Combined Heat and Power

[Strategy]

Brief Description

The concept of utilizing the excess heat from reciprocating engines has been around since the first automobiles, which used some of this waste heat for the passenger space temperature control. In commercial applications, the concept of “Combined Heat and Power” (CHP) has not had a strong backing until the last few years, when the cost of energy and sustainability concepts became wide spread. Recently, major manufacturers of engine driven generators have started offering complete CHP systems.

Combined Heat and Power (CHP) is fundamentally using the waste heat from a prime mover driving an electrical generator or a mechanical load, to augment thermal needs. This is different than co-generation which uses this waste heat to generate additional electricity.

CHP systems can be either internal combustion or external combustion heat engines used to generate power. A portion of their unused heat is captured and utilized to augment other thermal needs.

Internal combustion engines can be reciprocating engines or combustion turbines. An external combustion system is typically a boiler which produces steam to drive a steam turbine.

Most drivers are 30 to 40% thermally efficient, leaving a considerable amount of waste heat. The specific driver type determines both the amount of excess heat as well as the temperature available. With CHP, typical fuel cycle efficiencies of 30 to 40% can be increased to 60 to 70%.

Applications

An ideal CHP candidate would be a 24/7 operation with relatively flat electrical and thermal loads. Hospitals, prisons and laundry facilities are prime examples. The best suited applications are where electrical utilities are high and gas prices are low. There are a number of reasons where liquid or solid fueled systems simply cannot compete with gaseous fueled systems

To achieve the most benefit from any CHP system, it should be sized based on a large baseline thermal load duration for at least 7000 operating hours per year coupled with a matching electrical load profile which is the easier of the two to identify.

Pittfalls

Common pitfalls include the following:
Inadequate Feasibility Analyses
Inaccurate Site Engineering Data
Incomplete Financial Data
Inexperienced CHP Evaluation/Design Team
Failure to coordinate early on with local Utility Company and Environmental Agencies
Did not implement conservation first, CHP second
Did not consider factors that enhance CHP

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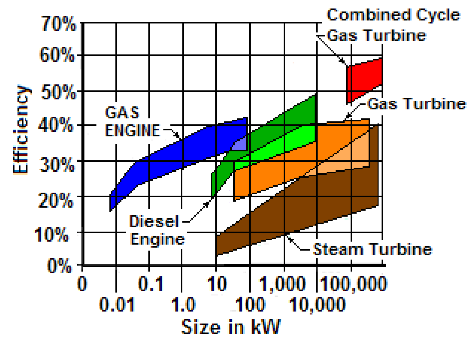
Did not consider installation strategic plan



Design Notes

SIZING THE SYSTEM

- The initial consideration should be determining the thermal loads and establishing a thermal load profile for each month of the year. Next, the temperature of the thermal requirements needs to be determined. The requirement could be hot water or steam. If it is steam, the temperature and pressure required must also be determined.
- The thermal requirements and the electrical requirements are then used to size the unit as well as for the selection of the most suited driver

DRIVER SELECTION

- The selection of the driver will depend upon the type, size and temperature of the thermal loads. Another factor includes the Thermal/Power Ratio (T/P) in making a selection. For 1-10 T/P consider gas turbines. For 0.5-1.5 T/P consider reciprocating engines.
- There are a number of factors which dictate the type of driver most suited for a specific application. While internal combustion reciprocating engines provide good fuel economy and are well suited for varying electrical loads and part load applications, they do have drawbacks. Turbocharged units must be loaded to 40% or more to provide adequate energy to the turbocharger. They are also limited to extracting low temperature heat from the jacket water and oil cooling water systems. (Below 210°F). Exhaust heat recovery is limited to cooling the flue gas to no less than 350°F to prevent acid formation. (Exhaust heat accounts for approximately 33% of the excess heat)
- Attempts to ebulliently cool reciprocating engines have led to cracked heads, cracked blocks and severe valve train maintenance. This should be avoided!
- Internal combustion turbines suffer high maintenance costs when applied in varying load or start /stop operation. They are best suited for a constant load and extended operational periods. The recoverable waste heat is from the exhaust and typically can provide substantial temperatures required for steam production. The negative side of turbines is high fuel consumption and de-rates for altitude and temperatures.

