Catalog of CHP Technologies

Section 1. Introduction

U.S. Environmental Protection Agency
Combined Heat and Power Partnership

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The September 2017 revision incorporated a new section on packaged CHP systems (Section 7).

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Section 1. Introduction

Combined heat and power (CHP) is an efficient and clean approach to generating electric power and useful thermal energy from a single fuel source. CHP places power production at or near the end-user's site so that the heat released from power production can be used to meet the user's thermal requirements while the power generated meets all or a portion of the site electricity needs. Applications with steady demand for electricity and thermal energy are potentially good economic targets for CHP deployment. Industrial applications particularly in industries with continuous processing and high steam requirements are very economic and represent a large share of existing CHP capacity today. Commercial applications such as hospitals, nursing homes, laundries, and hotels with large hot water needs are well suited for CHP. Institutional applications such as colleges and schools, prisons, and residential and recreational facilities are also excellent prospects for CHP.

The direct benefits of combined heat and power for facility operators are:

- **Reduced energy related costs** – providing direct cost savings.
- Increased reliability and decreased risk of power outages due to the addition of a separate power supply.
- Increased economic competitiveness due to lower cost of operations.

In addition to these direct benefits, the electric industry, electricity customers, and society, in general, derive benefits from CHP deployment, including:

- **Increased energy efficiency** – providing useful energy services to facilities with less primary energy input.
- **Economic development value** – allowing businesses to be more economically competitive on a global market thereby maintaining local employment and economic health.
- **Reduction in emissions that contribute to global warming** – increased efficiency of energy use allows facilities to achieve the same levels of output or business activity with lower levels of fossil fuel combustion and reduced emissions of carbon dioxide.
- **Reduced emissions of criteria air pollutants** – CHP systems can reduce air emissions of carbon monoxide (CO), nitrogen oxides (NO_x), and Sulfur dioxide (SO_2) especially when state-of-the-art CHP equipment replaces outdated and inefficient boilers at the site.
- Increased reliability and grid support for the utility system and customers as a whole.
- **Resource adequacy** – reduced need for regional power plant and transmission and distribution infrastructure construction.

CHP systems consist of a number of individual components – prime mover (heat engine), generator, heat recovery, and electrical interconnection – configured into an integrated whole. The type of equipment that drives the overall system (i.e., the prime mover) typically identifies the CHP system. The purpose of this guide is to provide CHP stakeholders with a description of the cost and performance of complete systems powered by prime-mover technologies consisting of:

1. Reciprocating internal combustion engines
2. Combustion turbines
3. Steam turbines
4. Microturbines
5. Fuel cells

In 2008, the EPA CHP Partnership Program published its first catalog of CHP technologies as an online educational resource for regulatory, policy, permitting, and other interested CHP stakeholders. This *CHP Technology Guide* is an update to the 2008 report[1]. The Guide includes separate, detailed chapters on each of the five prime movers listed above. These technology chapters include the following information:

- Description of common applications
- Basic technology description
- Cost and performance characteristics
- Emissions and emissions control options
- Future developments

Packaged CHP Systems

In September 2017, the EPA CHP Partnership added a new section (Section 7) to the Catalog that provides information on packaged CHP systems. Specifically, the section discusses:

- The evolution of packaged CHP systems
- Significant attributes
- Applications
- Technology description
- Cost and Performance characteristics
- Emissions and emission control options

This introduction and overview section provides a discussion of the benefits of CHP technologies, a summary comparison of the five main prime-mover technology systems, and a discussion of key CHP benefits. There is also an appendix that provides the formulas for the various performance measurements used in the Guide.

1.1 Overview of CHP Technologies

The five technologies described in the Guide make up 97 percent of the CHP projects in place today and 99 percent of the total installed CHP electric capacity. **Table 1-1** shows the breakdown by each prime mover technology.

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[1] Catalog of CHP Technologies, U.S. Environmental Protection Agency Combined Heat and Power Partnership Program, December 2008.

Table 1-1. U.S. Installed CHP Sites and Capacity by Prime Mover

Prime Mover	Sites	Share of Sites	Capacity (MW)	Share of Capacity
Reciprocating Engine	2,194	51.9%	2,288	2.7%
Gas Turbine*	667	15.8%	53,320	64.0%
Boiler/Steam Turbine	734	17.4%	26,741	32.1%
Microturbine	355	8.4%	78	0.1%
Fuel Cell	155	3.7%	84	0.1%
Other	121	2.9%	806	1.0%
Total	**4,226**	**100.0%**	**83,317**	**100.0%**

* includes gas turbine/steam turbine combined cycle
Source: ICF CHP Installation Database, April 2014

