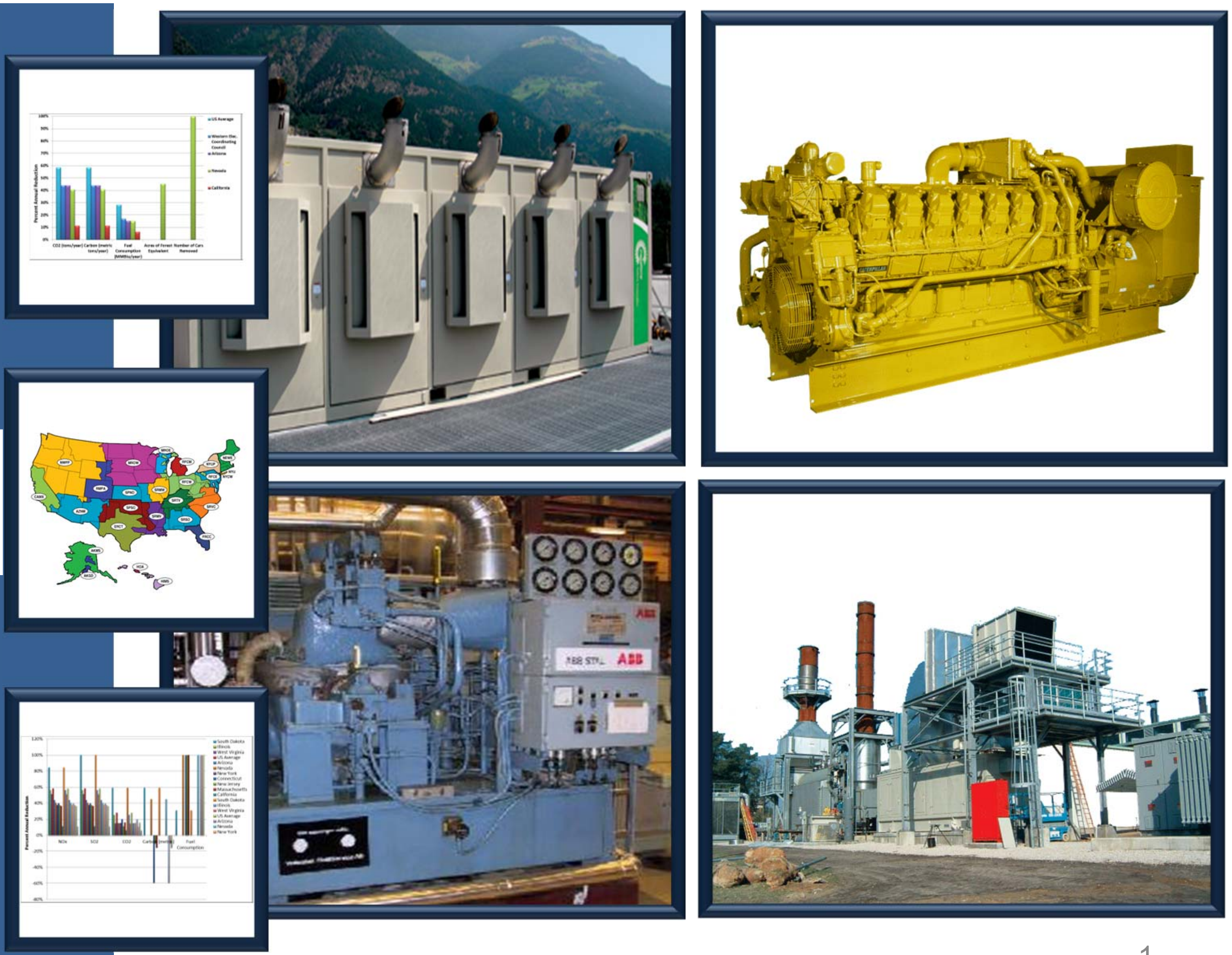
CHP Technology Update

Technical Workshop



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Representing the Interests of America's Industrial Energy Users since 1978

Richard Sweetser
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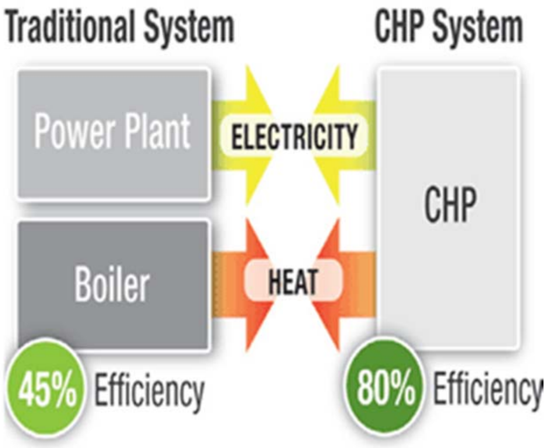
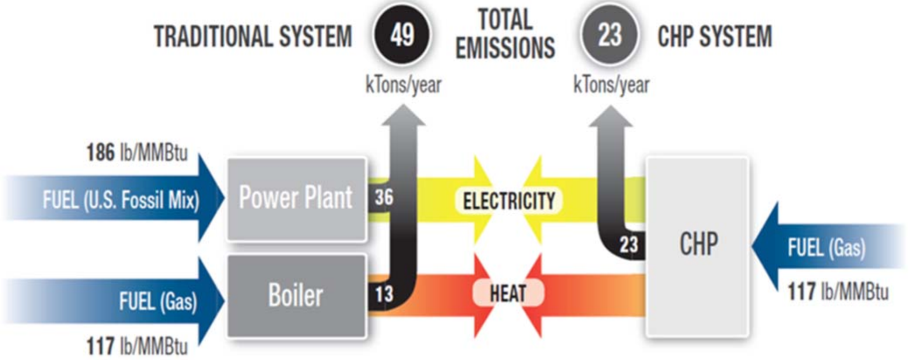
Application Center

Assumptions

- Bob tells me you are all really smart.
- You Fundamentally understand CHP, but particularly want to catch up of the industry, technology and approaches.
- Since you are experts on boilers, I will concentrate on non-boiler based technologies in the technology portion of this presentation.





CHP & the Second Law of Thermodynamics

- **“The law that entropy always increases, holds, I think, the supreme position among the laws of Nature.**

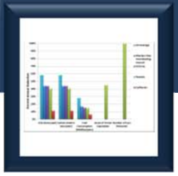
- **If someone points out to you that your pet theory of the universe is in disagreement with Maxwell's equations — then so much the worse for Maxwell's equations.**

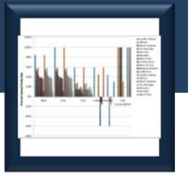
- **If it is found to be contradicted by observation — well, these experimentalists do bungle things sometimes.**

- **But if your theory is found to be against the second law of thermodynamics I can give you no hope; there is nothing for it but to collapse in deepest humiliation.”**

- **Sir Arthur Stanley Eddington, The Nature of the Physical World (1927)**

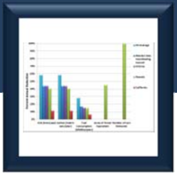
CHP Technology 101 Schema

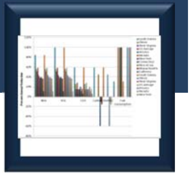




- **Overview of CHP Technologies and components**
- **The Second Law and Energy Efficiency**
- **Power components**
  - **Microturbines**
  - **Reciprocating Engines**
  - **Combustion Turbines**
  - **Steam Turbines**
- **Thermal Systems**
- **Packaged/Modular Systems**
- **Fuel Cells**
- **Implications of output based standards for CHP**
- **Questions**

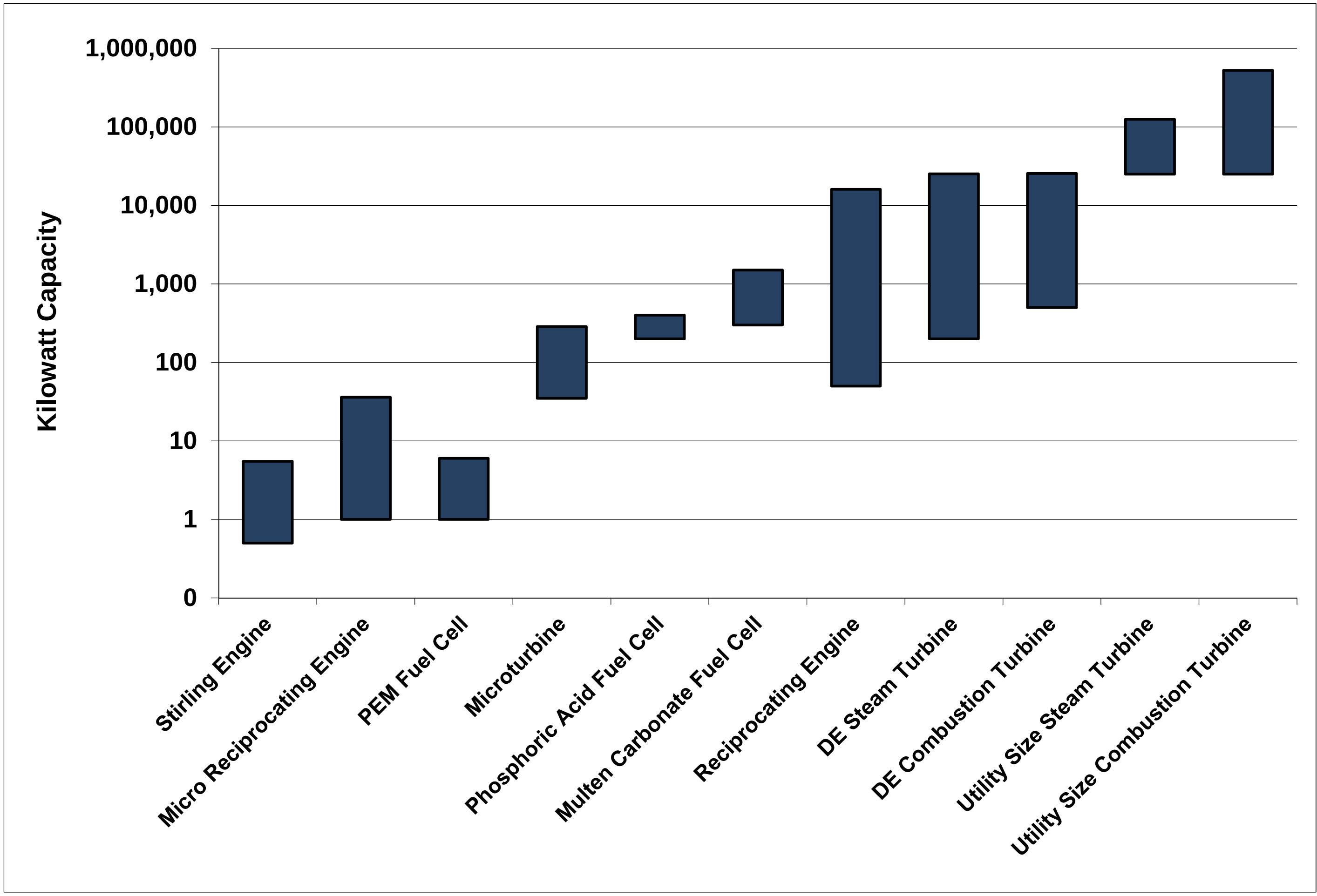
CHP Power Systems





DG Technologies	Standby Power	Baseload Power Only	Demand Response Peaking	Customer Peak Shaving	Premium Power	Utility Grid Support	CHP
Stirling Engines: 1 kW to 5 kW	x						x
Micro-Reciprocating Engines: 1 - 35 kW	x						x
Fuel Cells: PEMFC, PAFC, MCFC & SOFC: 1 - 1.5 MW	x	x			x		x
Reciprocating Engines: 50 - 16 MW	x	x	x	x	x	x	x
Gas Turbines: 500 kW to 100+ MW		x		x	x	x	x
Steam Turbines: 500 kW to 25+ MW		x			x		x
Microturbines: 35 kW to 250 kW	x	x	x	x	x	x	x
Fuel Cells: 1 kW to 1.2 MW+		x			x	x	x

