Integrated CHP Using Ultra-Low-NOx Supplemental Firing

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ABSTRACT

The objective of the work presented is to deploy Gas Technology Institute's (GTI's) Flexible Combined Heat and Power (FlexCHP) system to deliver power and steam while holding Nitrogen Oxides (NOx), Carbon Monoxide (CO), and Total Hydrocarbon (THC) emissions below the California Air Resources Board (CARB) 2007 Fossil Fuel Emissions Standard for Distributed Generation (DG). This system, appropriately designated as FlexCHP-65, combines a Capstone C65 microturbine, a GTI-developed supplemental Ultra-Low-NOx (ULN) burner, and a 100 Horsepower (HP) heat recovery boiler by Johnston Boiler Company.

The supplemental ULN burner has demonstrated increased energy efficiency while meeting the 2007 Fossil Fuel Emissions Standard without the use of catalytic exhaust gas treatment. Preliminary laboratory testing with a 2.2 million Btu/h supplemental burner firing the exhaust from a 60-kW Capstone microturbine proved the capability of the system to deliver final stack NOx below 0.07 lb/MWh. Additional testing showed that the burner can be successfully scaled up to 7.5 million Btu/h. This also indicates the possibility of integration with megawatt-scale engines such as the Solar Mercury 50. Evaluation of a 3.5 million Btu/h burner firing with exhaust gas from a 65-kW Capstone microturbine is following the path to reduce NOx formed in the turbine and deliver final NOx emissions in the stack at levels which have not been achieved without Selective Catalytic Reduction (SCR). The resulting Combined Heat and Power (CHP) packages promise to make DG implementation more attractive, mitigate greenhouse gas emissions, improve the competitiveness of industry, and improve the reliability of electricity.

Market Barriers and Opportunities

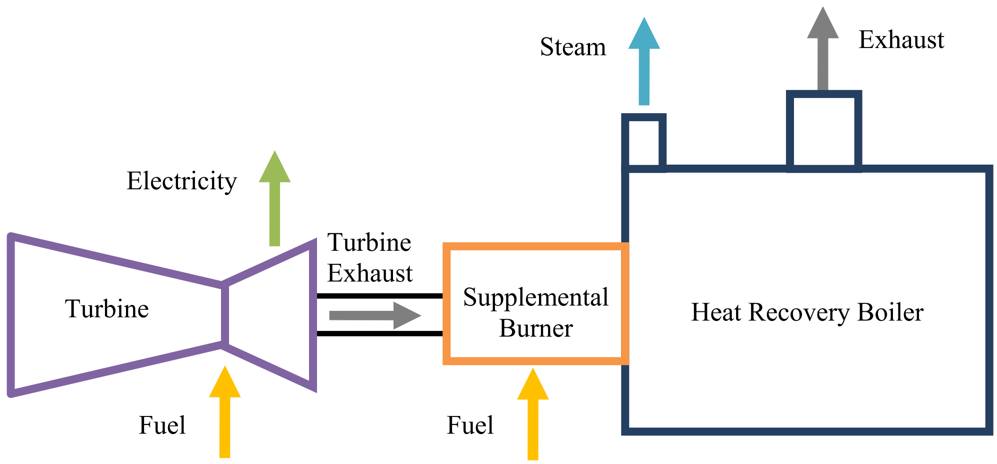
Gas turbines have a number of beneficial features that have led to their widespread application for Combined Heat and Power (CHP), including their relatively simple design, low capital cost per kilowatt, low maintenance requirements, and lower emissions as compared to reciprocating engines. However, because of the need to operate at high excess air (225-550%), exhaust losses from gas turbine based CHP systems are relatively high and offer an opportunity for further cost savings.

A common approach to recoup some of the energy loss is through the use of supplemental burners (i.e. duct or parallel burners) to combust additional fuel in the oxygen-rich Turbine Exhaust Gas (TEG) and to raise the temperature for better downstream heat recovery in a boiler as shown in Figure 1. For example, with natural gas as the fuel and a final flue gas temperature of 275°F, reducing the excess air from 355% to 15% decreases the stack loss from 46% to 17% (higher heating value basis).

Even with low-NOx duct or parallel burner designs, however, CHP systems have encountered difficulty in satisfying stringent output-based emissions criteria, such as the 2007 California Air Resource Board (CARB) Fossil Fuel Emissions Standard. With these emissions criteria defined on a per unit energy output basis, distributed generation systems must achieve high efficiencies, in addition to low pollutant concentration levels in the stack for compliance.