All of the technologies described convert a chemical fuel into electric power. The energy in the fuel that is not converted to electricity is released as heat. All of the technologies, except fuel cells, are a class of technologies known as *heat engines*. Heat engines combust the fuel to produce heat, and a portion of that heat is utilized to produce electricity while the remaining heat is exhausted from the process. Fuel cells convert the energy in the fuel to electricity electrochemically; however, there are still inefficiencies in the conversion process that produce heat that can be utilized for CHP. Each technology is described in detail in the individual technology chapters, but a short introduction of each is provided here:

- ***Reciprocating engines,*** as shown above, make up over half of the CHP systems in place, though, because of the generally smaller system sizes, less than 3 percent of total capacity. The technology is common place – used in automobiles, trucks, trains, emergency power systems, portable power systems, farm and garden equipment. Reciprocating engines can range in size from small hand-held equipment to giant marine engines standing over 5-stories tall and producing the equivalent power to serve 18,000 homes. The technology has been around for more than 100 years. The maturity and high production levels make reciprocating engines a low-cost reliable option. Technology improvements over the last 30 years have allowed this technology to keep pace with the higher efficiency and lower emissions needs of today's CHP applications. The exhaust heat characteristics of reciprocating engines make them ideal for producing hot water.

- ***Steam turbine*** systems represent 32 percent of U.S. installed CHP capacity; however, the median age of these installations is 45 years old. Today, steam turbines are mainly used for systems matched to solid fuel boilers, industrial waste heat, or the waste heat from a gas turbine (making it a combined cycle.) Steam turbines offer a wide array of designs and complexity to match the desired application and/or performance specifications ranging from single stage backpressure or condensing turbines for low power ranges to complex multi-stage turbines for higher power ranges. Steam turbines for utility service may have several pressure casings and elaborate design features, all designed to maximize the efficiency of the system. For industrial applications, steam turbines are generally of simpler single casing design and less complicated for reliability and cost reasons. CHP can be adapted to both utility and industrial steam turbine designs.

- ***Gas turbines***, as shown, make up over 60 percent of CHP system capacity. It is the same technology that is used in jet aircraft and many *aeroderivative* gas turbines used in stationary applications are versions of the same engines. Gas turbines can be made in a wide range of sizes from microturbines (to be described separately) to very large *frame* turbines used for central station power generation. For CHP applications, their most economic application range is in sizes greater than 5 MW with sizes ranging into the hundreds of megawatts. The high temperature heat from the turbine exhaust can be used to produce high pressure steam, making gas turbine CHP systems very attractive for process industries.

- ***Microturbines***, as already indicated, are very small gas turbines. They were developed as stationary and transportation power sources within the last 30 years. They were originally based on the truck turbocharger technology that captures the energy in engine exhaust heat to compress the engine's inlet air. Microturbines are clean-burning, mechanically simple, and very compact. There were a large number of competing systems under development throughout the 1990s. Today, following a period of market consolidation, there are two manufacturers in the U.S. providing commercial systems for CHP use with capacities ranging from 30-250 kW for single turbine systems with multiple turbine packages available up to 1,000 kW.
- ***Fuel cells*** use an electrochemical or battery-like process to convert the chemical energy of hydrogen into water and electricity. In CHP applications, heat is generally recovered in the form of hot water or low-pressure steam (<30 psig) and the quality of heat is dependent on the type of fuel cell and its operating temperature. Fuel cells use hydrogen, which can be obtained from natural gas, coal gas, methanol, and other hydrocarbon fuels. Fuel cells are characterized by the type of electrochemical process utilized, and there are several competing types, phosphoric acid (PAFC), proton exchange membrane (PEMFC), molten carbonate (MCFC), solid oxide (SOFC), and alkaline (AFC). PAFC systems are commercially available in two sizes, 200 kW and 400 kW, and two MCFC systems are commercially available, 300 kW and 1200 kW. Fuel cell capital costs remain high due to low-volume custom production methods, but they remain in demand for CHP applications because of their low air emissions, low-noise, and generous market subsidies.

Table 1-2 and **Table 1-3** provide a summary of the key cost and performance characteristics of the CHP technologies discussed in the CHP Technology Guide.

