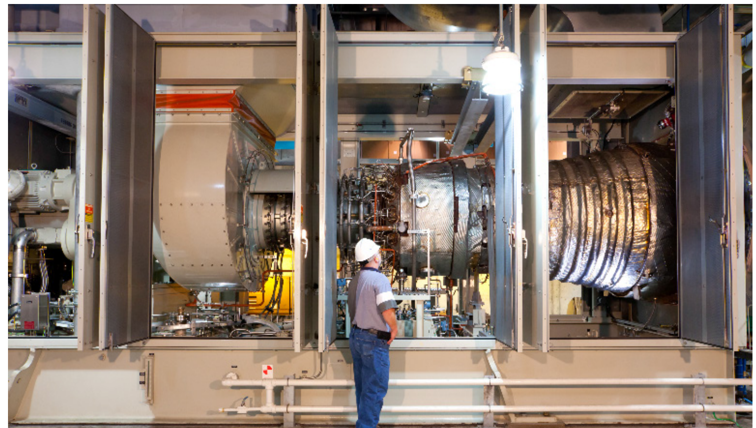
Gas Turbines

Gas turbines are available in sizes ranging from approximately one to more than 300 megawatts (MW) and are used to meet diverse power needs, including propulsion (e.g., aircraft, ships, and trains), direct drive (e.g., pumps and compressors) and stationary electricity generation. For electricity generation, gas turbines are available in a wide range of capacities and configurations, ranging from relatively small microturbines (described in a separate fact sheet[1]) to very large turbines used for central station power generation. For CHP applications, gas turbines typically have favorable economics in sizes greater than five MW. Gas turbines are well suited for industrial and institutional CHP applications because the high temperature gas turbine exhaust can either be used to generate high pressure steam or used directly for heating or drying. **Table 1** provides a summary of gas turbine attributes.



Gas turbine CHP installation at a university.
Photo courtesy of Solar Turbines

Applications

Gas turbines are used extensively for CHP, particularly at industrial and large institutional sites. Gas turbines account for 52 GW of installed CHP capacity in the U.S, representing 64% of the total installed CHP capacity.[2] More than 80% of this gas turbine CHP capacity is in large combined cycle plants[3] that export power to the electric grid. The remaining gas turbine CHP capacity is made up of simple cycle gas turbine CHP systems, typically less than 40 MW. Gas turbines are ideally suited for CHP applications because their high-temperature exhaust can be used to generate process steam at conditions as high as 1,200 pounds per square inch gauge (psig) and 900 °F or used directly in industrial processes for heating or drying.

Table 1. Summary of Gas Turbine Attributes

Size range	Simple cycle turbines are available in sizes from 30 kW (known as microturbines) up to 300 MW (there are a few products that exceed 300 MW).
Thermal output	Gas turbines produce high temperature exhaust, and thermal energy can be recovered from this exhaust to produce steam, hot water, or chilled water (with an absorption chiller). The exhaust can also be used directly for industrial process drying or heating.
Part-load operation	The electrical generation efficiency of gas turbines declines significantly as the load is decreased. Therefore, gas turbines provide the best economic performance in base load applications where the system operates at, or near, full load.
Fuel	Gas turbines can be operated with a wide range of gas and liquid fuels. For CHP, natural gas is the most common fuel.
Reliability	Gas turbines are a mature technology with high reliability.
Other	Gas turbines have relatively low emissions and require no cooling. Gas turbines are widely used in CHP applications and have relatively low installed costs.

1 U.S. Department of Energy, Combined Heat and Power Technology Fact Sheet Series – Microturbines, 2016.

2 U.S. DOE Combined Heat and Power Installation Database, data compiled through December 31, 2015.

3 Combined cycle CHP systems use some of the thermal energy from a gas turbine to produce additional electricity with a steam turbine.

Technology Description

Gas turbines are constant pressure open cycle heat engines that are characterized by the Brayton thermodynamic cycle. Primary gas turbine hardware subsystems include a compressor, a combustion chamber, and an expansion turbine. **Figure 1** shows an industrial gas turbine configured for CHP. The CHP arrangement includes a gas turbine that drives an electric generator with exhaust heat used to produce steam in a heat recovery steam generator (HRSG).

