Zero Emission Power Generation Technology Development

Final Report

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ABSTRACT

Clean Energy Systems (CES) was previously funded by DOE's *Vision 21* program. This program provided a proof-of-concept demonstration that CES' novel gas generator (combustor) enabled production of electrical power from fossil fuels without pollution.

CES has used current DOE funding for additional design study exercises which established the utility of the CES-cycle for retrofitting existing power plants for zero-emission operations and for incorporation in zero-emission, "green field" power plant concepts. DOE funding also helped define the suitability of existing steam turbine designs for use in the CES-cycle and explored the use of aero-derivative turbines for advanced power plant designs.

This work is of interest to the California Energy Commission (CEC) and the Norwegian Ministry of Petroleum & Energy. California's air quality districts have significant non-attainment areas in which CES technology can help. CEC is currently funding a CES-cycle technology demonstration near Bakersfield, CA. The Norwegian government is supporting conceptual studies for a proposed 40 MW zero-emission power plant in Stavager, Norway which would use the CES-cycle. The latter project is called Zero-Emission Norwegian Gas (ZENG).

In summary, current engineering studies: (1) supported engineering design of plant subsystems applicable for use with CES-cycle zero-emission power plants, and (2) documented the suitability and availability of steam turbines for use in CES-cycle power plants, with particular relevance to the Norwegian ZENG Project.

TABLE OF CONTENTS

INTRODUCTION

Clean Energy Systems, Inc. (CES) has developed zero-emission, fossil-fueled power generation technology, integrating proven aerospace technology into conventional power systems. The core of CES' process involves replacing steam boilers and flue gas cleaning systems with "gas generator" technology adapted from rocket engines. The gas generator burns a combination of oxygen and gaseous hydrocarbon fuel to produce a mixed drive gas of steam and carbon dioxide (CO_2) at high temperature and pressure to power conventional and advanced steam turbines. High thermal efficiencies are obtained for utility-sized power plants, but with no atmospheric emissions. Possible fuel sources include renewable gasified biomass, natural gas, and coal syngas. The CES cycle is a net producer of water when used with air-cooled condensers.

After driving multi-stage steam turbines, the exhaust gas is cooled and separated into its components—water and CO_2 (Figure 1). The water is reused in the gas generator and the CO_2 can be either sold or stored. Gas generator technology has been used for decades in aerospace applications, including the Space Shuttle's main engines, where hydrogen and oxygen are combusted to produce pure steam at high temperature and pressure. Likewise, high-temperature, high-pressure steam turbines have been used successfully in aerospace applications. Every component in the CES process has been commercially proven and standardized in power generation or other industries.

The CES Process

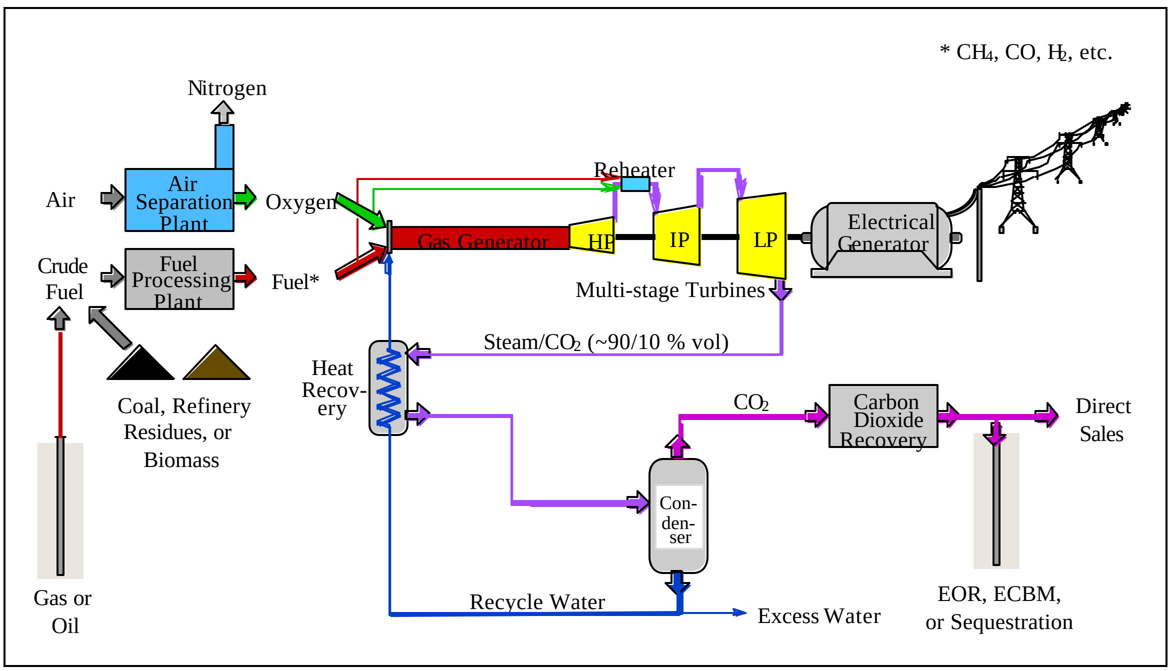

Figure 1

CES' objective is to apply gas generators to terrestrial power generator, initially in non-compliant air quality regions, and become the "gold standard" for efficient, clean, fossil-fuel based main-grid power generation.

