U.S. DEPARTMENT OF
ENERGY
Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

Combined Heat
and Power
Technology Fact
Sheet Series

CHP Technologies: Steam Turbines

Steam turbines are a mature technology used in a wide range of direct drive applications. Relatively small steam turbines are used to drive compressors and pumps, while larger steam turbines are used for marine propulsion and electricity generation. For electricity production, steam turbines have been used since the late 1800s and remain an integral part of the power generation sector. Most electricity generated today is produced by steam turbines installed in central station power plants. In addition to relatively large central station power plants, steam turbines are also used in smaller capacity industrial and commercial applications to generate electricity, including combined heat and power (CHP) applications.

Steam Turbines for CHP

A steam turbine is a type of prime mover that converts thermal energy in high-pressure steam into mechanical (rotating) power, which can then be used to drive a generator to produce electricity. The steam driving the turbine is most often produced in fired boilers that can be fueled by a wide variety of fuels, including natural gas, oil, coal, process waste, and renewable biomass. Steam turbines can also be driven by steam generated by waste heat recovered from process operations or exhaust through heat recovery steam generators (HRSGs).

Backpressure Steam Turbine Installation at an Ethanol Plant in Lena, Illinois.

Photo courtesy of Midwest Onsite Energy Technical Assistance Partnership (TAP)

In CHP applications, steam at lower pressure is extracted from the steam turbine and used for process or district heating, or the steam can be converted to other forms of thermal energy, including hot or chilled water. Steam turbines can also be installed to duplicate the function of a pressure reducing valve (PRV). In this CHP configuration, the steam turbine serves the same purpose as the PRV by reducing steam pressure but has the added benefit of generating electricity. For redundancy purposes, steam turbines that serve as PRVs are typically installed in parallel with a conventional PRV.

Table 1. Summary of Steam Turbine Attributes for CHP Applications

Attribute	Description
Size Range	Steam turbines are available in sizes ranging from less than 100 kW to more than 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.
Start-Up	Dependent on the steam (boiler start-up time).
Part-Load Operation	Steam turbines have relatively good part-load performance, but efficiency does decline as power output is reduced.
Fuel	Boilers and HRSGs are used to create steam that drives steam turbines. Boilers can utilize a wide range of fuels, including natural gas, oil, coal, process waste, and renewable biomass. HRSGs can recover exhaust heat from a variety of industrial processes generated from firing fuels or process wastes or from exothermic process reactions.
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 for boiler/steam turbine systems can reach or exceed 80%.

Applications

Based on data from the CHP Installation Database,[1] there are more than 530 sites in the United States that are using steam turbines paired with boilers for CHP operation. These boiler/steam turbine CHP installations represent 25% of the installed CHP capacity in the United States—around 20 GW.[2]

Steam turbine-based CHP systems are primarily used in industrial processes with large steam loads and where solid or waste fuels are readily available for boiler use. Steam turbine systems are most commonly found in paper mills as there is usually a variety of waste fuels from hog fuel to black liquor. Chemical plants are the next most common industrial user of steam turbines, followed by food processing (particularly sugar and palm oil mills) and wood products. Other common users of steam turbine CHP are university campuses, hospital complexes, and district heating systems, all with large steam loads and a need for energy reliability and efficiency.

Figure 1 shows the top applications for CHP steam turbines in terms of the number of sites and total capacity. This includes boiler/steam turbine systems, backpressure steam turbines, and steam turbines paired with HRSGs for waste heat recovery. The figure does not include combined cycle systems, where HRSGs and steam turbines are applied to the exhaust of gas turbines to produce additional power in an integrated package.

