Biodiesel Fueled CCHP System

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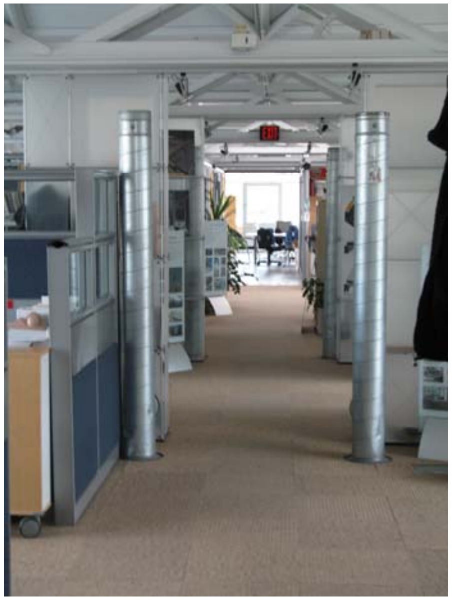
Purpose of Research

- Demonstrate use of renewable fuel and heat recovery in an advanced office building.
- Assess the effectiveness and efficiency of meeting power, heating, and cooling requirements of the Intelligent Workplace.

The Intelligent Workplace

- ample, operational windows with blinds and external reflectors
- highly insulated façade
- under floor utility supply
- flexible wall, furnishings arrangements
- hydronic cooling/heating
- radiant and convective cooling/heating units
- dedicated, dehumidified ventilation
- factory built/ site assembled construction



Energy consumption: one quarter of conventional office building

IW Energy Supply System (IWESS) Guidelines

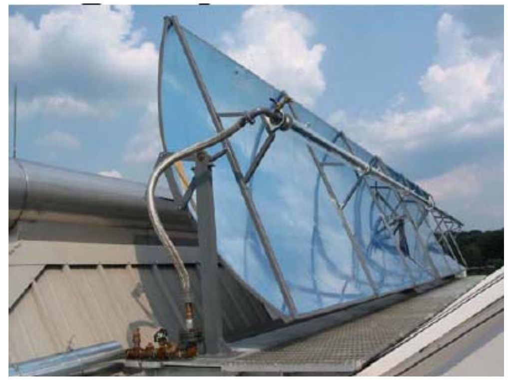
- provide energy for IW operation from the sun and from a renewable fuel
- distribute cooling/heating in the IW by circulating chilled/heated water
- ventilate the IW by ample fresh conditioned, temperature and humidity, air
- generate power for the IW from the renewable fuel; recover heat at suitable temperatures for cooling/heating/ventilation
- install, operate, evaluate, integrate a combined cooling/heating/power/ventilation, CHPV, system, in the IW
- provide energy to the IW at an efficiency twice that of a conventional energy supply
- develop how this system might be cost effective
- assist in disseminating, commercializing, deploying the technology

IWESS Rationale

- high energy impact of operating buildings: 40% of primary energy, 70% of electrical power generated
- reduced impact requires architecture, engineering
- distributed generation, combined C/H/P/V, renewable fuel and solar energy
- integrated: system, space, grids, operation/control
- simulation: includes building space, schedules, ambient conditions, equipment, operation/control; calculates performance; effects of design and operation
- develop, demonstrate, specific instance; generalize

IWESS Components

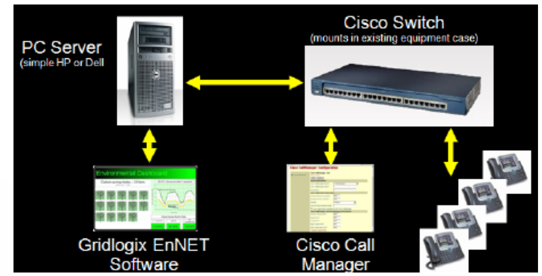
- solar thermal heat supply with a hot water driven absorption chiller and a heat recovery exchanger

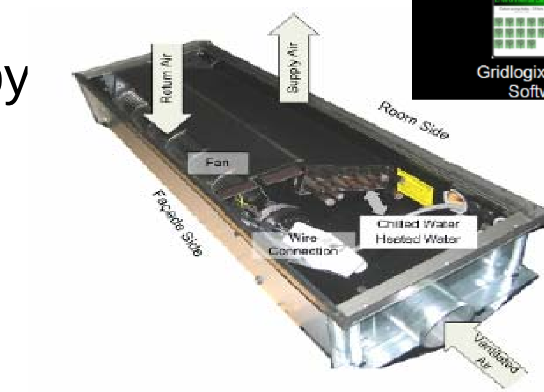


- biodiesel engine generator with heat recovery equipment for steam and hot water; steam driven absorption chiller

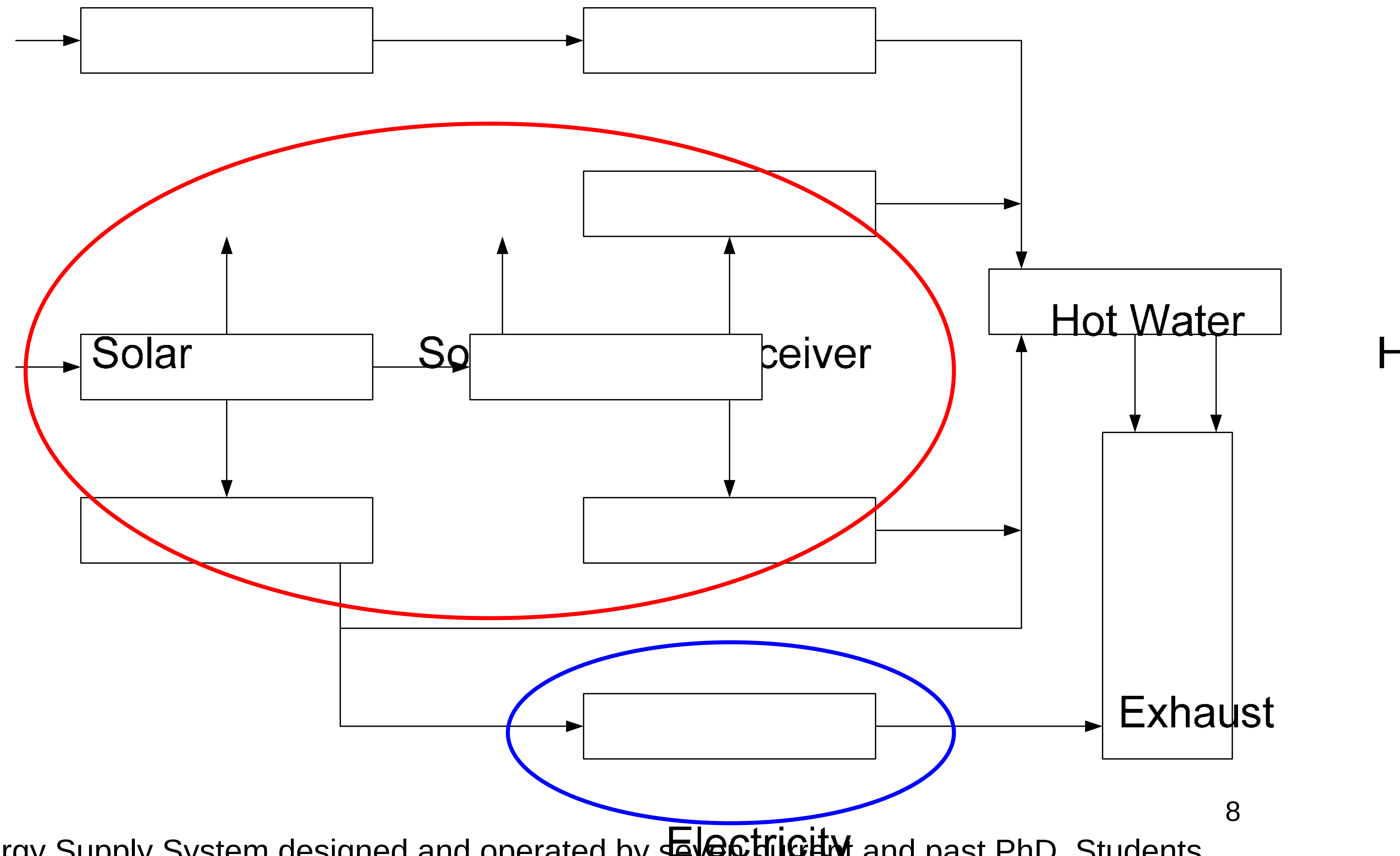
IWESS Components

- fan coil and radiant cooling/heating units with advanced controls
- ventilation system with an enthalpy recovery wheel, heat pump, and desiccant dehumidification wheel
- operable windows; other façade elements
- building grids: power, steam, chilled water, heated water, natural gas



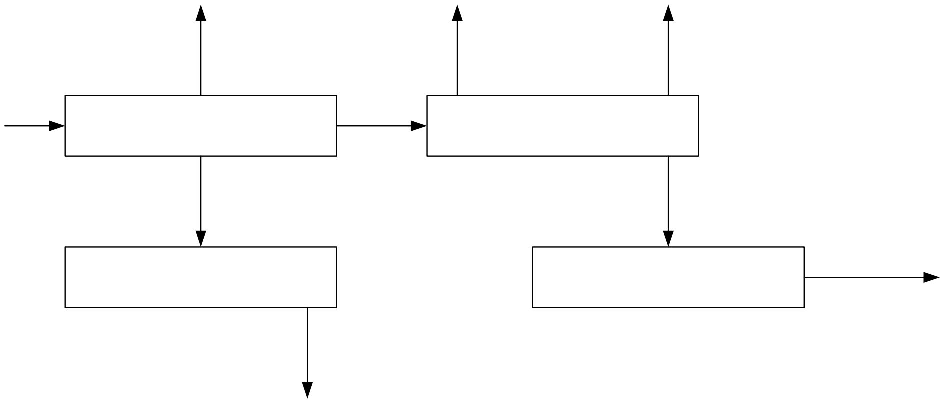


IWESS Flow Diagram



IW Energy Supply System designed and operated by seven current and past PhD. Students.