EXECUTIVE SUMMARY

CES is preparing for commercial application of its technology, which enables production of electrical power via combustion of fossil fuels without pollution. This report consists of two parts: (1) engineering design of subsystems to support CES-cycle power plants, and (2) engineering design of a 40 MW, fossil-fuel, zero-emission power plant to be located in Norway.

Part (1): To enable re-powered or new power plants to support CES-cycle requirements, CES is modifying the design of existing plant subsystems and also creating new subsystem designs. Engineering support under DOE contract DE-FC26-04NT42095 was used to aid engineering design of future plant subsystems to support the CES-cycle.

Part (2): The second case involves preliminary design and trade studies for the first commercial sale of a CES gas generator: a 40 MW, zero-emission, fossil-fueled power plant in Norway. The Norwegian Ministry of Petroleum and Energy co-funded (1 million NOK; 150,000 USD), with Lyse Energi (1 million NOK; 150,000 USD), a feasibility study to create a Zero-Emission Norwegian Gas (ZENG) power plant. The feasibility study concluded in September 2004. DOE project funding was used to conduct engineering analytical efforts defining availability and suitability of current and advanced steam turbines, and the feasibility of modifying gas turbines to work with CES technology. The steam turbine survey (*Survey of Turbo-machinery Suppliers for ZENG Project, Fern Engrg Report 5909-08-2, 23 Mar 04*) and gas turbine engineering study (*Integration of Commercial Gas Turbine Technology into a Clean Energy Systems Zero-Emissions Power Plant, Fern Engrg Report 5909-08-3, 7 Jun 04*) were conducted by Fern Engineering, Inc. of Cohasset, MA.

DOE project funding has helped advance realization of zero-emission power generation by:

(1) Supporting engineering design of plant subsystems applicable for use with CES-cycle zero-emission power plants, and
(2) Documenting the suitability and availability of steam turbines for use in CES-cycle power plants, with particular relevance to the Norwegian ZENG Project.

This project included <u>three key objectives</u>:

(1) Provide sufficient engineering and project development support to complete engineering design for required plant subsystems in CES-cycle plants;
(2) Identify existing steam turbines that can be used for near-term CES-cycle plants, targeting a "notice to proceed" for turbine construction in the first quarter of 2005; and
(3) Study and develop means to modify and employ gas turbine technology in CES-cycle plants.

For subsystem support of future CES-cycle plants, key issues addressed were:

- Engineering design of major plant subsystems for CES-cycle plants, especially feed water, natural gas, oxygen, and condenser systems; and
- Validation of the CES gas generator's control system interface with plant subsystems.

For the Norwegian feasibility study, key issues addressed were:

- Determination of optimal gas generator configuration for the power plant's steam source—single vs. multiple gas generators (single gas generator selected for cost-reduction reasons);
- Definition and cataloging of steam turbines which can be used in near-term CES-cycle power plants;
- Preparation of a procurement specification for ZENG steam turbines (future task for CO2 Norway); and
- Report on the feasibility of employing gas turbine technology in CES-cycle power plants and modifications needed thereto.

EXPERIMENTAL

Work to be accomplished using DOE funding was defined in a Statement of Work, which provided support for the **CES Gas Generator Subsystems** (Task 1) and a **Steam Turbine Feasibility Study** (Task 2):

TASK 1 Design Support for Gas Generator Systems

Subtask 1.1 Equipment Specifications. *SOW: Design, engineer, and specify requirements for the oxygen system, feed water pumps, and gas compressor to provide consumables (oxygen, natural gas) and cooling water for the CES gas generator system. Provide project oversight for the specified systems.*

Oxygen System. In performing this task, vendors were asked to propose oxygen systems to provide high-pressure oxygen at required pressures and flow rates to the gas generator. For smaller oxygen demand levels (2-5 MW), oxygen from an on-site cryogenic (liquid) oxygen storage tank was the most viable solution. For units greater than 5 MW or for those operating at high usage rates (e.g. 24/7), air separation units were more practical. For installations lacking an air separation unit, cryogenic storage tanks would be replenished by truck delivery. In both cases, liquid oxygen will be pumped to high pressure, vaporized in a heat exchanger, and then supplied to the gas generator as gaseous oxygen. Pressure to the gas generator would be regulated at 110.3 bar (1,600 psig).

Initial design and engineering studies were conducted in July and August 2004 based on the usage rates of smaller CES-cycle plants. A 5 MW plant size was the initial design baseline. A typical CES-cycle plant includes a cryogenic oxygen storage tank, high-pressure cryogenic pump, vaporizer, accumulator(s), control and pressure relief valves, control system, and civil engineering requirements.

Natural Gas System. Similarly, design and engineering construction approaches were assessed for a natural gas compressor “skid” to supply gaseous fuel at high pressure to a gas generator. The gas compressor skid assumed natural gas fuel from a commercial pipeline and its compression to 110.3 bar (1,600 psig) for use in the gas generator’s combustion process. The design incorporates tight pressure fluctuation limits (<0.5%) which drives system design vis-à-vis piping and pressure control/relief valve configurations.

Feed Water System. Standard power plant feed water systems are not designed for the high pressure (124.1 bar—1,800 psig) nor slightly acidic (pH ~4.5) feed water used by the CES gas generator. Consequently, new feed water supply systems will needed to provide high pressure feed water to the gas generator and to handle its slightly acidic, de-ionized (DI) water. The selected design utilizes stainless steel piping for the high pressure/high temperature portions of the feed water system and plastic piping for low pressure/low temperature portions. As many plant feed water tanks utilize carbon steel (which corrodes in 4.5 pH water), new feed water holding tanks made of resin compounds were specified. In general, stainless steel and chlorinated poly-vinyl chloride (CPVC) is utilized for piping and stainless steel for pumps. These corrosion-resistant materials easily meet CES-cycle “standards.” As a net producer of high quality water from its combustion process, the gas generator will produce excess water that can be used either to replenish the feed water system's DI water supply or to augment cooling water for plant cooling towers.

