

Combined Heat and Power – Prime Mover Technologies

**Krishnan Umamaheswar, LEED AP, CEM, CDSM, DGCP
Gulf Coast Clean Energy Application Center**



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Before we begin...

- Presentation
 - Emailed to all attendees within 24 hours
 - Posted to www.gulfcoastcleanenergy.org
- Questions
 - Submit via Chat Feature
 - Answered via email
- Continuing Education Units (CEU)
 - Upon request



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Agenda

- Background
- Reciprocating Engines
 - Fundamentals
 - Performance Metrics
 - Typical Costs
- Gas Turbines
 - Fundamentals
 - Performance Metrics
 - Typical Costs



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Background

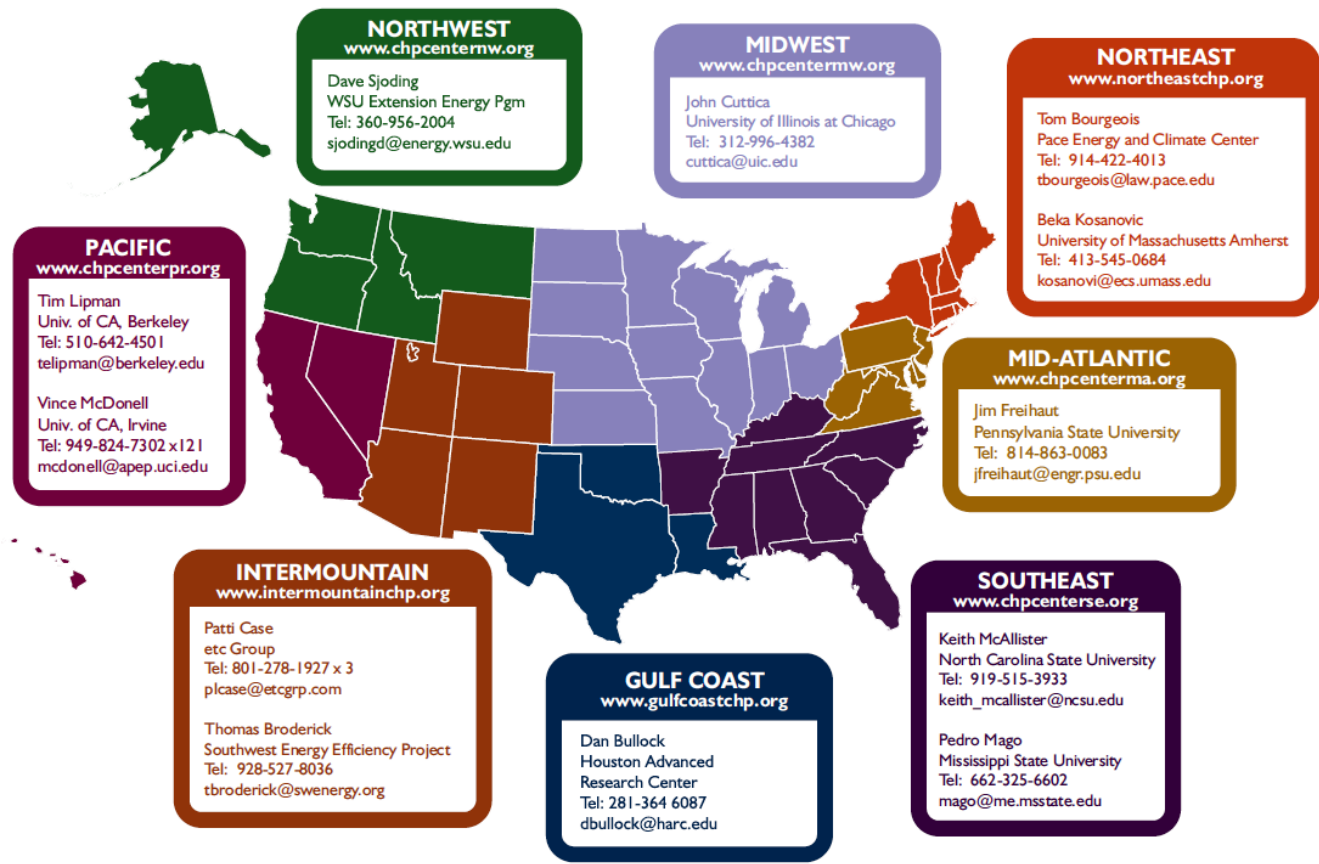


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Eight U.S. DOE Clean Energy Application Centers

DOE Clean Energy Application Center Locations, Contacts, and Web Sites



DOE Clean Energy Application Center Program Contacts	Ted Bronson DOE Clean Energy Application Center Coordinator Power Equipment Associates Phone: 630-248-8778 E-mail: tbronsonpea@aol.com	Bob Gemmer Industrial Technologies Program (ITP) Office of Energy Efficiency and Renewable Energy U.S. Department of Energy Phone: 202-586-5885 E-mail: Bob.Gemmer@ee.doe.gov	Patti Garland Distributed Energy/ CHP Program Manager Oak Ridge National Laboratory Phone: 202-586-3753 E-mail: Patricia.Garland@ee.doe.gov
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Primary Activities – Gulf Coast Application Center

- Promote CHP, Waste Heat Recovery & District Energy through
 - Education & Outreach
 - Website
 - Newsletters
 - Webinars
 - Workshops
 - Policy Initiatives
 - Educate legislators
 - Comment on dockets/rulings
 - Support TXCHPI (active CHP industry advocates in the region)
 - Project Support
 - Free or low cost CHP feasibility studies
 - Case Studies/Project profiles
 - Answer technical questions
 - Connect end-users to equipment manufacturers
 - Facilitate tours to CHP installations for prospective adopters
 - Manufacturer neutral and unbiased service



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CHP is a type of DISTRIBUTED GENERATION that

