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**BIODIESEL FUELED ENGINE GENERATOR WITH HEAT RECOVERY**

**Fred Betz**

Carnegie Mellon University  
Pittsburgh, PA, USA

**David Archer**

Carnegie Mellon University  
Pittsburgh, PA, USA

**Chris Damm**

Milwaukee School of Engineering  
Milwaukee, WI, USA

**Brian Goodwin**

Milwaukee School of Engineering  
Milwaukee, WI, USA

**ABSTRACT**

Carnegie Mellon University's departments of Architecture and Mechanical Engineering have teamed with Milwaukee School of Engineering's Mechanical Engineering department to design and install a biodiesel fueled engine-generator with heat recovery equipment to supply electric and thermal power to an office building on campus, the Intelligent Workplace (IW). The installation was completed in early September 2007, and is currently being commissioned. Full scale testing will begin in early 2008.

The turbocharged diesel engine-generator set is operated in parallel with the local electric utility and the campus steam grid. The system is capable of generating 25 kW of electric power while providing 18 kW of thermal power in the form of steam from an exhaust gas boiler. The steam is delivered to a double-effect Li-Br absorption chiller, which supplies chilled water to the IW for space cooling in the summer or hot water for space heating in the winter. Furthermore, the steam can be delivered to the campus steam grid during the fall and spring when neither heating nor cooling is required in the IW. Additionally, thermal energy will be recovered from the coolant to provide hot water for space heating in the winter, and for regenerating a solid desiccant dehumidification ventilation system in summer. All relevant temperatures, pressures, and flows for these systems are monitored via a building automation system. Pressure versus time measurements can be recorded in each cylinder of the engine. Emissions of nitric oxide (NO), nitrous oxide (NO<sub>2</sub>), Particulate Matter (PM), and carbon dioxide (CO<sub>2</sub>) are also monitored.

Upon completion of this installation and the system performance testing, the operation of the engine generator with its heat recovery components will be integrated with the other HVAC components of the IW including a parabolic trough solar thermal driven LiBr absorption chiller, a solid desiccant dehumidification ventilation system, and multiple types of fan coils and radiant heating and cooling devices. This energy supply system is expected to reduce the IW's primary energy

consumption by half in addition to the 75% energy savings already realized as compared to the average US office space.

**NOMENCLATURE**

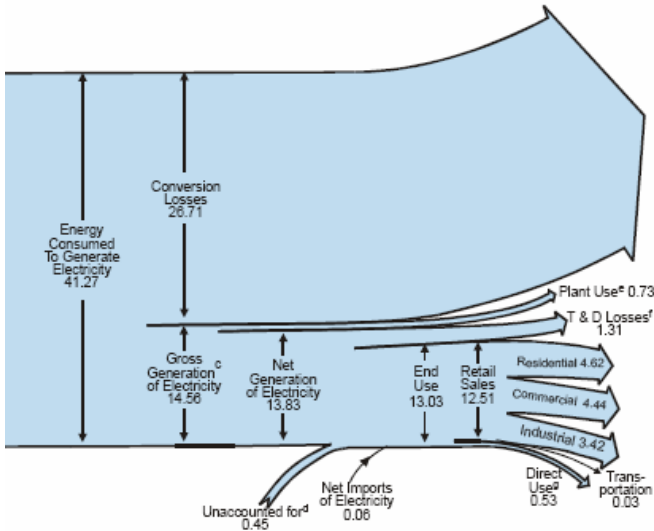
LiBr	Lithium Bromide
DG	Distributed Generation
CHP	Combined Heat and Power
HVAC	Heating Ventilation and Air Conditioning
BAS	Building Automation System
SLC	Soft Load Controller
ATS	Automatic Transfer Switch

**INTRODUCTION**

As energy demand in the U.S. and around the world increases along with increased strain on electrical transmission and distribution grids, the use of distributed generation (DG) and combined heat and power (CHP) systems is a viable approach to reducing energy costs, shortages, and lessening the impact of power generation on the environment. The increasing cost of building larger scale power generation facilities is making smaller scale DG systems more attractive. Furthermore, the continuing political issues with liquid fossil fuels and their environmental consequences is making biofuels more attractive to energy consumers.