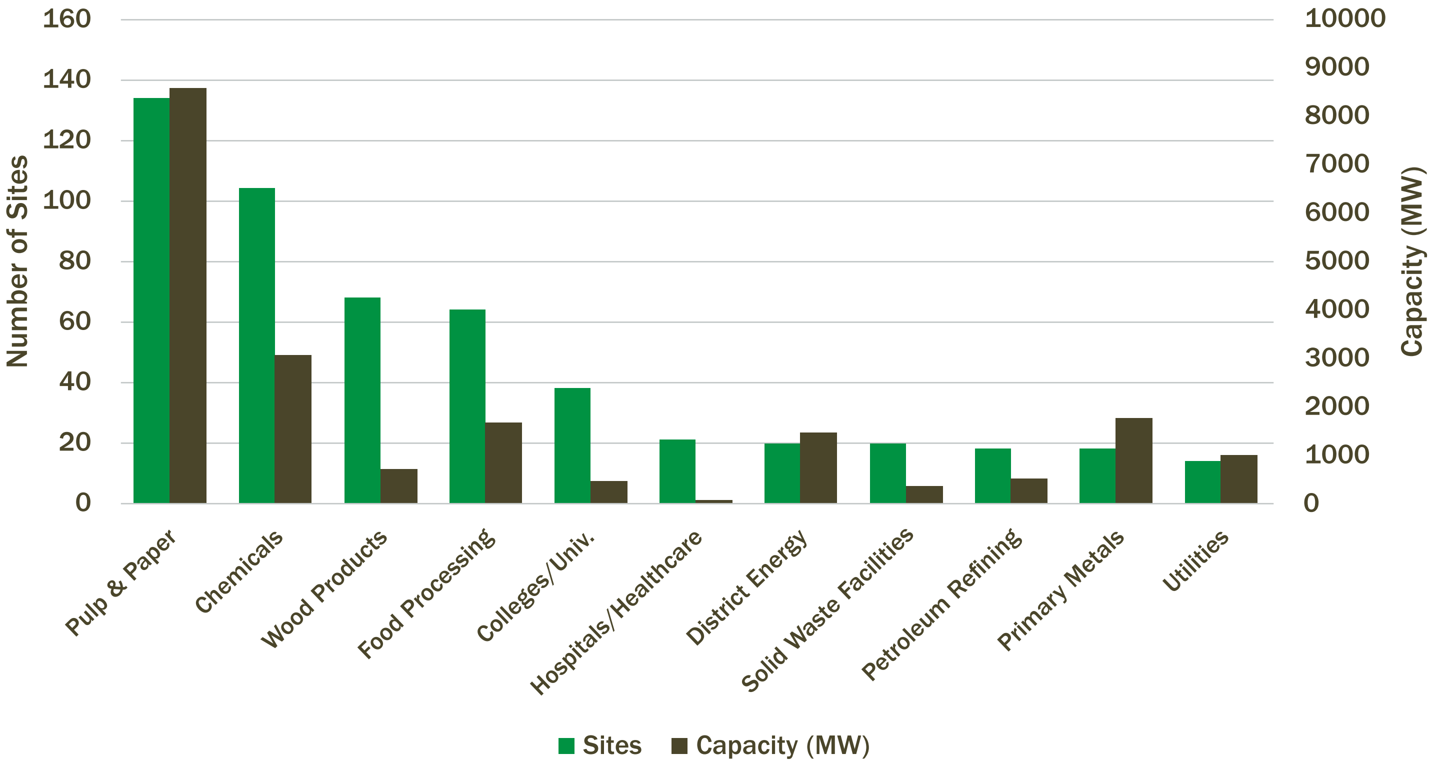

Figure 1. Number of CHP Steam Turbine Installations and Total Capacity by Application

In a boiler/steam turbine system, several different fuel types can be used, including waste fuels from industrial processes such as black liquor from pulp and paper mills. Other CHP prime movers (i.e., reciprocating engines and gas turbines) are limited to liquid and gaseous fuels, but boiler/steam turbine systems can use solid fuels, including renewable biomass in the form of agricultural residues, forest trimmings, wood waste, or waste from food processing facilities. Overall, renewable fuels (all types of biogas and biomass, including black liquor and municipal solid waste) account for nearly 8 GW of steam turbine CHP capacity, close to 40% of the total for boiler/steam turbine systems.

Steam turbines are also used in waste heat to power (WHP) systems, with over 60 installations across the United States, either in the form of backpressure steam turbines or HRSG/steam turbine systems. Backpressure steam turbine systems that produce power through converting high-pressure steam to low pressure can be used in existing steam systems in parallel to PRVs in both industrial and commercial applications. HRSGs are used at facilities where excess heat from industrial processes can be captured and utilized, including chemical processing, metal production, and oil refining facilities. While not as common as traditional fuel-fired boiler systems, WHP systems account for nearly 600 MW of CHP, with most of the capacity represented by chemical plants.