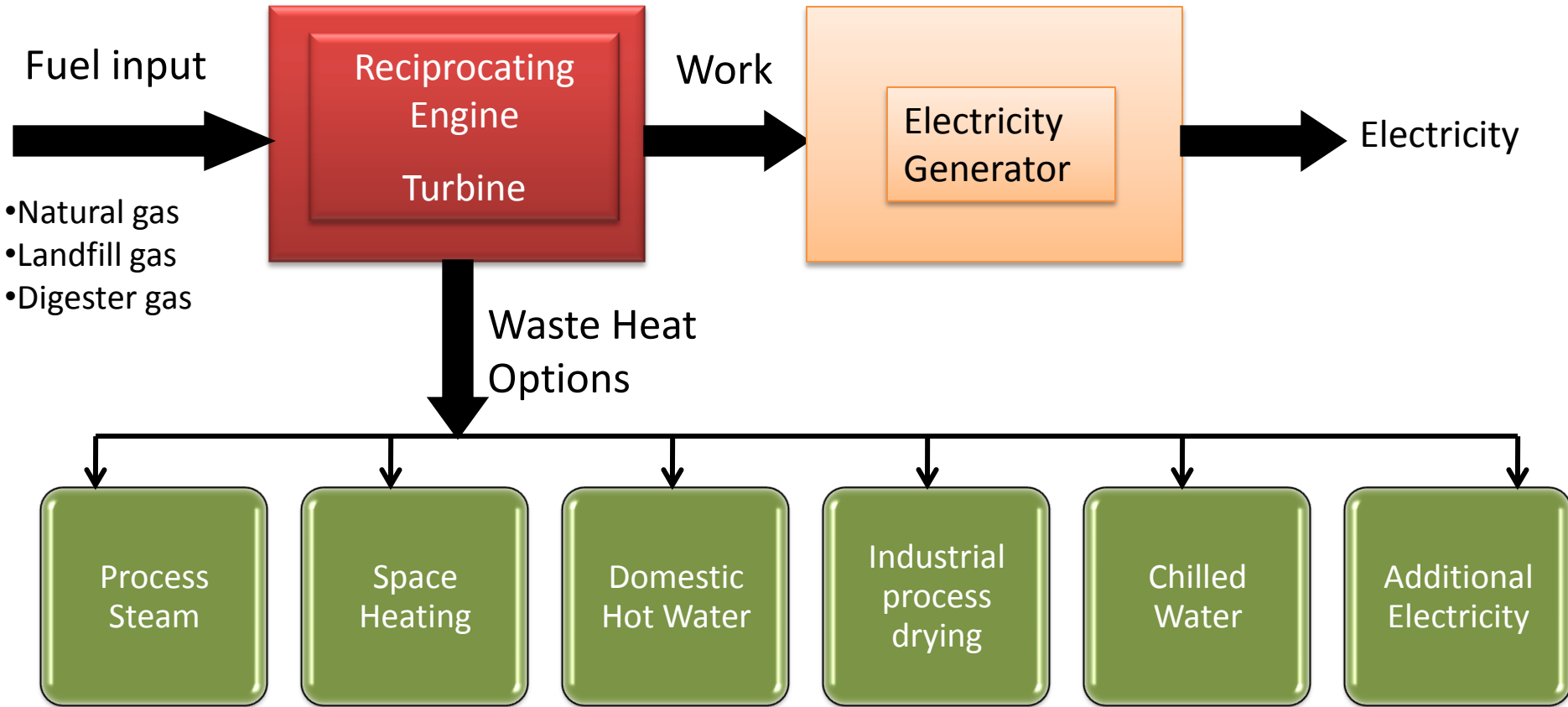
- is located in close proximity to the energy consumer – building, campus or industrial
- provides at least a portion of the facility's electrical load
- captures thermal energy for use in:
 - Cooling
 - Dehumidification
 - Water and space heating
 - Process heat



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CHP: Typical Schematic



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Reciprocating Engines



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Reciprocating Engines - Basics

- Two basic types
 - Spark Ignition
 - Compression Ignition
- Ranges from few kW to over 5MW
- Features
 - Start quickly
 - Good part load ratio
 - Low first-cost
 - High reliability (proper maintenance required)
 - Waste heat captured for
 - Hot water
 - Low pressure steam
 - Space heating
 - Single effect or Exhaust gas driven absorption chiller : chilled water
 - Natural gas SI engines: most common engine based CHP (~84%)

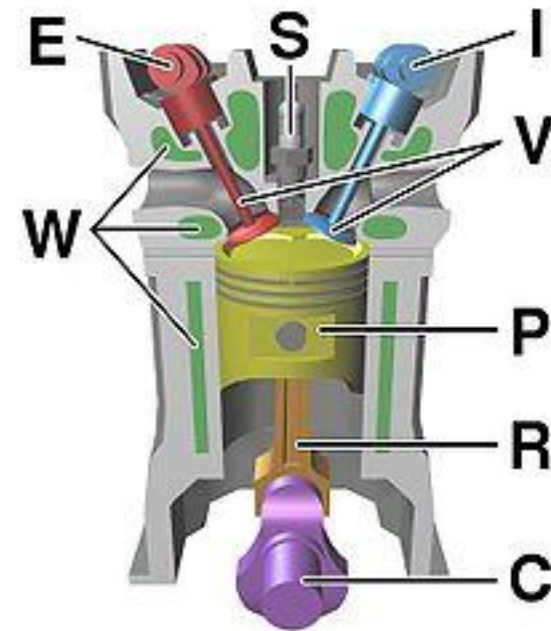


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Power Cycle (Otto Cycle)– Spark Ignition

- Intake Stroke
 - Introduction of air-fuel mixture into the cylinder
- Compression Stroke
 - Compression of air-fuel mixture (CR required ~9:1 to 12:1)
 - Subsequent ignition of compressed mixture by spark plug/ignition source
- Power stroke
 - Acceleration of the piston by the expansion of the hot, high pressure gases
- Exhaust stroke
 - Expulsion of combustion products from cylinder through the exhaust port



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Two Ignition Techniques – Spark Ignition

- Open chamber
 - Spark plug tip exposed in combustion chamber & directly ignites compressed fuel-air mixture
 - Typically stoichiometric air/fuel ratio reqd. (no unused O₂ or fuel after combustion)
- Pre-combustion chamber
 - Staged combustion process (2 chambers)
 - Spark plug located in small chamber above main chamber
 - Compressed mixture ignited in small chamber and shoots into main chamber
 - Technique can light up lean fuel-air mixtures



Lean Burn Engines

- Use high energy ignition technology (Pre-combustion chamber)
- Lower fuel-air mixtures
- Lower temperatures within cylinder
- Reduced NO_x emissions
- Can have Electric efficiencies 42% (LHV)
- Compromise between efficiency & NO_x emissions
 - Max efficiency results in higher NO_x
 - Tuning for lower NO_x results in 1 – 2 % points reduced electric efficiency (~40%)
- All major NG engine manufacturers offer lean burn engines
 - Advanced Reciprocating Engine Systems (ARES) Program:
<http://www1.eere.energy.gov/industry/distributedenergy/ares.html>



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Compression Ignition – Diesel Engines

- Diesel Cycle
- No spark plug or ignition
- Compression ratios – 12:1 to 17:1
- Cheaper ^x
- Very high Emissions
 - May produce as high as 20 times the NO_x of lean burn natural gas engines