Biodiesel CHP System Flow Diagram



Electricit

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Coolant

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Exchang

n Converter

Hot Water

Test Plan

- Four B100 fuels from different feedstocks
- Four load settings: 100%, 75%, 50%, 25% of prime power, 25 kWe
- Operate at different system modes: Heating, Cooling, Peak Shaving
- 300 gallons of biodiesel will provide approximately 150 hours of operation at 100% load for each fuel.

To Determine

- Component efficiencies, capacity, and optimal settings
  - Engine (fuel flow, smoke limit), steam generator, coolant heat exchanger
- Determine how best to integrate various building systems
  - Ventilation unit with desiccant regeneration
  - Steam driven absorption chiller
  - IW heating systems
- Environmental considerations (ozone, PM)
  - Engine timing vs. fuel type

Material and Energy Measurements at Design and Part Loads

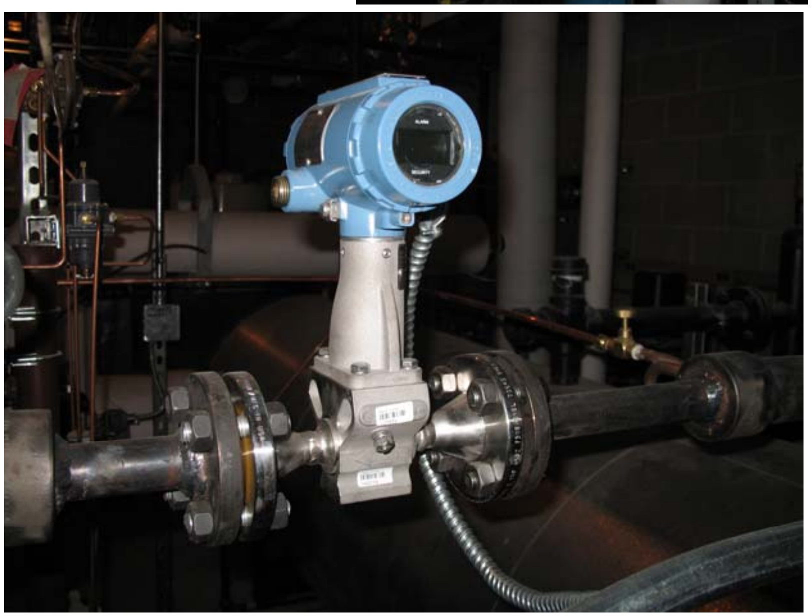
- Power generated
- Heat recovered from exhaust, coolant
- Flow (air, fuel, coolant, steam)
- Temperature (fuel, air, exhaust, coolant, steam)
- Pressure (steam)
- Pressure-time-crank angle in each cylinder

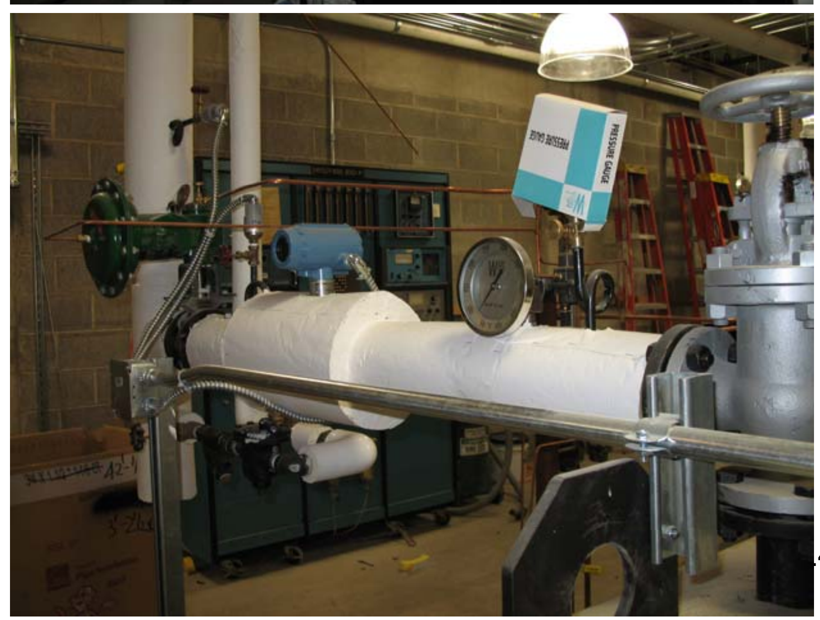
Emissions Monitoring

- Exhaust gas analyzer monitors:
  - O_2, NO, NO_2, CO_2, CO, HC
- NDIR particulate monitor:
  - 0.0 to 1.0 micron particulate matter
- Quartz and zircon filters, scanning mobility particle analyzer, aerosol mass spectrometer:
  - Measurements and analysis by Center for Atmospheric Particulates Studies at CMU
  - Testing will focus on organic compounds.
  - Results to be published in AAAR in October.

Experimental Setup

Images
- Coolant Heat Recovery
- Exhaust Temperatures
- Steam Flow
- Steam Flow, Temperature, Pressure

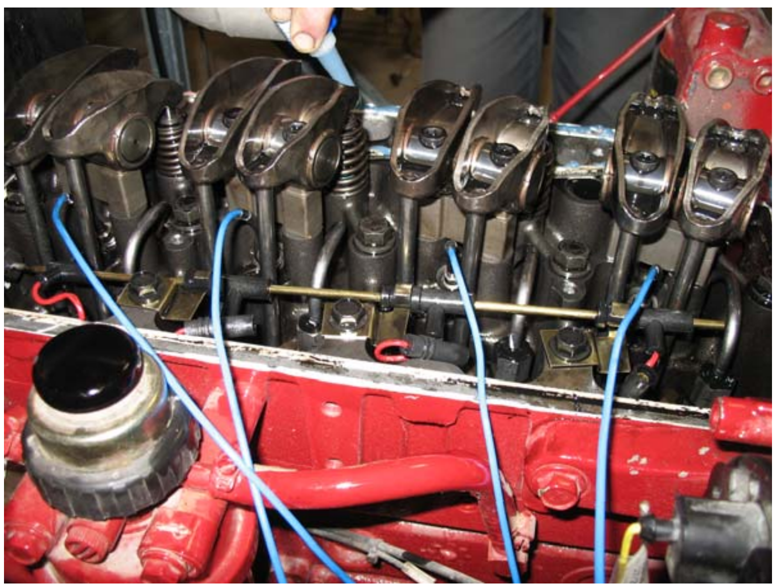




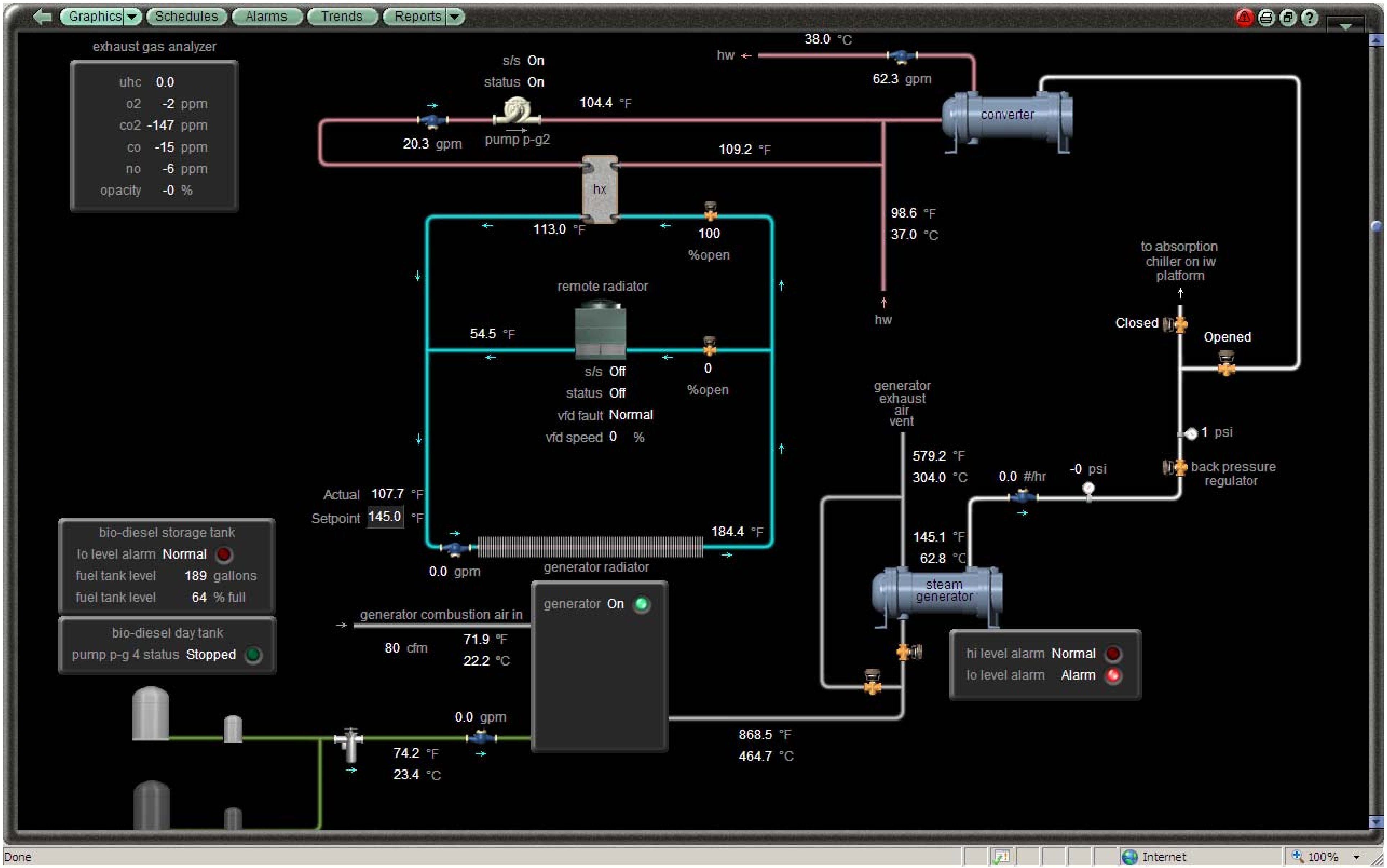
Experimental Setup

Images

- Automatic Transfer Switch / Soft Load Controller
- SLC Interface
- Cylinder Pressure Sensor Installation
- Turbocharger Temperature and Pressures



