The Gas is Greener…

According to studies done by the U.S. Environmental Protection Agency (EPA) and the Harvard School of Public Health, some 64,000 Americans die prematurely each year because of illnesses made worse by air pollutants. Despite fairly recent improvements in air quality made mainly through the improvement of automobile emissions technology, the American Lung Institute says that 66% of Americans live in areas failing to meet the National Ambient Air Quality Standards. Pollutants include ozone, particulate matter, carbon monoxide, and nitrogen dioxide, with industrial sources including electrical power generating plants producing the great majority. Some 25% of these plants will reach the end of their useful lives over the next five years and will require replacement, but with what?

The Energy Information Administration of the U.S Department of Energy (DOE) forecasts that U.S. electrical demand will increase by 15,000 megawatts (MW) annually through 2005. The World Energy Council puts additional global needs through 2010 at more than 550,000 MW. If obsolete plants are to be replaced by other plants burning hydrocarbon fuels, how can the addition of pollutants to the atmosphere be avoided? Clean Energy Systems (CES), a company founded by veterans of Aerojet's renowned rocket technology programs, may have an answer in its Environmentally Clean Power Generation System, which uses zero-emission steam technology, or ZEST.

A conventional gas turbine power plant works by mixing compressed air with fuel, which is then burned under constant pressure. The resulting hot gas is allowed to expand through a turbine to perform work. But burning substances such as petroleum in the presence of air creates a range of problems. At combustion temperatures, oxygen and nitrogen in the air combine to create nitrogen oxides. Additionally, when carbon-containing fuel is

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burned in the presence of air, the carbon combines with oxygen to form carbon dioxide (CO2), a greenhouse gas implicated in global warming.

This CO_2 is either captured and processed for commercial use or sequestered. Current sequestering practices call for injecting the CO_2 into layers of sandstone, limestone, dolomite, or chert, or injecting it deep into underground aquifers, where it will theoretically remain in solution for thousands of years. "However," says Ian Kennedy, associate dean of the University of California at Davis College of Engineering and director of the university combustion laboratory, "that's based on the theory that these aquifers are stable. CO_2 is a bit like nuclear waste in that it has a long lifetime, and if it comes out it's like taking the top off the soda bottle, and the CO_2 is in the atmosphere anyway." The CES technology makes it easier and more economical to collect and sequester CO_2 by burning clean fuel in the presence of pure oxygen.

How It Works

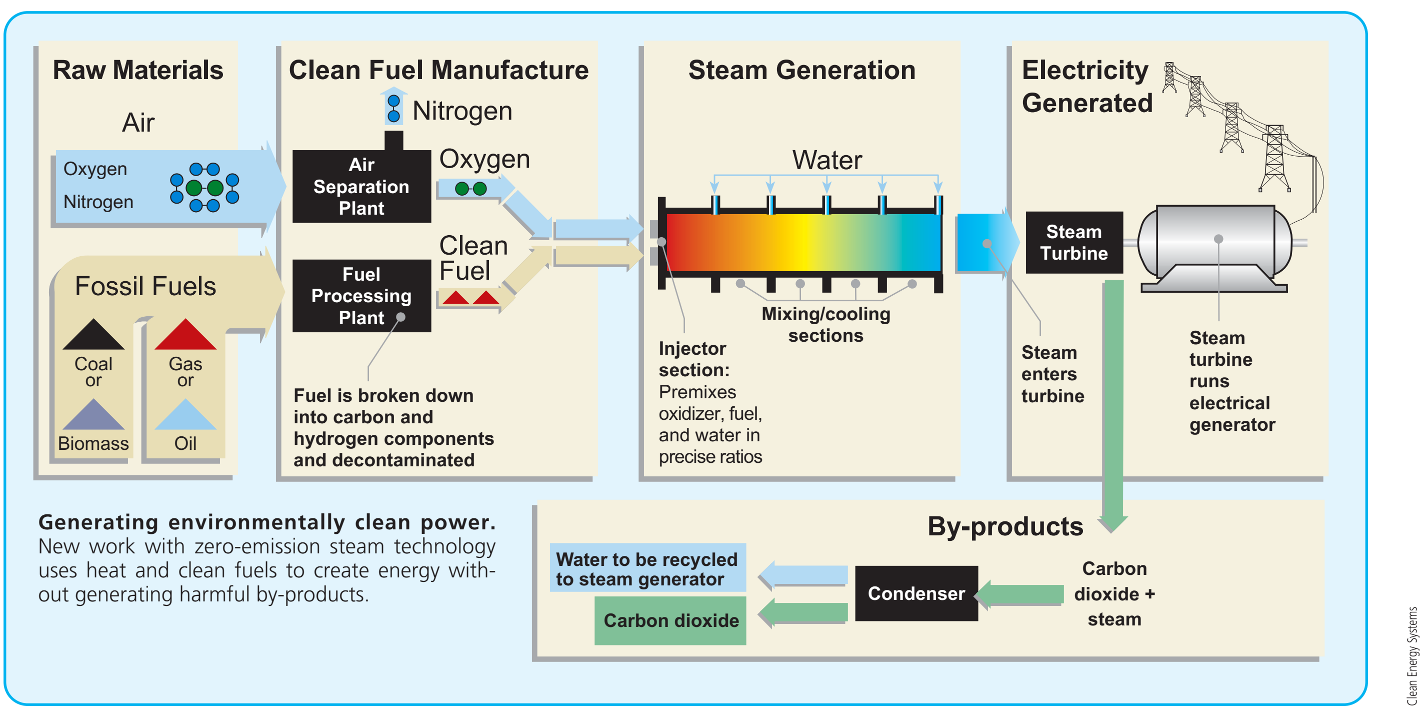
In the CES system, a separation plant removes oxygen from the air, which is then mixed with fuel, compressed, and delivered to a steam generator and reheater. The gas is burned in the presence of water, creating a very-high-temperature gas (1,200–3,200°F) that is composed almost entirely of CO_2 and water. The combustion gases, composed of approximately 90% water 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, which increases the temperature of the mixture. Next the gases flow through an intermediate pressure turbine, and then on to a low-pressure turbine, which generates electricity.