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Dual Fuel engines

- Predominantly fueled by natural gas with small % of diesel
- Operation – combination of Otto and Diesel cycle
- Diesel auto ignites and initiates combustion of air-natural gas mixture
- Three types
 - Low pressure gas injection
 - Requires 5 to 10 percent diesel fuel
 - Capacity is derated to avoid detonation
 - High Pressure gas injection
 - Reduces derating by injecting high pressure natural gas
 - However has high parasitic power offsetting benefits
 - Micropilot prechamber
 - Diesel injected in prechamber (similar to lean burn engine)
 - High energy torch ignites gas-air mixture
 - Wide variance in performance – derating, emissions, required modifications in retrofit applications



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Engine Speeds

- Classified as
 - High speed (1,000 – 3,600 rpm)
 - Medium speed (275 – 1,000 rpm)
 - Low Speed (58 – 275 rpm)
- Power output proportional to speed
- Greater the speed of the engine
 - Higher power
 - Smaller in size
 - Lower efficiency
 - More maintenance

Speed Classification	Stoic/ Rich Burn, Spark Ignition	Lean Burn, Spark Ignition	Dual Fuel	Diesel
High Speed	0.01 – 1.5 MW	0.15 - 3.0 MW	1.0 - 3.5 MW	0.01 – 3.5 MW
Medium Speed	None	1.0 - 6.0 MW	1.0 – 25 MW	0.5 – 35 MW
Low Speed	None	None	2.0 – 65 MW	2 – 65 MW



Turbocharging

- Typically all modern engines (>300 kW) have turbocharging
- Basically a turbine driven air intake compressor
- Boosts inlet air pressure – 3:1 to a 4:1 ratio
- After-coolers at turbocharger exit cool air to keep it a specified limit
- Result : More air/fuel combustion per engine stroke & more power



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Engine CHP – Acceptable Fuels & Considerations

- Most common is natural gas
- Spark ignition engines can operate on alternative gaseous fuels
 - LPG: propane & butane mixtures
 - Sour gas: unprocessed from gas well
 - Biogas: landfill, sewage and animal waste digester gas
 - Industrial waste gases: process off gases from refineries, chemical plants
 - Manufactured gases: low & medium Btu gas from gasification or pyrolysis
- Factors that impact operation & considerations
 - Volumetric heating value (Btu content of the fuel)
 - Autoignition characteristics & detonation tendency
 - Contaminants in the gas (Engine life & emissions)
 - Hydrogen containing fuels (may need special consideration)



Waste Heat Recovery – Engine CHP

- Waste heat captured from
 - Major heat Sources
 - Engine exhaust gases
 - Represents ~30% of input fuel energy
 - Exhaust temperatures – 850 to 1200 F
 - Can produce
 - » Hot water at about 230 F or
 - » Low-pressure steam (150 psig)
 - Jacket Coolant
 - Represents ~30% of input fuel energy
 - Can produce 200 – 210 F hot water
 - Minor Heat Sources
 - Lube oil cooler
 - Turbocharger intercooler/aftercooler (if equipped)



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Performance Characteristics – Engine CHP

- Part Load Performance
 - Drives synchronous generators at constant speed
 - As load decreases, heat rate increases and Efficiency decreases
 - At 50% load, efficiency is ~8-10% of the full load efficiency
 - Electric Efficiency at full load – 40%
 - Electric Efficiency at 50% load - ~36%
- Effect of Ambient conditions
 - Generally engines rated at 77 deg F and 1 bar
 - Efficiency & power reduced
 - 4% per 1000 feet above 1000 feet
 - 1% for every 10 deg F above 77 deg F



Natural Gas Engine CHP – Typical Performance Parameters

	System 1	System 2	System 3	System 4	System 5
Baseload Electric Capacity (kW)	100	300	800	3,000	5,000
Electrical Efficiency (percent), HHV	28.40%	34.60%	35.00%	36.00%	39.00%
Fuel Input (MMBtu/hr)	1.2	4.93	9.76	28.48	43.79
Required Fuel Gas Pressure (psig)	<3	<3	<3	43	65
Heat Recovered from Exhaust (MMBtu/hr)	0.28	1.03	1.85	4.94	7.01
Heat Recovered from Cooling Jacket (MMBtu/hr)	0.33	1.13	2.45	4.37	6.28
Heat Recovered from Lube System (MMBtu/hr)	0	0	0	1.22	1.94
Total Heat Recovered (MMBtu/hr)	0.61	2.16	4.3	10.53	15.23
Net Heat Rate (Btus/kWh)	4,383	4,470	4,385	5,107	4,950
CHP Efficiency	79%	78%	79%	73%	74%



Engine Based CHP- Maintenance

- Requires continuous maintenance
 - Parts & Materials : oil & air filters, gaskets, valves, piston rings, etc
 - Labor
 - Minor and major overhauls
- Can be done in-house or contracted out
 - ~0.7 to 2.0 cents/kWh (depends on engine size)
- Recommended Service
 - Routine inspections
 - Replacement of engine oil, filter, coolant & spark plugs (500 -2,000 hrs)
 - Top-end overhaul (8,000 -30,000 hrs of operation)
 - Cylinder head and turbocharger rebuild
 - Major Overhaul (30,000 – 72,000 hrs of operation)
 - Piston/liner replacement
 - Crankshaft inspection
 - Bearings
 - Seals



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Typical Engine CHP – Maintenance Metrics

Time Between Overhauls – (Thousand Operating Hours)					
Engine Speed	720 rpm	900 rpm	1200 rpm	1500 rpm	1800 rpm
Minor Overhaul	> 30	15 - 36	24 – 36	10-20	8-15
Major Overhaul	> 60	40 - 72	48 - 60	30 – 50	30 - 36

Typical Natural Gas Engine Maintenance Costs - 2007					
Maintenance Costs	System 1	System 2	System 3	System 4	System 5
Electricity Capacity, kW	100	300	800	3000	5000
Variable (service contract), 2007 \$/kWh	0.02	0.015	0.012	0.01	0.009
Variable (consumables), 2007 \$/kWh	0.00015	0.00015	0.00015	0.00015	0.00015
Fixed, 2007 \$/kW-yr	15	7	5	2	1.5
Fixed, 2007 \$/kWh @ 8000 hrs/yr	0.0019	0.0009	0.0006	0.0003	0.0002
Total O&M Costs, 2007 \$/kWh	\$0.022	\$0.016	\$0.013	\$0.010	\$0.009