Consider long term service contract for gas turbines that include 40,000 hour major overhaul.

OTHER CONSIDERATIONS

- Selecting the proper system for a specific application should also include minimal maintenance costs and high availability.
- The correct type of system should be sized not to exceed the thermal needs. While there are multiple fuels available, the preferred fuel is natural gas. The main advantages are elimination of storage and subsequent refilling. Another advantage is gas is billed as it is consumed not in advance.
- The power demand and the thermal requirements should occur simultaneously and not alter more than 10%. They should remain simultaneous at least 51% of the time with 100% being preferred.
- Since the electric power is generated first and excess thermal energy is recovered for use, the chief controls should be on the electrical load side.
- Depending on climate, thermal needs may be much lower during the summer. Using thermal energy to provide cooling using absorption chillers should be coordinated with the DPW. Operation and maintenance of absorption chillers requires experienced personnel. Finding thermal loads during summer months can be a huge challenge and should be addressed early on as required to make the project cost effective.
- Gas Turbines typically require 250 to 700 psig. Available natural gas pressure is usually around 50 psig so a compressor will usually be required.

CHP RULES OF THUMB

Rule 1. Do not cool the exhaust gases below 350°F due to acid formation.

- The recoverable heat can be calculated using the difference in enthalpy of exhaust gas at actual temperature and at 350oF.

Rule 2. All internal combustion engines require approximately 7 pounds of air per horsepower regardless of type and fuel.

Rule 3. For reciprocating units, the amount of inlet air is approximately:

- For four cycle engines, Intake CFM_i = CID x RPM / 3456 x E_v
- For two cycle engines, CFM_i = CID x RPM/1728 x E_v
- Where: CID is the cubic inch displacement. RPM is the revolutions per minute. E_v is the volumetric efficiency.

Rule 4. For reciprocating units, the exhaust flow in CFM is approximately:

- CFM_e =T_e(°R)/560 x CFM_i. Note: 560 is the rounded off conversion of °F to °R, °F + (459.6667) = °R
- Where: T_e is the anticipated exhaust temperature (measured or from below)
- Exhaust Temperatures:

Diesel naturally aspirated four cycle	1,000°F
Diesel Turbocharged four cycle	900°F
All natural gas units	1,200°F

- Air density ρ = (14.696 x 144)/(53.35 x 459.667) or 0.0763312 lbm/ft^3 @STP
- STP is standard temperature pressure 60°F and 14.696 psia.
- The average specific heat for exhaust gases is 0.2806 BTU/lbm-°F.

Rule 5. For reciprocating units, the pounds of exhaust per hour is approximately:

- Lbm-hr. = 4.57987 x CFM_e

Rule 6. The available heat which can safely be recovered is:

- Q = 0.2806 x (T_e-350) x lbm-hr.
- Where Q is in BTU and T_e is °F

Rule 7. For reciprocating units, the lubricating oil should run 15°F hotter than the jacket water.
This is to assure normal running clearances. Over cooling of the lube oil can cause pistons and rings to seize.
Rule 8. Maintain a 15 to 20 degree temperature rise across the engine jacket water system in reciprocating engines. Oil temperatures must remain about 10 to 15 degrees hotter than the water temperature to prevent seizures. High temperature differentials can also lead to seizures.

Some issues with reciprocating engine heat recovery include about 1/3 of the input heat is in the jacket water and oil cooling loop. This has severe limits as to how high a temperature can be extracted. The exhaust system also contains about 1/3 of the input heat and is limited to cooling the exhaust gases to about 350°F.

Gas Turbine performance factors include inlet pressure drop, outlet pressure drop, elevation, water injection and ambient temperature. Gas turbines provide high temperature waste heat in the range of 700 to 1000 deg F. The heat rate (Btu/kWh) ranges from 9000 to 20,000 (LHV).