Power Technologies Available

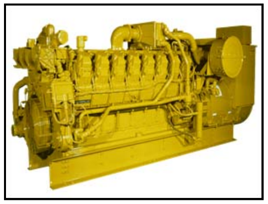


Distributed Generation Technologies

Boiler

Gas-turbine

Solid Oxide Fuel Cell



I.C. Engine Exhaust

Molten Carbonate Fuel Cell

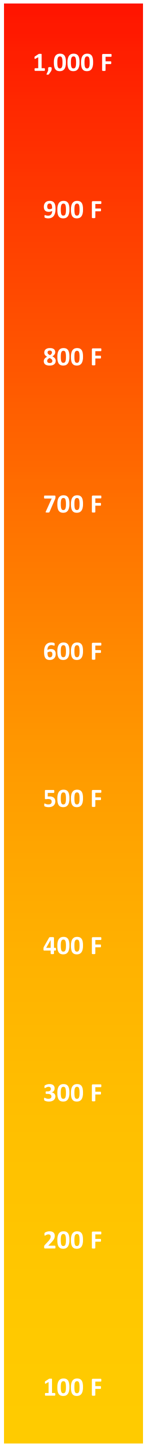
Microturbine

Phosphoric Acid Fuel Cell

Stirling

PEM Fuel Cell

I.C. Engine Jacket + Exhaust

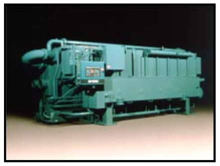


Thermally-Activated Technologies

Steam Turbine Centrifugal Chiller

Stirling

Steam Turbine Generator



Double-Effect Absorption Chiller

Single-Effect Absorption Chiller

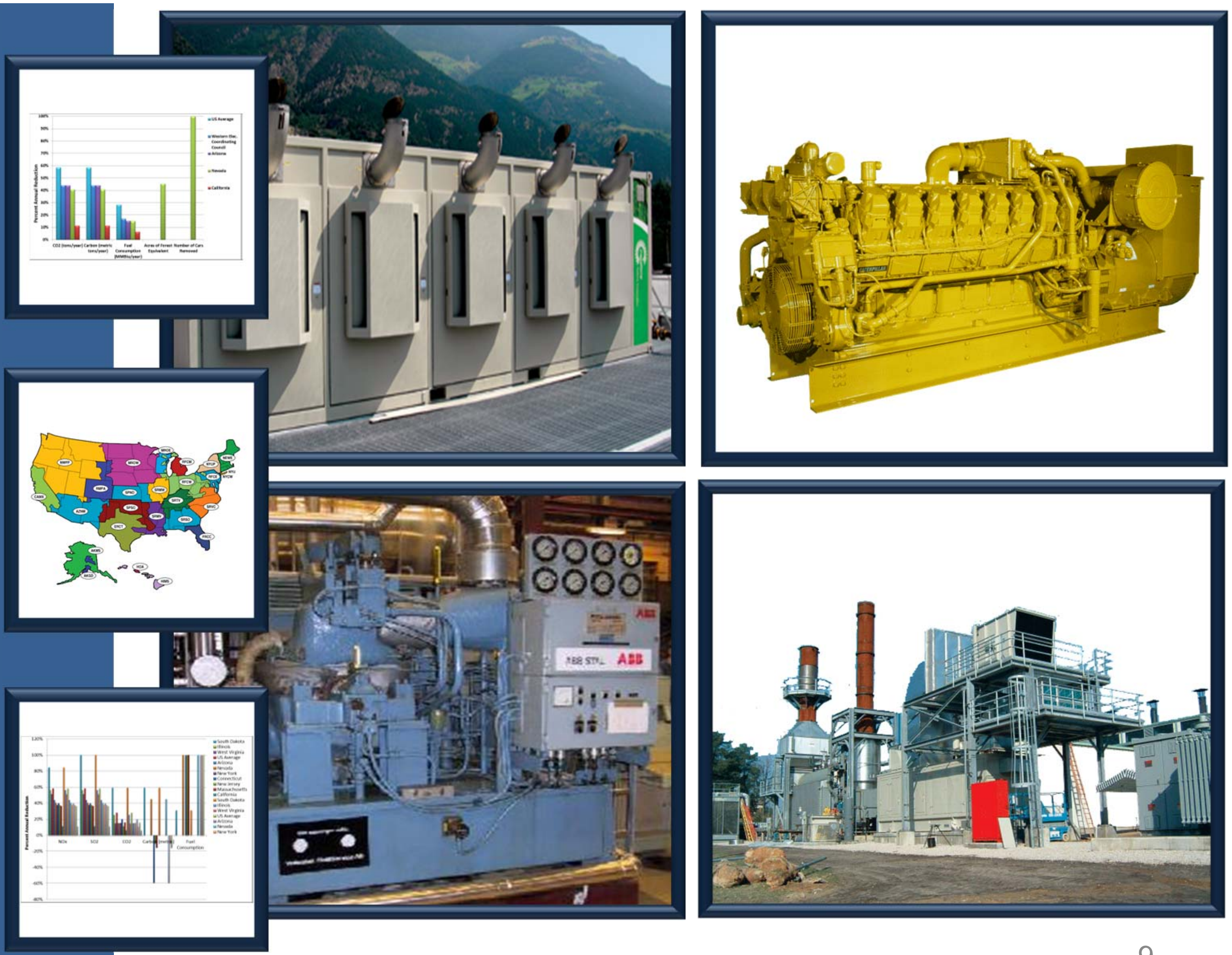
The Second Law and Energy Efficiency

- **The current methodology of using Net Electric Efficiency (η_E) and Overall Efficiency (η_o) either separately or in combination does not adequately describe CHP Performance:**
  - **η_E gives no value to the thermal output**
  - **η_o is an accurate measure of fuel utilization but does not differentiate the relative values of the energy outputs, and is not directly comparable to any performance metric representing separate power and thermal generation.**
  - **For CHP systems delivering power and heating (steam and/or hot water, or direct heating), the CHP electric effectiveness is defined as:**

$$\varepsilon_{EE} = \frac{W_E}{Q_{FUEL} - \Sigma\,(Q_{TH} / \alpha)}$$

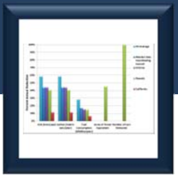
  - **Where α the efficiency of the conventional technology equals that otherwise would be used to provide the useful thermal energy output of the system (in the form of steam or hot water this would be a conventional boiler).**

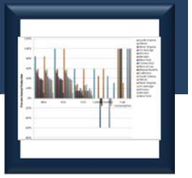
Technologies



Microturbines

Microturbines





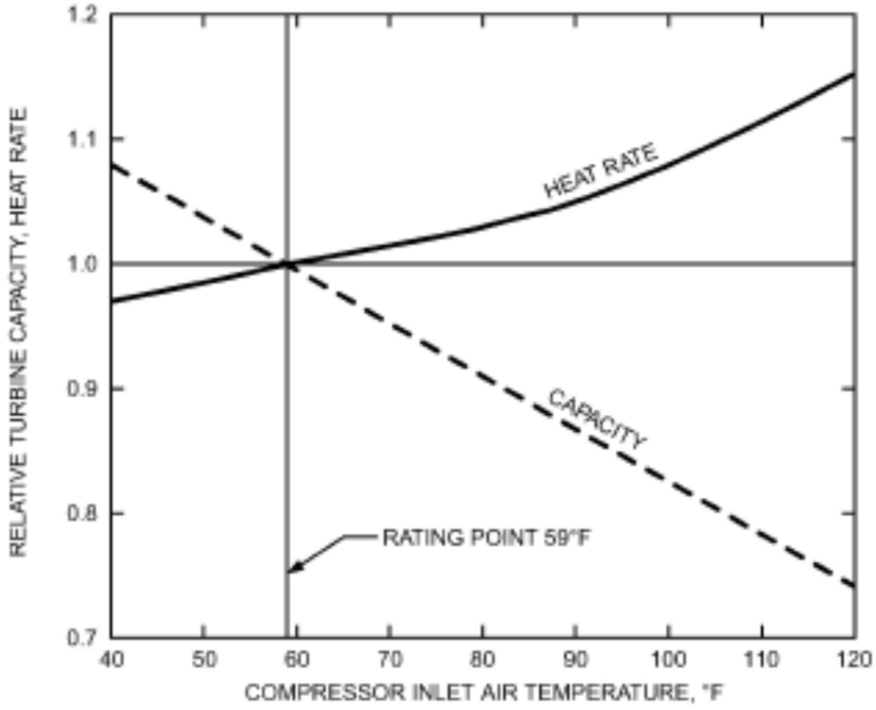
Shaft Efficiency (HHV)	range from 22% to 30% (HHV)
Availability	Should be greater than 96%, note fuel gas booster compressors currently reduce reliability.
Equipment Life (years)	10 year lifespan.
Fuel pressure (psi)	65 - 90 (may require fuel compressor on-board option for most systems)
Fuels (check mfg.)	natural gas, propane, diesel, landfill gas, digester gas, biodisel natural gas, sour gases (high sulfur, low Btu content), and liquid fuels such as gasoline, kerosene, and diesel fuel/heating oil.

Microturbines

Thermal output:	**400 to 600° F range, suitable for supplying a variety of building thermal needs.**
Size range:	**Microturbines available and under development are sized from 30 to 250 kW. (1,000 kW Module)**
Emissions:	**Low inlet temperatures and high fuel-to-air ratios result in NO_x emissions of less than 10 parts per million (ppm) when running on natural gas.**
Modularity:	**Units may be connected in parallel to serve larger loads and provide power reliability.**
Part-load operation:	**Because microturbines reduce power output by reducing mass flow and combustion temperature, efficiency at part load can be below that of full-power efficiency.**

Microturbines

Brayton Cycle

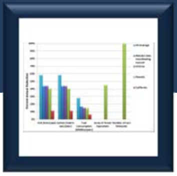


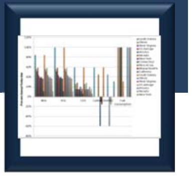
Microturbines

Nominal Capacity (kW)	30	65	100	250
Microturbine ($/kW)	$1,500	$1,300	$1,200	$1,100
Gas Booster Compressor	$140	internal	internal	internal
Heat Recovery	inc	inc	inc	inc
Controls/Monitoring	$179	$143	$120	$57
Total Equipment	$1,819	$1,443	$1,320	$1,157
Labor/Materials	$300	$200	$140	$112
Total Process Capital	$2,119	$1,643	$1,460	$1,269
Engineering and Fees	$130	$85	$64	$44
Project Contingency	$56	$50	$38	$34
Project Financing (interest during construction)	$31	$27	$21	$18
Total Plant Cost ($/kW)	$2,336	$1,805	$1,583	$1,365

Microturbines

Emissions Without Exhaust Control Options



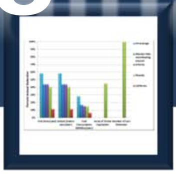


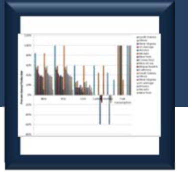
Electricity Capacity (kW)	30	65	100	250
Electrical Efficiency, HHV	21%	25%	26%	27%
NO_x, ppmv	9	9	15	9
NO_x, lb/MWh	0.54	0.50	0.80	0.53
CO, ppmv	40	9	15	25
CO, lb/MWh	1.46	0.30	0.49	0.72
THC, ppmv	< 9	<9	<10	<10
THC, lb/MWh	<0.19	<0.17	<0.19	<0.19
CO_2, (lb/MWh)	1,928	1,774	1,706	1,529
Carbon, (lb/MWh)	526	484	465	417

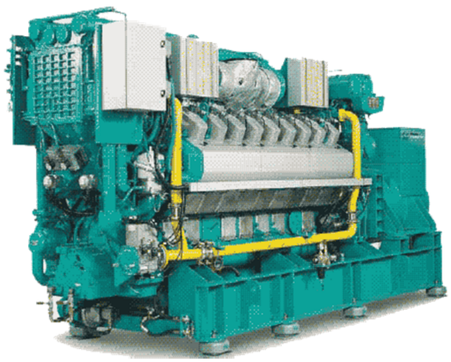
Microturbines

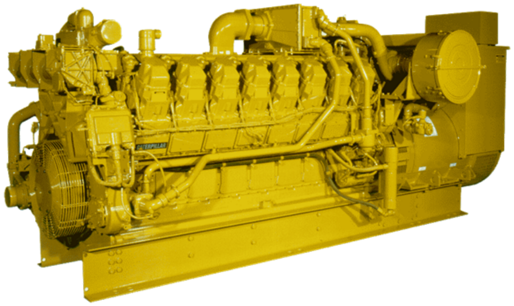
- **Many of the early entry microturbines currently in service are in resource recovery applications where fuel costs are negligible and unattended operation is key.**
- **Microturbines are currently operating in oil and gas production fields, wellheads, coal mines and landfill operations, where byproduct gases serve as ready and essentially free fuel that would otherwise be flared or allowed to escape to the atmosphere. These locations may be remote from the grid, and even when served by the grid, may experience costly downtime when electric service is lost due to weather, fire or animals.**
- **In CHP applications, the waste heat from the microturbine can be used to produce hot water, to heat building space, to drive absorption cooling or desiccant dehumidification equipment, and to supply other thermal energy needs in a building or industrial process**

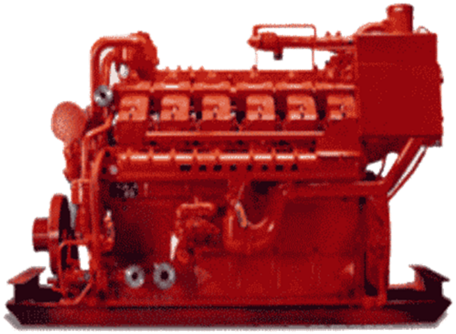
Reciprocating Engines



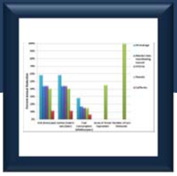


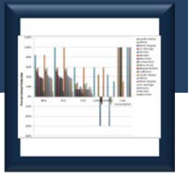






Reciprocating Engines



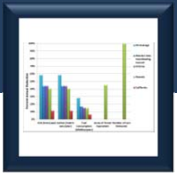


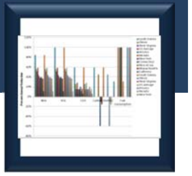
Types: two primary engine designs – the spark ignition Otto-cycle engine and the compression ignition Diesel-cycle engine.

Spark ignition engines are designed with either stoichiometric, rich-burn or lean-burn air/fuel ratios.

