator set to produce electricity; 5) a condenser in which carbon dioxide is separated from water; and 6) a process to pump the carbon dioxide into an injection well. Total capital installation cost of a 400 MW plant is $290 per kW. Electricity cost is $0.031/kWhr with carbon dioxide sequestering. The design and the economic analyses for 100 MW and 400 MW plants are discussed.

## INTRODUCTION

This paper describes a newly patented electric power generating process [1-5]2 that allows disposal of carbon dioxide ($CO_2$) and other exhaust gases into an injection well at an overall electric power generating cost that is competitive in today¹s market. For typical 50 to 500 MW fossil fuel electric power generating plants, the incremental energy required to inject the exhaust gases into an injection well is approximately 20 to 28 %. [6] In the case of the Clean Energy Systems, Inc. (CES) process the incremental energy required to sequester the exhaust gases is 3.4 %.

The CES process is based on the combustion of a hydrocarbon fuel with oxygen in a steam generator. For the purpose of this discussion, the hydrocarbon fuel will be considered to be natural gas (methane, $CH_4$), although the process is not limited to the combustion of natural gas, but could include, for example, gasified coal. In the CES process, the nitrogen and other gases are removed from air prior to combustion to make oxygen available for combustion.

The combustion products of methane and oxygen are $CO_2$ and water ($H_2O$). These combustion products power several turbines and then are delivered to a condenser. The $CO_2$ readily separates from the $H_2O$ in the condenser. The nearly pure $CO_2$ then is pumped into an injection well, while a portion of the condensed water is recycled to the steam generator. A unique feature of the CES process is that the energy penalty of separating the $CO_2$ and pressurizing the $CO_2$ to an injection pressure of 20.7 MPa (3000 lb/in$^2$)) is an acceptable 3.4 %. Although in the case of a conventional power plant, the $CO_2$ and oxides of nitrogen ($NO_x$) could be separated from the exhaust gases, that separation is difficult to accomplish completely at a competitive cost. [7]

The capital and operating costs of a CES power plant are less than that of a combined cycle power plant and the thermal efficiency is higher. On the other hand, separation of oxygen from air requires an oxygen plant and power to operate the plant. These two factors increase electric power generating costs. The stoichiometric combustion of $CH_4$ with oxygen ($O_2$) at 2.07 MPa (300 lb/in$^2$) gives rise to combustion products of $CO_2$ and $H_2O$ and a combustion temperature of 3187°C (5769°F). [8] This temperature permits a thermodynamic cycle to operate at a high Carnot efficiency. CES envisions that its technology will permit plant efficiencies of 67%, by operating future turbines at a temperature of 1760°C (3200 °F) and at a pressure of 22.1 MPa (3200 lb/in$^2$) using a Rankine cycle. For a temperature of 1760°C (3200 °F) the Rankine cycle provides a higher attainable efficiency (77.2%) than a combined cycle (67%). [9]

The turbines that operate at the above high temperature could become available in the next five to ten years. The U.S. Department of Energy has funded successful development and testing of a steam turbine that operates at an inlet temperature of 816 °C (1500°F) and a pressure and 10.3 MPa (1500 lb/in$^2$). This technology is applicable to the high-pressure turbine, while the aeroderivative cooled-blade technology (1427 °C, 2600°F) is readily transferable to the high-pressure and intermediate-pressure turbines featured in the CES system.