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[1] U.S. DOE Combined Heat and Power Installation Database, August 2024.

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

Technology Description

Types of Steam Turbines

A backpressure turbine (also referred to as a non-condensing turbine) exhausts all its steam flow to the facility's steam system at required process or building heating conditions (typical backpressure steam turbine arrangement shown in Figure 2). Usually, the delivered steam is near the saturation temperature. The term backpressure refers to the turbine exhausting steam at atmospheric pressures and above. The discharge pressure is established by the specific process or heating requirements. The most typical pressure levels for steam distribution systems are 50, 150, and 250 psig. The lower pressures are most often used in district heating systems, while the higher pressures are most often used in supplying steam to industrial processes.

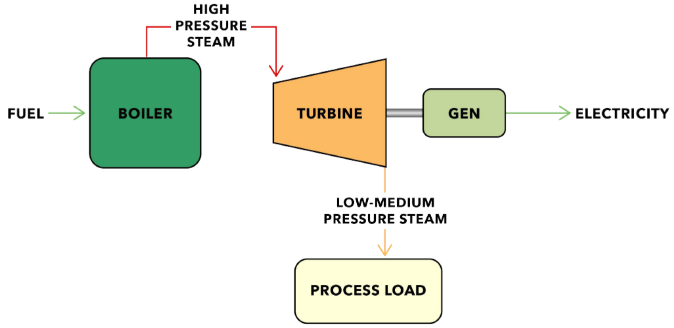

Figure 2. Backpressure Steam Turbine

Extraction turbines are another type of steam turbine used for CHP. An extraction turbine has one or more openings in its casing for extraction of a portion of the steam at some intermediate pressure for process or facility heating purposes. The remainder of the steam is expanded to below atmospheric pressure to a condenser, or it can be delivered to a low-pressure steam application as illustrated in Figure 3.

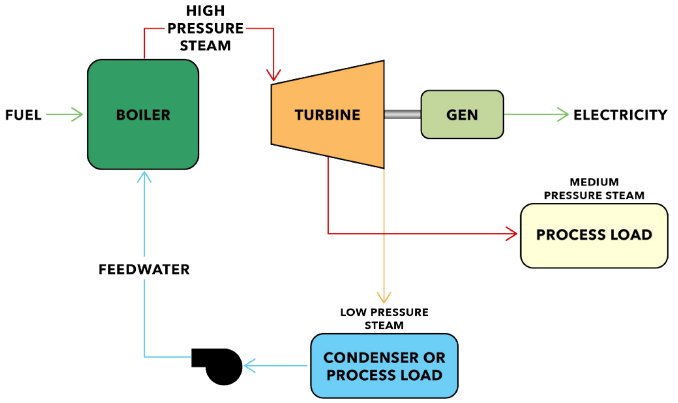

Figure 3. Extraction Steam Turbine

Condensing steam turbines—which are different from backpressure and extraction steam turbines—are commonly used by utilities for power generation. These power-only turbines exhaust directly to condensers that maintain vacuum conditions at the discharge of the turbine. Condensing turbine systems, which are not used for CHP, result in maximum power and electrical generation efficiency from the steam supply and boiler fuel.

Steam turbines can use induction generators or synchronous generators. Synchronous generators can operate independently from the grid, allowing them to continue operating during a utility power outage. Compared to synchronous generators, induction generators require an external source of electricity, and they can have high utility power factor correction charges due to the consumption of reactive power from the grid. Based on balancing performance and cost, induction generators are typically used with steam turbines under 1 MW, while synchronous generators are more often used with larger steam turbines.

Steam Turbine Stages and Valves

Stages

In a steam turbine, the steam pressure is reduced across one or more stages. Compared to multi-stage turbines, single-stage turbines are less complex and have lower capital costs. Multi-stage turbines, however, exhibit higher isentropic efficiencies and can produce more power compared to single stage turbines operating with the same high-pressure steam feed. Multi-stage turbines also offer more options for steam extraction at intermediate pressures. Single-stage turbines are generally used for power outputs up to 3 MW.

