Steam Turbines

Steam turbines are a mature technology and have been used since the 1880s for electricity production. Most of the electricity generated in the United States is produced by steam turbines integrated in central station power plants. In addition to central station power, steam turbines are also commonly used for combined heat and power (CHP) installations (see **Table 1** for summary of CHP attributes).

Steam turbine CHP installation at an industrial facility in New York.
Photo courtesy of Recycled Energy Development

Applications

Based on data from the CHP Installation Database,[1] there are 699 sites in the United States that are using steam turbines for CHP operation. These steam turbine CHP installations have an average capacity of 37 MW and a combined capacity of 26 GW, representing 32% of the installed CHP capacity in the United States.[2] The majority of these CHP steam turbines are used at industrial plants (e.g., paper, chemicals, and food), commercial buildings with high thermal loads (e.g., hospitals), and district heating sites (e.g., universities). Steam turbines are well suited to medium- and large-scale industrial and institional applications where inexpensive fuels such as coal, biomass, solid wastes and byproducts (e.g., wood chips), refinery residual oil, and refinery off gases are available.

Technology Description

A steam turbine is driven with high pressure steam produced by a boiler or heat recovery steam generator (HRSG). Unlike gas turbines or microturbines, steam turbines do not directly consume fuel. Rather, the fuel driving the process is the fired boiler or plant equipment that produces heat for the HRSG (e.g., a gas turbine).

Table 1. Summary of Steam Turbine Attributes for CHP

Size range	Steam turbines are available in sizes from under 100 kW to over 250 MW.
Thermal output	CHP configurations use backpressure or extraction steam turbines to generate power and thermal energy. Backpressure steam turbines produce low pressure steam while extraction turbines deliver both low pressure and medium pressure steam.
Part-load operation	Steam turbines have relatively good part-load performance, but efficiency does decline as power output is reduced.
Fuel	Boilers are commonly used to generate steam required for steam turbines, and boilers can utilize a wide range of fuels, including natural gas, oil, coal, and biomass. For CHP applications, steam turbines are often implemented when there is access to a low cost opportunity fuel that can be combusted in a boiler to generate steam.
Reliability	Steam turbines are a mature technology with excellent durability and reliability.
Other	Steam turbines are typically designed to deliver relatively large amounts of thermal energy with electricity generated as a byproduct of heat generation. Overall CHP efficiencies can reach or exceed 80%.

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

2 These statistics only include steam turbines integrated with boilers. The statistics do not include steam turbines driven by steam produced from heat recovery steam generators used in combined cycle CHP systems.

Steam turbines operate on the Rankine cycle (see **Figure 1**). In this thermodynamic cycle, water is pumped to high pressure and then heated to generate high pressure steam. The high pressure steam is then expanded through a steam turbine where steam energy is converted to mechanical power that drives an electrical generator. For CHP configurations, low pressure steam that exits the steam turbine is then available to satisfy on-site thermal needs. Condensed liquid is then returned to the pump, and the cycle is repeated.

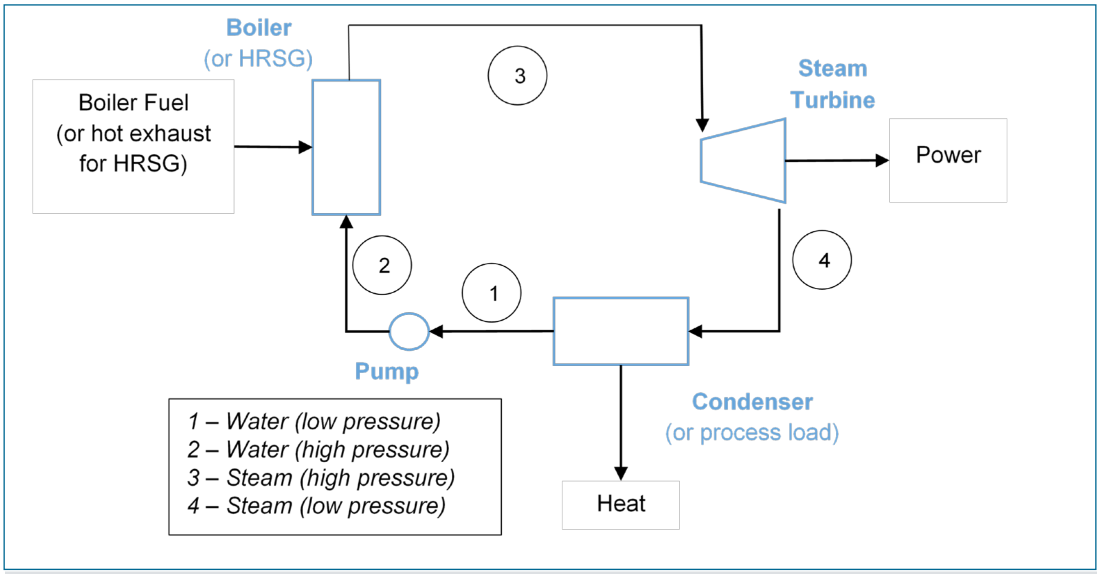

Figure 1. Components of a boiler/steam turbine.
Figure courtesy of U.S. Department of Energy