Related Technologies

Self-generation is a very close technology and has been utilized for several decades. Likewise, waste heat recovery has also been in practice for decades. The uniqueness of CHP is the combining of these two technologies. Examples of similar forms of heat recovery are turbochargers and recuperated cycle combustion turbines.

References

1. (CHP) Technology Potential in the United States – Department of Energy. https://www.energy.gov/.../CHP%20Technical20%Potential20%Study%203-31-2016
2. Evaluation of Combined Heat and Power Technologies for… https://www.cwwga.org/.../121_evaluationCHPTechnologiespreliminary[1].pdf
3. Distributed Generation and Combined Heat & Power System…-EIA https://www.eia.gov/analysis/studies/buildings/distrigen/pdf/dg_chp.pdf
4. Catalog of CHP Technologies Combined Heat and Power (CHP… https://www.epa.goc.chp/catalog-chp-technologies

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[Energy and Environment]

Energy Savings

While employing a CHP system does not reduce the energy requirements of a facility, it does provide a more efficient method of providing electrical and thermal energy at lower costs. The amount of savings realized will depend on the type system selected, the selection of either electrical or thermal load as the control, local utility rates and the cost of compliance with local, state and federal regulations. The installed cost and the continual maintenance will also depend on local labor rates.

Social Benefits

The associated social benefits are derived from lowered purchase of thermal energy. In turn, this reduces CO_2 and water consumption. Each individual utility provider has an associated water use and emission release per generated kWh. The thermal energy provided will reduce CO_2 emissions, and perhaps water depending on the existing utility for generating the thermal load.

Energy Impact

While CHP does not impact the onsite energy consumed, it does provide the Heat and Power at a reduced cost and reduced transportation losses. Source energy for electricity is 3.14 times the site demand and natural gas for heat is 1.05 times the site consumption. Utilization of waste heat recovery and power generation on site reduces the implied total energy impact. The CHP higher potential efficiencies offer the generation of power with less energy use. Typical overall efficiency for separate power and heat generation average about 45 to 50%. Reciprocating engine CHP systems range from about 70 to 85%, combustion turbine systems from 50 to 70%.

Environmental Impact

Each location is supplied power from a combination of different generation sources. These may include coal, oil of gas fired plants, hydropower, wind power etc. In turn, each specific location will have an associated CO2 output and an associated water consumption associated with the generation of power. Therefore, each individual CHP application must be evaluated against the impact of that locations purchased power and generated heat.
Newer lean urn technologies may offer reduced total emissions as well.

Guideline Principals[1]

While the Energy Independence and Security Act (EISA) 2007 and Energy Policy Act (EPAct) 2005 address energy conservation and funding options, it does not specifically address requirements for CHP systems. Executive orders 13424 and 13514 were revoked by EO 13693 on March 29 2015. The later EO addresses energy reduction techniques to include CHP.

Associated LEED Credits

Methodology for Modeling Combined Heat & Power for EAp2/c1 in LEED 2009
http://www.usgbc.org/resources/methodology-modeling-combined-heat-amppower-eap2c1-leed-2009

Properly sized CHP systems can result in high efficiency and significant overall energy reduction. The total contribution from the CHP system must first be added to any other renewable energy sources for the facility. It is the total reduction that dictates the actual LEED points achieved.

Combined Heat and Power

[Energy and Environment]

☒ Energy and Atmosphere (LEED 2009[2] BD+C)

- EAp2 Minimum Energy Performance (Required)
- EAc1 Optimize Energy Performance (1-19 points)

Level	Points
Certified	40-49
Silver	50-59
Gold	60-79
Platinum	80-110

Percent Improvement Over Baseline	Points
12%	1
14%	2
16%	3
26%	8
34%	12
48%	19

☒ Energy and Atmosphere (LEED v4[3] BD+C)

- EAp2 Minimum Energy Performance (Required)
- EAc2 Optimize Energy Performance (1-18 points NC)