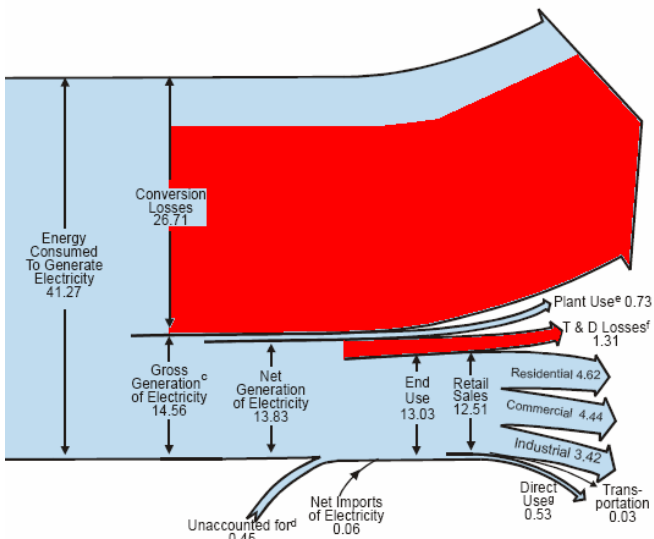
In recognition of the importance of distributed combined heat and power systems for decreasing adverse environmental impacts from power generation, there have been several studies of CHP performance optimization and economics (1, 2, 3, and 4). Furthermore, there is considerable interest in both characterizing and modeling the performance of distributed CHP systems (5). A model is concurrently being developed for the components of this CHP Installation.

Central power plants typically generate power with a 33.5% conversion efficiency and a 9.5% transmission and distribution loss as shown in Figure 1.



**Figure 1. 2006 U.S. Electricity Flow (adapted from reference 6)**

Therefore, only about 1/3 of the fuel energy consumed in a large power plant arrives at the end user's facility. In contrast, CHP facilities generate power at efficiencies ranging between 25% and 35% depending on the prime mover used and the reject heat, which can take the form of exhaust and/or coolant, can be utilized within the facility for heating and/or cooling when combined with the appropriate HVAC equipment. Thus, typical CHP installations achieve 65% to 85% utilization of the fuel energy as shown in Figure 2 (7, 8, and 9).



**Figure 2. Potential Energy Savings of CHP systems using Heat Recovery and Reduced Transmission and Distribution Losses (adapted from reference 6)**

### BUILDING DESCRIPTION

The Intelligent Workplace (IW) provides a test-bed for HVAC technology research and development. The IW is a 650 m<sup>2</sup> living and lived in laboratory, which is constantly changing to meet the demands of its occupants. The IW is situated atop a building with offices and classrooms as shown in Figure 3.



**Figure 3. The Intelligent Workplace (IW)**

The IW, through its architectural features, has already realized a 75% energy savings in lighting, heating, cooling, ventilation, and energy distribution. The architectural features include:

- day-lighting with glare control
- operable windows
- cool roof with ridge vents
- thermally broken façade
- raised floor with positive displacement ventilation
- radiant heating and cooling panels

In addition to the IW's passive features, a solid desiccant dehumidification based ventilation system with enthalpy recovery, a solar thermal driven absorption chiller system, fan coils with intelligent controls and a biodiesel fueled CHP system provide the necessary energy to light, cool, heat, ventilate, and dehumidify the IW. The IW is connected to the campus's energy grids, which allow for the importing and exporting of power, steam, and chilled water. The goal of all the active systems is to reduce the IW's energy consumption by an additional 50%.

### BUILDING LOADS

The IW has a 40 kW peak cooling load and a 50 kW peak heating load. The thermal loads are met by an 8 kW heat pump in the ventilation unit, a 16 kW solar thermal system and the biodiesel-fueled CHP system.