Subtask 1.2 Condenser Specification. *SOW: Design, engineer, and specify requirements for the steam turbine's condenser to make it capable of removing the non-condensable gases in the CES drive-gas.*

Condenser and Vacuum Pump. Because the CES-cycle entrains non-condensable gas (CO_2) within the turbine drive gas, condenser designs will differ from those supporting pure steam turbines. CES consulted with a variety of condenser fabricators to arrive at an optimal design solution. Alstom Power, Inc. was selected to design a condenser system based on their experience in and knowledge of condenser designs for geothermal plants. Geothermal plant condensers must deal with corrosive water mixtures and remove various non-condensable gases, characteristics similar to the CO_2 "non-condensable" gas formed during the CES combustion process and the subsequently slightly acidic condensate mixture. Alstom provided a design for a stainless steel condenser with the appropriate interior baffles for non-condensable gas removal. Alstom also specified an efficient (liquid ring) vacuum pump design to remove the non-condensable gases (e.g. CO_2) from the condenser.

Subtask 1.3 Gas Generator Installation Design. *SOW: Design, engineer, and specify installation (and integration) requirements for the gas generator and its control system.*

Of the three subtasks to be undertaken, this proved to be the most challenging and exacting. While laying out the installation process of the CES gas generator into a power plant was relatively straight-forward, integrating its control system into the plant was more involved. A programmable logic controller (PLC)-based control system was already designed and built for the gas generator. However, the control system also has to be integrated and made fully interactive with existing subsystem controls (analog or digital). This integration could be particularly problematic at re-powered plant installations. As this situation will occur each time an existing plant is re-powered, it was deemed more practical to develop a stand-alone, "integration" controller to serve as an interface between the digital CES gas generator controller and legacy plant subsystem controllers. Before proceeding with design of the integrating controller, CES performed an extensive Failure Modes and Effects Analysis (FMEA) to ensure plant and gas generator systems effectively monitored and controlled the gas generator under all potential conditions. The FMEA illustrated the detailed, interrelated nature of plant and gas generator monitoring instrumentation and controls, particularly with reference to automated shut downs of the combustion process. The architectural analysis and integrated control system design study will provide invaluable aids to the successful integration of gas generator control systems into new design and retrofit power plants..

TASK 2. Steam Turbine Feasibility Study for the ZENG Plant

Task 2.1 Drive Gas & Re-Heater Assessment. *SOW: Using drive gas composition, flow rates, temperatures, and pressures independently developed, CES will characterize the drive gas conditions which will be experienced by one or more steam turbines in the power generating island of the proposed power plant. An analysis will be done by CES to determine whether the use of a DOE/NETL-designed and -tested re-heater would significantly affect plant efficiencies* *at the power levels and operating conditions anticipated in the ZENG plant. Drive gases produced from natural gas and gasified coal will be analyzed as part of the CES study.*

CES prepared a report characterizing gas generator drive gas composition, temperatures, and pressures for the conditions expected at the steam turbines in the ZENG plant. This report (*40 MW Zero-Emission Norwegian Power Plant Preliminary Design Feasibility Study Report, Aug 04)* is summarized in Tables 1 and 2 (page 13). Fern Engineering used this CES information in surveying the availability of existing and advanced steam turbines and their applicability to the CES-cycle in the proposed ZENG power plant. .

CES also evaluated the utility of the DOE/NETL re-heater in a ZENG plant. This information is summarized in Table 3 (page 13). In this study, the re-heater increased net plant efficiency by 5.3 percentage points.

Task 2.2 Steam Turbine Identification and Operational Analysis. *SOW: A subcontract will be let to identify, from a qualified industry source, the best available steam turbines for the Stavanger plant. This analysis will look at both existing turbine technologies, and those technologies which might be brought to operational status with modest investment and in a reasonable time.*

A sub-contract was awarded to Fern Engineering, Inc. of Pocasset, MA to accomplish the steam turbine identification and analysis task. The Fern sub-contract had two key objectives: First, identify existing steam turbines compatible with the CES-cycle in a 40 MW ZENG plant, targeting a "notice-to-proceed" with construction in the first quarter of 2005. Second, identify what it would take to modify a gas turbine to work on the CES steam/CO_2 mixture. Key issues were system effects of the steam/CO_2 mixture; maximum available turbine temperatures—530°C (985°F), 565°C (1,050°F), 620°C (1,150°F); issues relating to start up and gland seals (where carbonic acid could be present); and avoidance of final-stage condensing. This information will be used in the next phase of plant definition, preparing a procurement specification for turbines. Fern Engineering's *Survey of Turbo-machinery Suppliers for ZENG Project, Fern Engrg Report 5909-08-2, 23 Mar 04* identifies steam turbine models of existing designs suitable for the ZENG plant and can be made available from CES for the cost of its printing.