References

1. Guiding Principles for Federal Leadership in High Performance and Sustainable Buildings www.wbdg.org/pdfs/hpsb_guidance.pdf
2. USGBC LEED Reference Guide for Green Building Design and Construction, 2009 Edition
3. USGBC LEED Reference Guide for Green Building Design and Construction, v4

Combined Heat and Power

[Product and Environment]

Product images

Small gas turbine packaged CHP

Reciprocating engine CHP system

Payback

Project payback is influenced by numerous factors, including local utility costs, the percent load on the generator, the percent utilization of the recovered heat, the required temperature of the working fluid, local labor costs etc. Each individual installation will require a complete Life Cycle Cost Analysis to determine the potential savings and the payback time required. With a properly sized system and appropriate heat needs typical paybacks can range in the 3 to 5 year bracket.

Vendors

NATURAL GAS ENGINES

In the US, electricity is generated at 60 Hz. Only engines that operate at a multiple of this do not require a gear box and subsequent horsepower losses. All considered engines should be industrial quality with a minimum life between overhauls of over 40,000 hours.

*Designates U.S. 60 Hz (multiple) engine manufacturers

- Caterpillar, (55 Kw – 3.4 Mw)*
- Cooper Cameron Corp, (350 Kw – 6.5 Mw)*
- Rolls-Royce Energy Systems, (3 Mw – 51 Mw), 50Hz compatible requires gearbox
- Wartsila NSD, (1 Mw – 16 Mw), 50Hz compatible requires gearbox

- Waukesha Engine Div., (6.5 kW – 3.3 Mw)*

TURBINES

- Solar Turbines
- Siemens
- GE
- Westinghouse

FUEL CELLS

- Allied Signal, (Solid Oxide Fuel Cells)
- Analytic Power Corporation, (Ammonia Cracker Hydrogen Source Fuel Cell - 2 Kw)
- Avista Corp., (2 Kw Polymer Electrolyte Membrane Fuel Cell)
- Ballard Power Systems, (Proton Exchange Membrane (PEM) Fuel Cell – 250 Kw)
- Energy Partners, (PEM up to 10 Kw)
- Energy Research Corporation, (Direct Fuel Cell – 2.5 Mw)
- H Power Corporation, (Proton Exchange Membrane Fuel Cells – up to 1 Kw)
- ONSI Corporation, (PC25™ Fuel Cell – 200 Kw)
- Plug Power, LLC, (Proton Exchange Membrane (PEM) Fuel Cell 7 Kw)

MICRO TURBINES

Micro turbines have very high fuel consumptions and suffer greatly with increased ambient temperatures and altitudes. Turbo machinery is rated at ISO conditions i.e. 59 ° F, 14.696 psia (Sea level) and 50% relative humidity.

- Capstone Turbine Corporation, (28 Kw)
- Honeywell Power Systems, (75 kW)
- Elliott/Bowman, (45 Kw and 65 Kw)
- Northern Research, (30 – 250 Kw)

Cost Range

Installation cost ranges depend directly on the type of equipment selected for the application. Larger systems are generally less expensive per unit output. Some basic guides for overall installed costs are:

- Reciprocating Engine (65 kW to 15 MW) — $1,433 - $2,900 per kW installed
- Micro Turbine (30 kW – 2 MW) — $2,500 - $4,300 per kW installed
- Gas Turbine (1 MW – 50 MW) — $1,250 - $3,300 per kW installed
- Fuel Cell (200 kW – 2 MW) — $4,600 - $10,000 per kW installed