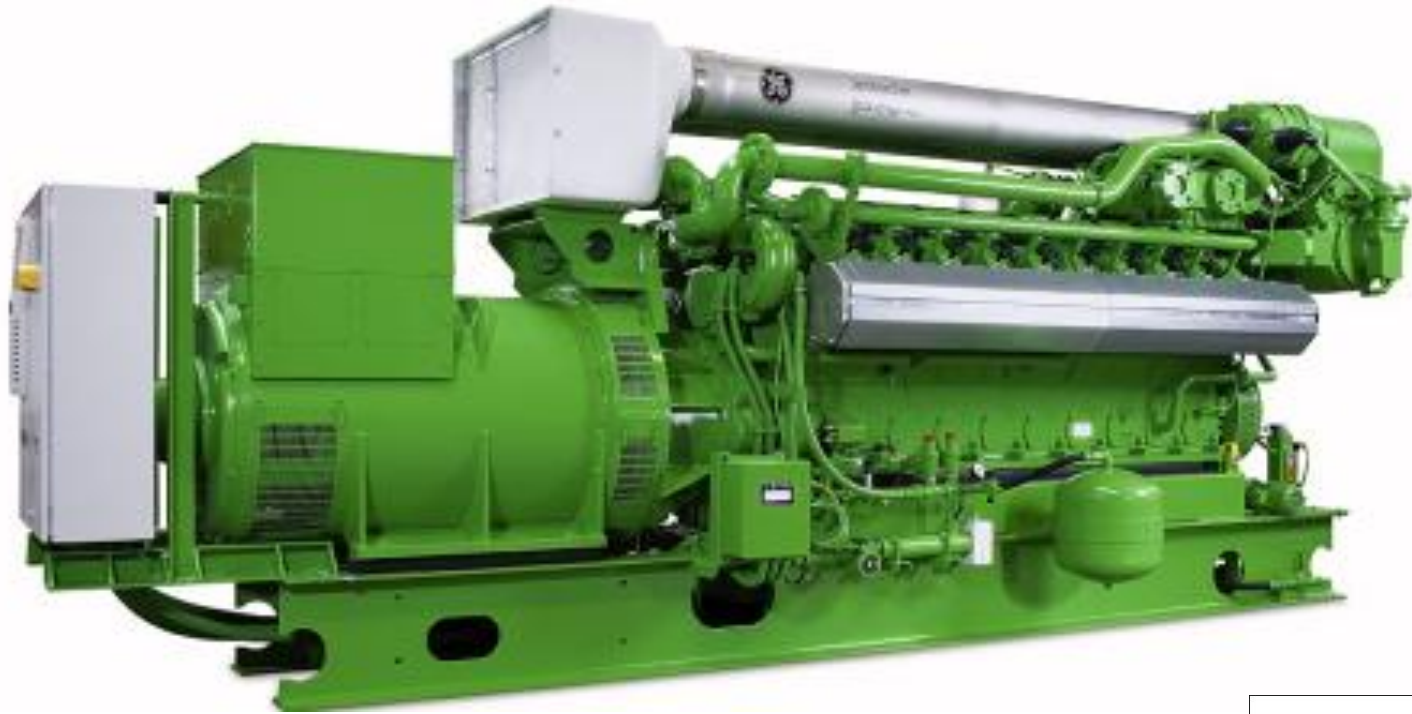
Source: SFA Pacific, Inc
EEA/ICF



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Engine Manufacturers



GE Jenbacher



CATERPILLAR®



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Several Others...

Estimated Capital Cost for Typical Natural Gas Engine Generators in Grid Interconnected, Combined Heat and Power Application (2007 \$/kW)

Cost Component	System 1	System 2	System 3	System 4	System 5
Nominal Capacity (kW)	100	300	800	3,000	5,000
Costs (\$/kW)					
Equipment					
Gen Set Package	\$1,000	\$880	\$760	\$520	\$590
Heat Recovery	\$110	\$240	\$190	\$80	\$50
Interconnect/Electrical	\$260	\$60	\$40	\$30	\$20
Total Equipment	\$1,370	\$1,180	\$990	\$630	\$660
Labor/Materials	\$340	\$300	\$250	\$240	\$250
Total Process Capital	\$1,710	\$1,480	\$1,240	\$870	\$910
Project and Construction Mgmt	\$200	\$180	\$150	\$90	\$70
Engineering and Fees	\$200	\$180	\$150	\$90	\$70
Project Contingency	\$70	\$60	\$50	\$30	\$30
Project Financing (interest during construction)	\$30	\$40	\$50	\$50	\$50
Total Plant Cost (\$/kW)	\$2,210	\$1,940	\$1,640	\$1,130	\$1,130



NO_x Emission Controls in Non Attainment Areas – Natural Gas Engine CHP : Special Consideration

- Will require treatment of Combustion gases
 - Three Way Catalytic conversion
 - Selective Catalytic Reduction (SCR)
 - Oxidation Catalysts
 - Lean NO_x catalysts
- As a result, capital costs will increase
 - Depending on system size Plant capital costs may be \$2,000/kW - \$1,400/kW (1 MW – 5 MW)



Gas Turbines



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Gas Turbines- Basics

- Two types
 - Aeroderivative (max ~50 MW)
 - Industrial frame (1 to 250 MW)
- Operates on the Brayton Cycle
- Ranges from 500 kW to over 250 MW
- Features
 - Electric Efficiencies (LHV) range between 22% - 40%
 - High Quality Waste Heat captured & can produce
 - High Pressure Steam
 - Space heating
 - Double/Triple effect or Steam turbine driven absorption chiller : chilled water
 - Additional Electricity: Steam Turbines
- Dual Fuel Capability Available
- Very clean electricity generation: reduced NO_x and CO₂



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Gas Turbines- Aero vs. Industrial

- Aeroderivative
 - Adapted from the airline industry
 - Lightweight
 - More expensive
 - Compression Ratio- 30:1
 - Better ability to start, shut down and handle load changes
- Industrial
 - Less Expensive
 - Rugged
 - Prefers to be base-loaded
 - Compression ratio – 16:1
 - Can operate longer between overhauls



Brayton Cycle – Gas Turbines & CHP

Components

– Gas Compressor

- Air is compressed in a compressor
- Adiabatic Process (No heat transfer)

– Combustion Chamber

- Fuel is burned, heating the compressed air
- Isobaric Process (Constant pressure)