User Interface, Data Acquisition, Controls

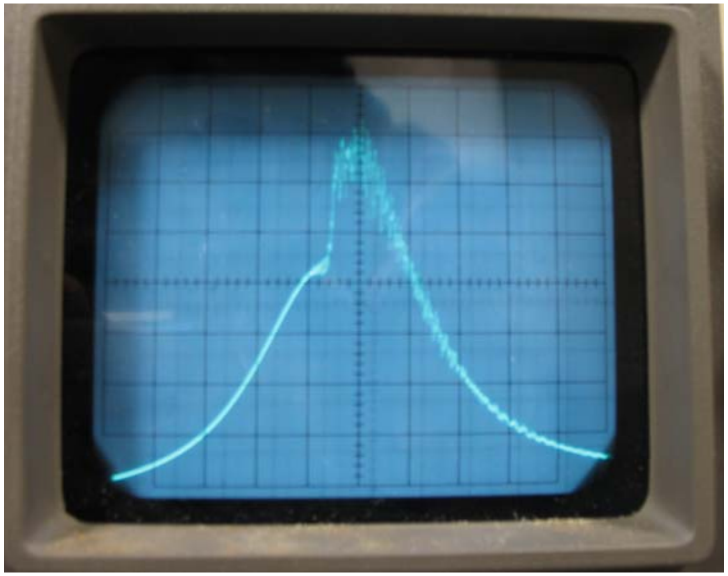


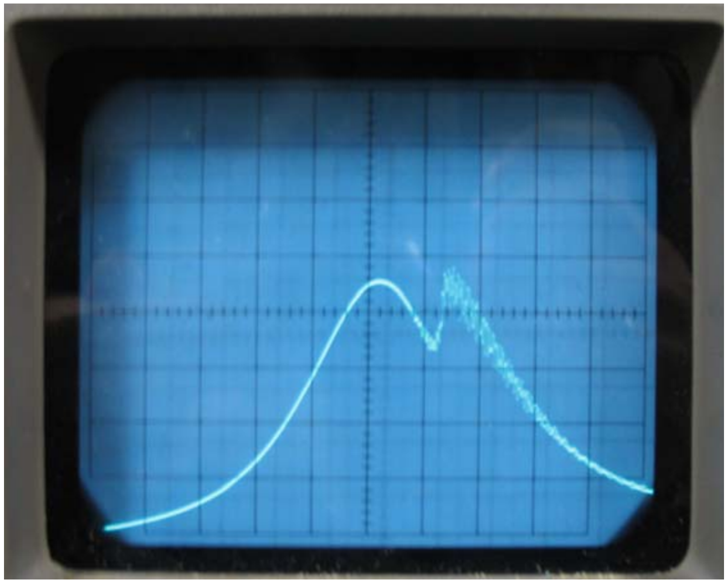
Commissioning Data

- Compared manufacturer data with experimental data
- Measured flows, temperatures, and pressures of air, fuel, coolant, and exhaust.
  - Values tracked within error limits of sensors
  - Manufacturer data shows engine's capability, whereas a CHP configuration operates below that rating for long term operation due to wear and tear.
  - Design system based on ~80% of spec sheet

Pressure - Time

- Engine starts with a typical pressure – time curve.
- As engine warms up the timing changes from injection at top dead center (TDC) to ~15 degrees after TDC.
- This is done to reduce the exhaust temperature thus reducing NOx emissions.
- However, this sacrifices some engine efficiency.
- It is hoped that using biodiesel can meet EPA regulations while operating at an optimal efficiency.

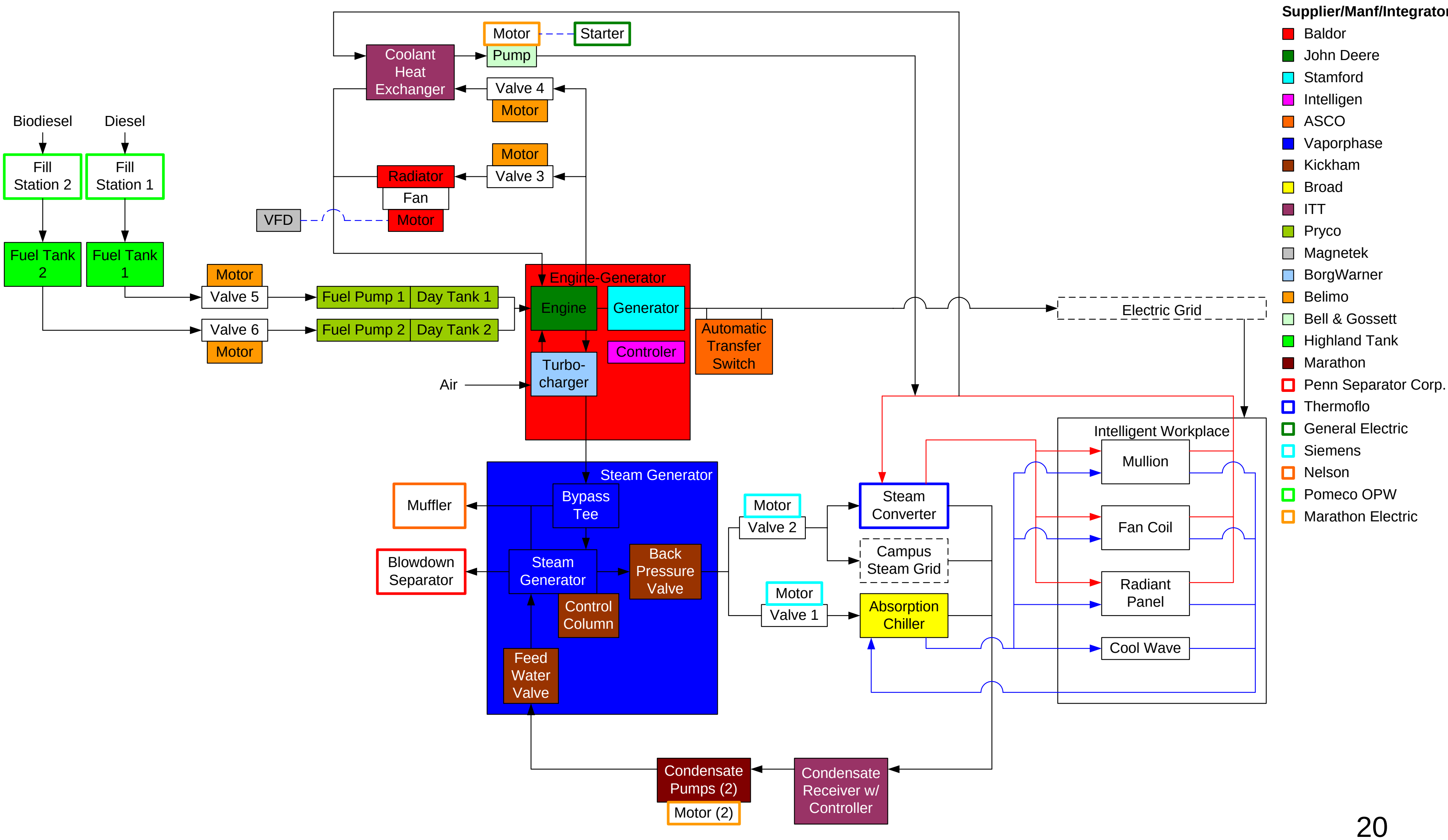




Commissioning Results

- Over 250 hours of operation over four loads
- Plant overall efficiency through winter: 77%
  - 30 psig steam and 190ºF coolant operating in parallel feeding the hot water converter
- Engine brake efficiency:
  - 6kWe = 6.8 kWm = 26%
  - 12kWe = 13.6 kWm = 32%
  - 18kWe = 20.5 kWm = 36%
  - 25kWe = 28.4 kWm = 37%