Task 2.3 Conceptual Plant Definition. *SOW: Develop an operational system concept that would employ CES gas generator technology in the safest, most practical, and efficient configuration for 40 MW plant operation. Identify any key operational differences between using natural gas or coal synthetic gas as a fuel source.*

CES developed six operational concepts (configurations) for use of the CES gas generator, which ranged from currently fielded systems to advanced turbines. These concepts for the ZENG power plant were forwarded to the ZENG project study leader, CO2 Norway. CO2 Norway, physically located in Norway, integrated CES recommendations into the ZENG Plant Feasibility Final Report. The ZENG Plant Feasibility Final Report, *Zero-Emission Norwegian Gas (ZENG), Phase I: Concept & Feasibility Study, Final Report—Draft, CO2-Norway AS, Rev 2, 15 Sept 04,* can be made available from CES for the cost of its printing.

RESULTS AND DISCUSSION

Design Support for CES Gas Generator Systems (Task 1)

The engineering design and project management support provided by the DOE contract enabled CES to design and/or modify existing plant support subsystems to meet requirements for CES-cycle (gas generator) operations. Initial design target was for CES-cycle zero-emission power plants in the range of 5 - 50 MW.

Subtask 1.1 Equipment Specifications (Oxygen System, Feed Water System, NG System)

Oxygen System. Design specifications for a generic oxygen system were laid down and a typical oxygen system designed and approved. The design features a cryogenic storage tank, high-pressure triplex cryogenic pump, atmospheric vaporizer, horizontal accumulators, pressure relief valves, pressure regulator for the main oxygen supply line (110.3 bar—1,600 psig), tertiary in-line gaseous oxygen filter (10µ), control system, and civil engineering work for the concrete foundations (rebar, pedestal design, unloading pad, equipment pad). System materials were specified from stainless steel (piping, filter housing, pump, storage tank), carbon steel (accumulators), copper (certain cryo-storage tank piping) and Monel (filter elements, pipeline "spool").

Subsequently, two additional protective features were incorporated into the oxygen system baseline design. First, a 10µ pre-filter was added to protect the cryogenic pump's head and valves from particulates entrained in the storage tank. The added filter was located in the feed line immediately ahead of the cryo-pump. An "off-the-shelf" filter design was able to meet system requirements which reduces procurement cost. Also, because this unit would filter oxygen as a liquid and fluid velocities will be relatively low, a less expensive stainless steel filter could be substituted for the normally mandated Monel filter element. Second, a dedicated pressure relief valve (PRV) was added to the system design in the main oxygen system supply line. This will provide protection for the gas generator's oxygen circuits should the oxygen system's main pressure control regulator fail. This additional PRV permits oxygen system (skid) pressures to be maintained at their design point, thus assuring full system flow rates while protect the gas generator from excessive oxygen pressure.

Feed Water System. A new design was generated for the plant feed water system to accommodate the high operating pressures (124.1 bar—1,800 psig) required. The design included a stainless steel high-pressure feed water pump, a stainless steel pressure regulator and a resin-based, gravity-fed DI water tank. Feed water pressure, temperature, and acidity constrained pipeline material selections to stainless steel (high pressure, high temperature), chlorinated poly-vinyl chloride (medium pressure/temperature), and poly-vinyl chloride (low pressure/temperature). A feedback DI water circuit was subsequently incorporated in the design to reduce potential pressure fluctuations under low/no-flow conditions at the pressure regulator.

Natural Gas System. Construction and installation designs were reviewed for a natural gas compressor skid. Following analysis, three additional features were added to a relatively "standard" baseline design. First, a pressure regulator was added to the natural gas (NG) supply line feeding the gas compressor skid. This mod will serve to reduce fluctuations in NG delivery pressure (prevent pressure surges driven by supply line fluctuations) thus providing a more stable

NG pressure to the gas generator. Second, a pressure relief valve was located immediately prior to the NG inlet on the gas compressor supply line. This design change lowers gas compressor operating temperature (because NG supply pressure can be increased to the design point without inducing pressure surges during low-flow conditions) and increases compressor life. Third, a 10µ tertiary filter was added to the NG supply line just prior to its connecting point to the gas generator. The extra filter minimizes potential NG particulate contamination coming from a faulty gas compressor coalescing (filter) unit. These minor design modifications provide a robust NG compressor skid scaleable to 50 MW.

Subtask 1.2 Condenser Specification (Condenser and Liquid Ring Vacuum Pump)

Condenser System. The gas generator's combustion products consist of water (steam) and CO_2. Consequently, as the drive gas exiting the turbine is condensed, it has entrained CO_2 which tends to make the condensate mildly acidic through the formation of carbonic acid. The condensate can reach ~ 4.5 pH, about the same as coffee. As adding chemicals to neutralize condensate pH creates particulate precipitation problems during the combustion process, a simpler solution was selected to eliminate the concern of condenser corrosion: use corrosive-resistant materials in condenser fabrication. In addition, a normal steam-cycle condenser is not equipped to deal with the non-condensable gas (CO_2) created in the CES-cycle. A geothermal-type condenser is more suited to the CES-cycle than normal steam condensers as they are designed to deal with non-condensable gases. Geothermal condensers also make use of vacuum pumps to remove CO_2 from the condenser case. Consequently, CES specified a design typical of a geothermal condenser: stainless steel wetted surfaces, internal baffles to help separate non-condensable gases from the condensate, and an appropriately-sized vacuum pump. CES provided specific heat values, steam and liquid condensate flow rates, and expected CO_2 rejection quantities to several condenser manufacturers before selecting Alstom Power, Inc's design for a condenser system. The Alstom design utilizes stainless steel on all surfaces "wetted" by the condensate and includes a standard-design liquid ring vacuum pump to remove non-condensable gases. Wetted surfaces in the vacuum pump are also specified to be stainless steel to eliminate corrosion concerns from any condensate accumulations.