Product types

1. INTERNAL COMBUSTION RECIPROCATING ENGINES

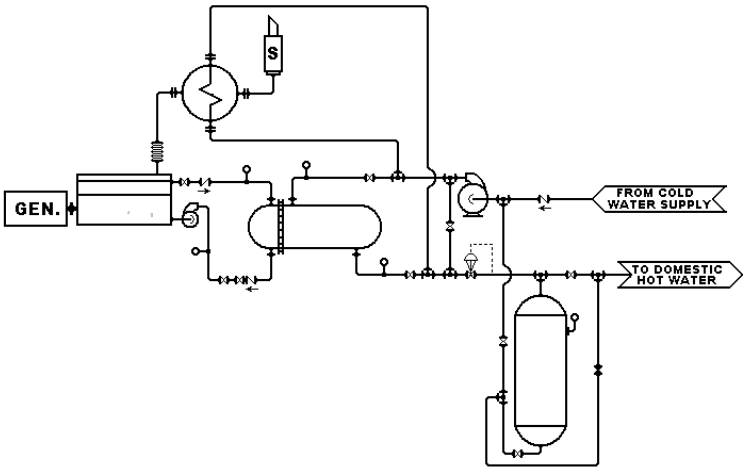
Maintenance Schedule:

- 25 years: 219,000 hrs.
- Annual preventive maintenance time: 175.2 hrs.
- Total preventive maintenance: 4,380 hrs.
- Time required for major overhaul: 336 hrs.
- Time required for minor overhaul (Heads and valves): 120 hrs.
- Time between minor: 20,000 hrs.
- Time between major: 50,000 hrs.
- Total minor over haul time: 960 hrs.
- Total Major over haul time: 672 hrs.

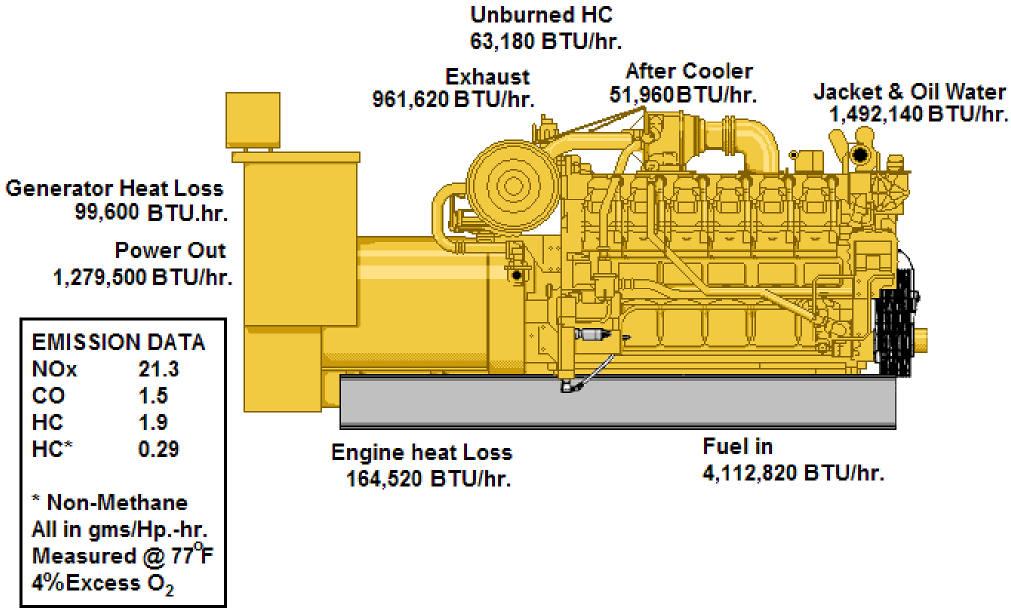
- Total available hrs. 211,834 hrs.
- Total Availability (%) 96.73%

This is advisable to utilize 95% availability to cover unscheduled outages.
(Source R.B. McMillan, PE, CEM)

- RULE OF THUMB: Use $0.015 per generated kWh for maintenance expenditures.



Heat Balance



The anticipated available heat from an internal combustion reciprocating engine can be calculated as follows:

A. Exhaust temperature:

- Diesel Naturally aspirated 4-cycle 1,000 °F
- Diesel Turbocharged 4-cycle 900 °F
- Natural Gas (all) 4-cycle 1,200 °F

B. Exhaust temperature factor:

- T_f= (Exhaust Temperature +459.667)/519.667

C. Inlet air flow

- CFM_i = 10.5*Hp or CFM_i = 7.83*kWe
- The average specific heat for exhaust gases is approximately 0.2806 BTU/lbm/ °F.
- CFM to lbm-hr.
- Air density: ρ =(14.696 * 144)(1)/(53.35*459.667) or 0.0763312 lbm/ft^3
- lbm-hr. = 4.57987*CFM

D. The available heat which can be safely recovered is:

- Q = 0.2806*(E_t -350)*lbm-hr.
- Where: E_t is the exhaust temperature in °F.