## ANTICIPATED BENEFITS OF THE CLEAN ENERGY SYSTEMS TECHNOLOGY

The CES technology permits large-scale industrial power generation with zero exhaust gas emissions to the atmosphere at a competitive cost. The benefit of zero gas emissions to the atmosphere has been well documented and has been reiterated at the 1997 Kyoto Conference in Japan. Under the Kyoto Protocol, the United States would cut its emissions of greenhouse gases (such as $CO_2$) to 7% below 1990 levels. The yearly cost to the U.S. economy could range from $50 to $250 billion. [10]

The Environmental Protection Agency and Harvard School of Public Health analyses of morbidity and air quality conclude that 64000 Americans die prematurely every year because of illnesses made worse by air pollutants. [11] These figures have been developed through statistical analyses, both prospective and retrospective, of mortality in large populations comparing days of high and low air pollution. Most notable was a study by Harvard researchers over a period of seventeen years which tracked premature deaths in six U.S. cities. [12]

Despite air quality improvements, particularly through lowering automobile emissions, the American Lung Association reports that 66 per cent of Americans live in areas failing to meet the National Ambient Air Quality Standards. [13] The hazardous air pollutants are ozone, particulate matter, carbon monoxide, sulfur dioxide, nitrogen dioxide, and lead. Electric power generating plants are significant contributors to the sulfur dioxide and nitrogen dioxide pollutants.

Sulfur dioxide is a gaseous compound formed by the burning of sulfur-containing fossil fuels, such as coal and oil. For most healthy people, sulfur dioxide is a temporary irritant which in some cases can become a persistent aggravation including triggering of asthma attacks. [14-16]

In the case of children, studies have found that increased levels of sulfur dioxide in conjunction with particulate matter may trigger deficits in lung function. [17,18]

Oxides of nitrogen ($NO_x$) pose a direct health threat itself as well as play a major role in the formation of photochemical pollutant ozone. [19] Nitrogen dioxide is converted into fine nitric acid aerosols and causes severe damage deep within the lungs. According to the American Automobile Association, automobiles produced 19 per cent of national $NO_x$ emissions in the year 1970, 12 per cent in 1997, and are projected to produce 11 per cent in the year 2005. [20] Industrial sources, including electric power generating plants produce the remainder.

A study was made in Sao Paulo, Brazil of the effect of respirable particles, oxides of nitrogen, sulfur dioxide and carbon monoxide on mortality of elderly persons of 65 years and older. An increase in respirable particles to 100 micrograms/$m^3$ increased overall mortality by 13 per cent. [21] Data collected in a Beijing, China hospital in 1995 indicated that between the most polluted days and the least polluted days nonsurgery outpatients visits increased by 20 per cent as a result of an increase in sulfur dioxide concentration in the air and increased by 17 per cent as a result of an increase in total suspended particles. [22]

In 1995, the U.S. electric power generation industry installed production base totaled 716 GW ($0.72 \times 10^6$ MJ/s). [23] In the next five years, 25 % of the electric power generating plants in the U.S.A. will reach their life span and will need to be replaced. [24] If all the plants that reach their life span in five years were replaced by plants based on the CES non-polluting technology, yearly $NO_x$ emissions would be reduced by approximately $1.6 \times 10^9$ kg ($3.5 \times 10^9$ lb) and $CO_2$ emissions by $0.5 \times 10^{12}$ kg ($1.1 \times 10^{12}$ lb) thereby reducing health hazards, global warming and medical treatment costs of persons affected by pollution related illnesses. Furthermore, this electric power plant replacement would make a substantial contribution to the U.S. goal of reducing greenhouse gas emissions as agreed upon at the 1997 Kyoto Conference.

## DESCRIPTION OF THE CLEAN ENERGY SYSTEMS PROCESS

A schematic diagram of the process is shown in Figure 1. An air separation plant is used to separate oxygen from air. These plants are in operation in numerous locations throughout the world. Oxygen from the plant and natural gas are compressed and are delivered to a steam generator and reheater. Figure 2 is a schematic diagram of the steam generator.

The combustion gases, consisting of approximately 90% $H_2O$ and 10% $CO_2$ by volume, are delivered to a high-pressure turbine. After expansion through the turbine, the gases flow through a second steam generator, called a reheater, to increase the temperature of the $CO_2$ and $H_2O$ mixture and thereby increase the cycle efficiency. The gases are then delivered to an intermediate-pressure turbine and after that to a low-pressure turbine. The turbines drive an electric generator to generate electricity. The pressures and temperatures at the various locations of Figure 1 are shown in the table of the figure. In the near-term, the cycle will have an efficiency of 56%, while in the long-term, when the high-temperature turbines are available, the cycle efficiency will range from 63 to 67% depending on the unit size.