Subtask 1.3 Gas Generator Installation Design (Gas Generator and Control System)

Gas Generator and Control System. Design of the installation of the gas generator was very straightforward and uncomplicated. The programmable logic controller (PLC)-based control system for the gas generator, designed and tested during the summer of 2003, proved to be very flexible and accommodating to new requirements. However, designing an "integration" controller to interface with power plant analog and/or digital control systems required extended design and analysis effort. Following a detailed analysis of typical plant requirements, CES created a "boilerplate" power plant integration controller design. To validate what looked to be a promising design, CES obtained external funding to construct a prototype integration controller and proof-test it. The testing showed the prototype controller to operate effectively in conjunction with the existing gas generator control system. It reduced the need for manual operator interventions, significantly reduced system start-up times, and sped data compilation. When the CES-cycle is introduced into power plant, hardware changes to the integration controller and "tuning" of its software programs will be necessary to accommodate differing legacy sensor systems and control loops.

Steam Turbine Feasibility Study (Task 2)

Task 2.1 Drive Gas & Re-Heater Assessment (Drive Gas Composition, Re-Heater Contribution to Plant Efficiencies)

CES analyzed the drive gases created by both the CES gas generator and DOE re-heater and derived drive gas compositions, flow rates, temperatures, and pressures which would be seen by the steam turbines of a CES-cycle power plant. This information was forwarded to Fern Engineering who used these drive gas baselines to evaluate which existing steam turbine designs and manufacturers were most suitable for use in a ZENG (CES-cycle) power plant. Table 1 details typical drive gas composition when using natural gas. Table 2 provides gas composition when synthetic gas ("syngas") derived from gasified coal is utilized.

Drive Gas Composition, CES-Cycle
Natural Gas Case

Gas Specie	Gas Generator	Re-Heater
H_2O	93.02%	91.70%
CO_2	6.78%	8.06%
O_2	0.129% (1,290 ppm)	0.154% (1,540 ppm)
N_2	0.044% (440 ppm)	0.052% (520 ppm)
Argon	0.022% (220 ppm)	0.0267% (267 ppm)

Table 1

Drive Gas Composition, CES-Cycle
Coal Syngas Case

Gas Specie	Gas Generator	Re-Heater
H_2O	88.56%	84.51%
CO_2	11.25%	15.26%
O_2	0.129% (1,290 ppm)	0.154% (1,540 ppm)
N_2	0.044% (440 ppm)	0.052% (520 ppm)
Argon	0.022% (220 ppm)	0.0267% (267 ppm)

Table 2

CES also ran a study on the expected contribution to plant efficiencies of a DOE/NETL-designed drive gas re-heater. The re-heater was evaluated against similar configurations, power levels, and operating conditions in the ZENG plant concepts. Table 3 shows the study results of two configurations similar except for use of a re-heater.

Re-Heater Contribution to
CES-Cycle Plant Efficiency

Configuration	Re-Heater		
	Yes	No	Efficiency
40 MW ZENG Concept II	X		40.3 %
40 MW ZENG Concept IV		X	35.0 %
Improvement			**5.3 %**

Table 3

Task 2.2 Steam Turbine Identification and Operational Analysis (Fern Study)

Utilizing CES-derived drive gas composition, temperature, and mass-flow rates, Fern Engineering, Inc. conducted a survey of the steam turbine and gas expander market for commercially available turbines suitable for the 40 MW ZENG power plant. Based on the results of their survey, Fern recommended the approach listed in Table 4 (*Survey of Turbomachinery Suppliers for ZENG Project, Fern Engrg Report 5909-08-2, 23 Mar 04*).

Suitable Steam Turbines for CES-Cycle Plants

Turbine	Turbine Type	Inlet Temp	Inlet Press	Drive Gas Flow Rate	Outlet Press
High Press Turbine	Standard back pressure ST	565°C (1,050°F)	62 –140 bar (900–2,030 psi)	39 kg/sec (86 lbs/sec)	15.5 bar (225 psi)
Intermediate Press Turbine	Hot Gas Expander	700°C (1,290°F)	15 bar (218 psi)	41.5 kg/sec (91.5 lbs/sec)	~1 bar (~14.5 psi)
Low Press Turbine	Geothermal Condensing Steam Turb	250°C (480°F)	39.4 bar (570 psi)	22 kg/sec (48 lbs/sec)	0.35 bar (5 psi)

Table 4

Only a limited number of vendors were interested in manufacturing steam turbines smaller than 100 MW (ZENG is targeted for 40 MW). However, Fern Engineering found available turbine / hot gas expanders to meet ZENG power plant requirements from Dresser-Rand (IPT), GE Conmec (IPT), Nuovo Pignone (LPT), Toshiba (LPT), and Ansaldo (LPT).

Task 2.3 Conceptual Plant Definition (CES and CO2 Norway Report)

CES proposed and evaluated six 40 MW zero emission power plant (ZEPP) concepts. These concepts are summarized in Table 5 from *CES Final Report, 40 MW Zero Emission Norwegian Power Plant, Preliminary Design Feasibility Study Report, August 2004*.