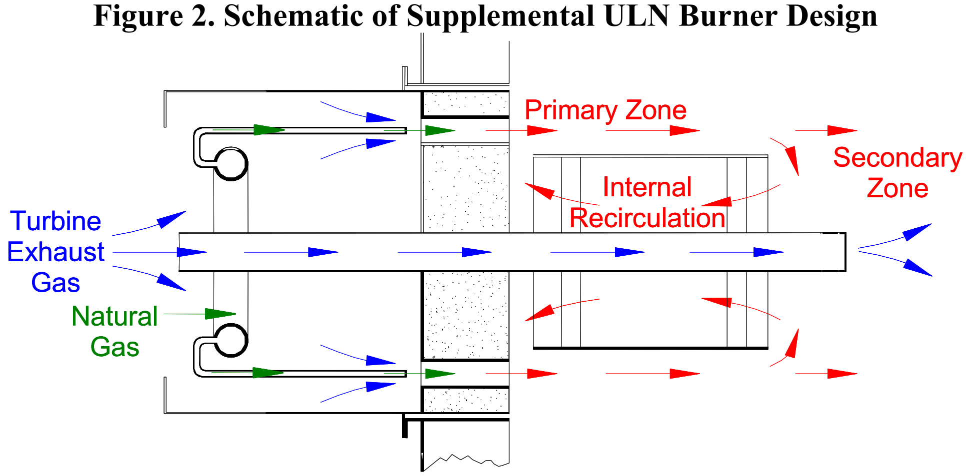
(Cox 2011). While post-combustion cleanup processes such as Selective Catalytic Reduction (SCR) are capable of reducing emissions below the required levels, these technologies increase capital cost by 10 to 25% (Agrawal 2001, Kaarsberg 1999). This is a significant barrier to adoption of distributed generation and CHP systems, especially for small to medium-capacity facilities (< 10 MW). Thus, there is a need for a low-cost, low-emission duct burner technology which can enable the deployment of high-efficiency CHP systems in the commercial and industrial sectors.

Figure 1. Heat Recovery of Turbine Exhaust through Supplemental Combustion



GTI has developed a low-cost supplemental ULN burner technology specifically designed to utilize high temperature (600-1000°F), high oxygen content (17-18 vol.-percent) turbine exhaust gas as an oxidant for combustion with natural gas. The burner provides an increase in total system efficiency by lowering exhaust oxygen levels to 3-6 vol.-percent and recovering waste heat from the turbine exhaust in the form of steam with a heat recovery boiler. To achieve the ultra-low NOx emissions level required by the CARB 2007 standard, GTI's innovative supplemental ULN burner employs staged combustion with engineered internal recirculation that exposes NOx and NOx precursors to a low temperature zone, thus limiting the production of thermal NOx. Figure 2 shows a schematic of the ULN burner design.

Figure 2. Schematic of Supplemental ULN Burner Design



In addition to stringent emissions criteria, the installed cost of CHP systems is a major barrier to implementation for small and medium-size industrial plants and commercial buildings (Chittum 2011). Consequently, GTI has developed a flexible, standalone CHP system (FlexCHP) that incorporates a microturbine, ULN burner, and integrated controls package to be adapted to a wide range of firetube boiler models. The FlexCHP system offers partially decoupled steam and electricity generation rates in a pre-engineered package that can be retrofitted to existing boilers, avoiding site-specific engineering costs, and greatly expanding the market potential for CHP.

Burner Development

The initial burner concept was designed to utilize turbine exhaust from a Capstone 60-kW microturbine at firing rates up to 2.2 million Btu/h. Development activities were carried out in GTI laboratory facilities on a 20-inch diameter water cooled chamber which simulates the conditions of a firetube boiler. On a volume per volume basis, stack NOx emissions, after supplemental firing, were lower than NOx emissions from the gas turbine, even in the case of the ultra-low NOx emissions (3.4 ppmv on a 15% O_2 basis)[1] from the Capstone microturbine. The data in Table 1 show NOx levels as much as 35% below those produced by the gas turbine alone.