According to CES, this cycle will have a near-term operating efficiency of 56% (meaning that 56% of the thermochemical energy available in the oxygen and fuel is converted to electricity), versus a projected 60–65% efficiency—and CO_2 sequestration—when high-temperature turbines become available. This is compared with efficiency ratings in the 60% range for current combined-cycle plants without sequestration.

Once through the turbines, the gases are passed to a condenser, where the CO_2 and most of the water (some of which is used to control the temperature of the combustion process) separates from the mix. The CO_2 is first compressed from 2 pounds per square inch of air (psia) to 140 psia to remove any water. It is further cooled and liquefied at 40°F and delivered to an injection well. The liquid CO_2 can be pumped to 3,000–5,000 psia with very little energy penalty (the amount of a plant's output required to do work at the expense of plant efficiency). The energy penalties for the separation and pressurization of CO_2 and pressurization for injection are 3.4% for the CES process compared with 20–45% for other fossil fuel plants—a number kept low because the CO_2 separates out naturally as the steam condenses.

Test projects of ZEST systems to date have burned methane to fuel the process, although CES president Stephen Doyle says other fuel alternatives such as gasified coal, alcohols, hydrogen, and carbon monoxide, as well as natural gas, petroleum, and biomass, could also be used, although some would require processing before combustion. According to CES, the only time significant fuel processing before combustion would be required would be if coal, heavy petroleum, or biomass were being used. Removing nitrogen from the air prior to combustion removes the nitric oxides link—oxides of nitrogen play a role in ozone formation, and nitrogen dioxide can be converted into fine nitric acid aerosols, which cause severe deep lung damage. The fuel must also be free of sulfur to eliminate the formation of sulfur dioxide, an irritant that can trigger asthma attacks, or sulfuric or sulfurous acids, which could, at sufficiently high levels, corrode plant machinery.

Roger Anderson, a member of the CES Board of Fellows for Science, says, "In respect to ash and sulfur, the fuel need not contain any less of these components than is presently acceptable in currently operating gas turbine systems. In respect to nitrogen, a specific limit has not been established, but levels of several percent by volume in both oxygen and fuel are analytically predicted to yield nitrogen oxide concentrations of less than one part per million in the turbine exhaust." Long-term, he says, the recovered



Generating environmentally clean power. New work with zero-emission steam technology uses heat and clean fuels to create energy without generating harmful by-products.

Producing Pure Oxygen

Key to the functioning of the Clean Energy Systems (CES) power plant is production of the pure oxygen needed for the advanced combustion system. More than just pumping in outside air, obtaining pure oxygen requires separating oxygen from the other, less-desirable components of our atmosphere.