CCHP Systems Integration

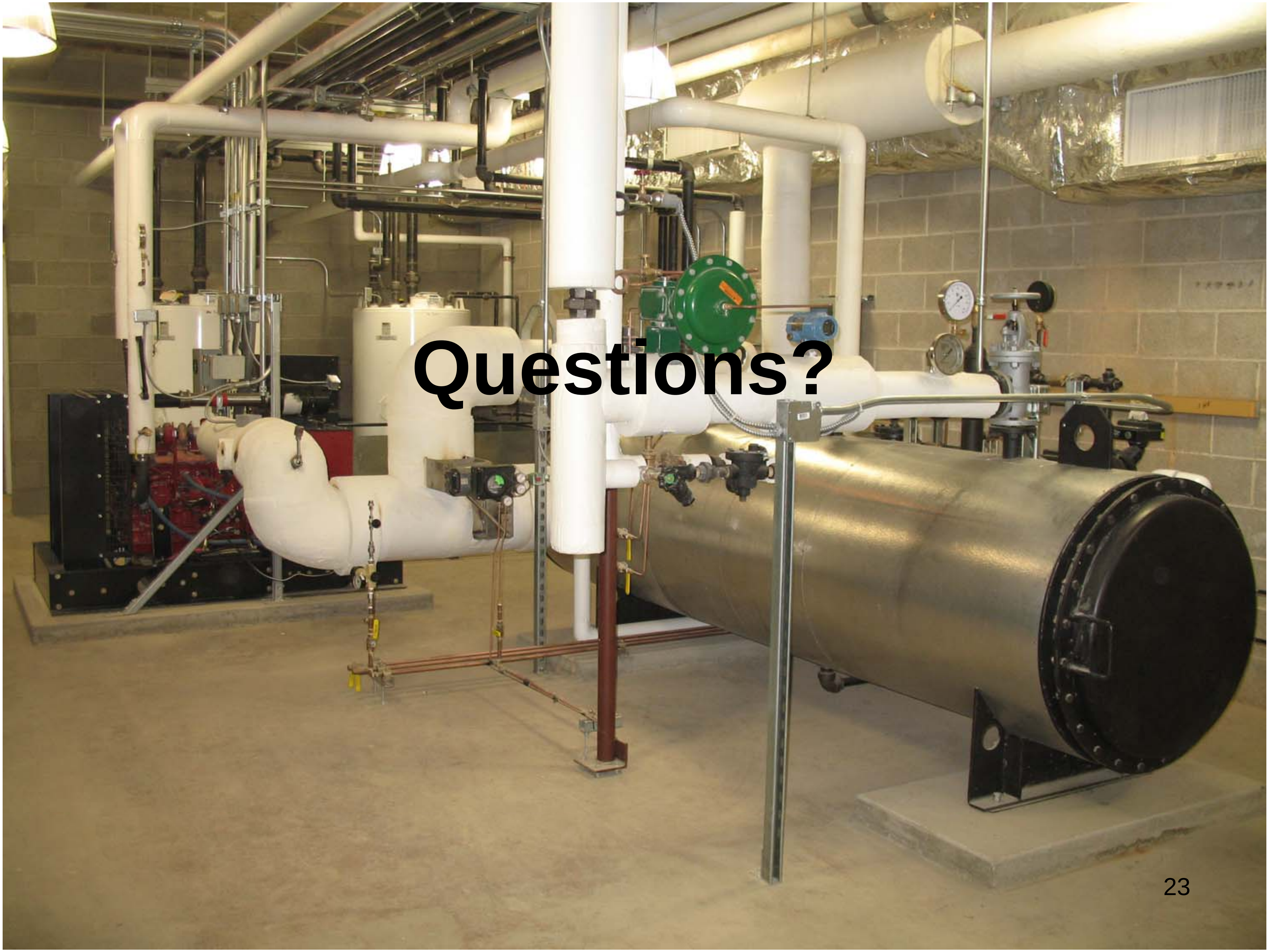


Future Work

- Complete testing according to plan
- Validate performance model
- Systems integration with solid desiccant dehumidification unit.
- Completion of “Cylinder pressure – crank angle – time” measurement system leading to fuel injection adjustments.
- Test additional biodiesel/alternate fuels (WVO, animal fat, biodiesel-ethanol mixtures, cellulosics, high pressure vegetable oil.)
- Streamlining system (components and controls)

Supported by

- U.S. Department of Energy, National Energy Technology Laboratory
- Pennsylvania Department of Environmental Protection, Energy Harvest
- Pennsylvania Infrastructure Technology Alliance
- Advanced Building Systems Integration Consortium
- CTI Biofuels (Pittsburgh, PA)
- Lehigh University
- Center for Atmospheric Particulate Studies, CMU

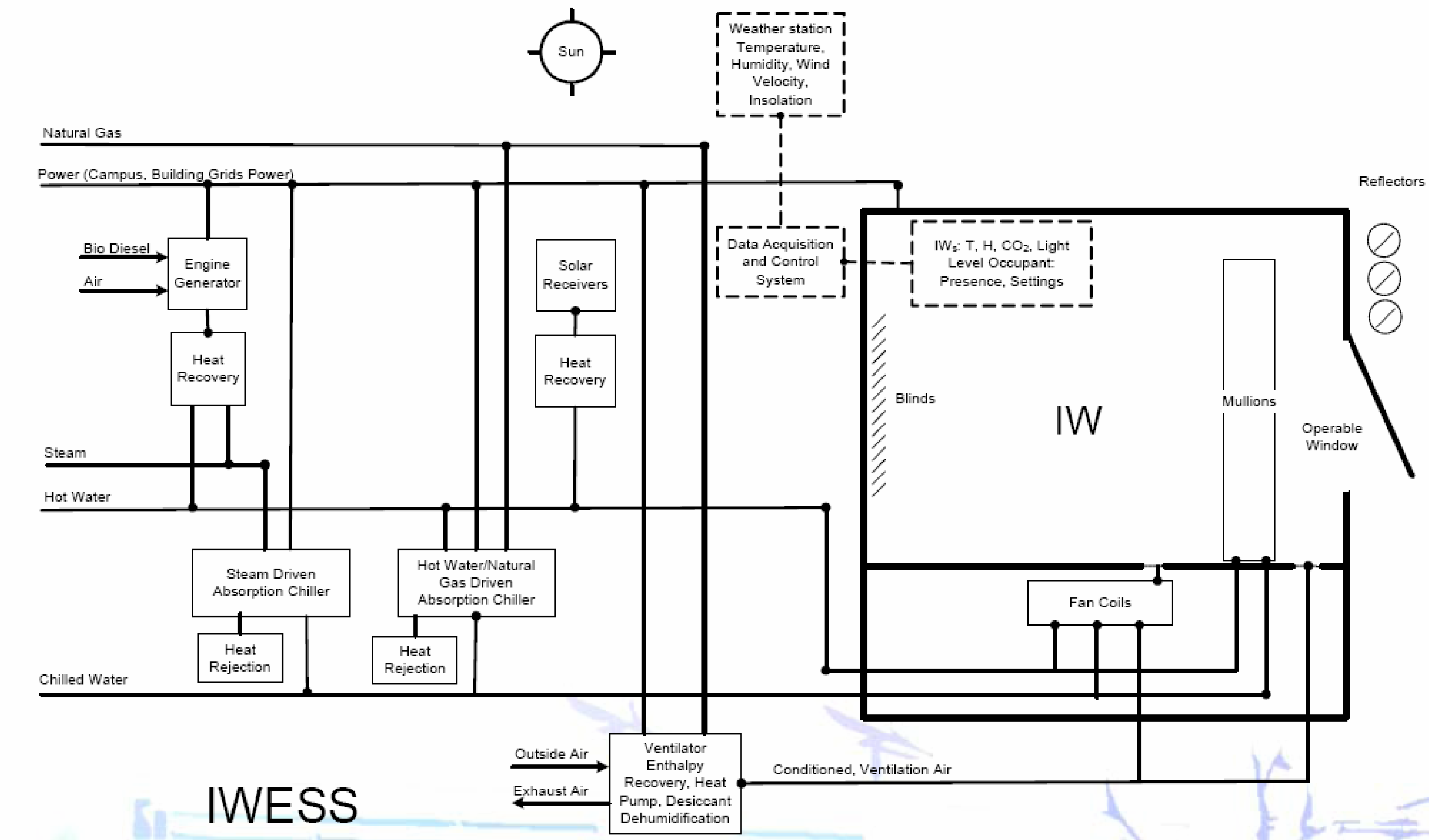


Questions?

Additional Slides

- The following slides are incomplete and were not presented at the 2008 ASME Energy Sustainability Conference

IWESS Components Integrated with IW through Grids



Potential of CHP in Buildings

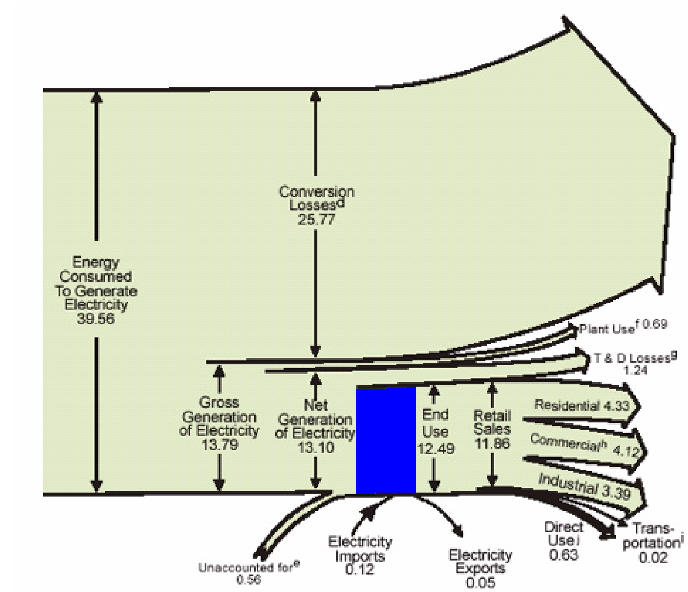
- Individual buildings
- Buildings within a larger facilities network?
- Offices, laboratories, data centers?