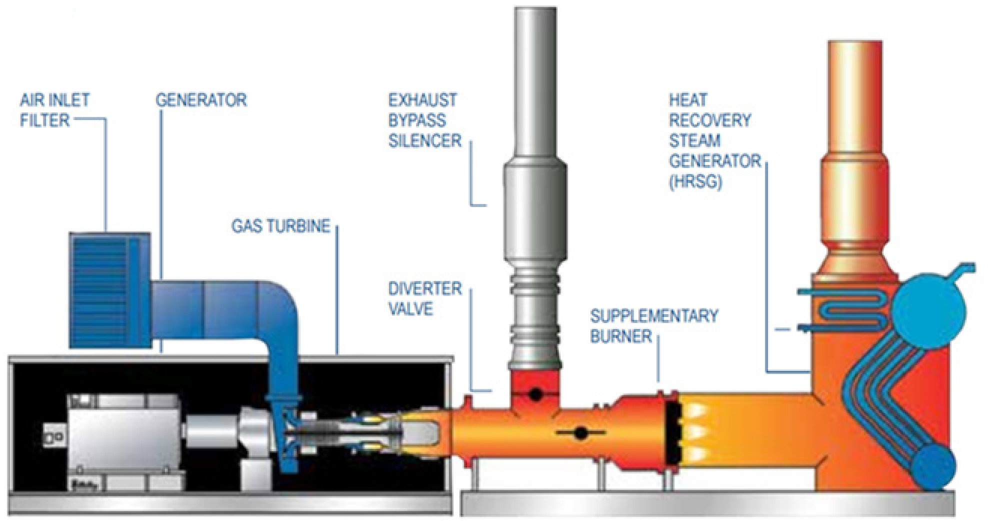


Figure 1. Gas turbine configuration with heat recovery.
Graphic credit Energy Solutions Center.

Figure 2 highlights the key components of a simple cycle gas turbine. The compressor heats and compresses the inlet air which is then further heated by the addition of fuel in the combustion chamber. The hot air and combustion gas mixture drive an expansion turbine, producing enough energy to provide shaft power to the generator or mechanical process and to drive the compressor. The power produced by an expansion turbine and consumed by a compressor is proportional to the absolute temperature of the gas passing through the system. Consequently, it is advantageous to operate the expansion turbine at the highest practical temperature consistent with economic materials and internal blade cooling technology and to operate the compressor with an inlet air flow temperature as low as possible. Higher temperature and pressure ratios result in higher efficiency and specific power, or power-to-weight ratio. Thus, the general trend in gas turbine advancement has been towards a combination of higher temperatures and pressures. While such advancements increase the manufacturing cost of the machine, the higher value, in terms of greater power output and higher efficiency, provides net economic benefits.

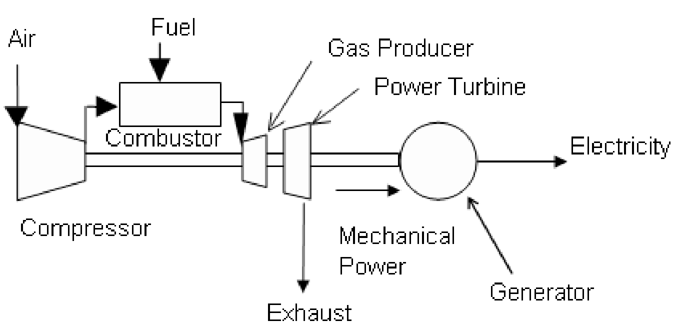


Figure 2. Components in a simple cycle gas turbine.
Graphic credit ICF International.