Table 1. Summary of 2.2 million Btu/h ULN Burner Performance

	Capstone C60 Microturbine	Capstone C60 Microturbine + Supplemental ULN Burner
Turbine Output [kW]	50	50
Burner Input [million Btu/h]	--	2.11
O_2 [vol %]	17.8	8.1
NOx [vppm]	3.4	2.2
CO [vppm]	9	5

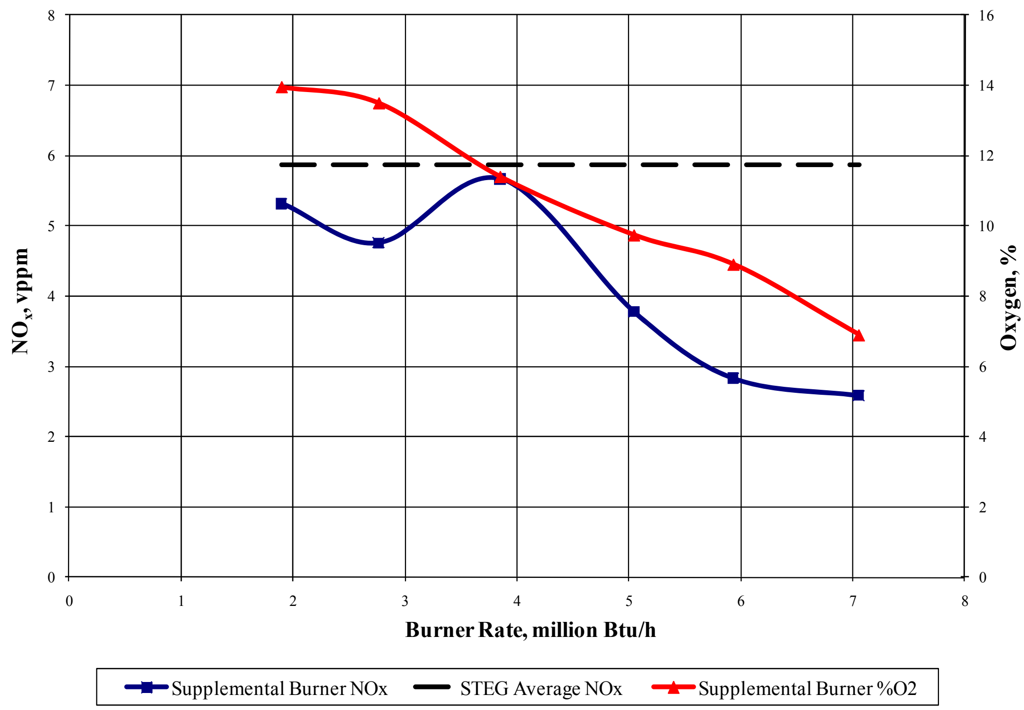
Following successful development at 2.2 million Btu/h firing rate, efforts turned towards scaling the technology for application to larger turbines, such as the 4.6 MW Solar Mercury 50 turbine. The supplemental ULN burner was designed and evaluated at firing rates up to 7.5 million Btu/h on a 40-inch water cooled firetube boiler simulator at GTI facilities. Because a Solar Mercury 50 turbine was unavailable for testing, the Turbine Exhaust Gas (TEG) was simulated with a mixture of flue gases from a low NOx auxiliary burner and dilution air post combustion to closely match the exhaust gas constituents and exhaust temperature of the turbine (705 °F, 16.4% O_2, 5 vppm NOx). The volume of Simulated Turbine Exhaust Gas (STEG) generated could be varied over a turndown of three to one, while maintaining uniform NOx emissions.

Figure 3 shows NOx emissions and oxygen concentrations as a function of burner firing rate. A dashed line represents the average NOx concentration measured in the STEG across the firing range. In all cases, the NOx concentration measured downstream of the supplemental burner was the same or lower, than the NOx concentration measured in the STEG. Overall NOx concentrations decreased as the burner firing rate increased. Although not shown, CO and THC

[1] All emissions are corrected to 15 percent oxygen unless otherwise noted.

emissions remained below 50 vppm at all test points. The oxygen concentration varied over the firing range while maintaining a fixed amount of STEG.