After the gases have passed through the turbines, they are delivered to a condenser that provides the low temperature sink of the thermodynamic cycle. In the condenser, most of the $H_2O$ condenses and the $CO_2$ separates from the gaseous mixture. Part of the condensed water is recirculated to the steam generator to control the temperature of the combustion process. The remaining water is a useable by-product. A compressor takes the low pressure, humid $CO_2$ from the condenser and compresses it to a higher pressure via a heat exchanger that condenses additional $H_2O$ from the $CO_2$. The $CO_2$ is compressed to the required downhole pressure and is delivered to an injection well.

Any sequestering of $CO_2$ generated either in a conventional power plant process, or in the CES process, will require energy. The energy penalties for the separation of $CO_2$ and pressurizing the $CO_2$ to an injection pressure of 20.7 MPa (3000 $\text{lb/in}^2$) for various processes are given in Table 1. The energy penalty for the CES process is 3.4 per cent compared to 20 to 45% for other fossil fuel plants. Furthermore, the CES process does not exhaust any $CO_2$ nor $NO_x$ to the environment. Conventional power plants cannot economically separate the $CO_2$ completely from the exhaust gases and will emit approximately 15 per cent of the $CO_2$ to the environment in addition to emitting $NO_x$ to the environment.

Table 1 - Comparison of Power Plant Energy Penalty for $CO_2$ Injection into Injection Well.

| Plant Type, 100 MW Size | Energy Penalty, % Output Power |
|---|---|
| CES Cycle | 3.4 |
| Combined Cycle | 20 |
| Gas Turbine Cycle | 28 |
| Conventional Steam Cycle | 41 to 45 |

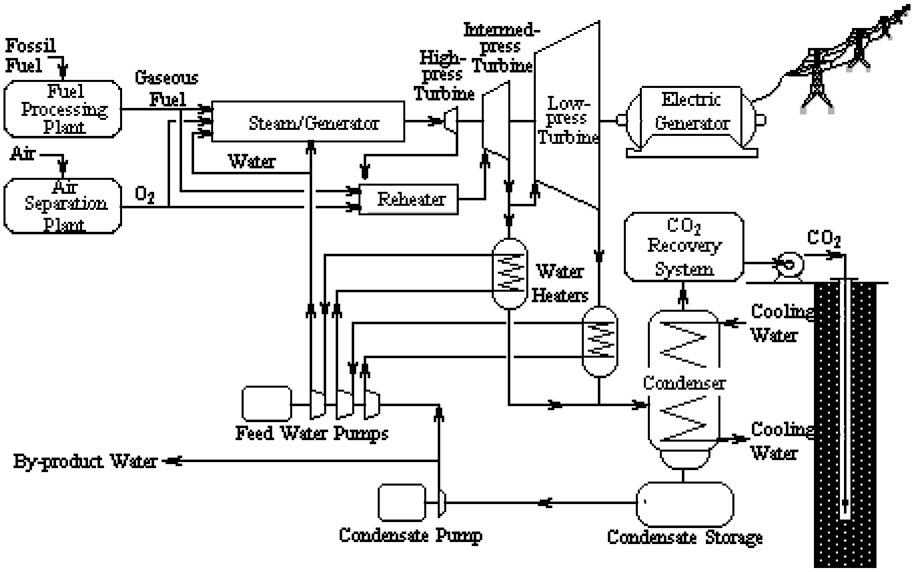
## CARBON DIOXIDE INJECTION INTO AN INJECTION WELL

Injection of $CO_2$, or carbonated brine, into subterranean formations has been used by the oil industry for more than a half century for the enhancement of secondary oil recovery. [25-28] The process of injecting $CO_2$ from an electric power generating plant into a subterranean formation needs to be carried out at minimum cost, rather than to recover oil. Hence, optimum injection conditions may be different from the conditions governing enhanced oil recovery