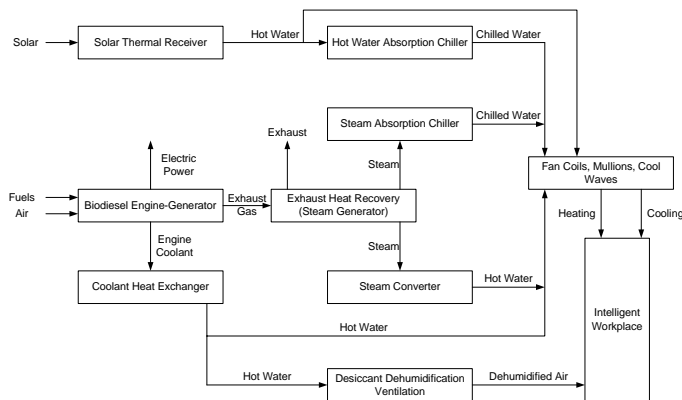
The CHP system was sized so that heat recovery from the exhaust can produce 16 kW of 87 psig (7 bar) steam to an absorption chiller. In order to provide this heat, a 25 kW Diesel engine generator has been equipped with a fire tube type steam generator for exhaust heat recovery, shown in Figure 4. Heat recovery from the engine coolant produces additional thermal power (approximately 20 kW).



**Figure 4. Biodiesel Fueled Engine Generator with Heat Recovery System**

### SYSTEMS INTEGRATION

Figure 5 shows how the CHP system is integrated with the other IW HVAC components.



**Figure 5. IW HVAC Systems Integration**

The engine is a 2.4 liter turbocharged compression ignition engine. The engine has a compression ratio of 20.5 to 1 and has been operating at an average efficiency of 30% based on the fuels lower heating value (10). While the engine is capable of operating with a 32 kW output (36 kW standby), the control system sets the maximum at 25 kW for a prime power generation configuration to minimize wear on the engine. Therefore, the engine consistently operates with lower temperatures and flows than those listed in the engine's specification sheet. A detailed analysis of the turbocharger is under way with measured the temperature and pressures of the compressor and expander.

The electrical power output from the 88% efficient generator (10) is paralleled with the local utility grid in order to allow the engine to operate in a thermal dispatch mode. The soft load controller and automatic transfer switch allows flexible power output and allows the CHP system to operate in an "island mode" as well as an export mode.

The engine's coolant energy can be removed using a standard radiator and fan, which is mounted outside the building or a plate and frame heat exchanger that operates in parallel with the IW's heating system. During the summer the coolant energy will be routed to the ventilation system to regenerate the desiccant. Currently, the ventilation system uses a natural gas burner to provide regeneration air at a temperature of 185°F.

The steam generator operates like a fire tube boiler using the high temperature exhaust of the engine. One of the draw backs to using a steam system is that the smallest commercially available steam generator that can operate at 87 psig is sized for a 200-250 kW engine. Therefore, it takes approximately nine hours for the 25 kW engine to bring the steam generator up to a 360°F operating temperature. The water volume is approximately 200 gallons and there is just over 1,000 pounds of steel used in the construction of the steam generator, which explains the large thermal capacitance. However, when the steam generator reaches its operating conditions of 87 psig and 360°F, a steam flow rate of 70 lb/hr is realized, which supplies the IW's heating system and the campus steam grid.

### EQUIPMENT SELECTION

The primary components of the CHP system were selected based on a number of factors including fuel availability, power output, exhaust temperature, and cost. As stated, the CHP system was sized to fit a 16 kW steam driven absorption chiller. Therefore, a high temperature thermal output of 18 to 20 kW was required. A gas microturbine was considered but the smallest commercially available unit generates 30 kW of electric power and more thermal power than required for this application. Furthermore, using a renewable fuel was a key design criterion for this project. As biodiesel was easier to source than biogas for the microturbine, this contributed to the selection of a Diesel engine. Finally, cost was a key driver which precluded the use of a fuel cell. Diesel engine suppliers provided quotes between \$1,000 and \$1,200 per kilowatt, as compared to the \$8,000 per kilowatt that a fuel cell supplier provided. Therefore, a Diesel engine (shown in Figure 6) was selected for this application.