Figure 3. NOx and Oxygen Output for 7.5 million Btu/h ULN Burner



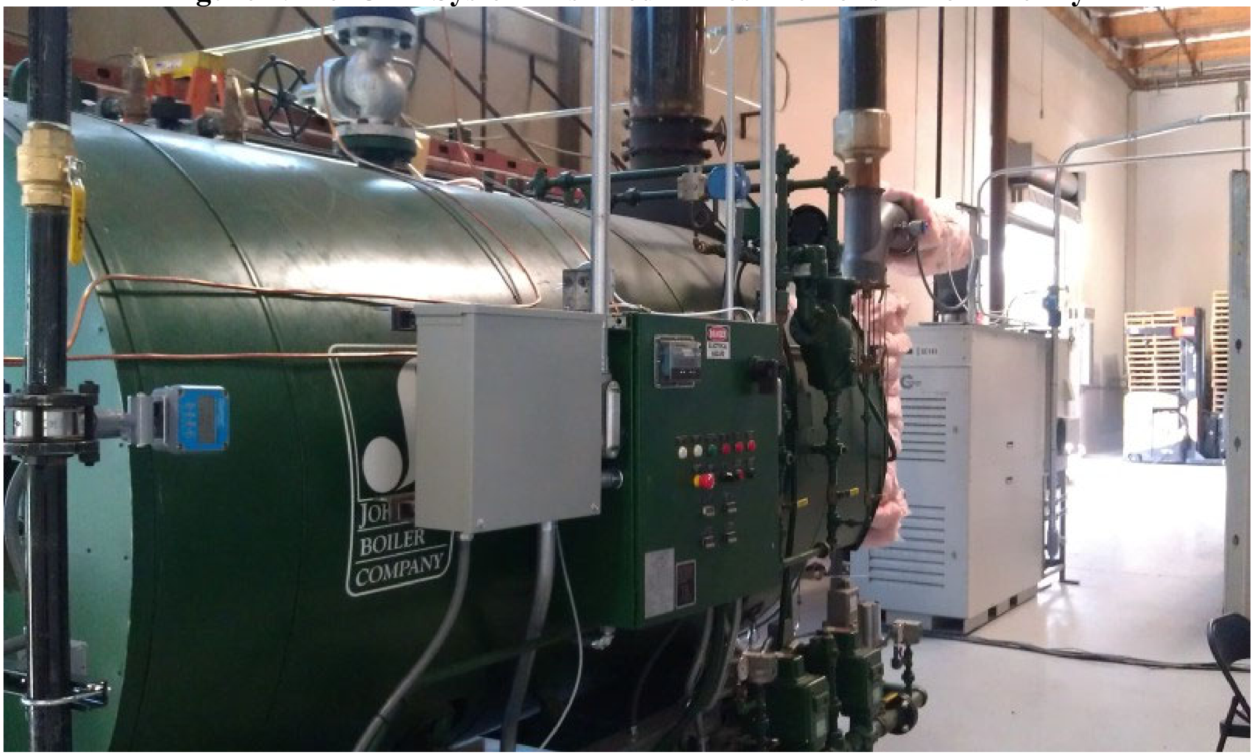
Technology Demonstration

Following development activities, the supplemental ULN burner was incorporated into a flexible, pre-engineered CHP system, termed FlexCHP-65, which combines a Capstone C65 microturbine, a 100 HP heat recovery boiler by Johnston Boiler Company, and custom controls package. The controls package allowed for remote operation of the turbine and integration with the boiler steam demand and safety relays. This also served as a data acquisition system to collect information from the full array of pressure, temperature, and flow sensors installed on the FlexCHP that are used to characterize system performance and efficiency.

The FlexCHP system was installed at a food processing facility located in Southern California. The microturbine was set to operate at full load capacity to generate a base load of 60 kW of electricity for the facility. Fluctuating steam demands in the facility were satisfied by varying the firing rate of the supplemental burner. Figure 4 shows the complete system as installed at the demonstration host site.

While operating at full load, the microturbine drew 863 MBtu/h of natural gas and delivered a net power output of 59.6 kWe, giving a turbine electrical efficiency of 23.6%. Under these conditions the exhaust exits the turbine at 615 °F with 17.8 % O_2. With the supplemental burner operating at full fire capacity (2.7 million Btu/h permit limit), the final stack temperature was 233 °F with 6.6 % O_2. Based upon these flue gas conditions and an estimation of jacket losses the overall system efficiency can be calculated at 84.2%. This is a marked increase in system efficiency as compared to the microturbine operating alone.