Speed Classification	Engine Speed, rpm	Stoichiometric/ Rich Burn, Spark Ignition (Natural Gas)	Lean Burn, Spark Ignition (Natural Gas)	Dual Fuel	Diesel
High Speed	1,000 - 3,600	0.01 - 1.5 MW	0.15 - 3.0 MW	1.0 - 3.5 MW	0.01 - 3.5 MW
Medium Speed	275 - 1,000	None	1.0 - 16.0 MW	1.0 - 25 MW	0.5 - 35 MW
Low Speed	60 -275	None	None	2.0 - 65 MW	2.0 - 80 MW

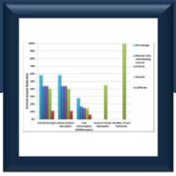
Reciprocating Engines

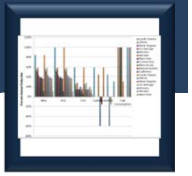




Shaft Efficiency (HHV)	**range from 25% to 40% (HHV) - diesel engines are more efficient than natural gas engines because they operate at higher compression ratios**
Availability	**Greater than 96%**
Equipment Life (years)	**20-30 years while smaller engines (<1 MW) tend to have shorter lifespan.**
Fuel pressure (psi)	**1-65 (may require fuel compressor for larger sized engines > 5 MW)**
Fuels	**natural gas, propane, diesel, landfill gas, digester gas, biodisel**

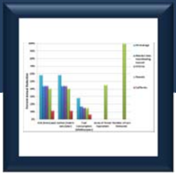
Reciprocating Engines

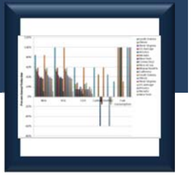




Nominal Capacity kW	100	300	800	3,000	5,000
Engine Combustion	Rich	Lean	Lean	Lean	Lean
Shaft Efficiency (HHV)	27	30	33	36	38
Fuel Input (MMBTU/hr)	1.15	3.29	10.05	29.1	41
Required Fuel Gas Pressure (psig)	<3	<5	<10	<45	<65
Engine Speed (rpm)	1,800	1,800	1,200	900	720

Reciprocating Engines

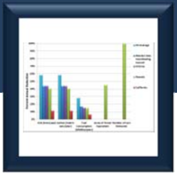


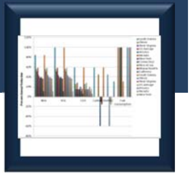


Nominal Capacity (kW)	100	300	800	3,000	5,000
Gen Set Package Costs ($/kW)	$338	$299	$350	$520	$585
Heat Recovery	$267	$233	$116	$85	$52
Interconnect/Electrical	$338	$117	$52	$29	$16
Total Equipment	$943	$649	$517	$633	$653
Labor/Materials	$467	$520	$493	$281	$260
Total Process Capital	$1,409	$1,169	$1,010	$914	$913
Project and Construction	$306	$205	$157	$124	$124
Engineering and Fees	$168	$105	$59	$53	$53
Project Contingency	$56	$44	$36	$33	$33
Project Financing (interest during construction)	$31	$33	$40	$72	$72
Total Plant Cost ($/kW)	$1,970	$1,556	$1,303	$1,195	$1,193

Reciprocating Engines

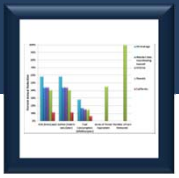
Emissions Without Exhaust Control Options

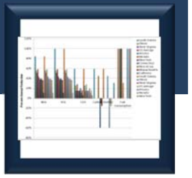




Electricity Capacity (kW)	100	300	800	3,000	5,000
Engine Combustion	Rich	Lean	Lean	Lean	Lean
NO_x, (gm/bhp-hr)	15	2	1	0.5	0.5
NO_x, (ppmv @ 15% O_2)	1,100	150	80	44	46
NO_x, (lb/MWh)	2.43	1.16	1.08	0.92	0.31
CO, (gm/bhp-hr)	12	1.8	2.6	2.8	2.2
CO, (lb/MWh)	37.32	5.51	8.09	8.55	6.83
VOC, (gm/bhp-hr)	0.7	0.2	1	1.4	0.4
VOC, (lb/MWh)	2.24	0.66	3.05	4.2	1.1
CO_2, (lb/MWh)	1,338	1,316	1,166	1,139	1,051
Carbon, (lb/MWh)	365	359	318	311	287

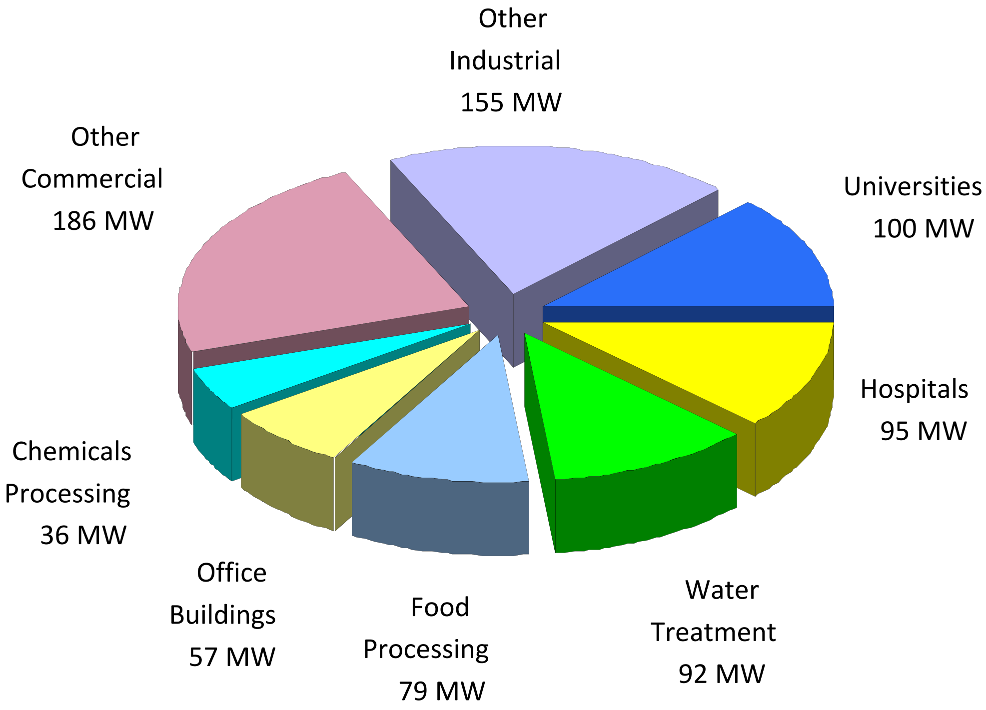
Reciprocating Engines



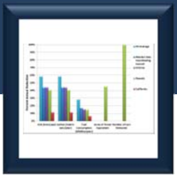


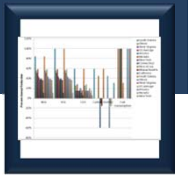
- *Emissions Reduction*
  - **Stoichiometric or Rich Burn Engines: Three-Way Catalyst –is the basic automotive catalytic converter process that reduces concentrations of all three major criteria pollutants – NOx, CO, and VOCs. The TWC process is also called nonselective catalytic reduction (NSCR). NOx and CO reductions are generally greater than 90%, and VOCs are reduced approximately 80% in a new, properly controlled TWC system.**
  - **Lean-Burn Engines: This technology selectively reduces NOx to N2 in the presence of a reducing agent. NOx reductions of 80 to 90% are achievable with SCR. Higher reductions are possible with the use of more catalyst or more reducing agent, or both. The two agents used commercially are ammonia (NH3 in anhydrous liquid form or aqueous solution) and aqueous urea.**

Reciprocating Engines



Reciprocating Engines



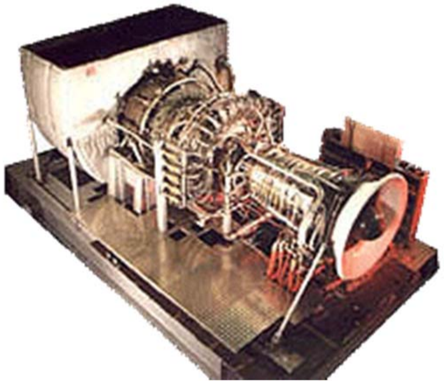


- Reciprocating engines are widely used in the U.S. and Europe for industrial, commercial and institutional power generation and CHP.
- Reciprocating engines start quickly, follow load well, have good part load efficiencies, and generally have high reliabilities.
- Multiple reciprocating engine units are used to increase overall plant capacity and availability.
- The economics of engines in on-site generation applications is enhanced by effective use of the thermal energy contained in the exhaust gas and cooling systems, which generally represents 60 to 70% of the inlet fuel energy.

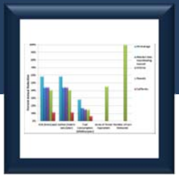
Reciprocating Engines

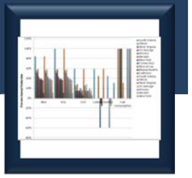
- There are four sources of usable waste heat from a reciprocating engine:
  - exhaust gas
  - engine jacket cooling water
  - lube oil cooling water
  - turbocharger cooling
- Heat can be recovered in the form of hot water or LP steam (<30 psig).
- MP steam (<150 psig) can be recovered from the exhaust gas, but only about one half of the available thermal energy from a reciprocating engine.
- Generally, the hot water and low pressure steam is appropriate for space heating, potable water heating, and to drive an absorption chiller or desiccant dehumidifier.

Combustion Turbines



Combustion Turbines



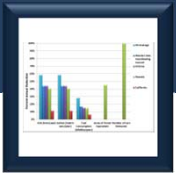


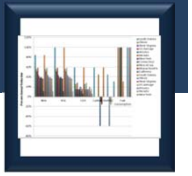
Types: Combustions Turbines are generally two-shaft designs and are classified as either *aeroderivative* or industrial. *Aeroderivative* gas turbines for stationary power are adapted from their jet and turboshaft aircraft engine counterparts. While these turbines are lightweight and thermally efficient, they are usually more expensive than products designed and built exclusively for stationary applications. The largest aeroderivative generation turbines available are approximately 40 MW in capacity and 40% (HHV) simple cycle efficiencies. *Industrial* or frame gas turbines are available in the 1 to 500 MW capacity range. They are less efficient and much heavier. Industrial gas turbines are approaching simple cycle efficiencies of approximately 36% (HHV) and combined cycle efficiencies of 55%.

Combustion Turbines

Shaft Efficiency (HHV)	range from 23% to 38* % (HHV)
Availability	should be greater than 98%
Equipment Life (years)	20+ year lifespan.
Fuel pressure (psi)	100 - 500 (likely to require fuel compressor)
Fuels	natural gas, synthetic gas, landfill gas and fuel oils. Often designed to operate on gaseous fuel with a stored liquid fuel for backup so as to obtain the less expensive interruptible rate for natural gas.

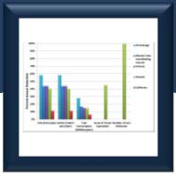
Combustion Turbines

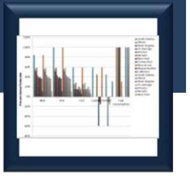




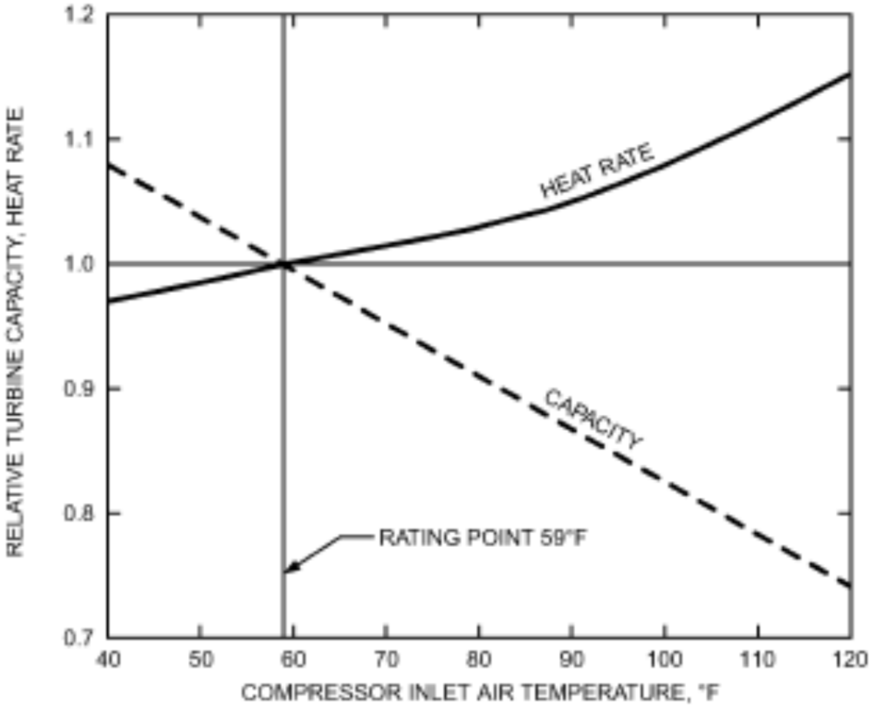
Thermal output:	**high quality (high temperature ~ 900 to 1,050 F) thermal output. High-pressure steam can be generated or the exhaust can be used directly for process drying and heating.**
Size range:	**500 kW to 25 MW (up to 500 MW for central station power), and can be selected to match the electric demand of most end-users (institutional, commercial and industrial).**
Emissions:	**lean premixed burners produce NO_x emissions below 25 ppm, with laboratory data down to 9 ppm, and simultaneous low CO emissions acceptable to regulators and safety personnel in the 50 to 10 ppm range. Further reductions in NO_x can be achieved by use of selective catalytic reduction (SCR) or catalytic combustion to achieve single-digit (below 9 ppm) NO_x emissions.**
Part Load Operation:	**gas turbines reduce power output by reducing combustion temperature, efficiency at part load can be substantially below that of full power efficiency.**