40 MW ZEPP Concepts
Original Proposals

Concept	Details	Plant Efficiency
I	CES Steam/CO_2-cycle for top cycle + Heat Recover Steam Generator (HRSG) and conventional pure-steam turbine(s) for bottom cycle	29%
II	CES Steam/CO_2-cycle and low-pressure Air Separation Unit (ASU)	31%
III	CES Steam/CO_2-cycle and high-pressure ASU	35%
IV	CES Steam/CO_2-cycle and integrated high-pressure ASU	38%
V	CES Steam/CO_2-cycle, integr high-press ASU, and auxiliary N_2 turbine	40%
VI	Advanced CES Steam/CO_2-cycle, integrated high-pressure ASU, auxiliary N_2 turbine, and high-temperature, aero-derivative intermediate pressure turbine	48%

Table 5

Concept I CES-cycle drive gas from the gas generator is directed through two corrosion-resistant turbines mounted in series (HPT and IPT), with the exhaust from the IPT going to a HRSG. In the HRSG, heat is transferred from CES-cycle drive gas to pure steam which, in turn, drives additional conventional turbines. A low-pressure ASU supplies O_2, natural gas is supplied by a separate source, and an atmospheric condenser condenses the steam/CO_2 gas leaving the HRSG. CO_2 is pumped and cooled in stages to remove remaining water and to pressurize the CO_2 to sequestration pressure. Net plant efficiency is aproximately 29%.

Concept II A LPT is added to the CES-cycle steam turbine train in Concept I (HPT + IPT + LPT). The O_2 source remains a low-pressure ASU and natural gas continues to be supplied by a separate source. In this concept, the HRSG and additional turbine train are eliminated. LPT exhaust is condensed in a sub-atmospheric condenser. CO_2 continues to be pumped and cooled in stages to remove remaining water and to pressurize dry CO_2 to sequestration pressure. Net plant efficiency increases slightly to 31%.

Concept III Same as Concept II except that a high-pressure ASU is substituted for the low-pressure unit. This reduces O_2 separation and compression requirements. Net plant efficiency improves to 35%.

Concept IV Same as Concept III except the high-pressure ASU is integrated into the CES power plant, increasing net plant efficiency to 38%.

Concept V Adds an auxiliary N_2 turbine to Concept IV increasing net plant efficiency to 40%.

Concept VI Replaces the Concept V's IPT with an aero-derivative unit with cooled blades. The higher temperatures feasible with this system illustrates the increase in efficiency of CES ZEPP plants with increasing IPT turbine temperature. Net plant efficiency rises to approximately 48%.

Fern Engineering utilized earlier CES zero-emission power plant (ZEPP) configurations to compare industrial turbines to aero-derivative turbines. These ZEPP configurations were taken from a CES conference report provided in Feb 2004 in Phoenix, AZ (*Integration of CES Technology with Air Separation Units, Gas Turbines, and Steam Turbines into Zero-Emission Power Plants*). Fern compared two variations, one using industrial turbines plus a re-heater (ZEPP #3) and one using aero-derivative turbines (ZEPP #4). The base case configurations are listed in Table 6.

ZEPP Concepts for Comparison of
Industrial Turbines vs Aero-Derivative Turbines

ZEPP Concept	Details	Plant Efficiency
III	Intermediate-pressure (30 bar—435 psi) CES Steam/CO_2-cycle GG, integrated high-pressure ASU, auxiliary N_2 turbine, **aero-derivative** HPT coupled to air compressor. IPT is separately coupled to 1st generator, with LPT coupled to 2nd generator (configuration applicable for 40-200 MW plants).	43-53%
IV	As in *ZEPP III*, except exhaust from IPT feeds HRSG and steam from HRSG drives commercial high pressure (83 bar—1,200 psi) three-stage steam turbine (HPT + IPT + LPT) coupled to 2nd generator (configuration applicable for 40-200 MW plants)	43-53%

Table 6

ZEPP III Gas generator sends medium-pressure CES-cycle drive gas—30 bar (435 psi) to an aero-derivative HPT coupled to an air compressor. The HPT exhaust feeds an IPT coupled to a generator. The IPT exhaust feeds a low pressure LPT—1 bar (14.5 psi) coupled to a second generator. An expander turbine using heated N_2 drives a third, auxiliary generator. CO_2 is pumped and cooled in stages to remove remaining water and to pressurize dry CO_2 to sequestration pressure. Net plant efficiency is 43-53%, depending on turbine temperatures—514°C-1,427°C (958°F-2,600°F) and pressures—0.69 bar-30.3 bar (10 psi-440 psi).

ZEPP IV Configuration is the same as ZEPP III except the aero-derivative IPT exhausts into a Heat Recovery Steam Generator (HRSG) which, in turn, feeds a commercial steam turbine train (HPT + IPT + LPT) that is connected to a second generator. Net plant efficiency is 43-53%, depending on turbine temperatures—514°C-1427°C (958°F-2,600°F) and pressures—0.69 bar-30.3 bar (10 psi-440 psi).

CES tasked Fern Engineering to perform a study on integrating commercial gas turbine technology into a CES-cycle ZEPP. Gas turbines have the advantage of much higher inlet temperatures than either steam turbines or gas expanders and include an air compressor which is a natural fit with the compressor required for the ASU in a ZEPP. Fern selected ZEPP #4, a configuration with lower capital costs, as the focus of its study. In addition to the CES GG, ZEPP #4 incorporates a two-stage, aero-derivative steam turbo-generator (HPT + IPT), a HRSG, a N_2-driven turbo expander, and a conventional, three-stage steam turbo-generator (HPT + IPT + LPT) driven from the HRSG. The results of *Fern Engineering, Inc Report No. 5909-08-3, Integration of Commercial Gas Turbine Technology into a Clean Energy Systems Zero-Emissions Power Plant* are synopsized in Table 7.