Figure 4. FlexCHP System Installed at Host Demonstration Facility

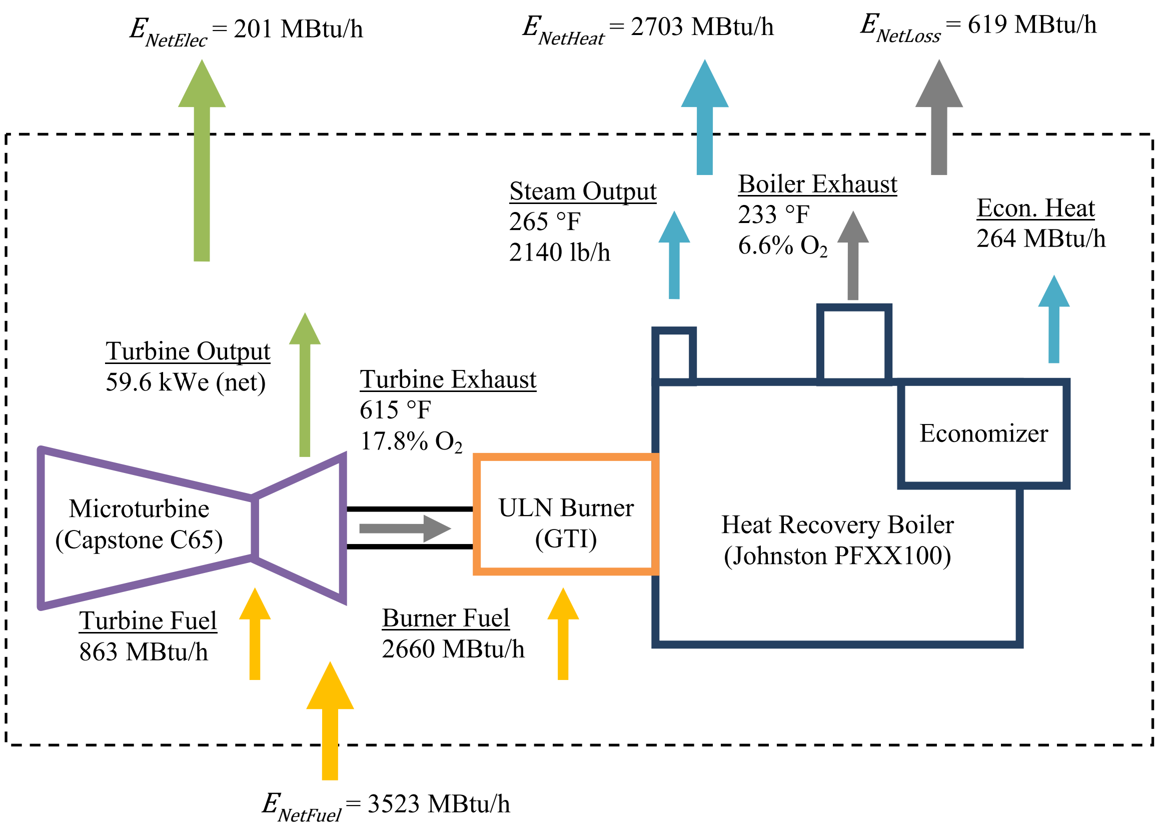


To further characterize the efficiency of the FlexCHP system a full set of measurements was obtained to quantify all energy inputs and outputs. The fuel inputs were determined from gas flow rate measurements and higher heating values acquired from the local gas company. Net electrical output was quantified from power meter measurements and estimations of other minor electrical power inputs (feed water pump, etc). Steam energy output was determined from measurements of the boiler steam pressure, feed water flow rate, and feed water temperature. Hot water energy recovery was quantified by water flow rate and temperature inlet/outlet measurements at the economizer. An overview of the FlexCHP performance and associated energy flows as measured at the host facility is shown in Figure 5. Based on this energy flow methodology, the overall system efficiency is calculated to be 82.4%.

The value of the FlexCHP system can be highlighted by comparing it to the alternative scenario of a separate microturbine and boiler installed at a user facility as shown in

Figure 6. This is an apt comparison, as this would be a more common installation for a plant seeking to generate the same quantities of electricity (via microturbine) and steam. If all of the process conditions are considered to be the same as those measured during the host facility demonstration, the boiler efficiency could be calculated to be 84.2%, based on flue gas conditions of 233 °F and 6.6% O_2 and estimated boiler jacket losses. Thus, to achieve the same steam (2,140 lb/h) and hot water (264 MBtu/h) output, a fuel input of 3,210 MBtu/h would be required for the boiler burner. The performance of the microturbine would remain unchanged for this scenario, with the exception that all of the turbine exhaust energy would be lost through the stack.

Figure 5. Overview of FlexCHP Energy Flows for Operation at Full Load Capacity



The total output from a facility operating under these conditions would be 2,906 MBtu/h for a combined input of 4,073 MBtu/h, yielding an overall efficiency of 71.3%. Thus, the FlexCHP system provides more than an 11 percentage point increase in system efficiency for the same equipment and capital investment. Further, the quantity of pollutant is greatly reduced for the FlexCHP system since the turbine exhaust pollutant concentrations are decreased along with the overall mass flowrate of stack gases.

In addition to quantifying system efficiency during the field demonstration, NOx, CO, and THC emission levels were measured across the full range of supplemental burning firing rates. Figure 7 shows NOx emissions for the FlexCHP system in comparison to the microturbine. The supplemental ULN burner provides a significant reduction in NOx emissions for all firing rates, with a decrease of up to 48%. CO and THC emissions for the FlexCHP system were measured to be near zero for all conditions, providing further pollutant reduction levels in comparison to the microturbine.