Combustion Turbines

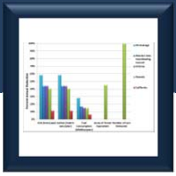


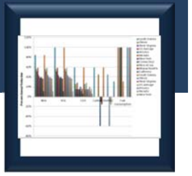


Brayton Cycle



Combustion Turbines

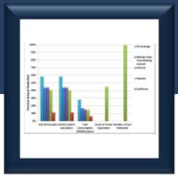


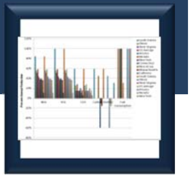


Nominal Turbine Capacity (kW)	1,000	5,000	10,000	25,000	40,000
Combustion Turbines ($/kW)	$616	$417	$407	$401	$373
HRSG	$228	$99	$60	$48	$39
Water Treatment System	$27	$22	$15	$9	$5
Electrical Equipment	$137	$82	$64	$47	$35
Other Equipment	$132	$69	$59	$54	$44
Total Equipment	$1,141	$690	$605	$559	$497
Materials	$131	$78	$70	$56	$49
Labor	$318	$199	$178	$143	$112
Total Process Capital	$1,590	$968	$854	$758	$658
Management	$114	$69	$61	$56	$50
Engineering	$58	$35	$26	$20	$16
Project Contingency	$79	$48	$43	$38	$33
Project Financing	$118	$72	$63	$56	$48
Total Plant Cost	$1,959	$1,191	$1,046	$928	$804

Combustion Turbines

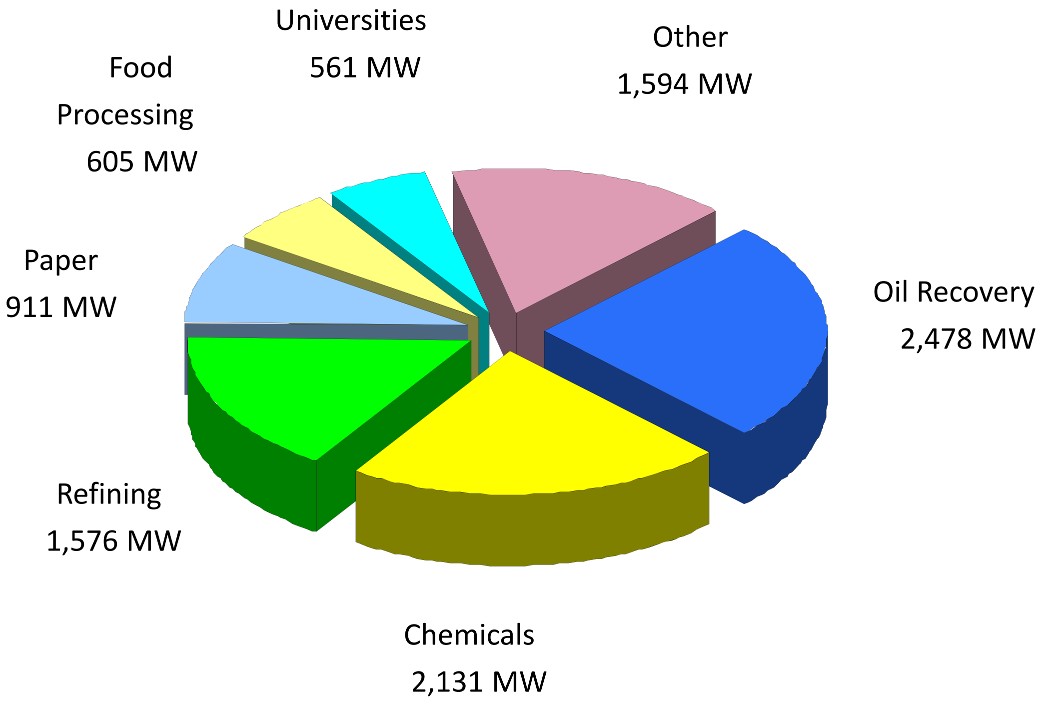
Emissions Without Exhaust Control Options





Electricity Capacity (kW)	1,000	5,000	10,000	25,000	40,000
NO_x, ppm	42	25	25	25	9
NO_x, lb/MWh	2.43	1.16	1.08	0.92	0.31
CO, ppmv	20	20	20	20	20
CO, lb/MWh	0.71	0.56	0.53	0.45	0.41
CO_2, lb/MWh	1,887	1,510	1,411	1,193	1,106
Carbon, lb/MWh	515	412	385	326	302

Combustion Turbines

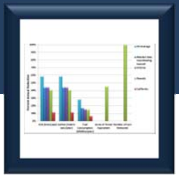


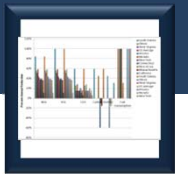
Installed Base Circa 2003

Combustion Turbines

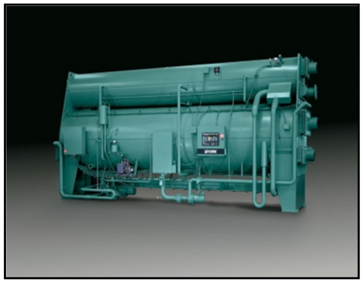
- **Typical industrial application for small gas turbines is a chemicals plant with a 25 MW simple cycle gas turbine supplying base load power to the plant with an unfired heat recovery steam generator (HRSG) on the exhaust. Approximately 29 MW thermal (MW_{TH}) of steam is produced at anywhere from 150 to 1,000 psig for process use within the plant.**
- **Typical commercial/institutional application for small gas turbines is a college or university campus with a 5 MW simple cycle gas turbine. Approximately 8 MWth of 150 to 400 psig steam is produced in an unfired heat recovery steam generator and sent into a central steam loop for campus space heating during winter months or to absorption chillers to provide cooling during the summer.**

Thermal Systems





Liq – Liq HX



Single-Effect Absorption Chiller

Desiccant Air Conditioner

Double-Effect Absorption Chiller

ORC

Steam Turbine Centrifugal Chiller

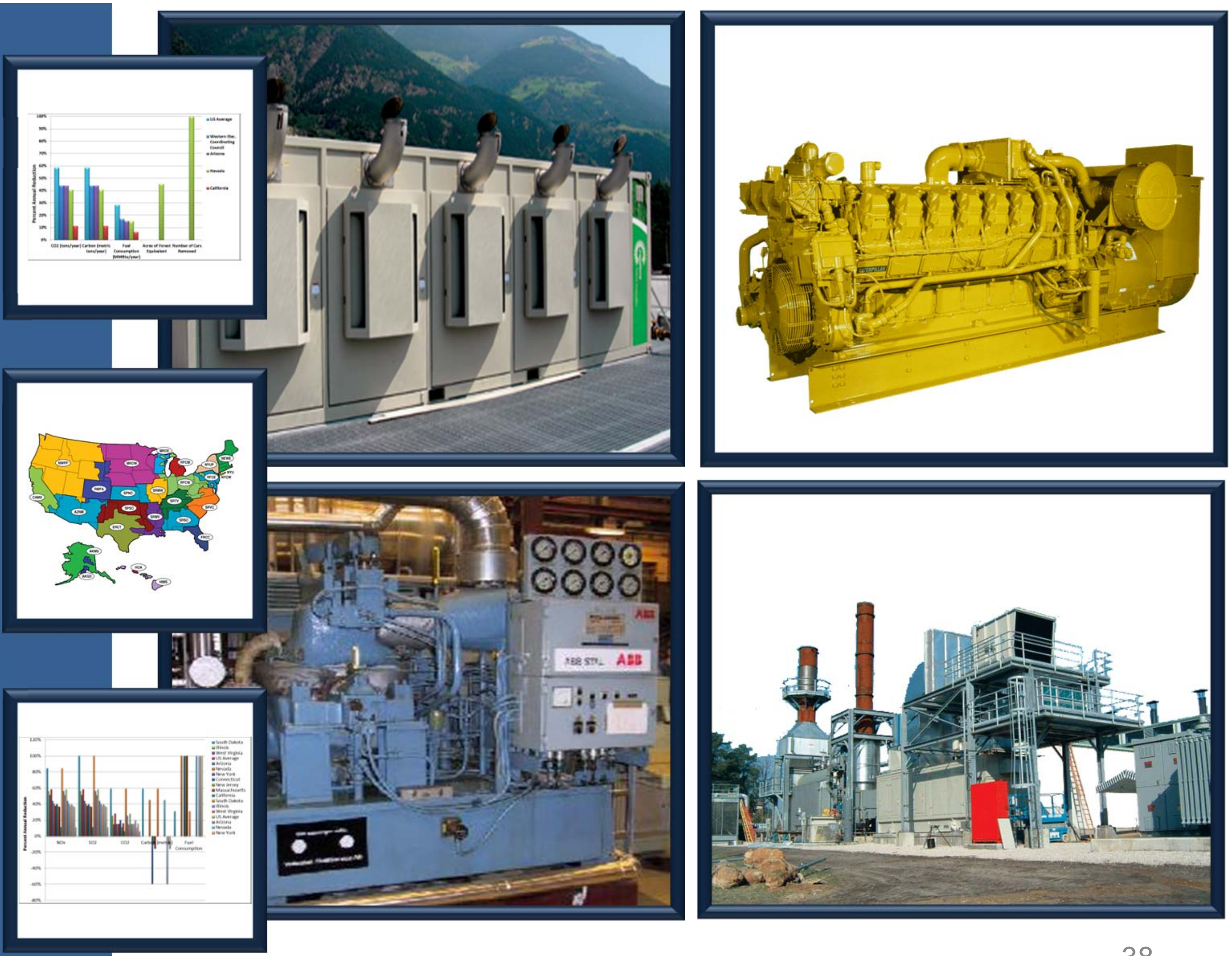
Steam Turbine Generator

Stirling Engine

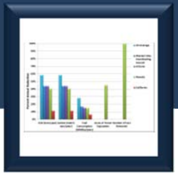
Packaged / Modular Systems

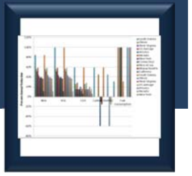
Future Technologies

Note: Some of the technologies are available today and provide value, but generally at a high cost requiring incentives or specific value propositions to be economically applied today.

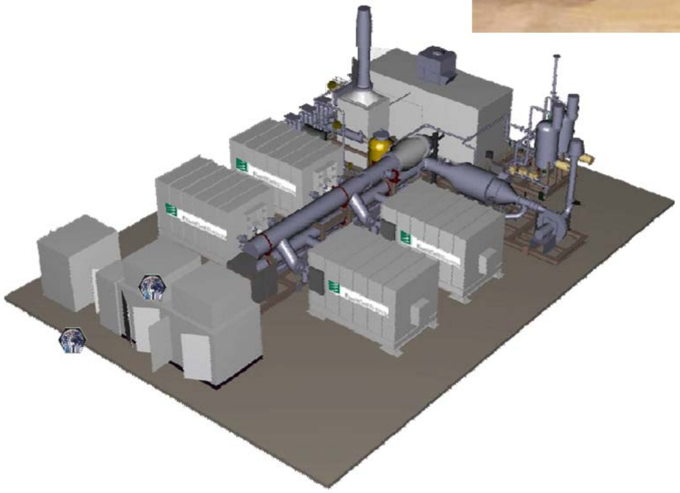


Fuel Cells

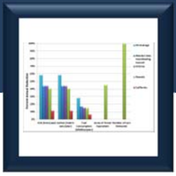


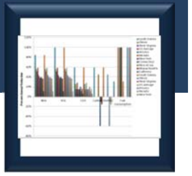




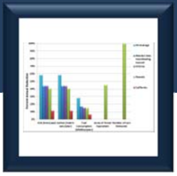
Fuel Cells

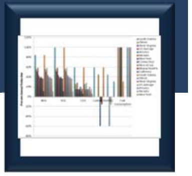




There are four primary fuel cell technologies. These include phosphoric acid fuel cells (PAFC), molten carbonate fuel cells (MCFC), solid oxide fuel cells (SOFC), and proton exchange membrane fuel cells (PEMFC). The technologies are at varying states of development or commercialization. Fuel cell stacks utilize hydrogen and oxygen as the primary reactants. However, depending on the type of fuel processor and reformer used, fuel cells can use a number of fuel sources including gasoline, diesel, LNG, methane, methanol, natural gas, “waste was” and solid carbon

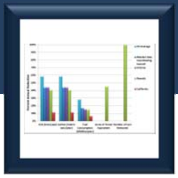
Fuel Cells

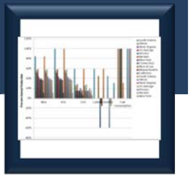




The fuel (hydrogen) enters the fuel cell, and this fuel is mixed with air, which causes the fuel to be oxidized. As the hydrogen enters the fuel cell, it is broken down into protons and electrons. In the case of PEMFC and PAFC, positively charged ions move through the electrolyte across a voltage to produce electric power. The protons and electrons are then recombined with oxygen to make water, and as this water is removed, more protons are pulled through the electrolyte to continue driving the reaction and resulting in further power production. In the case of SOFC, it is not protons that move through the electrolyte, but oxygen radicals. In MCFC, carbon dioxide is required to combine with the oxygen and electrons to form carbonate ions, which are transmitted through the electrolyte.