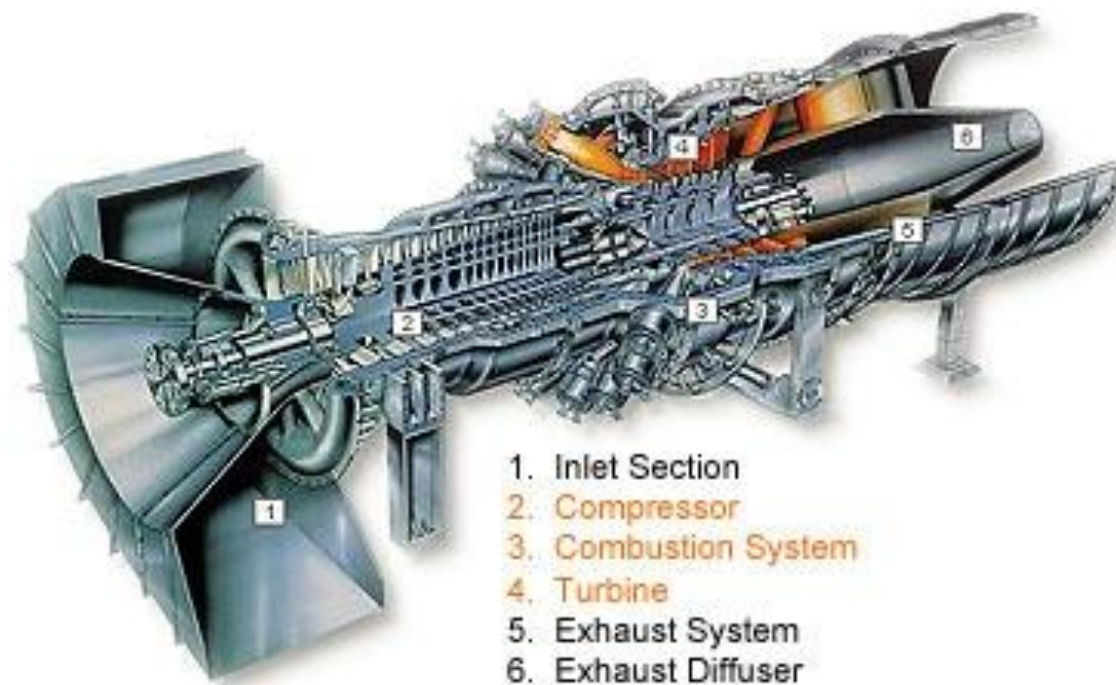
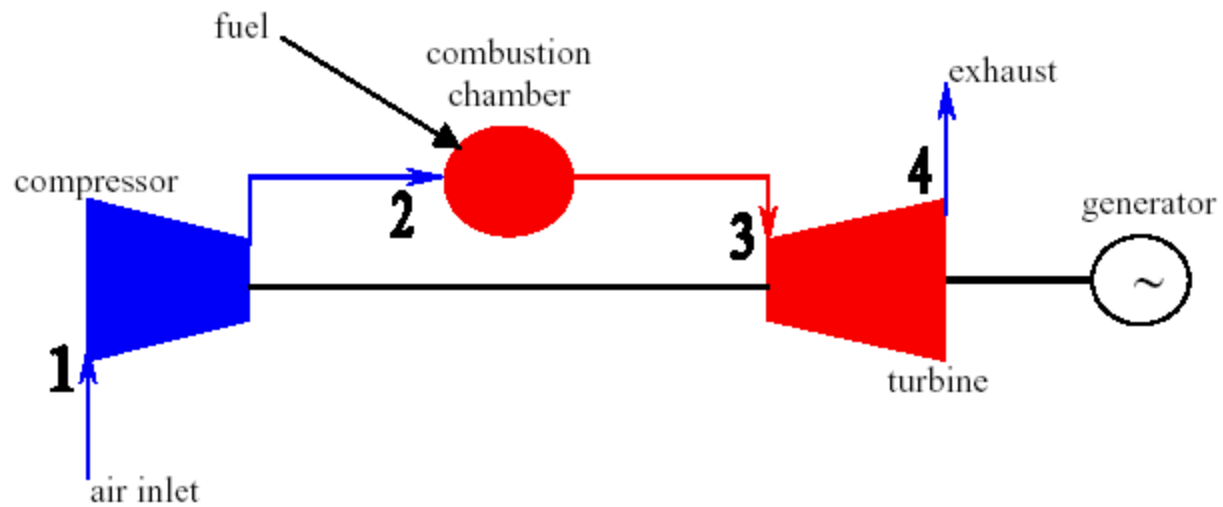
– Expansion turbine

- Heated & Pressurized air expands over turbine blades
- Work Extracted to drive generator

– Heat Rejection

- Exhaust Gases vented
- Heat captured from the exhaust gases





1. Inlet Section
2. Compressor
3. Combustion System
4. Turbine
5. Exhaust System
6. Exhaust Diffuser

Courtesy of Siemens Westinghouse



Factors Affecting Efficiency

- Pressure ratio
- Efficiency of compressor & turbine elements
- Turbine Blade Cooling requirements
- Turbine Inlet air temperature
- Ambient Air temperature
- Altitude
- Intended Use – More power or more heat?
- Part Load or Full Load
- Performance Enhancements
 - Inlet Air Cooling (To compressor)
 - Recuperation
 - Heat Recovery



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Fuel Supply Pressure

- Turbines need gas pressure typically greater than normal C&I service
 - 100 psig gas pressure for the smallest
 - Significantly higher for larger turbines
- Supply pressure can be significant, while calculating project economics due to
 - Cost of the potential on-site compression system
 - Power consumed by the on-site gas compression system

	System 1	System 2	System 3	System 4	System 5
Turbine Electric Capacity (kW)	1,000	5,000	10,000	25,000	40,000
Turbine Pressure Ratio	6.5	10.9	17.1	23.1	29.6
Required Compression Power (kW)					
55 psig gas supply pressure	8	82	198	536	859
150 psig gas supply pressure	Not needed	35	58	300	673
250 psig gas supply pressure	Not needed	Not needed	22	150	380