Steam turbines for CHP applications are classified as either non-condensing or extraction. A non-condensing turbine, also referred to as a backpressure turbine (see **Figure 2**), exhausts steam directly to an industrial process or to a steam distribution system. In a backpressure turbine, common pressure levels are 50, 150, and 250 psig, with lower pressures often used in district heating systems; higher pressures are more typical for industrial processes.

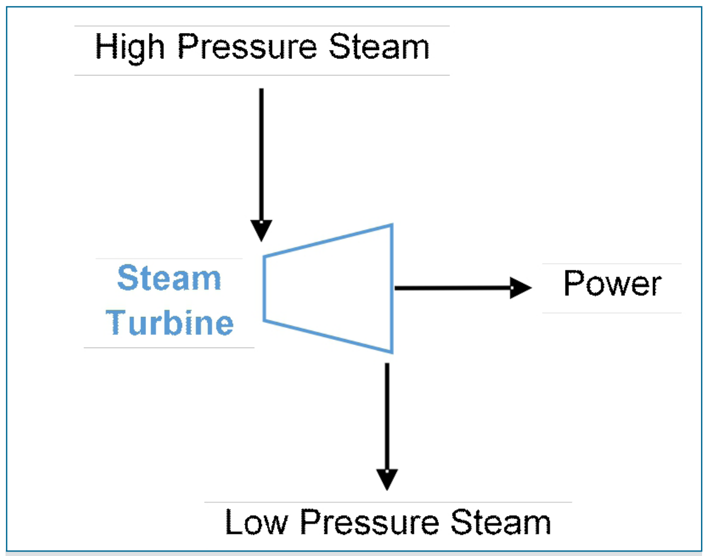

Figure 2. Non-condensing (backpressure) steam turbine.
Figure courtesy of U.S. Department of Energy

An extraction turbine has one or more openings in its casing to extract steam at an intermediate pressure. The extracted steam is then used in CHP configurations that require steam pressures higher than pressures available from backpressure steam turbines.

Regardless of steam turbine type – backpressure or extraction – the primary objective of most steam turbine CHP systems is to deliver relatively large amounts of thermal energy, with electricity generated as a byproduct of heat generation. Therefore, most steam turbine CHP systems are characterized by low power to heat ratios, often below 0.2.

Performance Characteristics

Table 2 shows performance characteristics for three representative backpressure steam turbines used in CHP applications with electric power capacities of 500 kW, 3 MW, and 15 MW. As indicated, all three systems have overall efficiencies near 80%[3] and power to heat ratios of 0.1 or lower. High overall efficiencies and low power to heat ratios are common characteristics for steam turbines configured for CHP applications.

Interior view of steam turbine blades.
Photo courtesy of Siemens

3 The overall CHP efficiency for a backpressure boiler/steam turbine system is typically slightly lower than the boiler efficiency.

Capital and O&M Costs

Major subsystems required for a complete steam turbine CHP plant include a boiler or HRSG, steam loop, and a steam turbine. In addition, a control system is needed and emission reduction hardware may be required depending on local air quality requirements. The steam turbine is just one cost component in a complete CHP plant. As an example, for a steam turbine CHP plant burning solid biomass, the installed cost for the complete CHP plant will be roughly $5,000/kW or higher. The installed cost for the steam turbine and electrical generator will represent approximately 15% to 25% of this total installed cost. These cost estimates are rough guidelines and are only intended to offer a perspective on the relative cost for the turbine/generator components that are integrated into a complete steam turbine CHP installation.

Table 3 shows capital costs and operation and maintenance (O&M) costs for three representative backpressure steam turbines. As indicated, installed costs for the turbine/generator range from approximately $670/kW to $1,140/kW, with costs on a per kW basis declining as capacity increases. The turbine/generator costs in **Table 3** include the steam turbine, generator, and generator control system. The costs do not include the boiler, steam loop, and controls.

Non-fuel O&M costs range from 0.6 to 1.0 ¢/kWh for the three steam turbines shown in **Table 3**. Similar to capital costs, there are economies of scale, and the O&M costs decline on a per kWh basis as the steam turbine capacity increases. The O&M costs shown in **Table 3** are for the steam turbine/generator subsystem and do not include O&M expenses for the boiler and steam loop.