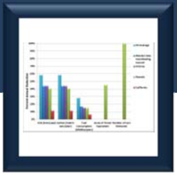
Fuel Cells

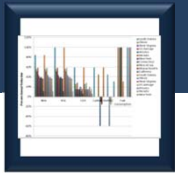




	PAFC	SOFC	MCFC	PEMFC
Commercially Available	Yes	No	Yes	Yes
Size Range	200 kW	1 kW – 250 kW	300 kW – 1.5 MW	3-250 kW
Fuel	Natural gas, landfill gas, digester gas, propane	Natural gas, hydrogen, landfill gas, fuel oil	Natural gas, hydrogen	Natural gas, hydrogen, propane, diesel
Efficiency (HHV)	36%	43%	43%	32%
Heat recovery*	(hot water)	(hot water, steam)	(hot water, steam)	(140 F water)

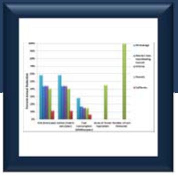
Fuel Cells

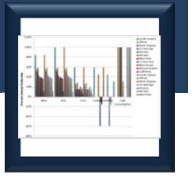




Nominal Capacity (kW)	5	200	300	1,500	250
Fuel Cell Type	PEMFC	PAFC	MCFC	MCFC	SOFC
Equipment ($/kW)	$9,360	$4,500	$4,350	$3,500	$8,550
Heat Recovery	$ 800	$400	$300	$140	$100
Grid Isolation Breakers	$110	$275	$110	$110	$121
Total Equipment	$10,270	$5,175	$4,760	$3,750	$8,771
Materials and Labor	$ 330	$110	$330	$253	$363
Total Process Capital	$10,600	$5,285	$5,090	$4,003	$9,134
Project Construction	$143	$308	$110	$99	$182
Engineering and Fees	$66	$99	$66	$33	$73
Project Contingency	$99	$88	$99	$55	$109
Total Plant Cost (2003 $/kW)	$10,908	$5,780	$5,365	$4,190	$9,497

Fuel Cells

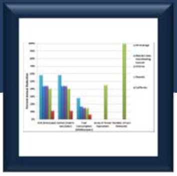


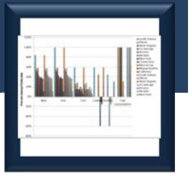


CARB Pre-certified Fuel Cells
200 kW, PAFC
5 kW, PEMFC
300 kW, MCFC
1 MW, MCFC

CARB 2007 Pre-certification		
	DG Units	**CHP**
NOx	**0.5**	**0.7**
CO	**6.0**	**6.0**
VOCs	**1.0**	**1.0**
PM	**≤ 1 grain/100 scf**	**≤ 1 grain/100 scf**

Fuel Cells





- **Premium Power: Current high prices of fuel cell systems may be justified by their higher efficiency, low emissions, reduced vibration and noise, potential for high availability and reliability, good power quality, and compatibility with zoning restrictions.**

- **Remote Power: Remote power applications are generally load-following operations with extended operating hours. As a result, on a long-term basis, emissions and fuel-use efficiency become more significant.**

- **Power Quality: Correct power factors and harmonic characteristics in support of the grid.**

Questions

For more information:

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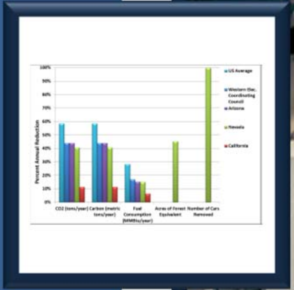
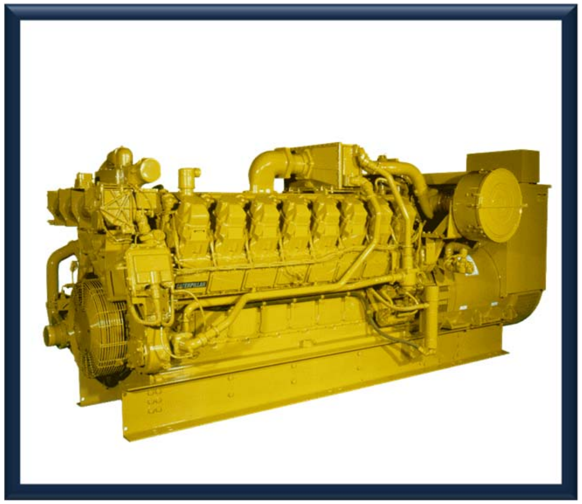
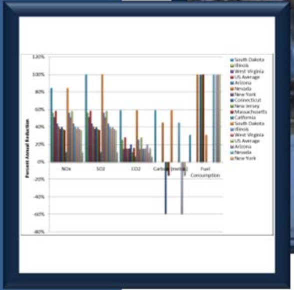




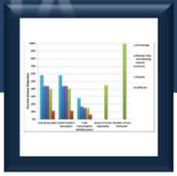


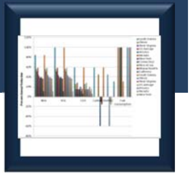
Carbon Calculation Complexity

ASHRAE Handbook: "Combined heat and power (CHP). Simultaneous production of electrical or mechanical energy and useful thermal energy from a single energy stream."

$$NetEmissions = CHP - DisplacedThermal - DisplacedElectricity$$

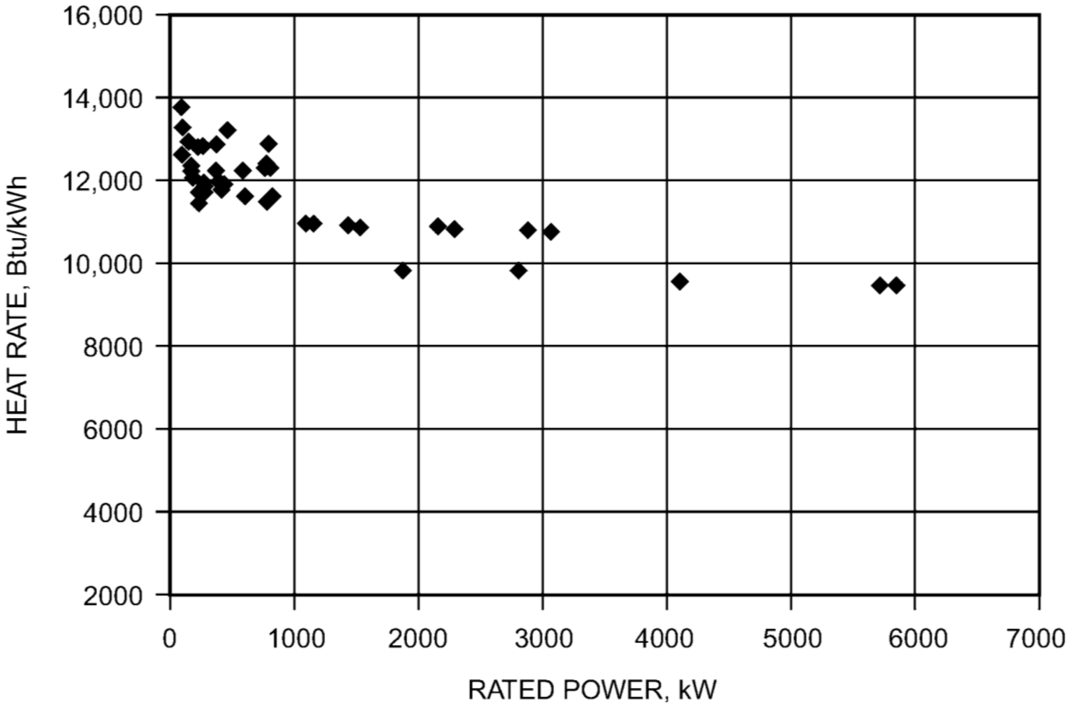
Carbon Calculation Complexity





- Calculating full fuel cycle emissions from fuel input is relatively straightforward.
- Calculating full fuel cycle emissions saved by thermal energy recovered from the CHP generator requires knowledge of the thermal system.
- Displacing electricity from the grid requires an understanding of the power plants whose electricity would be displaced by the electricity generated by the CHP plant (e.g. nuclear, baseload coal, hydro, combined-cycle, cycling coal, oil and gas, peaking plants; etc.).

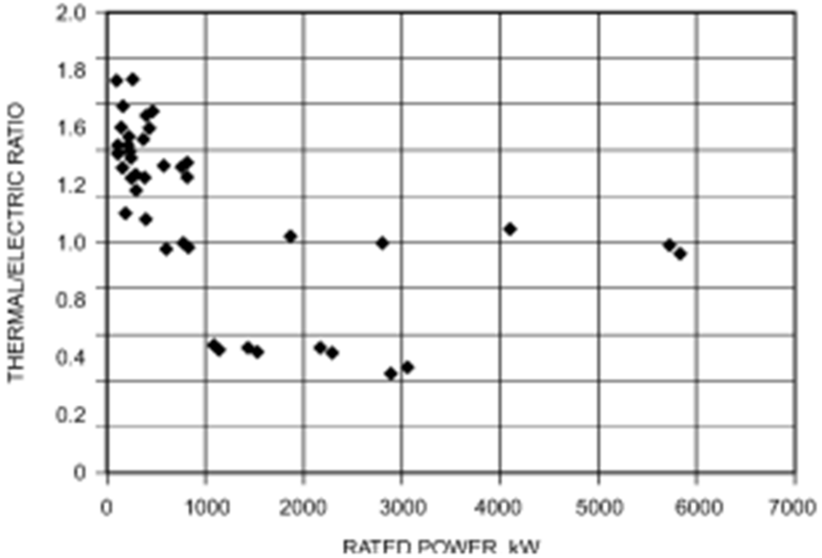
NG Engine Performance



Heat Rate (HHV) of Spark Ignition Engines

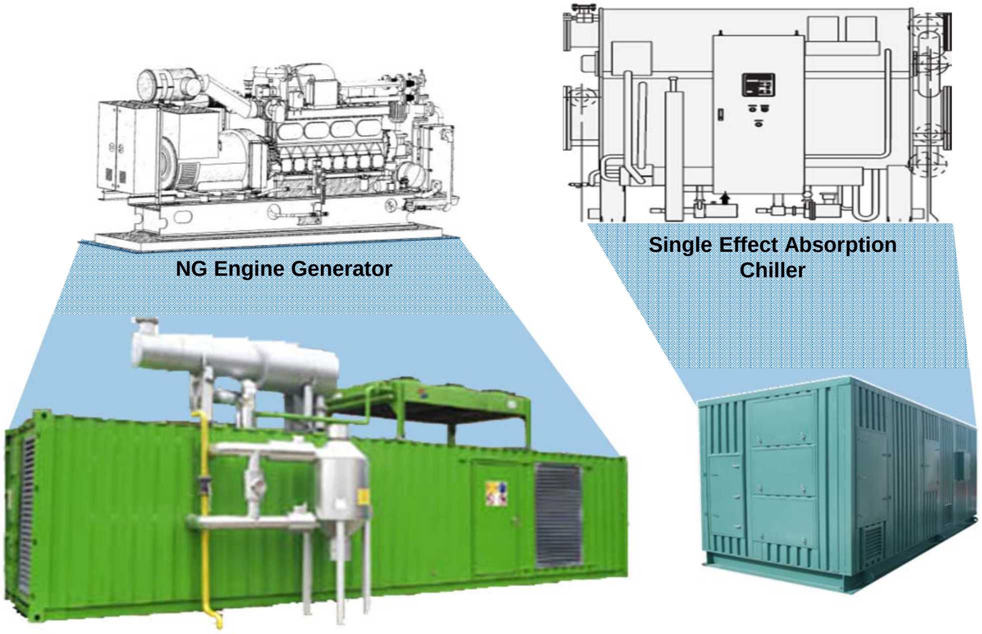
Thermal-to-electric ratio

- **Thermal-to-electric ratio** is a measure of the useful thermal output for the electrical power being generated. For most reciprocating engines, the recoverable thermal energy is that of the exhaust and jacket.