E. Typical Gas engine de-rate schedule.

- 3% per 1,000 feet over 2,500
- 1.9% per 10 °F over 85 °F

2. EXTERNAL COMBUSTION SYSTEMS

External combustion systems such as steam boilers can operate in varying load conditions, shifting the steam loads between heating and power generation.

Boilers essentially take the heat of combustion and direct it over tube passes containing water which is in turn heated. The output can be hot water or steam. The steam can be saturated or super-heated depending on the boiler design and intended use.

Although fuel types affect the output to some extent, the amount of excess air and the control of the burners as a function of demand on the system play a greater role in the efficiency of the operation

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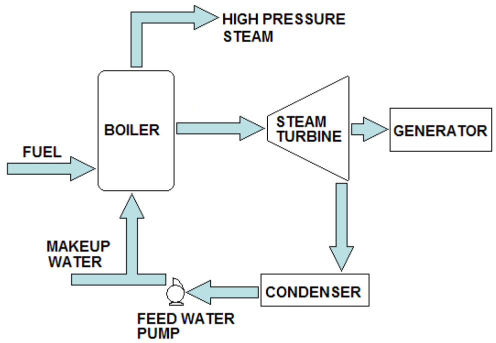
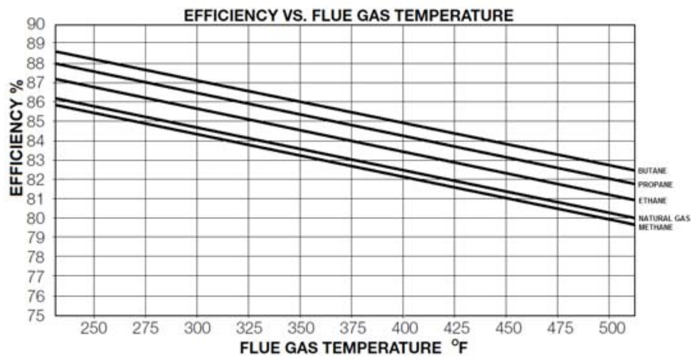
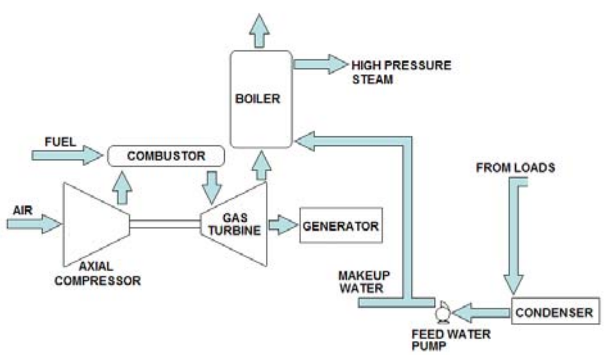