**Figure 6. 25 kW Engine Generator Set**

## CONTROLS

There are several control loops within this CHP system that allow for robust control of the system while also assuring safe operation. The engine controller monitors oil pressure, coolant temperature and level, as well as battery conditions. The Soft Load Controller (SLC) and the Automatic Transfer Switch (ATS) shown in Figure 7 take over control of the governor in the engine to vary the speed to aide in paralleling the engine to the grid. The SLC and ATS monitor the grid's voltage and phase so that the generator output matches the grid. As the generator will lock to the grids voltage and phase the SLC and ATS don't control anything except the power level in operation, but they do operate the engine at startup and shut down and monitor any disruptions in the grid or the engine and open breakers to protect either the grid or the generator from failures.



**Figure 7. Soft Load Controller (SLC) and Automatic Transfer Switch (ATS)**

The steam generator has its own stand alone pneumatic control system that has three principle tasks. First, it makes sure that the steam generator does not run dry. It can call for makeup water based on the output of a low level alarm and if makeup water is not available, it will bypass the exhaust around the steam generator. The second principle task for the control system is to maintain the set point pressure inside the steam generator using a back pressure control valve. The steam pressure is measured inside the steam generator and at the point of use. If the steam pressure at the point of use is less than the pressure in the steam generator, then the back pressure control valve will restrict the flow of steam. The purpose of this controller is to prevent a sudden drop in steam pressure and swelling of the liquid content in the steam generator. The third principle task is to match heat input to the output steam flow. The exhaust gas flow to the steam generator is modulated by the bypass control valve to maintain a set point pressure of the output steam flow. This arrangement allows the steam generator

to operate at partial loads, while the engine operates at full power.

The coolant system controller is designed to prevent the engine from over heating. This is accomplished by removing heat either through a plate and frame heat recovery exchanger or a remotely mounted radiator with an air fan. The coolant controller has two modulating valves which allow the controller to proportion flows to control the amount of heat removed. This arrangement allows the engine to operate at full power, while only recovering a portion of the coolant energy. This controller is a part of the overall Web-based building automation system (BAS). The BAS operates the overall dispatch of the CHP system and logs all of the sensor data. The previously mentioned controllers all function together to allow the system to address varying thermal and electrical energy demands.

## EXPERIMENTAL SETUP

The experimental setup measures the necessary data for a complete thermodynamic analysis as well as gaseous and particulate emissions.

The fuel system includes a differential flow meter, which measures the flow rate of the fuel going to the engine, and the flow rate of the fuel returning from the engine, and provides a differential output. A fuel temperature measurement is also obtained using a strap-on thermocouple. A strap-on thermocouple was required as the fuel flow lines are only 1/2" in diameter and fitting a probe inside the flow would have been a large obstruction. Finally, an ultrasonic level sensor has been installed at the top of each 300 gallon fuel tank to provide a back fuel consumption measurement. All of the fuel consumption measurements will be independently checked using a weigh scale and a five gallon tank.

The air intake has an inline flow meter and a thermocouple installed as well as differential temperature and pressure measurements across the compressor side of the turbocharger as shown in Figure 8.



**Figure 8. Turbocharger Instrumentation Setup**

The engine exhaust has multiple measurements including; differential temperature and pressure measurements across the expander side of the turbocharger, three exhaust temperature

measurements, and an emissions suite. The three exhaust temperatures (engine exhaust, exhaust heat recovery outlet, and stack) allow for calculating the amount of heat recovered and the amount bypassed.

The exhaust heat recovery steam system has two pressure measurements and one flow measurement. It was assumed that the steam generated would be saturated; therefore no thermocouple would be required.

Pressure sensors shown in Figure 9 have been installed in each cylinder of the engine together with a rotary encoder on the engine shaft to provide precise measurements for pressure – crank angle – time analyses for each cylinder.



**Figure 9. Pressure Sensor Installation (blue wires are data lines)**

The measurements will be analyzed (by heat release rate analysis) to characterize the combustion process of the various fuels.