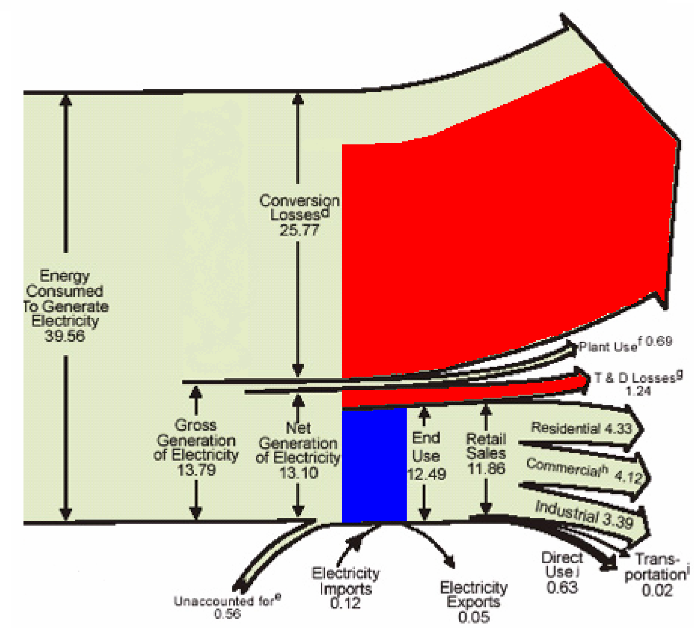
Commissioning Data Comparison

System	Specification	Data	Notes
Air System			
Max. temp. rise, amb. to inlet	15 F (8C)		
Engine Air Flow	99 CFM (2.8 m3/min)	83 CFM at 25 kWe	Steady rise in flow rate versus power (6 kW = 64 CFM, 12kW = 68 CFM, 18kW = 74 CFM)
Intake Manifold Pressure	9 psig (64 kPa)	0.5 psig (6kWe), 1.1 psig (12kWe), 1.8 psig (18kWe), 2.5 psig (25 kWe)	
Fuel System			
Total Fuel Flow	185 lb/hr (84 kg/hr)		No Measurement Available
Fuel Consumption (6 kW)	4.7 lb/hr (2.1 kg/hr)	2.1 kg/hr	Verified with weigh tank measurement
Fuel Consumption (12 kW)	7.0 lb/hr (3.2 kg/hr)	3.6 kg/hr	Verified with weigh tank measurement
Fuel Consumption (18 kW)	9.8 lb/hr (4.4 kg/hr)	4.8 kg/hr	Verified with weigh tank measurement
Fuel Consumption (25 kW)	13.3 lb/hr (6.1 kg/hr)	6.4 kg/hr	Verified with weigh tank measurement
Fuel Consumption (32 kW)	17.9 lb/hr (8.1 kg/hr)	NA	Soft load controller will allow a maximum power of 25 kW
Cooling System			
Engine Heat Rejection	1303 BTU/min (23 kW)	18 kW at 25 kWe	
Coolant Flow	24 GPM (91 L/min)	10.2 GPM	Spec assumes radiator attached to engine
Thermostatic Valve start to open	185 F (82 C)		Verified by comparing start of coolant flow and coolant temperature
Thermostatic Valve fully open	201 F (94 C)		Verified by comparing by observing steady flow above 201 F
Exhaust			
Exhaust Temperature	963 F (517 C)	930 F (499 C) at 25 kWe	
Max allowable back pressure	30 in-H2O (7.5 kPa)	14 in-H2O at 25 kWe	Used a pressure gauge mounted between the engine exhaust and steam generator

Advantage of Combined Heat and Power

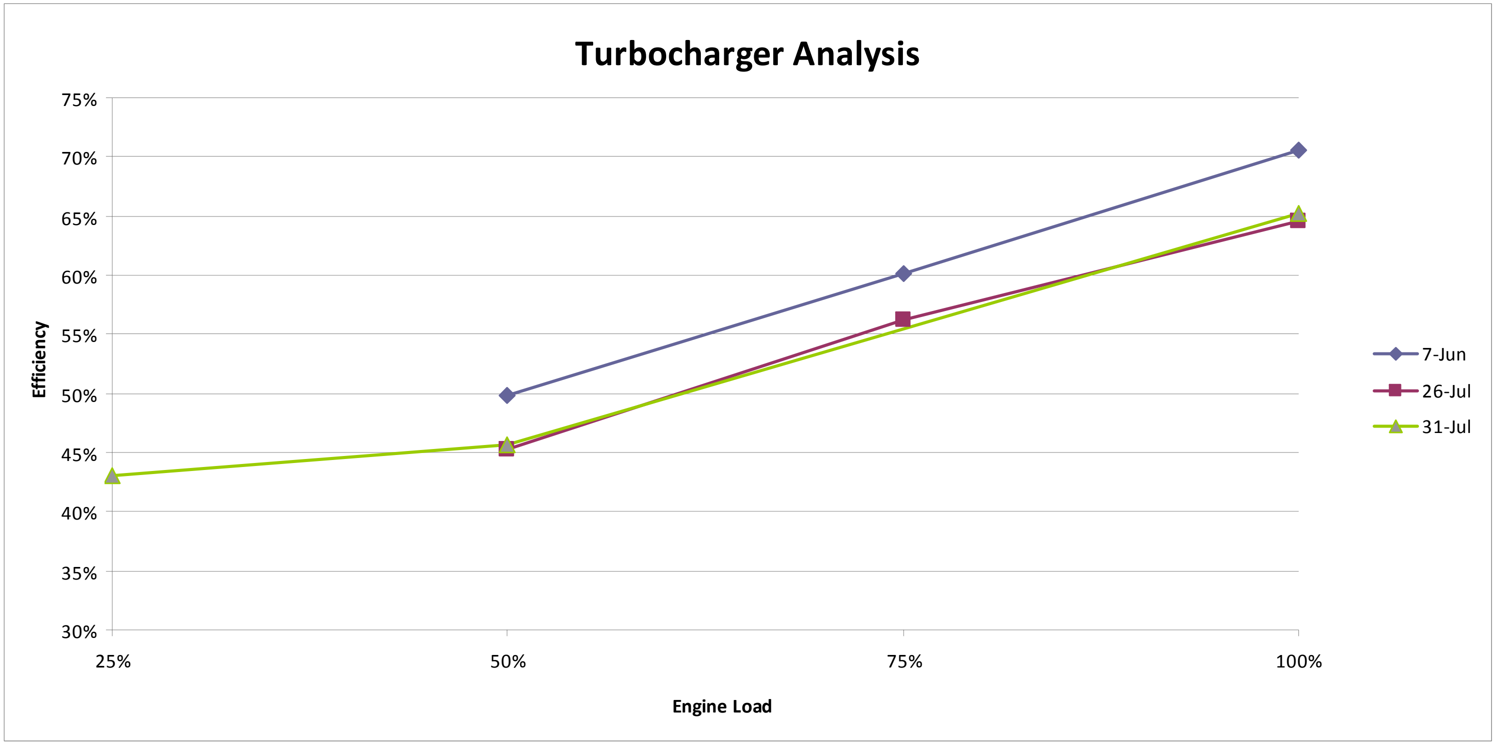
- Typical large power plants have an efficiency of 32% with transmission losses.
- Distributed generation with CHP can achieve an efficiency of greater than 80%.





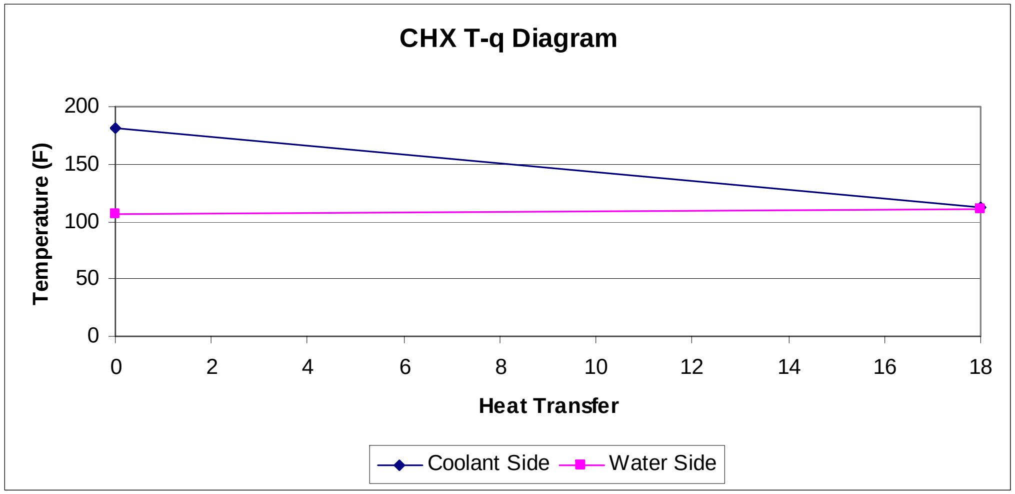
Ref: Adapted from EIA: 2002 US Electrical Energy Flow