Major commercial $CO_2$ injection projects carried out in the U.S. have shown that $CO_2$ can be successfully injected into sandstones, limestones, dolomites and cherts. The depths of injection have been from 610 m to 3292 m (2000 ft to 10800 ft) although no depth limitations are known. Formations with permeabilities as low as 0.2 md and thicknesses ranging from 2.44 m to 183 m (8 ft to 600 ft) have been used. The porosities ranged from 8 to 31 per cent. [28]

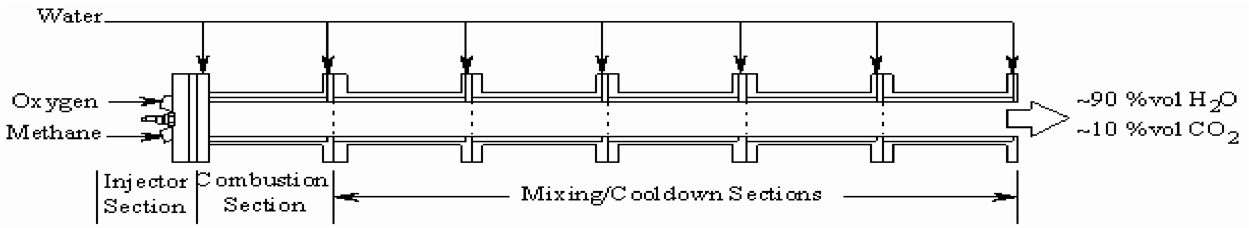
The National Petroleum Council developed a relationship for estimating $CO_2$ miscibility pressure and generated formation fracturing guidelines that have been successful in the past. [27] These guidelines can be used to avoid fracturing of the formation. Several investigators have modeled $CO_2$ injection using computer codes. [29,30] Factors used in these computer codes can be used to develop the economics of the CES process with $CO_2$ sequestration. Several field studies have been made of $CO_2$ injections into subterranean formations [31,32]

Figure 1. Schematic Diagram of CES Electric Power Generating Plant with $CO_2$ Injection into an Injection Well.



| Near-Term and Long-Term Conditions of CES Cycle | | |
|---|---|---|
| Location | Near-Term, 56% Efficiency | Long-Term, 63 - 67% Efficiency |
| Steam generator | 8.27 MPa (1200 lb/in$^2$) - 871°C (1600°F) | 22.1 MPa (3200 lb/in$^2$) - 1760°C (3200°F) |
| Reheater | 827 kPA (120 lb/in$^2$) - 1427°C (2600°F) | 1.5 MPa (218 lb/in$^2$) - 1760°C (3200°F) |
| Turbine Discharge | 82.7 kPa (12 lb/in$^2$) - 899°C (1650°F) | 101 kPa (14.7 lb/in$^2$) - 1060°C (1940°F) |

Figure 2. Schematic Diagram of the CES Steam Generator.



## COMPARISON OF ELECTRIC POWER PLANT PERFORMANCE AND ECONOMICS

Table 2 presents a comparison of the electric power generating costs of plants using both the CES cycle and the gas turbine combined cycle. The comparison is made for plants of 100 MW and 400 MW in size. The plants are assumed to have higher efficiency than plants that are in operation today. The pressures and temperatures at various locations in CES plants operating at near-term and at long-term conditions are given in the table of Figure 1.