Fern addressed five concerns in the use of aero-derivative turbines:

(1) Extracting all compressor discharge air to the ASU Though most gas turbines have the ability to bleed off some air flow at the compressor discharge port, most are not designed to have full discharge flow extracted from the pressure shell. However, recuperated (regenerated) gas turbines already send their full discharge flow to a heat exchanger. Consequently, a recuperated gas turbine would work well with the CES-cycle by removing its recuperator and sending all compressor discharge air to an ASU. Fern identified examples of recuperated gas turbines ranging from 1.4 to 60 MW (Table 7).

Commercially Available Recuperated Gas Turbines

	Power Output	Air Flow	Firing Temp	Press Ratio
Heron H-1	1.4 MW	5.14 kg/sec (11.33 lb/sec)	860°C 1,580°F	8.9
Solar Mercury 50	4.6 MW	17.96 kg/sec (39.00 lb/sec)	1,163°C 2,125°F	9.9
Rolls-Royce WR21	25.2 MW	72.05 kg/sec (158.84 lb/sec)	n/a	16.2
GE Frame 7B	60 MW	240.03 kg/sec (529.17 lb/sec)	1,004°C 1,840°F	11.5

Table 7

(2) Cooling aero-derivative hot-section components Cooling the hot section of any gas turbine is a critical design issue. Because the thermal conductivity of steam is higher than O_2 or N_2, the CES drive gas will result in greater heat transfer into the hot section components of a turbine even if the drive gas is at the same temperature as the gas turbine's combustor outlet design value. However, use of slightly superheated steam—232°C-260°C (450°F-500°F)—for cooling instead of air will counteract some of the increased heat transfer. Also, Fern noted that use of open-loop versus closed-loop cooling improves cooling performance and reduces design complexity. Fern estimated the development costs for using steam for blade-cooling of a typical recuperative gas turbine would be $10 million. Alternatively, use of high-temperature turbine blades—871°C (1,600°F)—would eliminate the need for steam cooling of hot-section components and permit minimal re-design of the gas turbine.

(3) Impact of H_2O-rich gas on thermodynamic performance Fern estimates that the higher temperature steam resulting from the CES-cycle would yield the following performance changes compared to normal LM2500 performance:
   a. Slightly higher power output (~ 6%)
   b. Lower turbine pressure ratio (17.6 vs 20.3)
   c. Lower mass flow of working fluid
   d. Significantly cooler high pressure turbine nozzle temperature
   e. Slightly lower power turbine inlet pressure
   f. Slightly hotter power turbine inlet temperature (lower nozzle temperature with steam cooling)
   g. Smaller turbine jet velocity ratios—slightly lower turbine efficiencies
   h. Hotter power turbine exhaust temperature

(4) Component stress loading With the exception of un-cooled components in a gas turbine, stress loading did not appear to be a concern. Power output, torque, temperatures, and operating pressures of an aero-derivative turbine operating on CES-cycle drive gas were well within the design envelope of the studied turbines.

(5) Changes to instruments and controls A control mechanism would be required for the flow discharging from the compressor to the ASU. The firing temperature control scheme for a two-shaft gas turbine should be applicable to the CES-cycle, but a single shaft turbine would have to be modified. Pressure and temperature control would also be needed for the slightly superheated steam being injected for blade cooling.

CONCLUSION

Design Support for CES Gas Generator Systems (Task 1)

The DOE/ NETL contract enabled CES to move quickly to resolve design and performance issues on the five primary support systems affected by introduction of a CES-cycle into power plant operations—oxygen, natural gas, feed water, condenser, and control system integration. These design exercises taught us the following.

Oxygen systems require design personnel who are experienced with high-pressure oxygen systems. While existing oxygen technologies meet CES-cycle requirements, safety issues and operational constraints can be minimized with proactive subsystem design. Knowledgeable designers can save procurement costs (specifying less expensive materials when appropriate—i.e. stainless steel filters in lieu of Monel filters where oxygen velocities are low), ensure subsystem protection (tertiary filters and pressure relief valves to protect critical components—i.e. cryo-pump and gas generator), and produce standardized subsystem designs.

Feed water system designers found centrifugal pumps preferable for achieving the smooth, constant feed water pressure required. Material selection was driven by pressure, temperature, and condensate pH. The slight acidity of the feed water dictated use of corrosion-resistant materials (i.e. stainless steel, poly-vinyl chloride, or chlorinated poly-vinyl chloride (CPVC)). Feed water pressure and temperature then determined which material would be the most cost-effective for particular line segments. Temperature and pressure permitting, use of CPVC in lieu of stainless steel reduces construction costs. In-line filters are desired to maintain system cleanliness at the micron level.

Natural gas (NG) systems can generally utilize standard industry designs. However, the NG compressors selected need to provide very stable delivery pressures (max pressure fluctuation < 0.5%). Achieving this pressure stability requires pressure regulation of pipeline NG supply and location of a pressure relief valve close to the gas compressor inlet. As with the Oxygen subsystem, a tertiary NG filter was deemed necessary to protect critical components (i.e. the gas generator).