Case Example

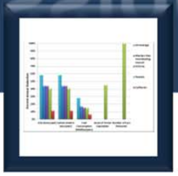
- **A CHP system using a lean-burn reciprocating engine providing 328 kW$_e$ of power and thermal energy to drive an 80 ton (281 kW$_{th}$) single-effect absorption chiller.**

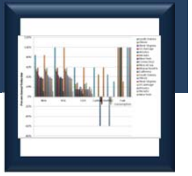


Modeled CHP Performance

	Fuel Used	Power Generated		Refrigeration Produced		Exhaust Recovered	Efficiency	
Month	MMBTU HHV	kWh	MMBTU HHV	Tons	MMBTU	at 0.70 COP MMBTU	Power HHV	HR HHV
January	2,432	232,137	792	56,619	679	971	32.6%	39.9%
February	2,196	209,672	715	51,140	614	877	32.6%	39.9%
March	2,432	232,137	792	56,619	679	971	32.6%	39.9%
April	2,353	224,649	767	54,792	658	939	32.6%	39.9%
May	2,432	232,137	792	56,619	679	971	32.6%	39.9%
June	2,353	224,649	767	54,792	658	939	32.6%	39.9%
July	2,432	232,137	792	56,619	679	971	32.6%	39.9%
August	2,432	232,137	792	56,619	679	971	32.6%	39.9%
September	2,353	224,649	767	54,792	658	939	32.6%	39.9%
October	2,432	232,137	792	56,619	679	971	32.6%	39.9%
November	2,353	224,649	767	54,792	658	939	32.6%	39.9%
December	2,432	232,137	792	56,619	679	971	32.6%	39.9%
Total Annual	28,630	2,733,224	9,326	666,640	8,000	11,428	32.6%	39.9%

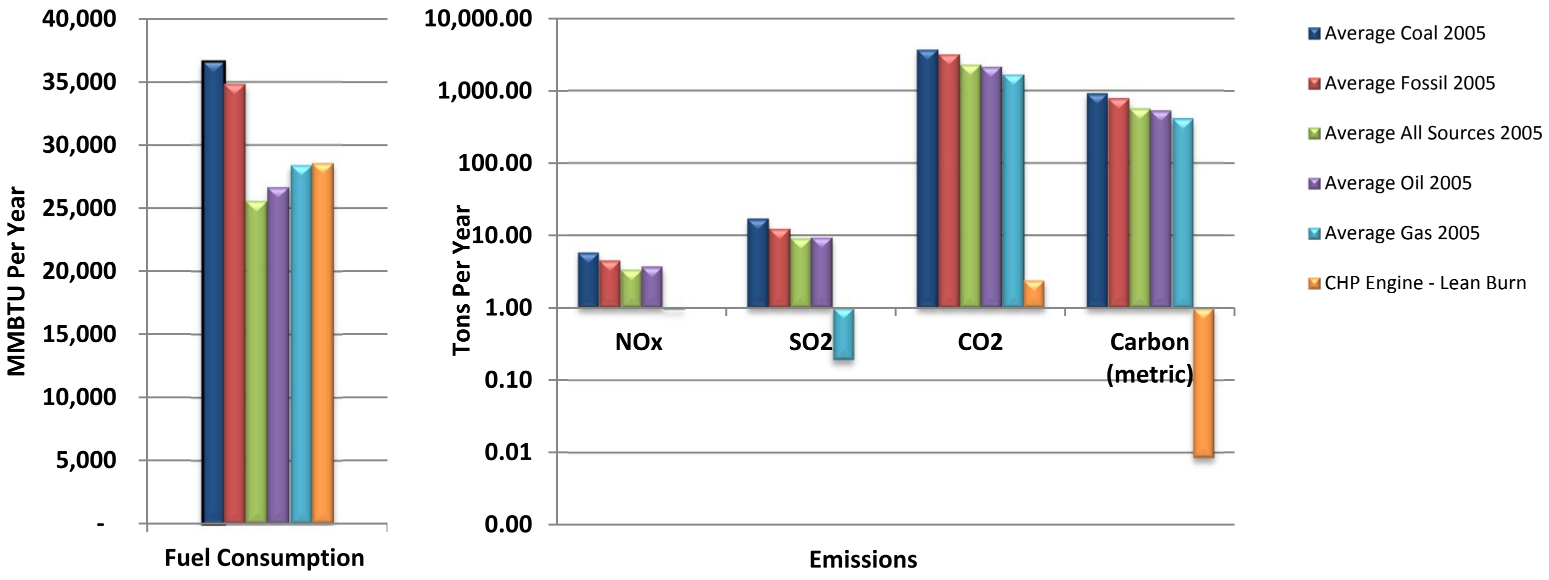
Engine Performance and Emissions





Lean Burn Natural Gas Engine		Annual performance		
BHP	458	3,818,355		
kWe	328	2,733,224		
Heat Rate MMBTUH LHV	3.12	27,799		
Heat Rate MMBTUH HHV	3.47	28,630		
Heat Rate Gigajoule per hour HHV	3.66	30,206		
Emissions		lbs	kg	tons
CO2 emissions lb/MMBTU	117.00	3,349,652	7,369,234	1,675
NOx g/bhp.hr	0.6	5,040	2,291	2.52
CO g/bhp.hr	2.5	15,033	6,833	7.52
NMHC g/bhp.hr	0.43	26	12	0.013
NMNEHC g/bhp.hr	0.25	16	7.2	0.008
PM10 g/bhp.hr	0.01	1	0.3	0.0003

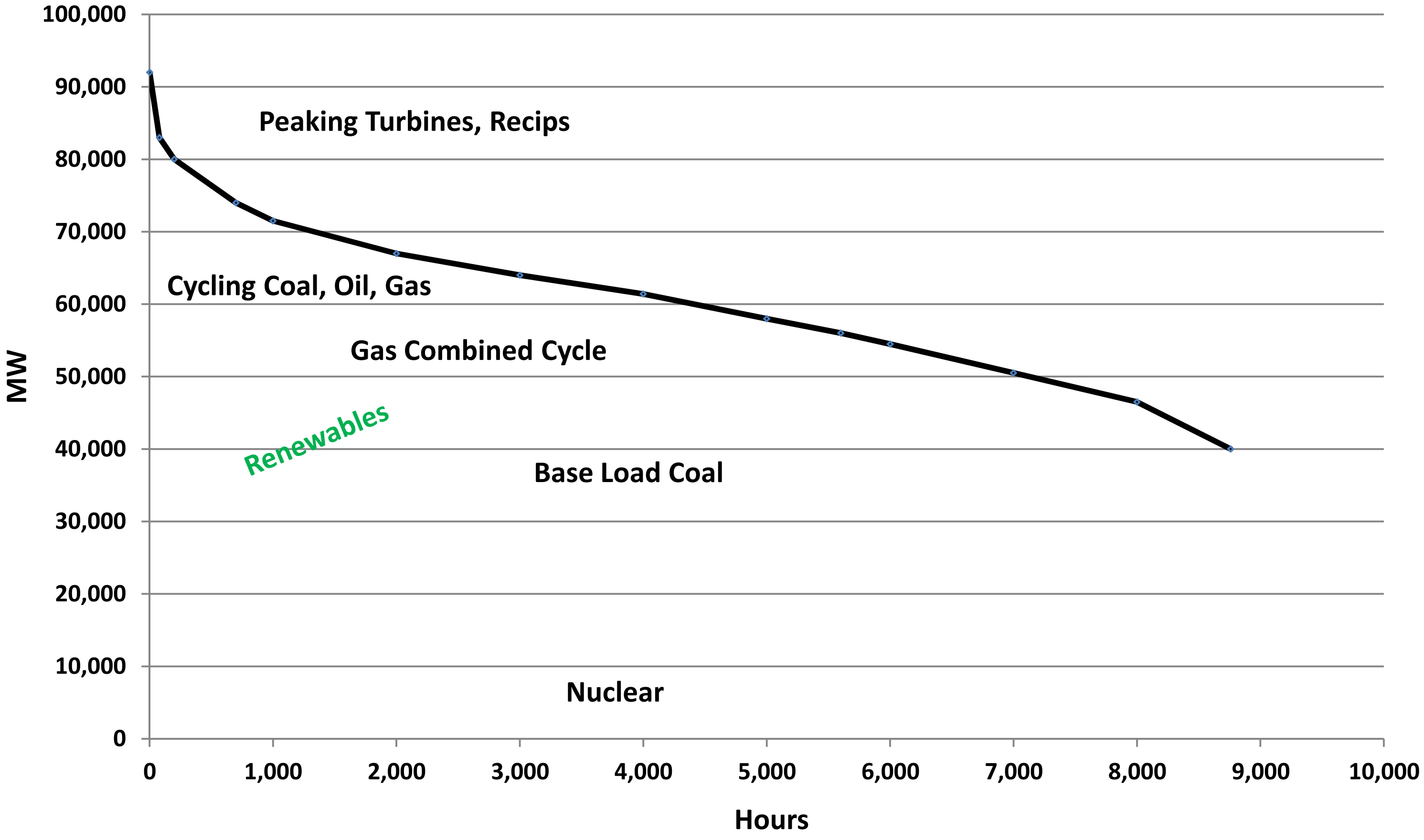
Comparative CHP and Electric Grid Fuel Consumption and Emissions



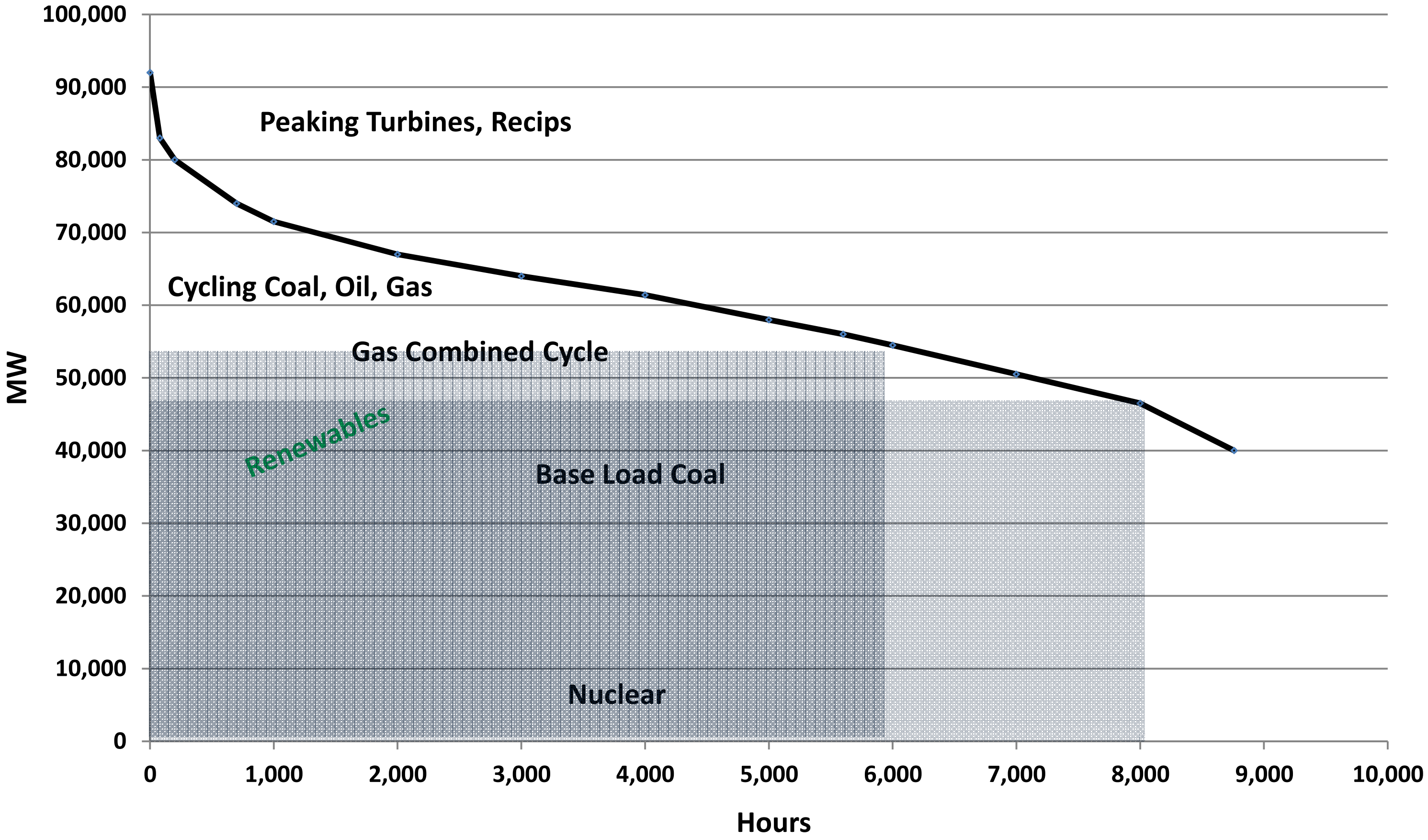
Calculation of the displaced grid energy and CO_2

- A key factor in estimating the energy and CO_2 emissions savings for CHP is determining the nature of the avoided central station generation.
- Should the calculation of the displaced energy and CO_2 emissions be based on the all-generation average of the region the facility is located in, the all-fossil average, the average for some specific fuel type, an estimate of marginal generation, or a projection of future installed generation?
- Currently, there is no consensus on what baseline to use for displaced power calculations, and different entities base their estimates on different comparisons.