The cost of injection of the $CO_2$ into an injection well needs to be integrated with the costs of operation of the power plant. To accomplish this, the costs of the various components of the power plant, the cost of operation of the plant in terms of fuel cost, labor, and amortization must be known. [33]

In Table 2, the contribution of capital installation cost to the overall cost of electricity generation is based on a plant life of 20 years, a fixed charge of 11% per year and a utilization factor of 85%. The cost of oxygen for the CES cycle is based on the purchase of oxygen from an oxygen separation plant located at the power plant site. The cost of $CO_2$ sequestering is based on pressurizing the $CO_2$ to 20.7 MPa (3000 lb/in$^2$) and injecting the $CO_2$ into an injection well located at the plant site. In the case of a plant operating on a combined cycle process, the sequestering cost includes the separation of $CO_2$ from combustion products. For the combined cycle it is assumed that 85% of the $CO_2$ and $NO_x$ can be separated from the combustion products at a competitive cost. The last two lines of Table 2 present the electricity cost in $/kWhr for plants without and with $CO_2$ sequestering.

For a 400 MW CES plant, the electricity cost is $0.030/kWhr without sequestering and $0.031/kWhr with $CO_2$ sequestering. The corresponding costs for a combined cycle are $0.028/kWhr without sequestering and $0.034/kWhr with $CO_2$ sequestering. Sequestering of $CO_2$ in the CES process increases electricity cost by approximately 3%. As plant sizes decrease, the economic advantage of the CES process becomes more pronounced.

Table 2. Comparison of Operating Costs of CES Cycle and Gas Turbine Combined Cycle

| **Plant Operating Factors** | **CES Cycle** | **Combined Cycle** |
|---|---|---|
| Capacity (MW) | 100---------400 | 100-------- 400 |
| Thermal Efficiency (%) | 63---------- 67 | 50--------- 60 |
| Capital Installation Cost, ($/kW) | 460---------290 | 740 --------60 |
| Natural Gas Cost ($/kg) | ---- 0.139 ---- | ----- 0.139---- |
| Oxygen Cost, ($/kg fuel) | 0.088---- 0.070 | ------ 0.00------ |
| $CO_2$ Sequestering Power (% of Output Power) | 3.4-------- 3.2 | 20.3------- 17.0 |
| Emissions of $CO_2$ (kg/MWhr) with sequestering | ------ 0.00------ | 60--------- 50 |
| Emissions of $NO_x$ (kg/MWhr) with sequest. | ------ 0.00 ------ | 0.014 to 0.055 |
| Unit costs | | |
| Capital Cost ($/kWhr) | 0.008----- 0.005 | 0.013----- 0.008 |
| Fuel Cost ($/kWhr) | 0.027----- 0.023 | 0.020----- 0.017 |
| Maintenance Cost ($/kWhr) | 0.004----- 0.002 | 0.005----- 0.003 |
| Total Cost Without $CO_2$ Sequestering ($/kWhr) | 0.039----- 0.030 | 0.038----- 0.028 |
| Total Cost With $CO_2$ Sequestering ($/kWhr) | 0.040----- 0.031 | 0.048----- 0.034 |

## CONCLUSIONS

The cost of producing electric power in new power plants, with zero emissions of exhaust gases to the atmosphere, is competitive if the new CES technology described in this paper were used. For a new 400 MW plant using future high- temperature steam turbines, the cost of electric power generation with $CO_2$ sequestering using the CES technology is $0.031/ kWhr. Using the same accounting method, the cost of generating electric power in future combined cycle plants without $CO_2$ sequestering is $0.028/kWhr and with $CO_2$ sequestering $0.034/kWhr. Furthermore, in the case of the CES non-polluting technology, zero amounts of $CO_2$ and NOx are released to the atmosphere. In contrast, a combined cycle power plant that uses $CO_2$ sequestering, part of the plant¹s $CO_2$ and $NO_x$ nevertheless are released to the atmosphere because separation of these gases from combustion products is difficult to accomplish completely at a competitive cost.

## FOOTNOTES

1 Clean Energy Systems, Inc. 1812 Silica Avenue, Sacramento, California 95815 U.S.A. (916) 925 - 8206. Clean Energy Systems, Inc. and CES are trademarks of Clean Energy Systems, Inc.

2 Numbers in square brackets refer to References.

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