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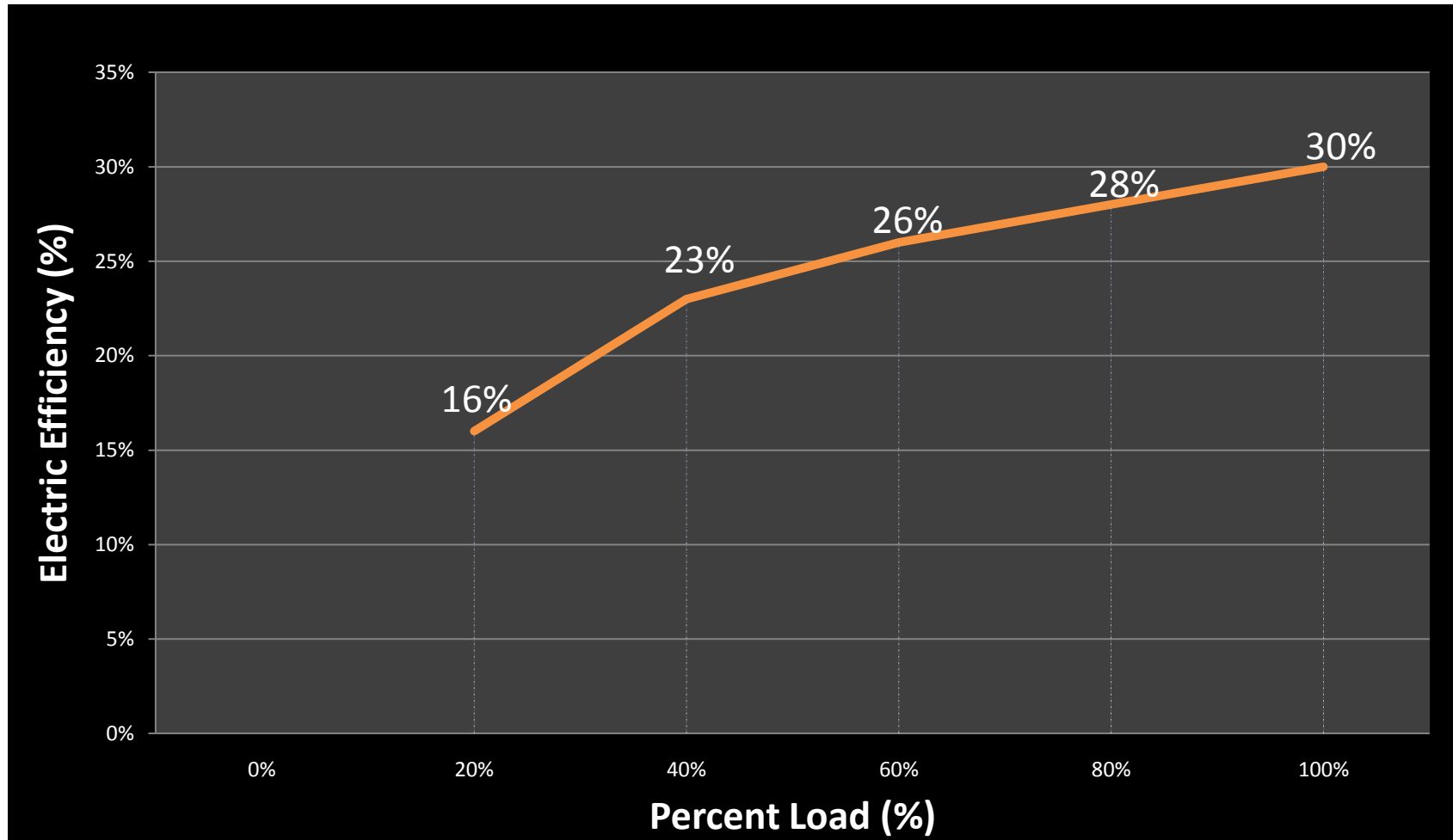
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Part Load Performance

- At part load Output reduced by lowering temperature of the exhaust gases to the expansion turbine (Stage 3)
- Change in operating conditions
 - Reduced Electrical Efficiency
 - Can result in similar overall CHP Efficiency to full load,
 - With proper design
 - Reduced shaft work, more waste heat and resultant capture
 - can be operational advantage
 - Emissions also increase



Part Load Performance (cont'd)



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Effects of Ambient Conditions

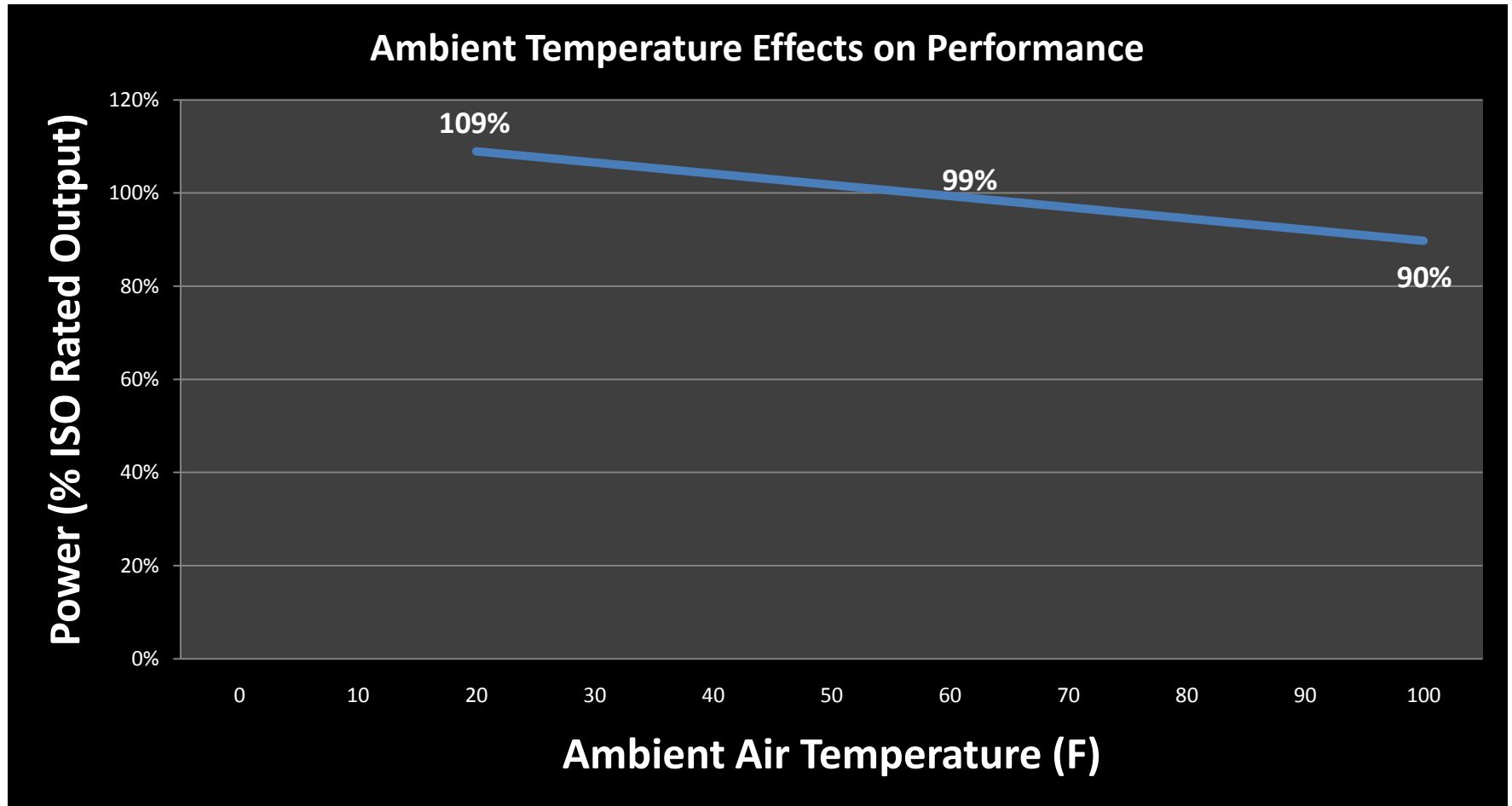
- Typically turbines rated at 59 deg F and sea-level
- At higher inlet air-temperatures
 - Power decreases due to decreased air flow mass rates (Hot air = less dense)
 - Efficiency decreases since compressor requires more power to compress air at higher temperature
- At higher altitudes
 - Power output decreases since, density of air decreases at altitudes above sea-level