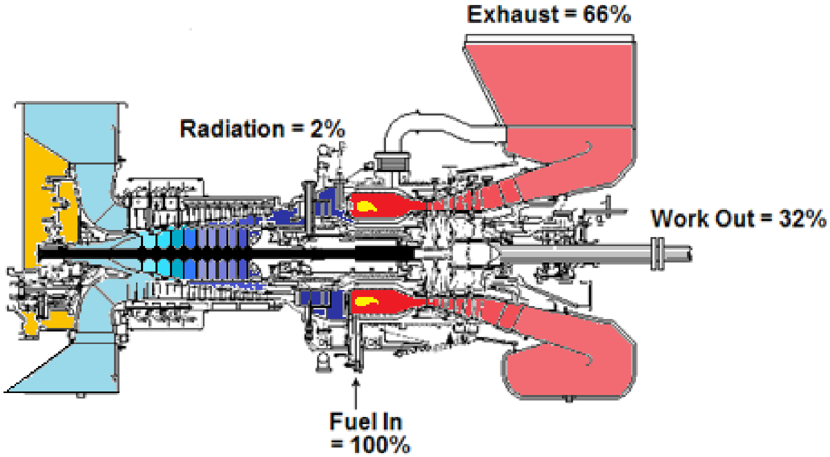


NATURAL GAS CONSUMPTION IN THERMS PER HOUR																		
		EFFICIENCY																
		60	62.5	65	67.5	70	72.5	75	76	77	78	79	80	81	82	83	84	85
BOILER HORSEPOWER	100	55.8	53.6	51.5	49.6	47.9	46.2	44.7	44.1	43.5	43.0	42.4	41.9	41.4	40.9	40.4	39.9	39.4
	125	69.8	67.0	64.4	62.0	59.8	57.7	55.8	55.1	54.4	53.7	53.0	52.3	51.7	51.1	50.4	49.8	49.3
	150	83.7	80.4	77.3	74.4	71.8	69.3	67.0	66.1	65.2	64.4	63.6	62.8	62.0	61.3	60.5	59.8	59.1
	200	111.6	107.2	102.0	99.2	95.7	92.4	89.3	88.1	87.0	85.9	84.8	83.7	82.7	81.8	80.7	79.7	78.8
	250	139.5	133.9	128.8	124.0	119.6	115.5	111.6	110.1	108.7	107.3	106.0	104.6	103.4	102.1	100.9	99.7	98.5
	300	167.4	160.7	154.5	148.8	143.5	138.6	133.9	132.2	130.5	128.8	127.2	125.5	124.0	122.5	121.0	119.6	118.2
	350	195.3	187.5	180.3	173.6	167.4	161.6	156.2	154.2	152.2	150.2	148.3	146.5	144.7	142.9	141.2	139.5	137.9
	400	223.2	214.3	206.0	194.8	191.3	184.7	178.6	176.2	173.9	171.7	169.5	167.5	165.3	163.3	161.4	159.4	157.6
	500	279.0	267.8	257.5	248.0	239.1	230.9	223.2	220.3	217.4	214.6	211.9	209.3	206.7	204.2	201.7	199.3	197.0
	600	334.8	321.4	309.0	297.6	287.0	277.1	267.8	264.3	260.9	257.5	254.3	251.0	248.0	245.0	242.0	239.1	263.3
	700	390.6	374.9	360.5	347.2	334.8	323.2	312.5	308.3	304.3	300.4	296.6	293.0	289.3	285.8	282.3	279.0	275.7
	800	446.4	428.5	412.0	396.8	382.6	369.4	357.1	352.4	347.8	343.4	339.0	335.0	330.6	326.6	322.7	318.8	315.1