Figure 6. Performance of Microturbine and Boiler Installed Separately

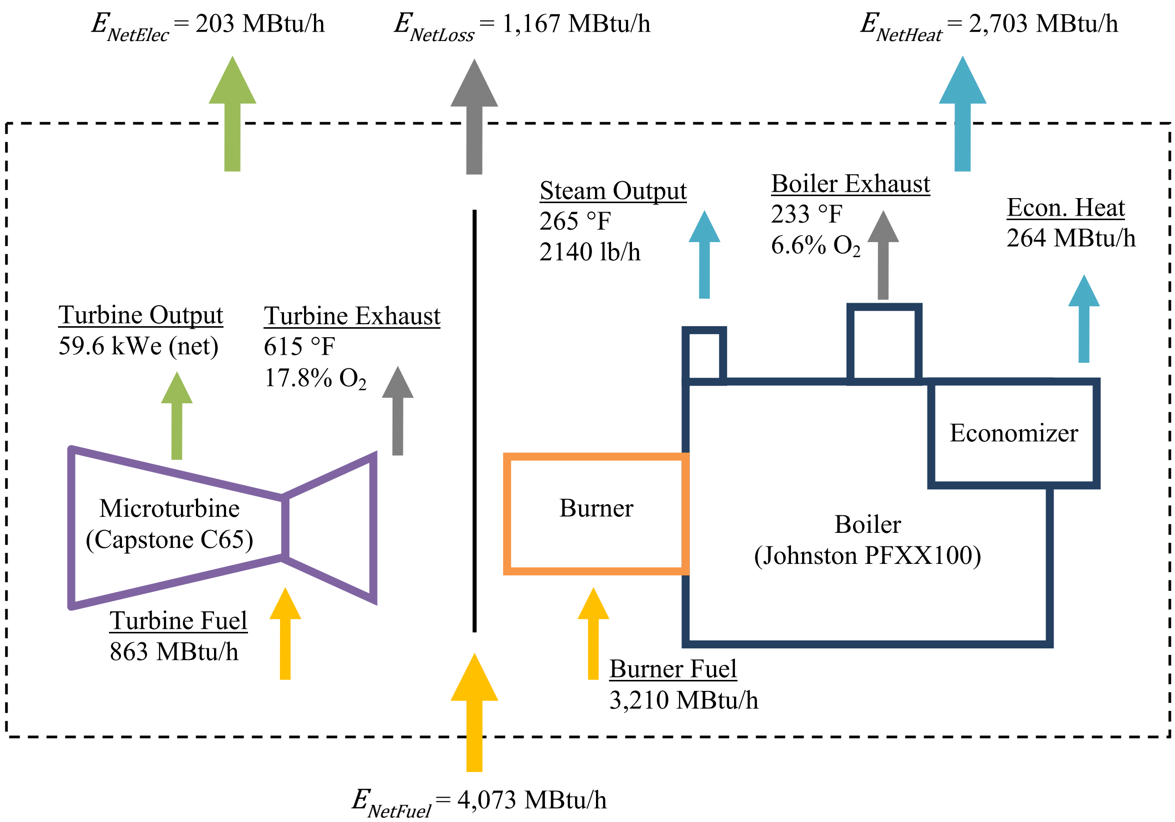
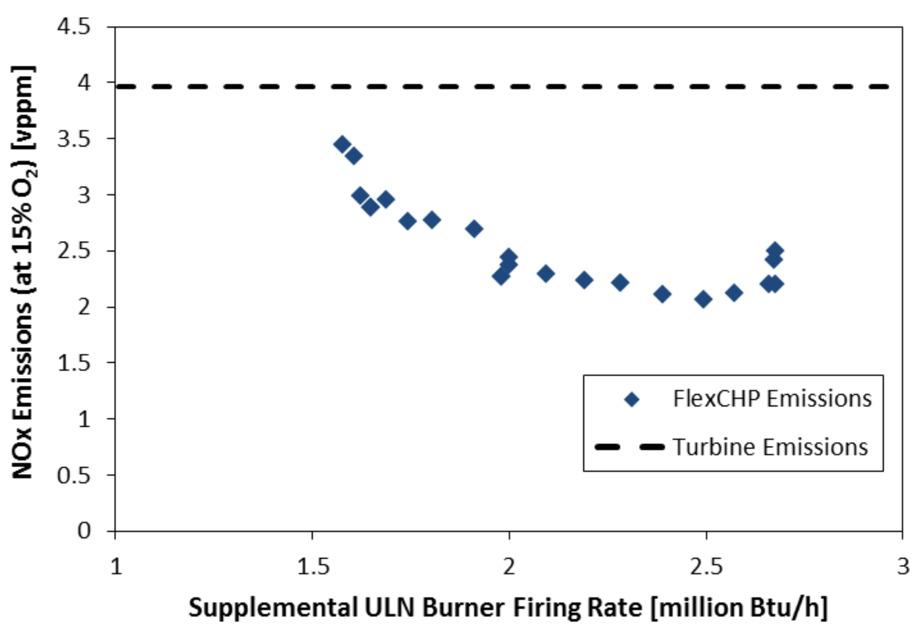
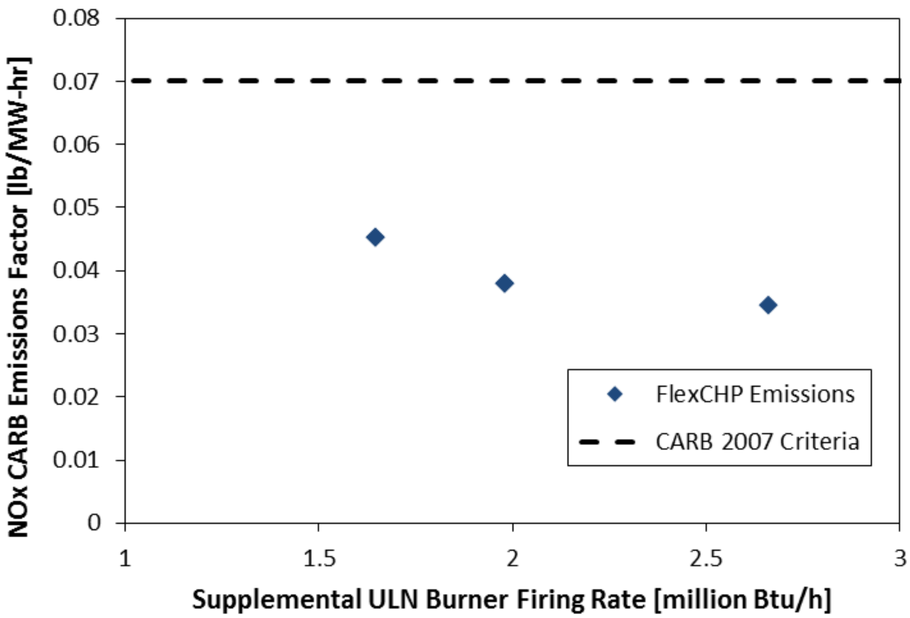