Condenser systems will be able to utilize geothermal-type condensers. Geothermal condensers already employ corrosion-resistant materials (stainless steel) on wetted surfaces to handle the low pH condensate, have interior baffling to channel non-condensable gases (CO_2), and utilize corrosion-resistant vacuum pumps to remove the CO_2. Plant retrofit designers should plan to incorporate a new condenser for CES-cycle plants.

Control systems will require interface “controllers” to integrate the gas generator’s PLC with plant analog and digital control systems. A separate interface controller was deemed more cost effective than modifying the already-designed gas generator PLC. It is expected that hardware and software in the interface controller will need to be adapted to meet local power plant legacy systems needs.

CES analyzed both off-the-shelf support and new equipment designs for their effectiveness in supporting the CES-cycle. CES learned that modifying existing sub-system designs was relatively straight-forward and cost-effective. Mostly, subsystem equipment design efforts focused on incorporating safety, reliability, and durability improvements.

This effort illustrates the benefit of qualifying existing power plants for conversion to zero-emissions in order to accelerate desirable technology development. CES now has baseline support system designs that can be readily transferred to new and existing power plants for the first generation of CES-cycle plants (5-50 MW class). CES expects the first commercial sale of a CES-cycle zero-emission, electrical power generation system to occur in mid-2005.

Steam Turbine Feasibility Study (Task 2)

Utilizing its prediction of drive gas composition (Table 1) in a CES-cycle ZENG power plant, improved plant efficiencies resulting from use of the DOE/NETL re-heater, and the analytical work performed by Fern Engineering, CES found use of a DOE-designed re-heater in a CES-cycle power plant increased plant efficiency by over 5 percent. CES also proposed six plant concepts utilizing the CES-cycle (gas generator) for a future ZENG power plant. A summary of the plant concepts and efficiencies follow:

> Concept 1: CES-cycle drive gas is directed through two corrosion-resistant steam turbines mounted in series. Exhaust is sent to HRSG, which (in turn) drives additional conventional steam turbines. Low-pressure ASU supplies O_2, atmospheric condenser condenses drive gas, CO_2 pumped in stages to sequestration pressure—plant efficiency ~29%
> Concept 2: Same as Concept 1 except: corrosion-resistant LPT added to CES-cycle drive train, HRSG and conventional turbine train eliminated, drive gas condensed in sub-atmospheric condenser—plant efficiency ~31%
> Concept 3: Same as Concept 2 except: high-pressure ASU substituted for low-pressure unit (reduces O_2 separation & compression requirements)—plant efficiency ~35%
> Concept 4: Same as Concept 3 except: high-pressure ASU is integrated into CES power plant—plant efficiency ~40%
> Concept 5: Same as Concept 4 except: auxiliary N_2 turbine added—plant efficiency ~40%
> Concept 6: Same as Concept 5 except: IPT replaced with aero-derivative unit with cooled blades—plant efficiency ~48%

In addition, CO2 Norway integrated: (1) analytical work done by CES, (2) information aggregated in the engineering survey and technical summary of suitable steam turbines from the Fern study, and (3) information on other aspects of plant design collected from third party sources and then compiled this information into a ZENG Plant Feasibility Final Report. The ZENG report concludes that construction and operation of a CES gas generator-equipped ZENG plant is both technically feasible and economically practical in the immediate future.

The ZENG studies provided standardized "baselines" for CES-cycle drive gas composition (from both natural gas and coal syngas), a well-researched inventory of steam turbines already suitable for CES-cycle drive gas, reasonable steps to converting an aero-derivative turbine to CES-cycle drive gas usage, and a family of concepts for Zero-Emission Power Plants at net plant efficiencies ranging from 29% – 48%. This menu of tools for building the "next generation" zero-emission power plant will help this useful technology move forward to its initial deployment and operation in commercial power production. The ZENG study also leverages Norwegian expertise and experience in designing and operating low- and no-emission plants to the U.S. industrial base.

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None

LIST OF ACRONYMS AND ABBREVIATIONS

ASU—Air Separation Unit
bar—0.98697 standard atmosphere; 10^5 newtons / square meter
CEC—California Energy Commission
CES—Clean Energy Systems, Inc. (Rancho Cordova, CA)
CH_4—Methane
CO_2—Carbon Dioxide
cryo-pump—Cryogenics (oxygen) Pump
cryo-storage—Cryogenics Storage (tank)
DI—De-ionized (water)
DOE—Department of Energy
FMEA—Failure Modes and Effects Analysis
GG—Gas Generator
H_2O—Water
HPT—High Pressure Turbine
HRSG—Heat Recovery Steam Generator
IPT—Intermediate Pressure Turbine
LPT—Low Pressure Turbine
LRVP—Liquid Ring Vacuum Pump
MW—Mega Watt; 10^3 Kilo Watts; 10^6 Watts
N_2—Nitrogen
NETL—National Energy Technology Laboratory
NG—Natural Gas
NOK—Norwegian Krone
PLC—Programmable Logic Computer
PRV—Pressure Relief Valve
ppm—Parts Per Million
psi—Pounds per Square Inch
psig—Pounds per Square Inch Gauge
ROV-xxx—Remote Operating Valve-xxx
SOW—Statement of Work
syngas—Synthetic Gas (from coal or bio-mass)
USD—United States Dollar
ZENG—Zero-Emission Norwegian Gas (power plant)
ZEPP—Zero-Emission Power Plant
°C—Degrees Celcius
°F—Degrees Fahrenheit
µ—Micron; 10^{-6} meters

APPENDICES

None