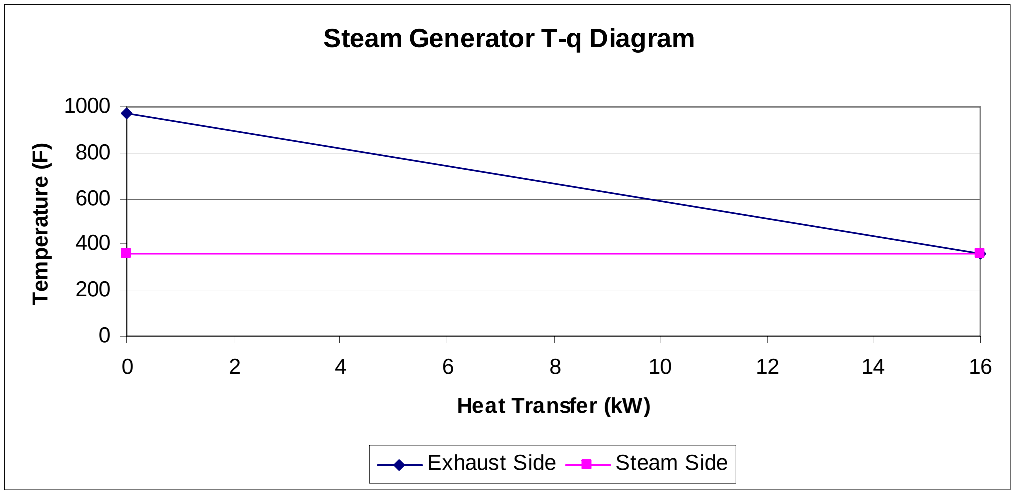
Turbocharger Analysis



Average Turbocharger Operating Data						
Load	Compressor Inlet Temperature (F)	Compressor Outlet Temperature (F)	Compressor Delta P (PSI)	Expander Inlet Temperature (F)	Expander Outlet Temperature (F)	Expander Delta P (PSI)
25%	90	116	0.39	518	463	1.73
50%	89	128	0.96	697	619	2.17
75%	93	156	1.84	926	825	2.90
100%	90	184	2.53	1099	972	4.07

Heat Exchanger T-q Diagrams





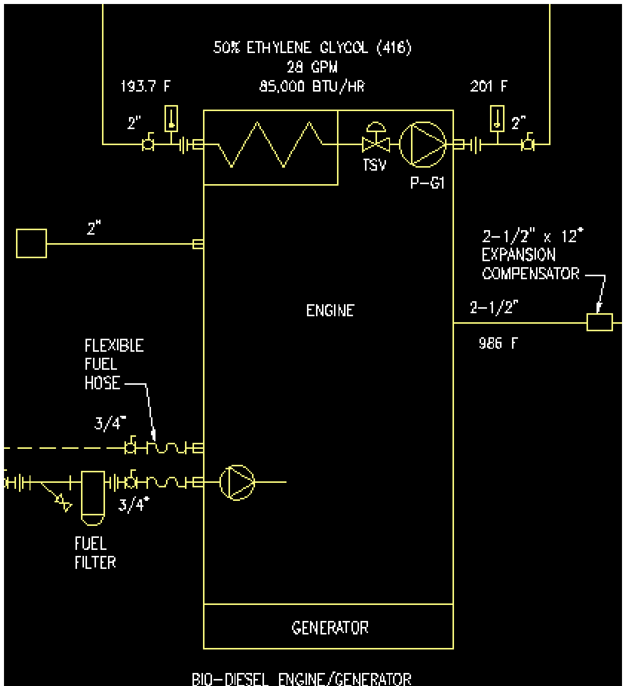
Biodiesel CHP

- 25 kW power for the IW
- 18 kW steam at 6 bar from engine exhaust for the absorption chiller; IW cooling
- 20 kW heated water at 90 C from engine coolant; IW heating and ventilation air dehumidification
- Excess energy sent to building/campus grids

Engine Generator Analysis Example

Engine – Generator Data

- Fuel



  – Flow rate
- Power
  – Electrical Power
- Combustion
  – 4x Cylinder pressure vs. Time (Piezotronics)

Engine – Generator

$\dot{Q}_{FUEL}[kW] = \dot{W}_{SHAFT}[kW] + \dot{Q}_{COOLANT}[kW] + \dot{Q}_{EXHAUST}[kW] + \dot{Q}_{MISC}[kW]$ where,

$\dot{Q}_{FUEL}[kW]$ is the rate at which fuel energy is input into the engine.

$\dot{W}_{SHAFT}[kW]$ is the rate at which shaft power is delivered to the generator.

$\dot{Q}_{COOLANT}[kW]$ is the rate at which coolant energy is rejected from the engine.

$\dot{Q}_{EXHAUST}[kW]$ is the rate at which exhaust energy is rejected from the engine.

$\dot{Q}_{MISC}[kW]$ is the rate at which miscellaneous energy such as radiated heat and friction is rejected from engine.

$$\dot{Q}_{FUEL}[kW] = \dot{Q}_{COOLANT}[kW] + \dot{Q}_{EXHAUST}[kW] + \dot{W}_{SHAFT}[kW] + \dot{Q}_{MISC}[kW]$$

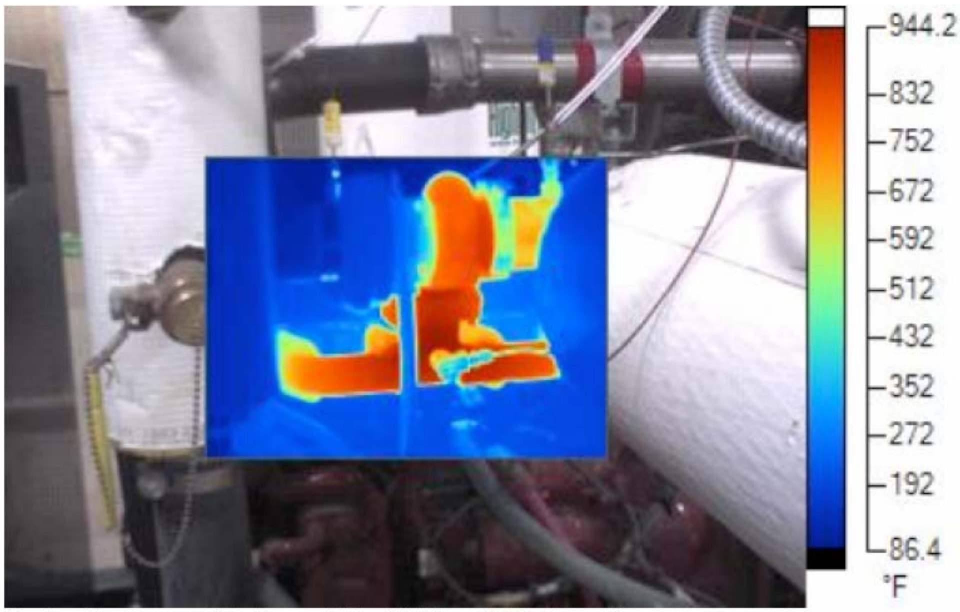
$$\dot{m}_{2,FUEL}\left[\frac{kg}{\sec}\right] \times LHV_{FUEL}\left[\frac{kJ}{kg}\right] = \dot{m}_{10,COOLANT}\left[\frac{kg}{\sec}\right] \times cp_{COOLANT}\left[\frac{kJ}{kg-{}^{o}C}\right] \times (T_{11} - T_{10})[{}^{o}C] +$$

$$\dot{m}_{3,EXHAUST}\left[\frac{kg}{\sec}\right] \times cp_{EXHAUST}\left[\frac{kJ}{kg-{}^{o}C}\right] \times (T_{7} - T_{3})[{}^{o}C] + \frac{\dot{W}_{ELECTRIC}[kW]}{\eta_{GENERATOR}} + \dot{Q}_{MISC}[kW]$$

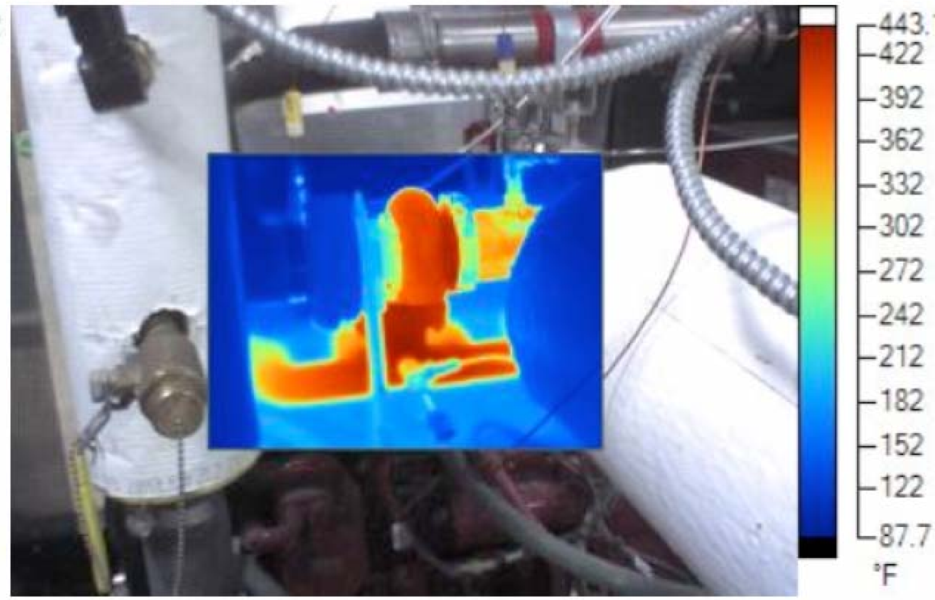
$$\eta_{ENGINE} = \frac{\dot{W}_{SHAFT}[kW]}{\dot{Q}_{FUEL}[kW]}$$

$$\eta_{PLANT} = \frac{\dot{W}_{ELECTRIC}[kW] + \dot{Q}_{COOLANT}[kW] + \dot{Q}_{EXHAUST}[kW]}{\dot{Q}_{FUEL}[kW]}$$