Figure 7. NOx Emissions of FlexCHP Relative to Microturbine



To characterize the system performance relative to the CARB 2007 Fossil Fuel Emissions Standard for integrated CHP installations, pollutant parts per million emissions levels were converted to pounds per megawatt hour output basis. The total electric and thermal output was characterized via the methodology previously outlined for calculating system efficiency. The pounds per hour of pollutant were determined from the stack concentration levels and exhaust mass flowrate. The NOx emissions for the FlexCHP relative to the CARB 2007 criteria are shown in Figure 8. At high fire conditions the FlexCHP emits 0.035 lb/MW-h of NOx which is 50% of the required level of 0.07 lb/MW-h. Similarly, CO and THC emissions were far below the mandated levels of 0.10 and 0.02 lb/MW-h, respectively, for all conditions evaluated.

Figure 8. NOx Emissions of FlexCHP Relative to CARB 2007 Standard



The results of the field demonstration have shown the FlexCHP capable of meeting the most stringent emissions regulations currently established for CHP systems. Moreover, it has shown a significant reduction in pollutant concentration levels in comparison to the microturbine operating alone. Further, the system has demonstrated a considerable improvement in efficiency in comparison to a conventional installation of a separate microturbine and boiler at a user facility.

Packaged Solutions

The many performance enhancements demonstrated by the FlexCHP system are achieved without significant increases to capital equipment costs. Moreover, because the technology offers a pre-engineered, packaged CHP system, installation costs are anticipated to be greatly reduced, as the need for extensive on-site engineering is eliminated.

To satisfy a broad range customer steam and electricity demands, development of multiple packaged systems is envisioned. In addition to the Capstone 65 kW turbine employed during the initial technology demonstration, the project team has identified Capstone 200 kW and 1000 kW and Solar's 4.6 MW Mercury 50 turbine systems as excellent candidates for the development of FlexCHP product package designs that will provide cost effective and reliable coverage of a wide market segment. The package designs will integrate these turbines with appropriately sized ULN supplemental burners and standard sized boilers by Johnston Boiler

Company to provide high efficiency CHP (>80%) that meets stringent NOx requirements (< 0.07 lb/MW-h). The packaged FlexCHP products proposed are outlined in Table 2.