Performance Characteristics

The efficiency of the Brayton cycle is a function of several factors, including pressure ratio, ambient air temperature, turbine inlet air temperature, compressor energy use, turbine blade cooling requirements, and specific engineering design requirements (e.g., recuperation, intercooling, inlet air cooling, reheat, steam injection, simple cycle, or combined cycle). Higher temperatures and pressure ratios result in higher efficiency, and the general trend in gas turbine advancement, therefore, has been towards a combination of higher temperatures and pressures. As indicated in **Table 2**, overall CHP efficiencies for gas turbines are typically in the range of 65% to 70%, although higher efficiencies can be achieved depending on site specific conditions and engineering design configurations. The power to heat ratio generally increases with gas turbine size (ranges from 0.58 to 1.03 for the representative systems shown in **Table 2**). A changing ratio of power to heat impacts project economics and may affect the decisions that customers make in terms of CHP acceptance, sizing, and the desirability of selling power. It is generally recommended to size a CHP system based on a site's thermal load demand; therefore, such power to heat ratios are important characteristics to consider. When less than full power is required from a gas turbine, the output is reduced by lowering the turbine inlet temperature. In addition to reducing power, this change in operating conditions also reduces efficiency. Typically, emissions increase as well at part load conditions, especially at half load and below.

Capital and O&M Costs

A gas turbine CHP plant has many interrelated subsystems. The basic package includes a gas turbine, gearbox, electric generator, inlet air and exhaust ducting, inlet air filtration, starting system, and an exhaust silencer. The basic package does not include extra equipment such as a natural gas fuel compressor, heat recovery system, water treatment system, or an emission control system (e.g., selective catalytic reduction and continuous emission monitoring).

Table 2. Gas Turbine Performance Characteristics

Description	System					
	1	2	3	4	5	6
Nominal Electric Power (kW)	3,515	4,600	7,965	11,350	21,745	43,069
Net Electric Power (kW)[4]	3,304	4,324	7,487	10,669	20,440	40,485
Fuel Input (MMBtu/hr, HHV)[5]	47.5	59.1	87.6	130.0	210.8	389.0
Useful Thermal (MMBtu/hr)	19.6	25.2	36.3	52.2	77.4	133.8
Power to Heat Ratio[6]	0.58	0.58	0.70	0.70	0.90	1.03
Electric Efficiency (%, HHV)	23.7%	25.0%	29.2%	28.0%	33.1%	35.5%
Thermal Efficiency (%, HHV)[7]	41.1%	42.7%	41.4%	40.2%	36.7%	34.4%
Overall Efficiency (%, HHV)	64.9%	67.6%	70.6%	68.2%	69.8%	69.9%

Note: *Performance characteristics are average values and are not intended to represent a specific product.*

Installed capital costs vary significantly depending on the scope of the plant equipment, geographical area, competitive market conditions, special site requirements, emissions control requirements, and prevailing labor rates. **Table 3** shows estimated capital costs for six representative gas turbine CHP systems used in typical applications. As indicated, there are economies of scale, with installed costs declining from $3,320/kW for a 3.3 MW system to $1,276/kW for a 40 MW system. Routine maintenance practices include online running maintenance, predictive maintenance, plotting trends, performance testing, vibration analysis, and preventive maintenance procedures. Typically, routine inspections are required every 4,000 hours to ensure that the turbine is free of excessive vibration due to worn bearings and rotors or damaged blade tips. A gas turbine overhaul is needed every 25,000 to 50,000 hours, depending on service, and typically includes a complete inspection and rebuild of components to restore the gas turbine to nearly original or current (upgraded) performance standards. Gas turbine maintenance costs can vary significantly depending on the quality and diligence of the preventative maintenance program and operating conditions.

Table 3. Gas Turbine Capital and O&M Costs

Description	System					
	1	2	3	4	5	6
Net Electric Power (kW)	3,304	4,324	7,487	10,669	20,440	40,485
Combustion Turbine ($/kW)	$908	$860	$683	$619	$563	$477
Emissions Control ($/kW)	$208	$174	$126	$92	$74	$65
Balance of Plant ($/kW)	$899	$712	$455	$389	$276	$231
Construction and Installation ($/kW)	$1,305	$1,072	$753	$698	$562	$503
Total Installed Cost ($/kW)	$3,320	$2,817	$2,017	$1,798	$1,474	$1,276
Total O&M (¢/kWh)	1.3	1.3	1.2	1.2	0.9	0.9

Note: *Costs are average values and are not intended to represent a specific product.*

4 Fuel compressor and other ancillary electric loads are estimated at 6% (i.e., net power assumed to be 94% of nominal power).