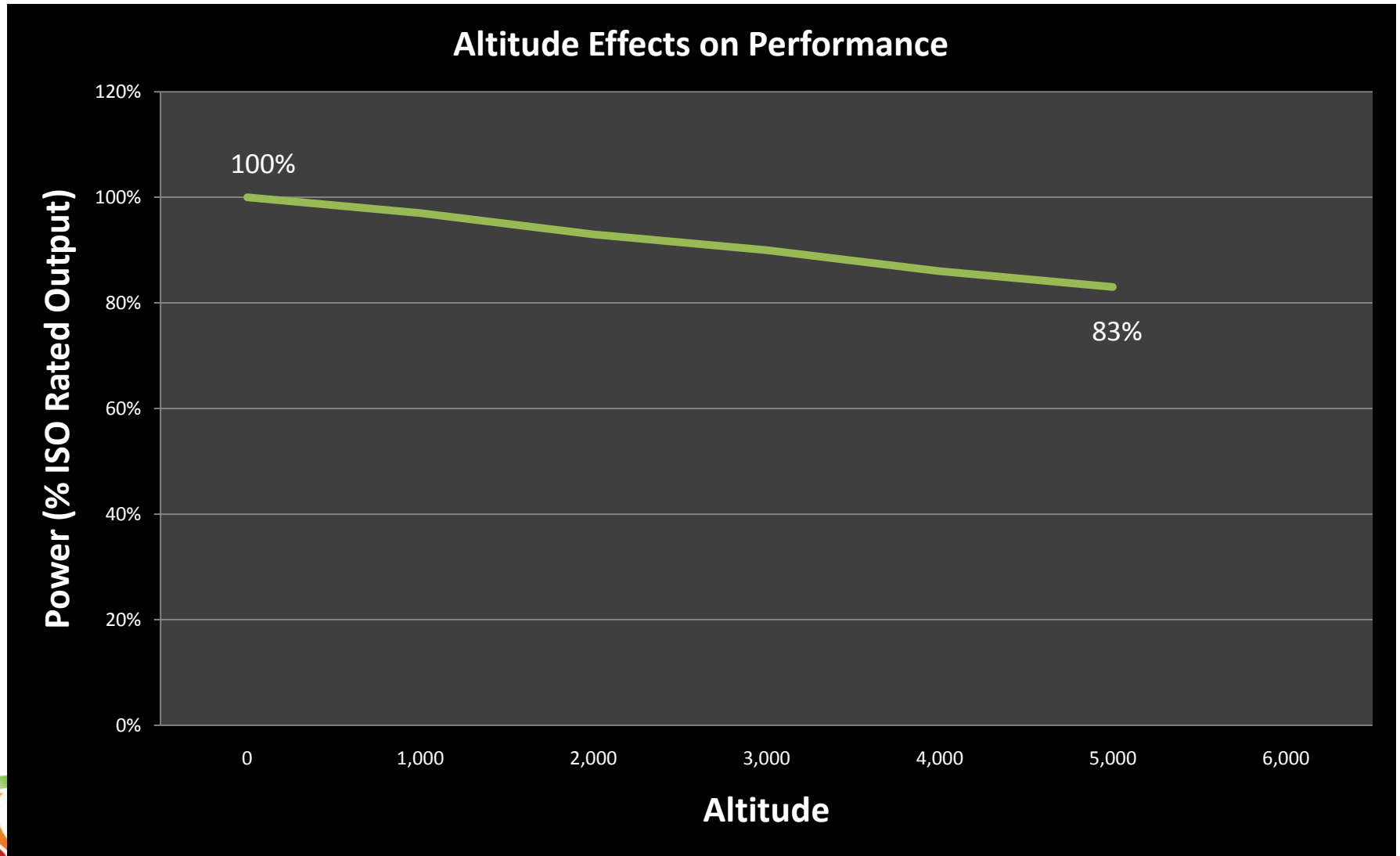
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Ambient Air Temperature vs. Power



Altitude Derate – Gas Turbine



Supplemental Firing

- Duct burners fueled by natural gas can raise exhaust gas temperature up to 1,800 F ahead of the Heat Recovery Steam Generator
 - Increase steam production by factor of 2
- Since exhaust gases are hot, fuel required is lesser for supplemental firing when compared to stand alone boiler
- Increases system flexibility
 - Ability to control steam production regardless of gas turbine operating mode
- Low NO_x burners (0.08 lb Nox/MMBtu) to minimize emissions



Recuperators

- Heat exchanger that captures waste heat from turbine exhaust and pre-heats compressed air entering the combustion chamber
- This results in reduced fuel use and higher electrical efficiency
- However, increased pressure drop results in power output deration
- When does one use recuperators?
 - Large number of operating hours (base load)
 - Cost of fuel is high
 - Desire for higher electric efficiency
 - Lower thermal needs (Exhaust gas energy reduced)
 - Only one combustion turbine
 - Mercury 50 by Solar Turbines: 4.2 MW
 - More common in microturbines (Small gas turbines <200 kW)



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Inlet Cooling

- When outside air conditions are the hottest & power is valued the most, turbine experiences significant power derate
- To mitigate this
 - Inlet air to the compressor can be cooled
- When does this make most sense?
 - Price of summer grid power may be extremely high
 - May result in demand charges on a ratchet basis for the whole year
 - Chillers are nearby with excess capacity (low construction costs for chill water pipe)
 - Excess waste heat availability
 - Convert to chill water using absorption chillers and run chilled water pipe to inlet of compressor



The Bookends

- Electric Loads >>> Thermal Loads
 - Use recuperator & inlet air cooling
 - No supplemental firing (duct burners)
- Thermal Loads >>> Electric Loads
 - Use supplemental firing to boost steam/heat production
 - Do not install recuperator
 - Inlet air cooling: cost considerations