Table 2. Steam Turbine Performance Characteristics When Integrated with a Natural Gas Boiler

Description	System		
	1	2	3
Net Electric Power (kW)	500	3,000	15,000
Fuel Input (MMBtu/hr, HHV)[4]	27.2	208.0	700.1
Steam Flow (lbs/hr)	20,050	152,600	494,464
Steam Inlet Pressure (psig)	500	600	700
Steam Inlet Temperature (°F)	550	575	650
Steam Outlet Pressure (psig)	50	150	150
Steam Outlet Temperature (°F)	298	373	380
Useful Thermal (MMBtu/hr)	20.0	155.5	506.8
Power to Heat Ratio[5]	0.086	0.066	0.101
Electric Efficiency (%, HHV)	6.3%	4.9%	7.3%
Thermal Efficiency (%, HHV)	73.3%	74.8%	72.4%
Overall Efficiency (%, HHV)	79.6%	79.7%	79.7%

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

Table 3. Steam Turbine Capital and O&M Costs

Description	System		
	1	2	3
Net Electric Power (kW)	500	3,000	15,000
Steam Turbine and Generator ($/kW)	$668	$401	$392
Installation and Balance of Plant ($/kW, not including boiler and steam system)[6]	$468	$281	$274
Total Installed Cost ($/kW)	$1,136	$682	$666
O&M (¢/kWh, steam turbine and generator)	1.0	0.9	0.6

4 Manufacturers often express fuel input and efficiency values based on the lower heating value (LHV) of the fuel. All quantities in this fact sheet are expressed based on higher heating value (HHV) unless noted otherwise. For natural gas, the ratio of LHV to HHV is approximately 0.9.

5 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.

6 Installation and BOP costs estimated at 70% of the turbine/generator capital cost.

Emissions

Steam turbine emissions depend on how the steam is generated (e.g., boiler or HRSG) and what type of fuel is used to generate the steam. **Table 4** shows NOx, CO, and VOC emissions based on EPA emission factors for boilers that are fired with natural gas and coal. A 500 kW steam turbine utilizing a natural gas fired boiler will have estimated NOx emissions in the range of 26-81 ppm (at 3% oxygen). A larger 15,000 kW CHP steam turbine integrated with a natural gas boiler will have estimated NOx emissions in the range of 81-226 ppm (at 3% oxygen). This 15,000 kW steam turbine, if integrated with a coal fired boiler, will have estimated NOx emissions in the range of 141-929 ppm (at 3% oxygen).

Table 4. Boiler/Steam Turbine Emission Characteristics for Natural Gas and Coal Combustion[7]

Description	System[8]				
	1[9]	2		3	
Power (kW)	500	3,000		15,000	
Boiler Fuel	Nat Gas	Nat Gas	Coal	Nat Gas	Coal
Emissions (ppm @ 3% oxygen)					
NOx	26-81	81-226	141-929	81-226	141-929
CO	111	111	23-833	111	23-833
VOCs	13	13	105-807	13	105-807
Emissions (lbs/MWh)[10]					
NOx[11]	1.7-5.3	6.8-19.0	13-88	4.6-12.8	9-59
CO[12]	4.5	5.7	1-48	3.8	1-32
VOCs[13]	0.29	0.37	3-27	0.25	2-18
Carbon Dioxide Emissions (lbs/MWh)					
Electricity Only	6,361	8,107	14,604	5,456	9,829
CHP w/Thermal Credit[14]	530	531	957	519	935

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

Table 4 shows CO_2 emissions for steam turbine plants based on the electric power output and on the complete CHP system. For the complete CHP system, CO_2 emissions are calculated with a thermal credit for fuel that would otherwise be used by an on-site boiler. With this credit, CO_2 emissions range from 519 to 531 lbs/MWh for natural gas boilers, and 935-957 lbs/MWh for coal fired boilers. 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. ■

7 NOx, CO, and VOC emission factors are based on EPA AP-42 values.

8 Emission factors for System #1 are based on boiler input < 100 MMBtu/hr. Emission factors for Systems #2 and #3 are based on boiler input > 100 MMBtu/hr.

9 System #1 is relatively small and would typically not be integrated with a coal fired boiler. Emissions for System #1 are only shown for natural gas boiler fuel.

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

11 NOx conversion (natural gas): NOx [lbs/MWh] = NOx [ppm @ 3% O2] / 824 / electrical efficiency [%, HHV] X 3.412. For coal, use factor of 732 instead of 824.

12 CO conversion (natural gas): CO [lbs/MWh] = CO [ppm @ 3% O2] / 1,354 / electrical efficiency [%, HHV] X 3.412. For coal, use factor of 1,203 instead of 1,354.

13 VOC conversion (natural gas): VOC [lbs/MWh] = VOC [ppm @ 3% O2] / 2,362 / electrical efficiency [%, HHV] X 3.412. For coal, use factor of 2,099 instead of 2,362.

14 The CHP CO2 emissions include a thermal credit for avoided fuel that would otherwise be used by an onsite boiler.

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