Cryogenic air separation, the technology currently in use, involves dropping the temperature of air down to cryogenic temperatures (nearly –170°C). Because the nitrogen component of air is liquid at –196°C (at 1 atmosphere), these separation units must also increase pressure to 8–10 times atmospheric pressure. Once pressurized, hydrocarbons, water, and carbon dioxide are removed from the compressed air, and the air is then cooled to cryogenic temperatures and piped into a distillation tower, where the oxygen settles to the bottom and the nitrogen to the top. The gases then go through a series of steps involving additional cooling and condensing, until the sought-after gas is withdrawn and sent to the end user. Cryogenic air separation plants are expensive, and they can also be quite large, with the distillation column being several stories tall and requiring extensive insulation (although new designs have decreased the floor space of the units somewhat).

One more recent approach is called membrane separation, a physical process based on specific characteristics of each molecule. Hollow tubes filled with thousands of very thin membrane fibers are exposed to an airstream under pressure. Ion transport membranes are solid materials that produce oxygen by passage of oxygen ions through ceramic materials containing selected inorganic oxide materials. Operating at high temperatures (over 480°C), the membranes convert oxygen molecules to oxygen ions at their surface. These ions are transported through the membrane by an applied voltage or pressure differential, and then reform to oxygen molecules at the other membrane surface.

CES says current cryogenic air separation plants can produce about 3,500 tons of oxygen per day, roughly enough to support a CES plant having a 200-megawatt output. Larger units, capable of producing in the 5,000 ton/day range, are possible with some improvements in current technology.

Researchers at companies such as Praxair and Air Products and Chemicals are now looking at ion transport membranes, which have the potential of providing pure oxygen at much lower costs. According to CES, such systems could reduce the energy consumed to produce oxygen by 50% and the capital cost by 25% over conventional cryogenic air fractionation processes. The company also points out that these plants could be easily integrated with advanced turbine systems that could economically provide pressurized air and heat to operate the system. **–Lance Frazer**

CO_2 will be used primarily for enhanced oil recovery, enhanced coalbed methane recovery, or simply sequestered. If levels of impurities exceed their solubility limits in the CO_2, the system will require a subsystem to extract the residual. "If the CO_2 is to be used as a food-grade or commercial commodity," he adds, "the required quality will be higher and thereby require added cleanup."

ZESTful Benefits

Doyle says multiple tests to date have shown zero emissions during plant operation, and adds that the process has been able to recover 100% of the CO_2 generated during operation. The cost of the technology compares well, too. Ray Smith, deputy associate director of the Energy & Environment Directorate at Lawrence Livermore National Laboratory in Livermore, California, believes CO_2 from the CES system could be deposited underground at less than $20 per ton of carbon, compared with $100 per ton required for removal of the gas from the exhausts of today's electrical plants.

The technology is also scalable, according to Doyle. "By simply changing the size of the gas generator and turbine, facility power can be raised from ten megawatts to four hundred. As a result, small cities, factories, or industrial complexes could set up their own on-site power plants," he says.

In addition to its direct energy applications, CO_2 from the CES system's plant operation could also be used to force oil out of oil wells. "In primary recovery," Doyle explains, "the oil is forced out of the ground by existing pressure, giving you the kind of [geyser effect] Hollywood loves. When that pressure dies down, secondary recovery techniques involve flooding the well with hot water and steam to raise the temperature and pressure underground and force out more oil, a process which still leaves thirty-five to fifty percent of the oil underground." In the 1990s, he notes, the industry discovered that pumping in CO_2 with the steam reduces the viscosity of the oil and thereby reduces the cost of recovering additional oil.

CES claims that 4% of the U.S. crude oil supply is produced from CO_2-injected fields. Their estimates indicate that if that figure is extrapolated to the entire U.S. oil production capacity, it would require CO_2 equivalent to the production from 90,000 MW of new gas-fired plants.

Jonathan Jordan, a senior associate with the American Petroleum Institute, a Washington, DC–based trade organization, affirms the process, but adds that it's not a widespread technology for several reasons. "You use large volumes of CO_2," he points out, "so the field has to be near enough to a source of CO_2 to make building a pipeline economical. Additionally, there are limiting factors to the usability of CO_2. For example, if you have an oil field high in sulfur, you won't want to mix in CO_2 because that would be roughly equivalent to an acid–base mix. You don't want to add CO_2 under any circumstances that would create an adverse chemical reaction. Also, the field would have to be free of a lot of faulting and discontinuity, and you'd need as few geologic impediments to flowing from one well to the next as possible."

Limiting Factors

One factor limiting CES's development of ZEST systems is the lack of steam turbine technology available that can function at the kinds of temperatures generated by the CES process. The upper limit in a conventional boiler is about 1,150°F, says Doyle, whereas with the CES system "our steam starts at three thousand degrees Fahrenheit and has to be cooled down to a level acceptable to existing turbines. We'd like to see some of the major gas turbine technology companies take that technology to make steam turbines run more efficiently."