3. TURBINES

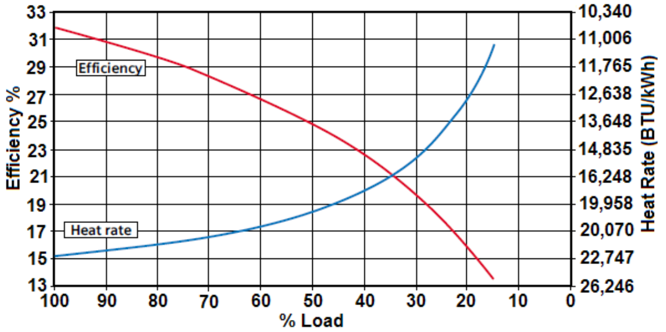
Heat Balance

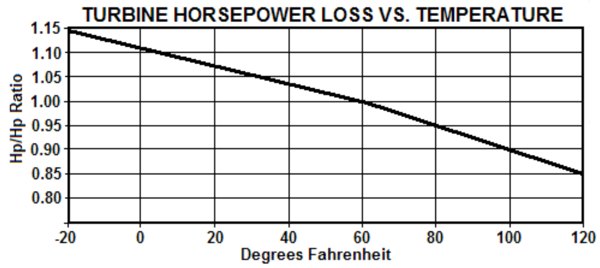


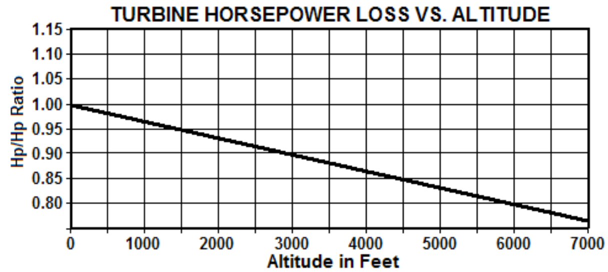
Turbines are generally small for their given output. They also have tremendous exhaust volumes due to the necessity of cooling combustion gases prior to entering the turbine blades. This excess air flow provides the opportunity for good heat recovery.

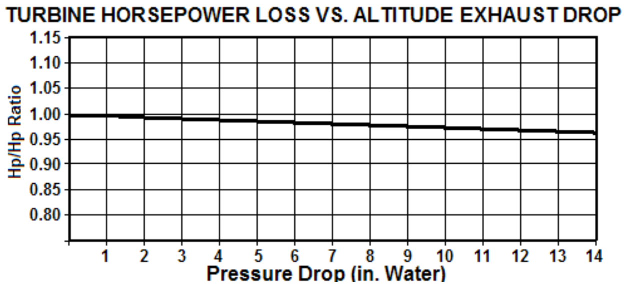
Turbines are best suited in applications where they are well loaded, the load remains relatively constant and they are not turned on and off. Thermal cycling of turbines cause major loss in expected life times and provide for potential failures.

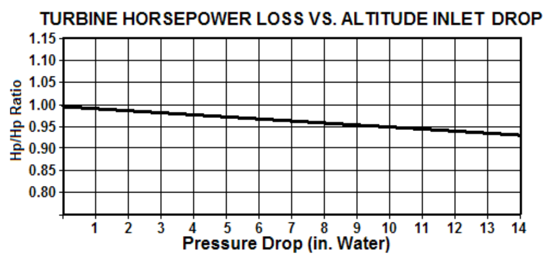
On the negative side, turbines exhibit higher heat rates than reciprocating engines. In general, turbine maintenance should be left to contract. Many companies now offer direct exchange programs for turbine components.











EXAMPLE
If a 500 kW turbine were applied @ 900 feet and ambient temperature of 100 degrees, with 8 inches of water inlet loss and 12 inches of water exhaust back pressure, what is its output?

- 1,000 x 0.90 x 0.96 x 0.97 x 0.96 = 804.6 BHp

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[Product and Environment]

Components The fundamental components of a CHP system include a form of driver, a power generator, a heat recovery system, water treatment equipment and may also include supplemental boilers to add any necessary energy to the system when steam is the working fluid. Most equipment manufactures now offer complete CHP packages which are built to specific requirements.

Warranty Info As might be expected, individual manufacturers offer different warranties for their specific equipment. Many consumers have opted for purchased warranty and maintenance contracts to protect their investments. Many manufacturers offer a two year warranty or 15,000 hours as standard with options to purchase additional coverage. Warranty and maintenance contracts are often offered together.

Code Restrictions All electrical generation equipment must meet or exceed the National Electrical Code standards.

Combined Heat and Power

[Specifications]

Guidelines

Perhaps the most important consideration is the selection of a proven industrial driver. These have life expectancies in excess of 50,000 hours. Secondly, driver speed should be an even multiple of the 60 Hz. Power used in the United States. Many foreign manufactures make drivers in multiples of 50 Hz which is common in Europe. Either the unit will need a gear box or need to be slowed to a multiple of 60 Hz. In either case the net result is horsepower losses.

The deciding factor in equipment selection is the amount and temperature of the working fluid. Reciprocating units are basically limited to producing hat water up to about 190 degrees. Turbines are more suited to steam production. Supplemental firing boilers are also an option.

Fundamentally micro turbines and fuel cell technology is still lagging and at this juncture will not produce favorable economics.