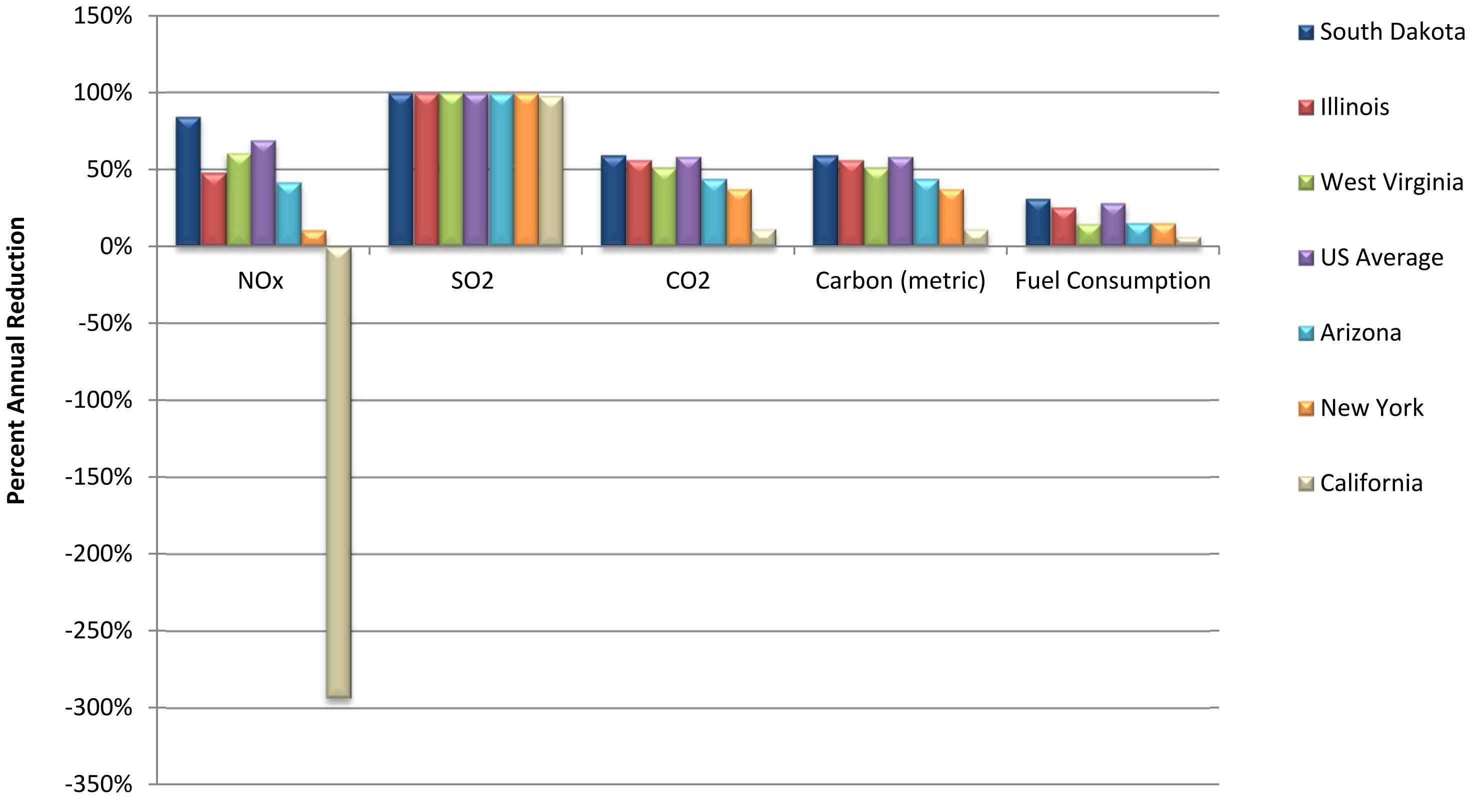
Central Midwest Load Duration Curve and Basic Displaced Mix



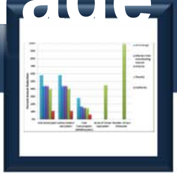
Typical CHP Operating Profiles

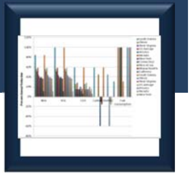


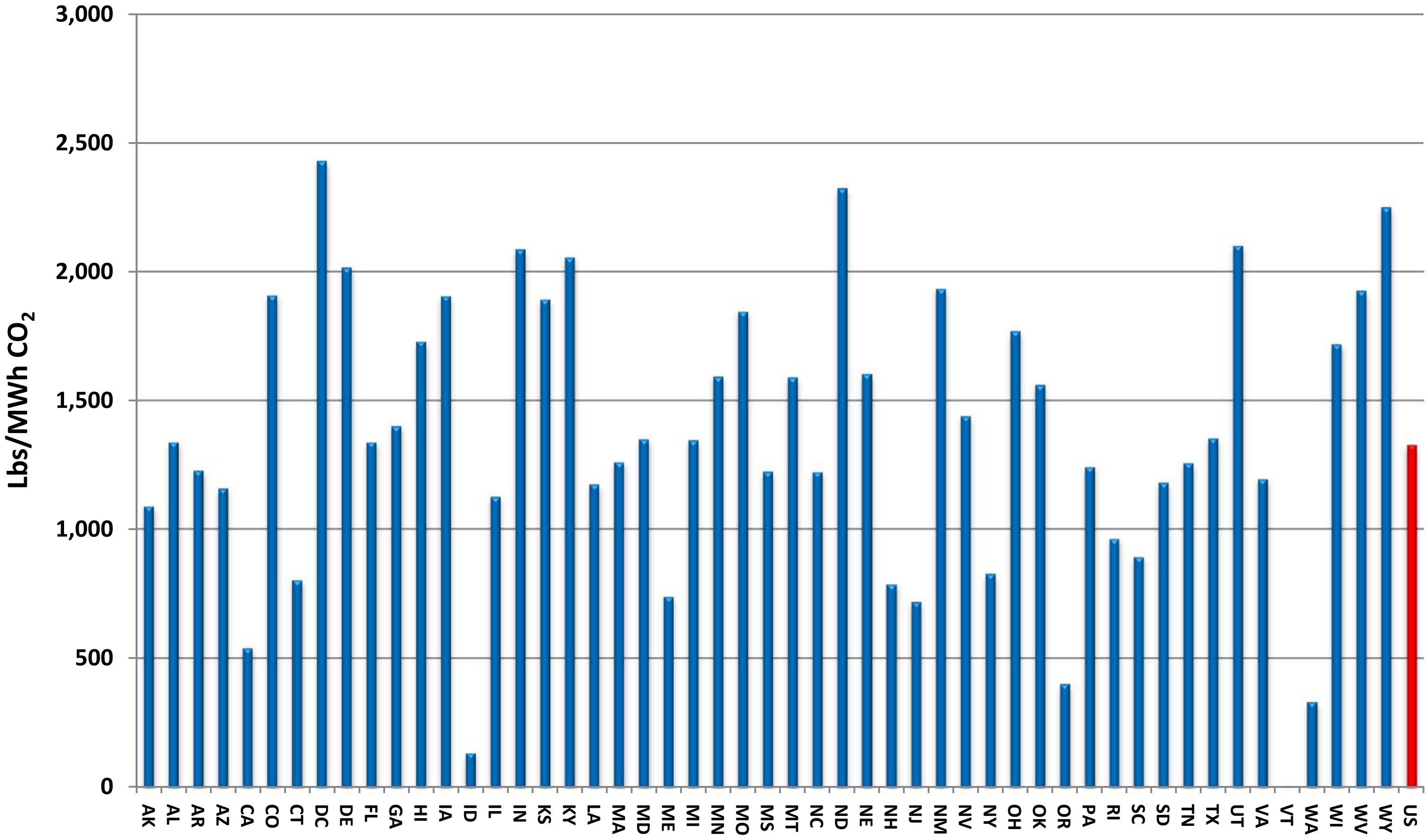
Percent Emissions Reduction Using Case Study CHP System



Lbs/MWh CO_2 Emissions Combustion Generation by State and US Average







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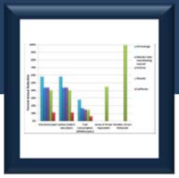
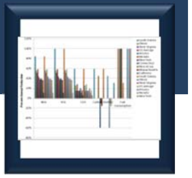
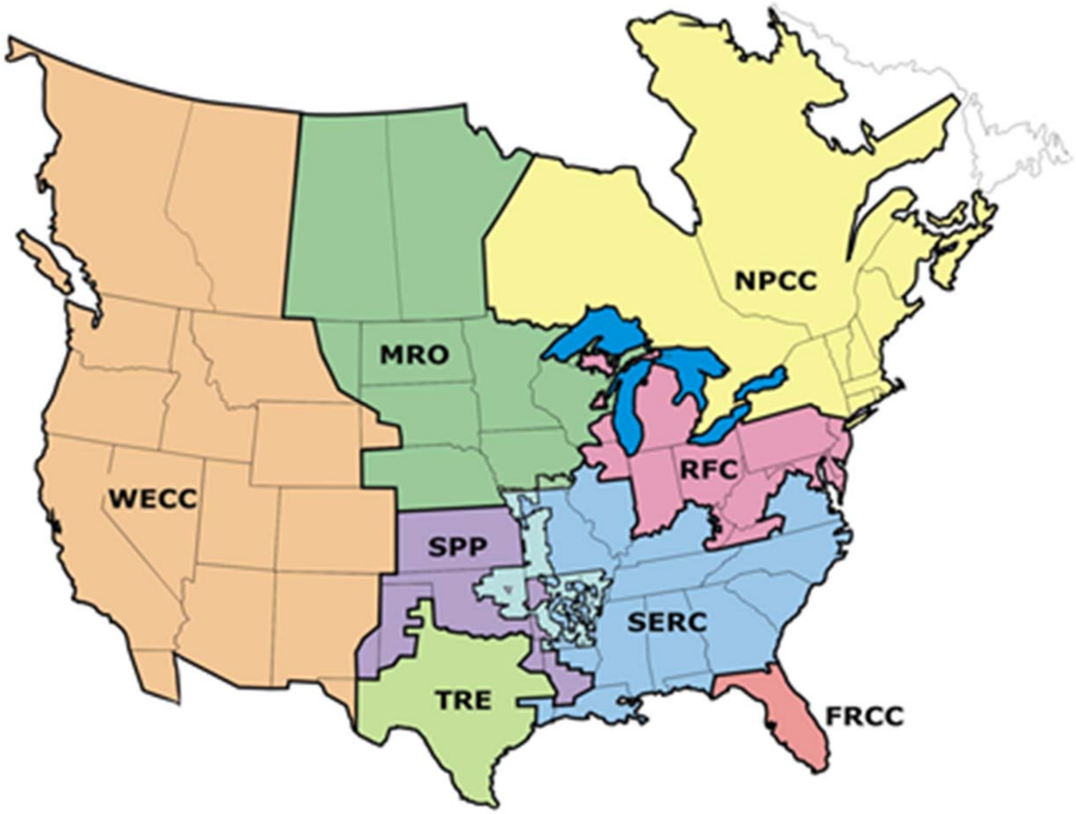
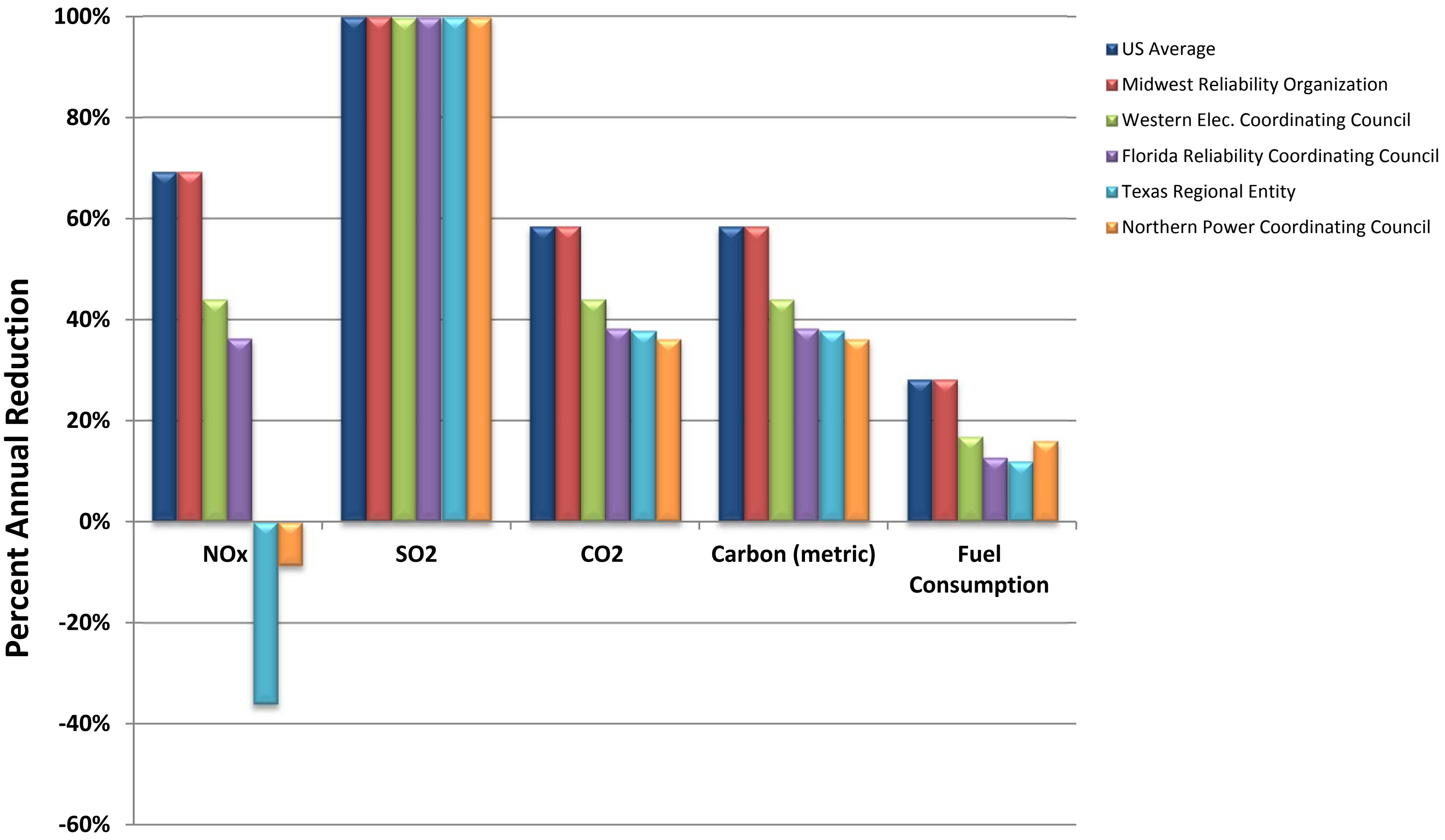
NERC Regions