Such turbines, which would operate at much higher temperatures and pressures than currently possible, are being developed under the DOE's Vision 21 Program, which seeks to develop a virtually pollution-free energy plant. According to Anderson, development work on gas turbines costing hundreds of millions of dollars has resulted in turbines operating at temperatures up to about 2,700°F. He adds that Japanese researchers are currently conducting development tests directed toward advanced steam turbines to operate at about 3,100°F. "If and when such turbines become available," he says, "efficiencies of zero-emission CES systems could approach sixty-five percent."

From October 2000 through January 2001, CES bench-tested a single-element gas generator at the combustion laboratory of the University of California at Davis. Kennedy says, "Generally, the tests CES did went quite well, but I think there are a few issues the company may have to confront as it develops. Pure oxygen as a combustion source isn't a new idea, but one of the things that has hindered its development is the economical production of the oxygen. CES has apparently decided they can generate the oxygen at an economical cost, but that may still be an issue." Kennedy also points out that pure O_2 burns at a high temperature, so a good deal of care must be taken that heat transfer doesn't create hot spots that could burn through walls. "And they're using injector technology with very fine passages, so clogging could be an issue," he says. Doyle says that CES has addressed these issues by using regenerative cooling in the combuster walls and water in the ignition zone to reduce combustion temperatures, as well as multiple filters to prevent clogging.

As CES works from bench scale to larger units, Kennedy believes they'll also have to deal with engineering issues that frequently crop up as a project is scaled up. "For instance," he says, "you could get instability issues, pressure fluctuations, which have been a problem in rocket motor design. And as far as capturing the CO_2, if you're just going to sequester it, then you can probably get by with some traces of argon, nitrogen, some of the other things that pop up in natural gas. But if you're selling it as a 'clean' concept, then you need to be really concerned about nitrogen and sulfur, and that makes fuel cost more of an issue."

Scaling Up

According to Smith, CES proposed to the DOE the construction of a 10 MW facility on Lawrence Livermore property as a demonstration of the integration of the entire CES concept. "We happen to have an oil field just across the street, so it would also give us the chance to study using CO_2 in enhanced oil recovery," he says. "It would also give us the opportunity to do the materials research needed to develop the new generation of turbines needed to handle the higher temperatures of the CES plant. That's the real limitation to this point."

Smith says CES proposed the project to the DOE Office of Fossil Energy as something that should be included in their budget planning, but so far, that hasn't happened. He says, "We're now planning a proposal for a four-megawatt plant [10–13% of the lab's daily power consumption during summer, enough to power 4,000 homes] that would drop the cost from seventy million dollars to twenty-four million dollars, and still let us achieve ninety percent of our research objectives."

There will still be engineering issues to work out, adds Smith. However, he says, "I do have to say that of the many technologies we've looked at for capturing and sequestering CO_2, the CES technology seems the best and most economical to produce pure CO_2. I think this technology would be valuable, both in terms of demonstrating a technological solution to CO_2 emissions and global warming, and generating power in places like California."

Smith says plant siting is frequently delayed because of emissions issues, and if a technology could be proven to produce no atmospheric emissions, it would expedite siting of these plants. "But a generator wants to see tens of thousands of hours of operation before they invest the kind of money it would take to build a large power plant," he says. Current combined-cycle plants in the 500–800 MW range run $400 million—"That's where projects like this come in," says Smith.

CES has received federal funding to build and hot fire–test a 10 MW generator, which would provide enough energy to meet the needs of "a good-sized college campus," says Doyle. He also confirms that an unnamed Southern California municipality is negotiating a contract with CES to build a power plant at a landfill location, where the plant could tap methane produced by the landfill as a fuel source. Additionally, the company recently received $2 million in California Energy Commission funding to support construction of a 0.5 MW plant in Antioch to demonstrate technologies for the separation and capture of CO_2. "These small-sized plants will enable us to demonstrate what is, to date, unproven hardware," Doyle says. "That's what industry wants. People don't want to make a huge investment to build a plant with unproven technologies. These plants will demonstrate that durability."

"In the final analysis," Kennedy says, "in this industry, economic success is often driven by regulation. I mean, you probably wouldn't pay for a catalytic converter on your car, but you need it because of environmental regulations. If there was a 'carbon tax,' it could be a big incentive for the development of this kind of technology."

Such incentives may have big environmental payoffs as well. "I think," Smith says, "to take a longer view of things, if [the Bush] administration wanted to use zero-emission power plant technology as an example of a technological solution to problems like CO_2 emissions, it could be a major step towards the thrust of the Kyoto accords."

Lance Frazer

Suggested Reading

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