Turbine CHP – Typical Performance Parameters

Performance Characteristics	System 1	System 2	System 3	System 4	System 5
Electricity Capacity (kW)	1,150	5,457	10,239	25,000	40,000
Electrical Efficiency (percent), HHV	21.27%	27.72%	28.44%	34.30%	37.00%
Fuel Input (MMBtu/hr)	18.5	67.2	122.9	248.6	368.8
Required Fuel Gas Pressure (psig)	82.6	216	317.6	340	435
Exhaust Flow (1,000 lb/hr)	51.4	170.8	328.2	571	954
GT Exhaust Temperature (Fahrenheit)	951	961	916	950	854
HRSO Exhaust Temperature (Fahrenheit)	309	307	322	280	280
Steam Output (MMBtu/hr)	8.31	28.26	49.1	90.34	129.27
Steam Output (1,000 lbs/hr)	8.26	28.09	48.8	89.8	128.5
Total CHP Efficiency (percent), HHV8	66.30%	69.80%	68.40%	70.70%	72.10%
Net Heat Rate (Btu/kWh)	7,013	5,839	6,007	5,427	5,180



Gas Turbine - Maintenance

- Daily maintenance
 - Visual inspection of filters and general site conditions
- Routine Maintenance practices
 - On-line running maintenance
 - Predictive maintenance
 - Plotting trends
 - Performance testing
 - Fuel consumption, heat rate & vibration analysis
- Inspections (4,000 hrs)
 - Check bearings, rotors & blade tips
 - Hot gas path boroscope inspections
 - NDT using dyes to ensure integrity
 - Combustion path checked for fuel nozzle cleanliness



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Gas Turbine – Maintenance (contd.)

- Major Overhaul (25,000 – 50,000 hrs)
 - Rebuild of components (restore to original)
 - Includes
 - Dimension inspections
 - Product upgrades
 - Turbine and compressor testing
 - Rotor removal
 - Inspection of thrust & journal bearings
 - Blade inspection
 - Setting packing seals
- Factors affecting maintenance costs
 - Diligence of preventive maintenance costs
 - Cycling (on-off) increases maintenance costs
 - Operating turbine above rated capacity
 - Operating on liquid fuels

O&M Costs	System 1	System 2	System 3	System 4	System 5
Electricity Capacity (kW)	1,150	5,457	10,239	25,000	40,000
Variable (service contract), \$/kWh	\$0.0060	\$0.0060	\$0.0060	\$0.0040	\$0.0035
Variable (consumables), \$/kWh	\$0.0001	\$0.0001	\$0.0001	\$0.0001	\$0.0001
Fixed, \$/kW-yr	\$40.0	\$10.0	\$7.5	\$6.0	\$5.0
Fixed, \$/kWh @ 8,000 hrs/yr	\$0.0050	\$0.0013	\$0.0009	\$0.0008	\$0.0006
Total O&M Costs, \$/kWh	\$0.0111	\$0.0074	\$0.0070	\$0.0049	\$0.0042



Turbine Manufacturers



Solar[®] Turbines

A Caterpillar Company

SIEMENS

 **Kawasaki**

Kawasaki Gas Turbines - Americas



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Several Others...

Estimated Capital Costs for Typical Gas Turbine-Based CHP Systems (\$000s)

Cost Component	System 1	System 2	System 3	System 4	System 5
Nominal Turbine Capacity (MW)	1	5	10	25	40
Equipment (Thousands of 2007 \$)					
Combustion Turbines	\$1,015	\$2,733	\$6,102	\$12,750	\$23,700
Electrical Equipment	\$411	\$540	\$653	\$1,040	\$1,575
Fuel System	\$166	\$177	\$188	\$251	\$358
Water Treatment System	\$74	\$180	\$293	\$370	\$416
Heat Recovery Steam Generators	\$508	\$615	\$779	\$1,030	\$1,241
SCR, CO, and CEMS	\$0	\$0	\$0	\$0	\$0
Building	\$0	\$0	\$0	\$0	\$0
Total Equipment	\$2,173	\$4,246	\$8,015	\$15,440	\$27,290
Construction	\$769	\$1,402	\$2,568	\$4,947	\$8,744
Total Process Capital	\$2,942	\$5,648	\$10,583	\$20,387	\$36,034
Project/Construction Management	\$271	\$402	\$664	\$1,279	\$2,260
Shipping	\$47	\$89	\$164	\$317	\$559
Development Fees	\$217	\$425	\$802	\$1,544	\$2,729
Project Contingency	\$116	\$177	\$276	\$532	\$940
Project Financing	\$230	\$431	\$799	\$1,540	\$2,721
Total Plant Cost	\$3,822	\$7,172	\$13,288	\$25,598	\$45,243
Actual Turbine Capacity (kW)	1,150	5,457	10,239	23,328	46,556
Total Plant Cost per net kW (2007 \$)	\$3,324	\$1,314	\$1,298	\$1,097	\$972
Complex Installation Capital Cost 2007 \$/kW	\$5,221	\$2,210	\$1,965	\$1,516	\$1,290

Complex Costs include

- Building to house CHP
- SCR
- Carbon monoxide catalyst
- Natural Gas Compressor
- Continuous Emissions Monitoring Systems



Contacts

Dan Bullock, MS, MPAff

Director

281-364-6087

dbullock@harc.edu

Ross Tomlin, MPAff

Clean Energy Policy

281-363-7922

rtomlin@harc.edu

Krishnan Umamaheswar, LEED^{AP}, CEM, CDSM, DGCP

Project Support

281-363-7906

ukrishnan@harc.edu

Ginny Jahn

Administrative Support

281-364-6051

gjahn@harc.edu

www.gulfcoastcleanenergy.org



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Upcoming Webinars

[Waste Heat Recovery using Organic Rankine Cycle](#)

Thurs., March 24; 10:00-11:00 a.m.

Host: Dan Bullock, Gulf Coast Clean Energy Center

Guest Speaker: Colin Duncan, Ormat Technologies

[Financing CHP Projects](#)

Wed., March 30; 10:00-11:00 a.m.

Host: Ross Tomlin, Gulf Coast Clean Energy Center

Guest speaker: John May, Stern Brothers

[Streamlining Project Development](#)

Tues., April 5; 10:00-11:00 a.m.

Host: Daniel Bullock, Director, US DOE Gulf Coast Clean Energy Application Center

[82nd Texas Legislative Session: Mid-Session Update](#)

Thur., April 14; 10:00-11:00 a.m.

Host: Ross Tomlin, Gulf Coast Clean Energy Center

Guest Speaker: Paul Cauduro, Executive Director, Texas CHP Initiative



U.S. DEPARTMENT OF ENERGY

Gulf Coast Clean Energy Application Center