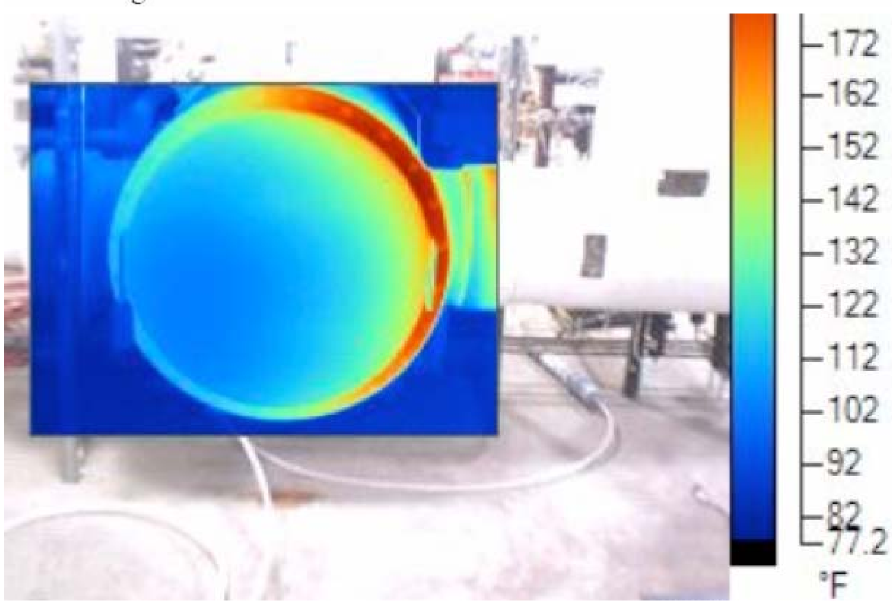
Infrared Losses at Various Loads



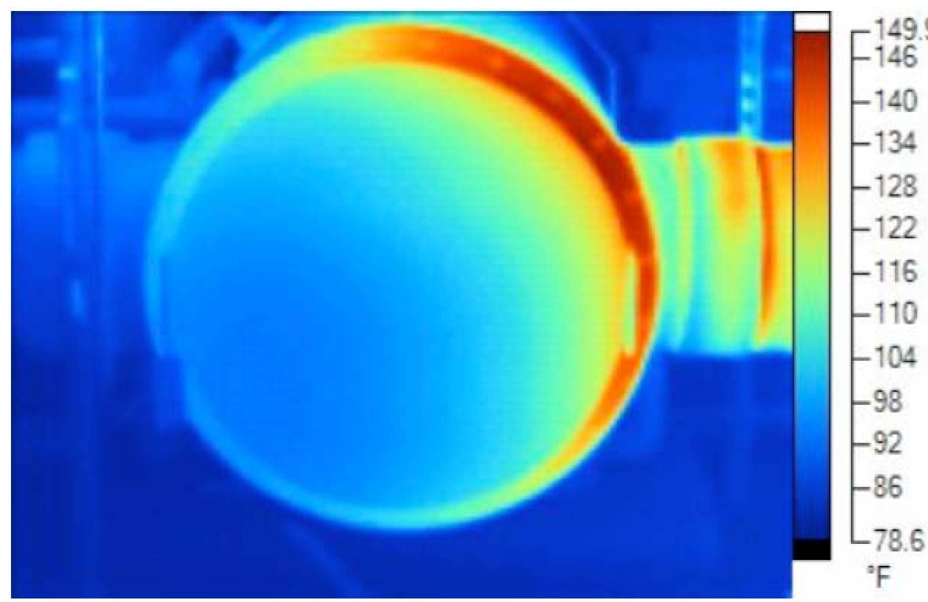
Turbocharger and Exhaust Manifold at 100% Load



Turbocharger and Exhaust Manifold at 25% Load



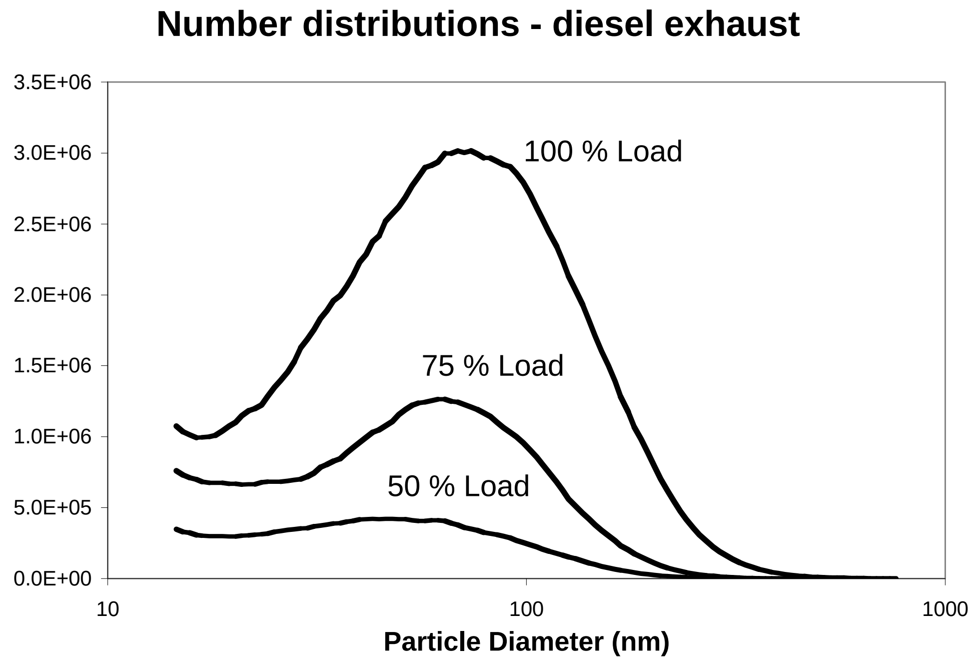
Steam Generator Inlet at 100% Load



Steam Generator Inlet at 50% Load

Emissions Measured

Off-Road Low Sulfur Diesel			
Compound	**50% load**	**75% load**	**100 % load**
O_2	15.22%	14.39%	7.98%
CO	0.07%	0.06%	0.06%
CO_2	4.66%	5.29%	7.21%
NO	237 ppm	NA	285 ppm
NO_2	4 ppm	NA	4 ppm
HC	8.74 ppm	10.69 ppm	12.11 ppm



Outline

- Title Page
- Purpose of Research
- Funded By
- Intelligent Workplace
- IWESS Flow Diagram
- Advantages of CHP
- Biodiesel CHP System Overview (2)
- Measurements Taken
- Experimental Setup (3)
- Test Plan
- Analysis (2)
- Commissioning (3)
- Results (1)

Combustion Analysis

- Biodiesel: $C_{19}H_{36}O_2$
- Air: $O_2+3.76N_2$

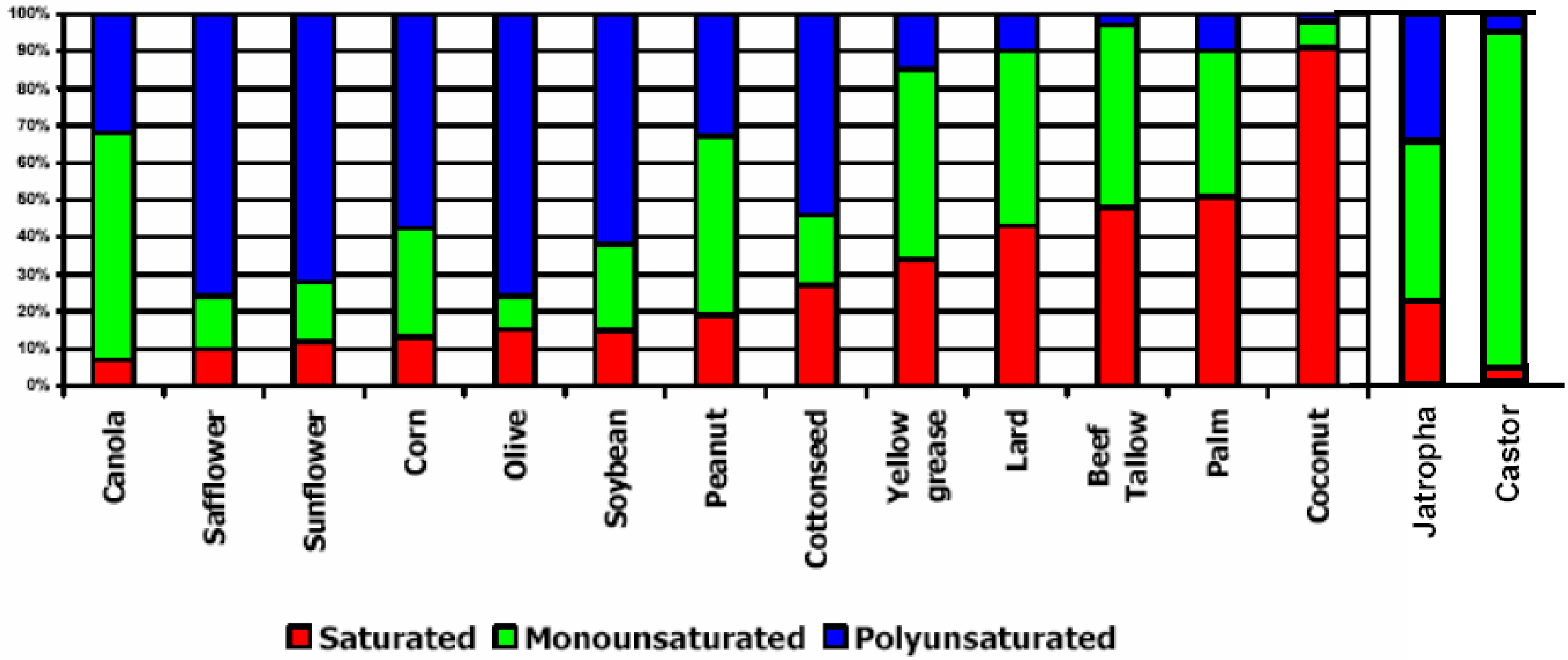
- Stoichiometric Equation:

$$C_{19}H_{36}O_2 + 27(O_2+3.76N_2) \rightarrow$$

$$19(CO_2) + 18(H_2O) + 101.52(N_2)$$

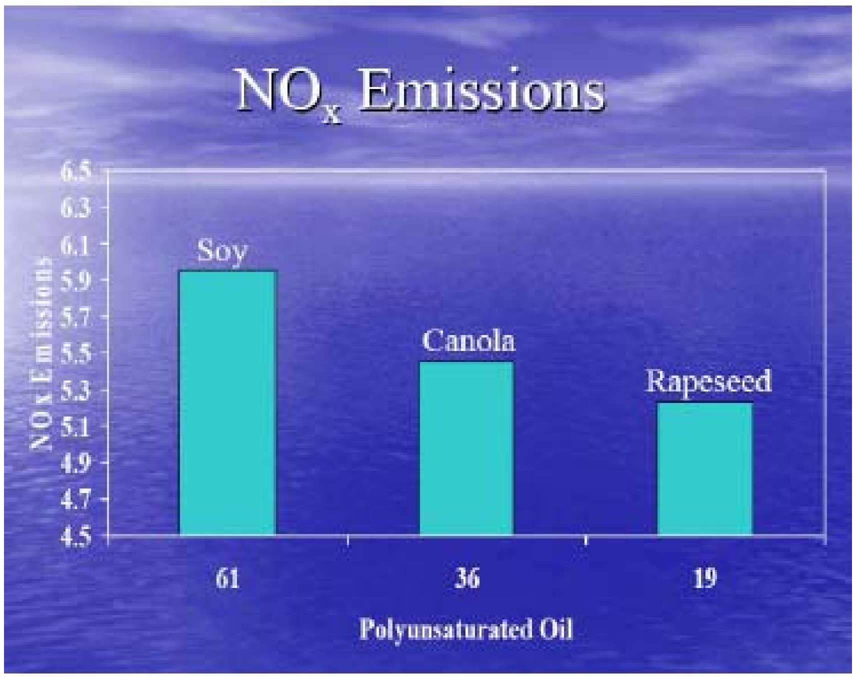
- $A/F)_s$ = 12.6 (Calculated)
- $A/F)_a$ = 23.9 (John Deere)
- $A/F)_m$ = 25.5 (Measured)

Variations in Emissions by Feedstock



Environmental Protection Agency. October 2002 Draft Technical Report, *A Comprehensive Analysis of Biodiesel Impacts on Exhaust Emissions*, (EPA420-P-02-001) (www.epa.gov/OMS/models/biodsl.htm).

Variations in Emissions by Feedstock



Producing biodiesel from Brassica crops in the Pacific Northwest, Jack Brown, University of Idaho, National Biodiesel Conference, San Diego, CA, February 6, 2006

Fuel Property	Saturated 0 double bonds	Monounsaturated 1 double bond	Polyunsaturated multiple double bonds
Freezing Point	High (-)	Medium	Low (+)
Cetane Number	High (+)	Medium	Low (-)
Oxidative Stability	High (+)	Medium	Low (-)
NOx Emissions	Reduction (+)	Medium Increase	Large Increase (-)

NREL, June 2004, Biomass Oil Analysis: Research Needs and Recommendations, NREL/TP-510-34796

13 Graboski et al., February 2003. *The Effect of Biodiesel Composition on Engine Emissions from a DDC Series 60 Engine*. NREL/SR-510-31461 and Kinast, J.A. March 2003. *Production of Biodiesel from Multiple Feedstocks and Properties of Biodiesel and Biodiesel/Diesel Blends*, NREL/SR-510-31460.

- Will use a variety of feedstock sources to verify this information and to expand upon it

Biodiesel Fuel

- Production: Transesterification
  - 10 parts oil + 1 part alcohol + catalyst → 10 parts biodiesel + 1 part glycerin
  - Meets ASTM D 6751
- Performance:
  - 5-10% power loss using B100 versus petrol-Diesel due to lower Heating Value
- Typical Emissions:
  - Different oils have different emissions

Emissions Reduction vs. Petrol-Diesel			
Emissions	Biodiesel (B100)	Biodiesel (B50)	Biodiesel (B20)
Sulfur	100%	48%	18%
Hydrocarbons	80%	60%	47%
Carbon Monoxide	60%	50%	36%
Particulate Matter	55%	47%	38%
Nitrogen Oxides	-5%	-2%	0%

Energy Content by Feedstock per Hectare

Crop Plant Oil Yield Estimates

Plant	Latin name	Kg Oil/ Hectare
corn	*Zea mays*	145
cashew nut	*Anacardium occidentale*	148
oat	*Avena sativa*	183
palm	*Erythea salvadorensis*	189
lupine	*Lupinus albus*	195
rubber seed	*Hevea brasiliensis*	217
kenaf	*Hibiscus cannabinus L.*	230
calendula	*Calendula officinalis*	256
cotton	*Gossypium hirsutum*	273
hemp	*Cannabis sativa*	305
soybean	***Glycine max***	**375**
coffee	*Coffea arabica*	386
linseed	*Linum usitatissimum*	402
hazelnut	*Corylus avellana*	405
euphorbia	*Euphorbia lagascae*	440
pumpkin seed	*Cucurbita pepo*	449
coriander	*Coriandrum sativum*	450
mustard	***Brassica alba***	**481**
camelina	*Camelina sativa*	490
sesame	*Sesamum indicum*	585
crambe	*Crambe abyssinica*	589
safflower	*Carthamus tinctorius*	655
buffalo gourd	*Cucurbita foetidissima*	665
rice	*Oriza sativa L.*	696

Plant	Latin Name	Kg Oil/ Hectare
tung oil tree	*Aleurites fordii*	790
sunflower	***Helianthus annuus***	**800**
cocoa	*Theobroma cacao*	863
peanut	*Arachis hypogaea*	890
opium poppy	*Papaver somniferum*	978
rapeseed	***Brassica napus***	**1,000**
olive tree	*Olea europaea*	1,019
paiassava	*Attalea funifera*	1,112
gopher plant	*Euphorbia lathyris*	1,119
castor bean	***Ricinus communis***	**1,188**
bacuri	*Platonia insignis*	1,197
pecan	*Carya illinoensis*	1,505
jojoba	*Simmondsia chinensis*	1,528
babassu palm	*Orbignya martiana*	1,541
jatropha	***Jatropha curcas***	**1,590**
macadamia nut	*Macadamia terniflora*	1,887
brazil nut	*Bertholletia excelsa*	2,010
avocado	*Persea americana*	2,217
coconut	*Cocos nucifera*	2,260
oiticia	*Licania rigida*	2,520
buriti palm	*Mauritia flexuosa*	2,743
pequi	*Caryocar brasiliense*	3,142
macauba palm	*Acrocomia aculeata*	3,775
oil palm	***Elaeis guineensis***	**5,000**

Tickell, Joshua. 2000. From the Fryer to the Fuel Tank

Key Terms & Definitions

- Biodiesel: A petrol-diesel substitute derived from vegetable oil as defined by ASTM D 6751. Not pure vegetable oil!
- Flex Fuel vs. Hybrid
  - Flex fuel uses more than one type of chemical fuel: Gasoline, Ethanol, Biodiesel, Diesel, etc.
  - Hybrid uses more than one type of power source: Electricity, Chemical fuel
- Combined Heat & Power: Using the reject thermal energy from a combustion process in a useful manner after generating power.

ASTM D 6751

Property	**ASTM**	**Method**	**Limits Units**
Flash Point Degrees C	D93	130 min.	
Water & Sediment	D2709	0.050 max.	% vol.
Kinematic Viscosity, 40 C	D445	1.9 - 6.0	mm2/sec.
Sulfated Ash % mass	D874	0.020 max.	
Sulfur	D5453		
S 15 Grade	15 max.	ppm	
S 500 Grade	500 max.	ppm	
Copper Strip Corrosion	D130	No. 3 max.	
Cetane	D613	47 min.	
Cloud Point Degrees C	D2500	Report	
Carbon Residue % mass	D4530*	0.050 max.	
100% sample			
Acid Number mg KOH/gm	D664	0.50 max.	
Free Glycerin % mass	D6584	0.020 max.	
Total Glycerin % mass	D6584	0.240 max.	
Phosphorus Content % mass	D 4951	0.001 max.	
Distillation Temp,			
Atmospheric Equivalent			
Temperature,			
90% Recovered Degrees C	D 1160	360 max.	
Sodium/Potassium	UOP 391	5 max, combined ppm	

- * The carbon residue shall be run on the 100% sample.
- # A considerable amount of experience exists in the US with a 20% blend of biodiesel with 80% diesel fuel (B20). Although biodiesel (B100) can be used, blends of over 20% biodiesel with diesel fuel should be evaluated on a case-by-case basis until further experience is available.
- [Reference: http://www.biodiesel.org/pdf_files/fuelfactsheets/BDSpec.PDF]