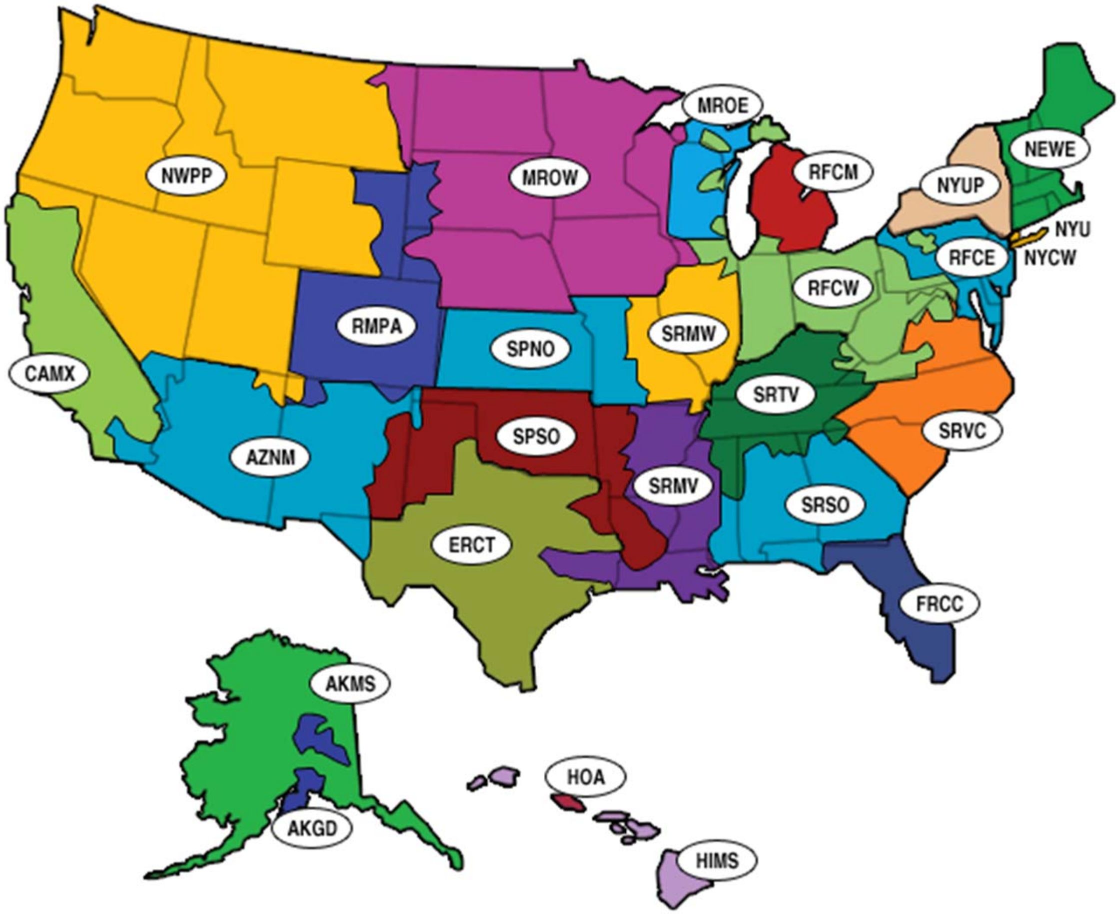




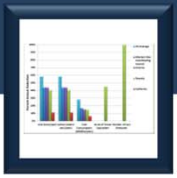
Annual Percent Emissions and Fuel Reduction by NERC Regions

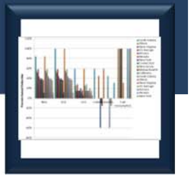


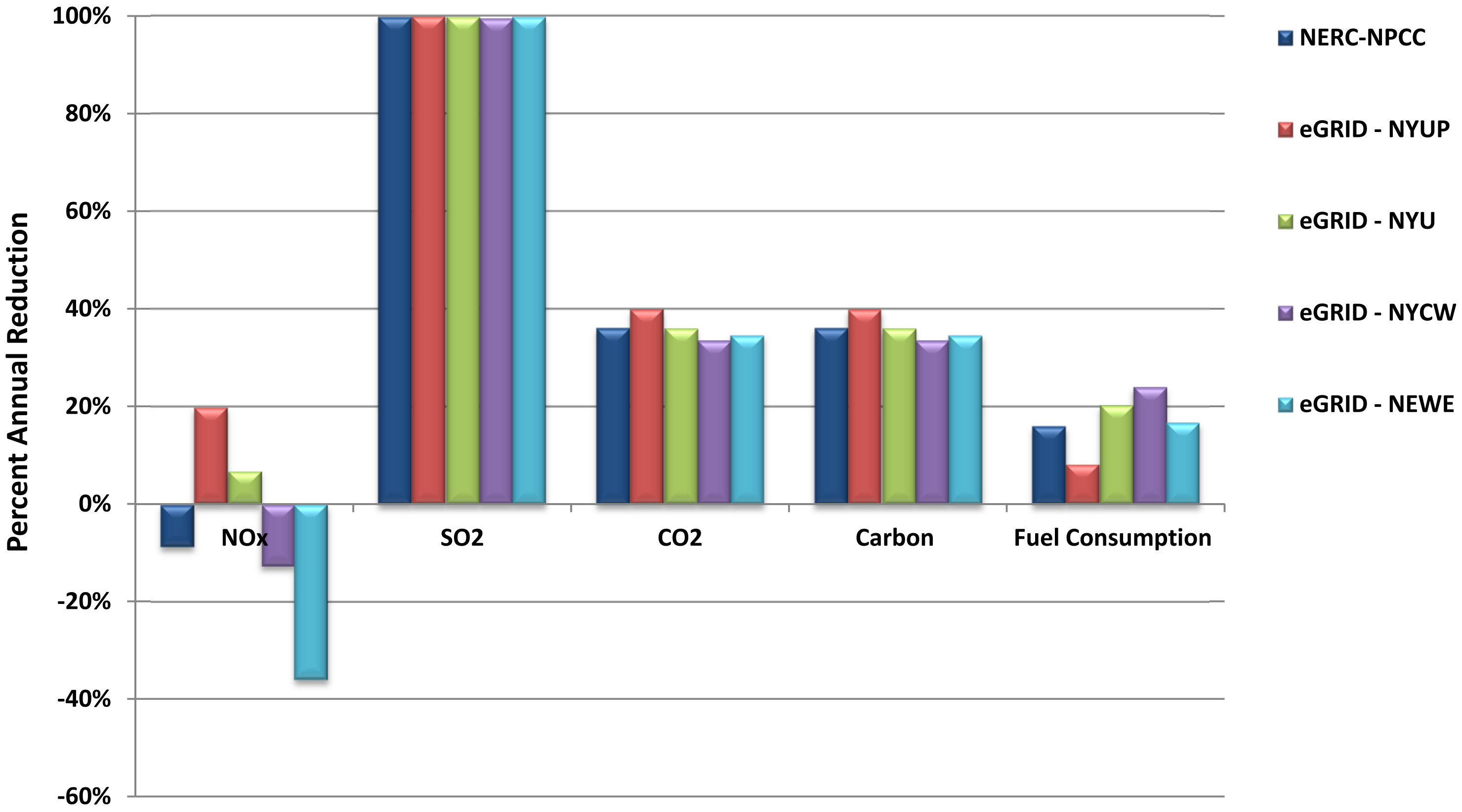
eGRID Subregions



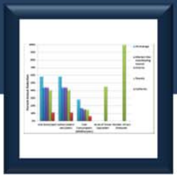
NERC NPCC region and associated eGRID subregions

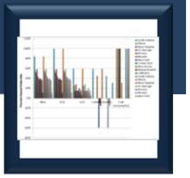


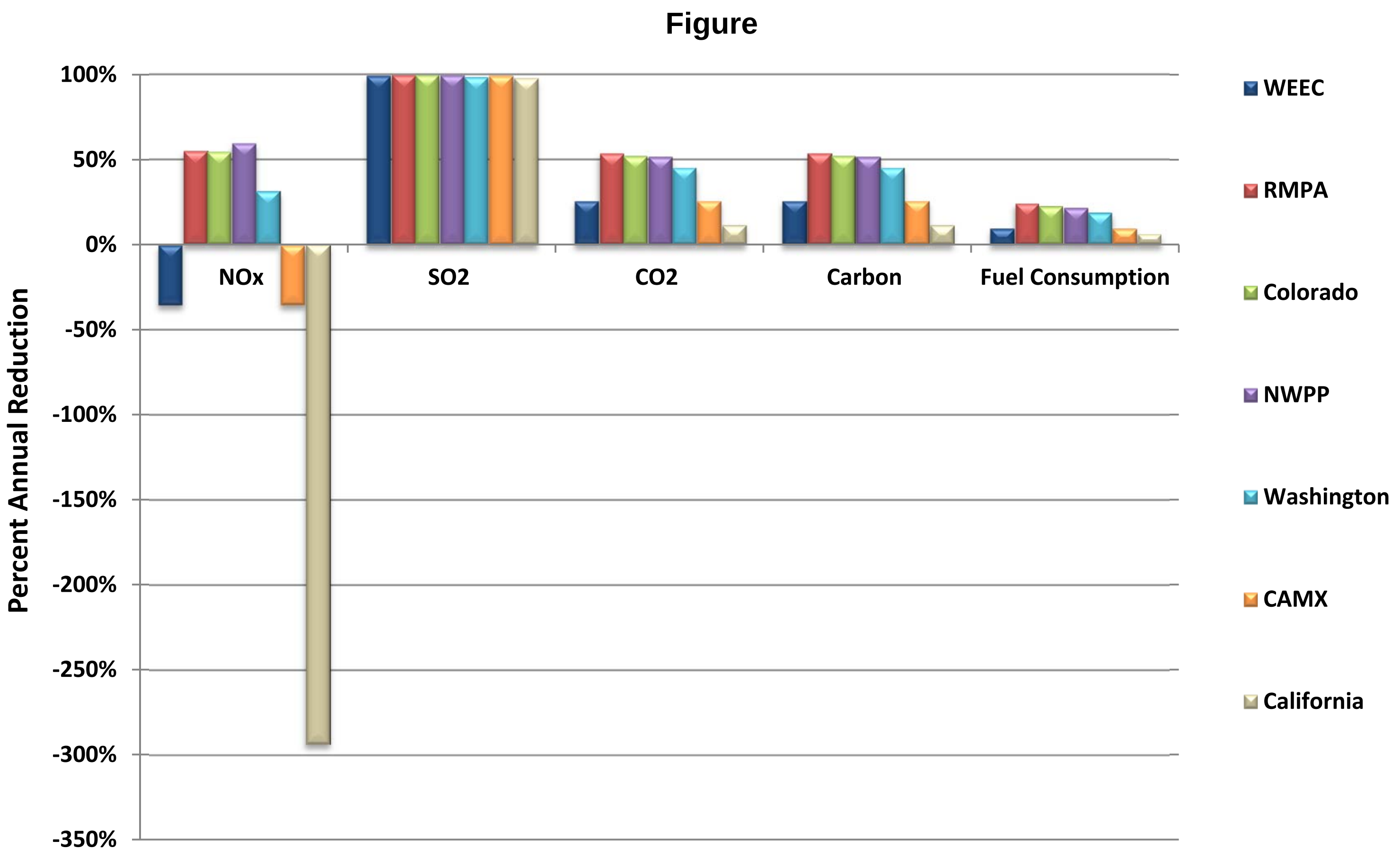




NERC WECC region and associated eGRID Subregions



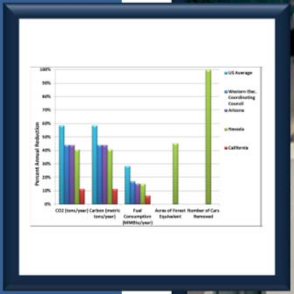


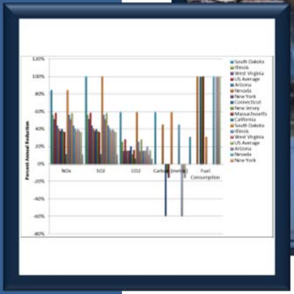


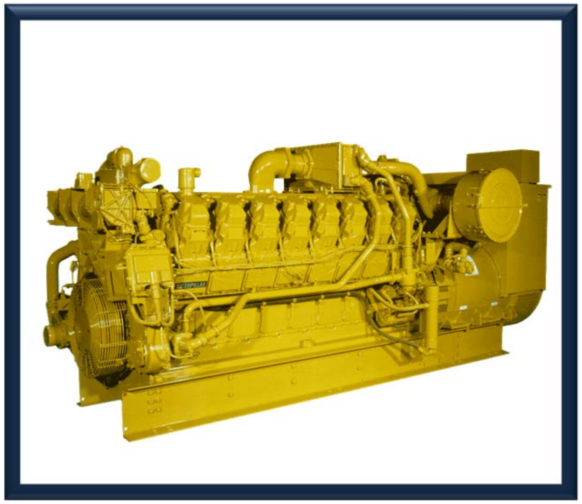
Conclusion

The CHP Emissions Calculator provides a logical method of calculating the NO_x, SO_2, CO_2/Carbon, and fuel (primary energy) impact of operating a CHP system. Using national average figures or even NERC regions is likely to cause significant differences in outcomes from the state level results. This is particularly true with regard to NO_x emissions. However, state figures are not recommended as they do not account for interstate power imports or exports. The eGRID subregions appear to be the most representative and logical means of calculating emissions and fuel savings for CHP plants.

Questions







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