Table 2. Packaged FlexCHP Systems

	FlexCHP-200 kW	FlexCHP-1000 kW	FlexCHP-4600 kW
Turbine Model	Capstone C200	Capstone C200 (qty. 5)	Solar Mercury 50
Turbine Input [million Btu/h]	2.28	11.4	45.15
Turbine Output [kWe]	200	1,000	4,600
Supplemental Burner Size [million Btu/h]	10	50	120
Steam Output [lb/h][a]	6770	34,360	88,790
Boiler Model	Johnston PFTX350	Johnston PFTX1600	Johnston PFTX 1800 (qty.2)
Boiler Horsepower [HP]	250	1500	3600

[a]Steam output considered for 150 psig steam pressure

The FlexCHP systems will be commercialized in the boiler market in regions of the U.S. that have high electric power costs and where CHP is already established as a commercially viable alternative to grid based electricity and on-site generation of thermal energy using natural gas. These regions include California and the Northeast. These products will typically be sold to facilities for integration with their existing infrastructure and will require to be vetted by engineering companies as well as facility owners.

Summary

The deployment of distributed generation CHP technologies capable of meeting the CARB 2007 output-based emissions standard has the potential to save energy, to increase productivity, and to reduce the burden on centralized power plants. In many cases, supplemental firing can boost heat output and thermal efficiency from gas turbine-based CHP in a cost-effective manner; however, conventional methods struggle to meet CARB 2007 NOx targets without Selective Catalytic Reduction (SCR).

GTI has developed an Ultra-Low NOx (ULN) burner technology designed to utilize high temperature (>500 °F), high oxygen content (>15 %) turbine exhaust as the oxidizing agent for combustion of supplemental natural gas. The burner design is specifically tailored to deliver heat for firetube boiler applications while offering optimal efficiency and minimal NOx emissions.

Initial burner development activities were carried out using a Capstone 60 kW microturbine. The 2.2 million Btu/h burner developed for this generator reduced NOx levels from 3.4 vppm in the incoming turbine exhaust to 2.2 vppm in the stack. Efforts to scale the technology for use with larger turbines, such as the Solar Mercury 50, resulted in the construction of a burner rated at 7.5 million Btu/h. Once again, NOx emissions from the burner were reduced in comparison to the incoming simulated turbine exhaust across the full range of firing rates.

The GTI-developed supplemental ULN burner was integrated into a flexible, pre-engineered CHP system, termed FlexCHP-65, which combines a Capstone C65 microturbine, a 100 HP heat recovery boiler by Johnston Boiler Company, and custom controls package. The FlexCHP system was installed a food processing facility in Southern California to meet facility electricity and steam demands. The microturbine was set to operate at full load capacity providing a net electrical output of 59.6 kWe with exhaust gas at 615 °F and 17.8 % O_2. With the supplemental ULN burner operating at full fire capacity (2.7 million Btu/h permit limit), the final stack conditions were 233 °F with 6.6 % O_2. This reduction in exhaust temperature and oxygen content allows for a substantial gain in heat recovery, boosting overall system efficiency to 84.2% as calculated from flue gas losses and an estimation of jacket losses. This is a substantial gain in efficiency as compared to the 71.3% efficiency which would be achieved for a CHP installation at the same facility with the microturbine and boiler operated independently to deliver the same electricity and thermal output.

The emissions performance of the FlexCHP system operating at the host far exceeds the 0.07, 0.10, and 0.02 lb/MW-h emission requirements for NOx, CO, and THC respectively, as designated by the CARB 2007 standard. Specifically, NOx levels were measured to be 0.035 lb/MW-h, which is only 50% of the required level. Further, in comparison to the microturbine operating alone, NOx, CO, and THC exhaust concentrations are reduced by 45%, 97%, and 78%, respectively for the FlexCHP system operating at full fire conditions.

As compared to a conventional CHP installation utilizing the same boiler and microturbine operated independently, the FlexCHP system offers a significant increase in system efficiency and reduction in NOx emissions. This substantial improvement in performance is achieved with a relatively minor increase in capital equipment cost for the integrated controls package. Moreover, installation costs for the packaged FlexCHP system are anticipated to be decreased in comparison to conventional CHP systems as the need for extensive site-specific engineering is mitigated. To satisfy a range of customer demands, several FlexCHP packaged systems are envisioned for 65 to 4,600 kW electricity and 2,000 to 88,000 lb/h steam output levels. The FlexCHP product line will offer customers significant energy savings, in a cost-competitive package capable of meeting the most stringent emissions standards currently established for CHP.

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