5 All quantities in this fact sheet are based on the higher heating value (HHV) of the fuel unless noted otherwise. The ratio of HHV to LHV is assumed to be 1.105 for natural gas.

6 Power to heat ratio is the electric power output divided by the useful thermal output. The quantities are expressed in equivalent units, and the ratio is unit-less.

7 Thermal energy is based on generating 150 psig saturated steam, with 7% of steam production bypassed to deaerator (i.e., 93% of total steam available for process).

Emissions

Table 4 shows typical emissions for gas turbine CHP plants operating on natural gas. Emissions are shown without after treatment control and with after treatment control consisting of a selective catalytic reduction (SCR) system to control NOx and an oxidation catalyst to control CO and VOCs. A number of technologies can be used to control emissions, including diluent injection, lean premixed combustion, SCR, CO oxidation catalysts, catalytic combustion, and catalytic absorption systems.

Table 4. Gas Turbine Emission Characteristics

Description	System					
	1	2	3	4	5	6
Net Power (kW)	3,304	4,324	7,487	10,669	20,440	40,485
Emissions before After Treatment (ppm at 15% oxygen)						
NOx	25	25	15	15	15	15
CO	50	50	25	25	25	25
VOC	5	5	5	5	5	5
Emissions with SCR and Oxidation Catalyst (ppm at 15% oxygen)						
NOx	2.5	2.5	1.5	1.5	1.5	1.5
CO	5.0	5.0	2.5	2.5	2.5	2.5
VOC	4.3	4.3	4.3	4.3	4.3	4.3
Emissions with SCR and Oxidation Catalyst (lbs/MWh)[8]						
NOx[9]	0.13	0.13	0.06	0.07	0.06	0.05
CO[10]	0.16	0.15	0.07	0.07	0.06	0.05
VOC[11]	0.08	0.08	0.06	0.07	0.06	0.05
CO_2 Emissions (lbs/MWh)						
Electricity only	1,682	1,598	1,368	1,424	1,206	1,123
CHP w/ thermal credit[12]	817	746	660	709	652	640

Note: *Emissions are average values and are not intended to represent a specific product.*

Table 4 shows CO_2 emissions for CHP systems based on the power output and on the complete CHP system. For the complete CHP system, CO_2 emissions are calculated with a thermal credit for natural gas fuel that would otherwise be used by an on-site boiler. With this credit, CO_2 emissions range from 640-817 lbs/MWh. For comparison, a typical natural gas combined cycle power plant will have emissions of 800-900 lbs/MWh, and a coal plant will have CO_2 emissions near 2,000 lbs/MWh. Emissions control technology for gas turbines has advanced dramatically over the last 20 years in response to regulatory changes that have continually lowered the acceptable emissions levels for nitrogen oxides (NOx), carbon monoxide (CO), and volatile organic compounds (VOCs). ■

8 NOx, CO, and VOC emissions expressed in units of lbs/MWh are based on electric output and do not include a thermal credit.

9 NOx conversion: NOx [lbs/MWh] = NOx [ppm @ 15% O2] / 271 / electrical efficiency [%, HHV] X 3.412.

10 CO conversion: CO [lbs/MWh] = CO [ppm @ 15% O2] / 446 / electrical efficiency [%, HHV] X 3.412.

11 VOC conversion: VOC [lbs/MWh] = VOC [ppm @ 15% O2] / 779 / electrical effiency [%, HHV] X 3.412.

12 The CHP CO_2 emissions include a thermal credit for avoided fuel that would otherwise be used in an onsite boiler. The boiler is assumed to operate on natural gas with an efficiency of 80%.

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