Gaseous and particulate matter emissions measurements will be made. Exhaust measurements of O<sub>2</sub>, NO<sub>x</sub>, CO<sub>2</sub>, CO, and hydrocarbons are available. The water in the exhaust is condensed out using a small heat exchanger. Particulate matter will be monitored with a light scattering instrument, quartz and Teflon filter samples and a scanning mobility particle analyzer. The quartz and Teflon samples as well as the scanning mobility particle analyzer use diluted exhaust at a ratio of 100 parts air, one part exhaust. Also, bags of exhaust at each load will be analyzed using an aerosol mass spectrometer.

### STARTUP AND COMMISSIONING

Start up for the CHP system was divided among three phases. First the engine was operated by the equipment supplier. Second, the engine generator was operated in parallel with the utility power supply using the SLC and ATS. This operation was a complex task as many of operating parameters required by the SLC and ATS are unique to this CHP application. Finally, the steam generator was cleaned by a boil out process, which involved keeping the water near boiling at atmospheric pressure for 24 hours in the presence of chemicals to remove any dust or

particles that may have entered the steam generator during fabrication or installation.

The principle task in commissioning was to verify that the system is capable of meeting the design criteria. The ability of the system to operate at several loads with the heat recovery system operating was verified. Furthermore, all the pipes, valves, wires, actuators, and sensors were inspected to confirm that they are properly connected and able to record data.

A combination of minor fabrication and installation errors were discovered during the commissioning process, which typically required simple fixes. However some parts had to be entirely replaced including an actuator that arrived faulty from the factory and a sensor and three transmitters that needed to be replaced.

Thus far, the engine has operated for 154 hours, generating 2,952 kWh of electrical energy and 4,457 kWh of thermal energy in the form of hot water and steam for space heating in the IW for the 2007-2008 Winter. Thus far, the engine generator has always started and paralleled to the utility upon request. The CHP energy utilization factor of this system has averaged 67% through the commissioning phase; however some sensors are still providing questionable readings.

### EXPERIMENTS

Several experiments are currently being conducted with the biodiesel fueled CHP system, which fit into four primary categories:

- energy output
- combustion
- emissions
- reliability and maintainability

Standard low-sulfur diesel and four biodiesel fuels derived from different feed stocks will be used during the experiments with batches of 250 gallons each. These experiments will provide approximately 50 hours of total run time. Each of these fuels will be tested at four load settings: 25%, 50%, 75%, and 100% of design.

The energy output experiments will measure the efficiency of the engine and the performance of the turbocharger shown in Figure 8 using the different biodiesel fuels while the heat flows delivered to the coolant, energy recovered from exhaust gases will be monitored. In addition to the engine analysis, the performance of the heat exchange equipment will be measured. The dispatch of this equipment to meet the demands of the steam driven absorption chiller and the ventilation system regeneration will be investigated.

One major goal of the emissions data is to study particulate matter and NO<sub>x</sub> emissions as many urban areas where CHP systems could be installed are out of attainment for the PM and ground level ozone national ambient air quality standards. NO<sub>x</sub> emissions are a precursor to ground level ozone. It is commonly assumed that the use of biodiesel fuel increases NO<sub>x</sub> emissions; however data show that the NO<sub>x</sub> emissions for biodiesel fuels have a strong correlation to the amount of polyunsaturated fat content in the fuel (11). Therefore, each fuel will be fully characterized prior to use and the emissions compared.

The engine's mechanical performance will be assessed by monitoring a number of components. A maintenance program will be developed with the engine manufacturer to inspect the fuel system, lubricants, injectors, and other components in the combustion process. With this data in hand, a maintenance program will be developed and engines may be tailored for use with biodiesel fuels as currently the only changes to the engine are for the sake of material compatibility. The pressure-crank angle data will also aid in adjusting the timing of the engine to optimize the operation of the engine based on fuel type, while minimizing harmful emissions.

#### **FUTURE WORK**

Over the next year the commissioning and the experiments described above will be completed. Additional construction work will address the integration of the ventilation system with the hot water output from the coolant system. Finally, the CHP controls system will be integrated with the other IW's other components to maximize interoperability and energy savings.

#### **ACKNOWLEDGEMENTS**

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