Valves

Steam flow entering a steam turbine is controlled by one or more control valves. The simplest arrangement is a single valve that controls the amount of steam delivered to the steam turbine. Multiple control valves, while mechanically more complex and expensive than single-valve designs, offer higher efficiencies by reducing pressure losses as the steam enters the steam turbine. Single-valve steam turbines are used for power outputs up to 10–15 MW, with multi-valve turbines more common in larger capacities.

Performance Characteristics

Small steam turbines used for power generation up to approximately 3 MW are typically designed as single-stage/single-valve machines. As steam turbines increase in size, more sophisticated multi-stage and multi-valve features are incorporated. These advanced features, while more complex and expensive, allow larger steam turbines to operate at higher isentropic efficiencies compared to smaller machines. Site-specific factors, including the inlet conditions and outlet requirements, can also affect the isentropic efficiency of a steam turbine system. Table 2 shows representative performance characteristics for five backpressure steam turbines used in CHP applications ranging in size from 250 kW to 25 MW.

Table 2. Steam Turbine Performance Characteristics[a,b]

Description		Steam Turbine Capacity				
		250 kW	500 kW	3 MW	10 MW	25 MW
Turbine Type		Backpressure	Backpressure	Backpressure	Backpressure	Backpressure
Stages		Single	Single	Single	Multi	Multi
Valves		Single	Single	Single	Single	Multi
Isentropic Efficiency[c]		60-70%	60-70%	65-72%	70-77%	80-85%
Example Steam Turbine Performance						
Steam Flow (klbs/hr)		16	20.7	114	368	864
Steam Inlet Conditions[d]	**Pressure (psig)**	300	500	650	750	800
	Temperature (°F)	450	550	650	700	750
Steam Outlet Conditions	**Steam Quality[e]**	98%	99%	100%	100%	100%
	Pressure (psig)	100	100	150	200	250
	Temperature (°F)	340	350	410	460	500
Actual Isentropic Efficiency		65%	65%	68.5%	74%	82.5%
Useful Thermal Energy (MMBtu/hr)		18.7	24.4	140	460	1,095

Notes:

a) Performance characteristics are not intended to represent a specific product.

b) Typical isentropic efficiencies inlet pressures and temperature, and outlet pressure from CHP steam turbine systems at each representative size were entered into the DOE's MEASUR tool, using these characteristics to calculate the steam flow, temperature, quality/phase, and useful thermal energy for the output from each system, assuming a 98% generator efficiency.

c) Isentropic efficiency is the ratio of actual steam turbine work output to work output if the steam turbine operated at ideal, or constant entropy (isentropic) conditions. The isentropic efficiency, which is always less than one, is a measure of how close a steam turbine approaches ideal operation.

d) Inlet steam is superheated.

e) Steam quality is a measure of moisture in the steam expressed as the percentage of steam vapor in the steam/water mixture.

Steam turbine system emissions are not included in this fact sheet, as the emissions depend entirely on how the steam is generated (e.g., boiler or HRSG) and what type of fuel is used to generate the steam.

Capital and O&M Costs

Table 3 shows capital costs and maintenance costs for the same representative steam turbines described in Table 2. These costs are based on simple installations for sites that have no challenging mechanical, electrical, or construction constraints. The costs shown in Table 3 are intended for comparison purposes and may vary significantly based on site-specific conditions and requirements. Equipment costs—which include the turbine, generator, and controls—range from $450 to $2,000 per kW. On a per kW basis, costs decline as capacity increases. Installation costs range from $200 to $700 per kW, and total installed costs (equipment + installation) range from $650 to $2,700 per kW. Maintenance costs are estimated to range from 0.5¢ to 1.0¢ per kWh.

Table 3. Capital and Maintenance Costs for Steam Turbines

Description	Steam Turbine Capacity				
	250 kW	500 kW	3 MW	10 MW	25 MW
Equipment ($/kW)	$2,000	$1,500	$700	$550	$450
Installation ($/kW)	$700	$500	$300	$250	$200
Installed Cost ($/kW)	$2,700	$2,000	$1,000	$800	$650
Maintenance (¢/kWh)	1.0	0.9	0.8	0.7	0.5

Note: Costs are not intended to represent a specific product.

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