Table 1-2. Summary of CHP Technology Advantages and Disadvantages

CHP system	Advantages	Disadvantages	Available sizes
Spark ignition (SI) reciprocating engine	• High power efficiency with part-load operational flexibility. • Fast start-up. • Relatively low investment cost. • Has good load following capability. • Can be overhauled on site with normal operators. • Operate on low-pressure gas.	• High maintenance costs. • Limited to lower temperature cogeneration applications. • Relatively high air emissions. • Must be cooled even if recovered heat is not used. • High levels of low frequency noise.	1 kW to 10 MW in DG applications
Compression ignition (CI) reciprocating engine (dual fuel pilot ignition)			High speed (1,200 RPM) ≤4MW < 80 MW for Low speed (60-275 RPM)

Table 1-2. Summary of CHP Technology Advantages and Disadvantages

CHP system	Advantages	Disadvantages	Available sizes
Steam turbine	• High overall efficiency – steam to power. • Can be mated to boilers firing a variety of gaseous, liquid or solid fuels. • Ability to meet more than one site heat grade requirement. • Long working life and high reliability. • Power to heat ratio can be varied.	• Slow start up. • Very low power to heat ratio. • Requires a boiler or other steam source.	50 kW to several hundred MWs
Gas turbine	• High reliability. • Low emissions. • High grade heat available. • No cooling required.	• Require high pressure gas or in-house gas compressor. • Poor efficiency at low loading. • Output falls as ambient temperature rises.	500 kW to 300 MW
Microturbine	• Small number of moving parts. • Compact size and light weight. • Low emissions. • No cooling required.	• High costs. • Relatively low mechanical efficiency. • Limited to lower temperature cogeneration applications.	30 kW to 250 kW with multiple unit packages up to 1,000 kW
Fuel cells	• Low emissions and low noise. • High efficiency over load range. • Modular design.	• High costs. • Fuels require processing unless pure hydrogen is used. • Sensitive to fuel impurities. • Low power density.	5 kW to 2 MW

Table 1-3. Comparison of CHP Technology Sizing, Cost, and Performance Parameters

Technology	Recip. Engine	Steam Turbine	Gas Turbine	Microturbine	Fuel Cell
Electric efficiency (HHV)	27-41%	5-40+%[2]	24-36%	22-28%	30-63%
Overall CHP efficiency (HHV)	77-80%	near 80%	66-71%	63-70%	55-80%
Effective electrical efficiency	75-80%	75-77%	50-62%	49-57%	55-80%
Typical capacity (MW_e)	.005-10	0.5-several hundred MW	0.5-300	0.03-1.0	200-2.8 commercial CHP
Typical power to heat ratio	0.5-1.2	0.07-0.1	0.6-1.1	0.5-0.7	1-2
Part-load	ok	ok	poor	ok	good
CHP Installed costs ($\$/kW_e$)	1,500-2,900	$670-1,100	1,200-3,300 (5-40 MW)	2,500-4,300	5,000-6,500
Non-fuel O&M costs ($\$/kWh_e$)	0.009-0.025	0.006 to 0.01	0.009-0.013	0.009-.013	0.032-0.038
Availability	96-98%	72-99%	93-96%	98-99%	>95%
Hours to overhauls	30,000-60,000	>50,000	25,000-50,000	40,000-80,000	32,000-64,000
Start-up time	10 sec	1 hr - 1 day	10 min - 1 hr	60 sec	3 hrs - 2 days
Fuel pressure (psig)	1-75	n/a	100-500 (compressor)	50-140 (compressor)	0.5-45
Fuels	natural gas, biogas, LPG, sour gas, industrial waste gas, manufactured gas	all	natural gas, synthetic gas, landfill gas, and fuel oils	natural gas, sour gas, liquid fuels	hydrogen, natural gas, propane, methanol
Uses for thermal output	space heating, hot water, cooling, LP steam	process steam, district heating, hot water, chilled water	heat, hot water, LP-HP steam	hot water, chiller, heating	hot water, LP-HP steam
Power Density (kW/m^2)	35-50	>100	20-500	5-70	5-20
NO_x (lb/MMBtu) (not including SCR)	0.013 rich burn 3-way cat. 0.17 lean burn	Gas 0.1-.2 Wood 0.2-.5 Coal 0.3-1.2	0.036-0.05	0.015-0.036	0.0025-.0040
NO_x ($lb/MWh_{TotalOutput}$) (not including SCR)	0.06 rich burn 3-way cat. 0.8 lean burn	Gas 0.4-0.8 Wood 0.9-1.4 Coal 1.2-5.0.	0.52-1.31	0.14-0.49	0.011-0.016

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[2] Power efficiencies at the low end are for small backpressure turbines with boiler and for large supercritical condensing steam turbines for power generation at the high end.

Key comparisons shown in **Table 1-3** are described in more detail below:

- **Electric efficiency** varies by technology and by size with larger systems of a given technology generally more efficient than smaller systems. There is overlap in efficiency ranges among the five technology classes, but, in general, the highest electric efficiencies are achieved by fuel cells, followed by large reciprocating engines, simple cycle gas turbines, microturbines, and then steam turbines. The highest electric efficiencies are achievable by large gas turbines operating in combined cycle with steam turbines that convert additional heat into electricity.
- **Overall CHP efficiency** is more uniform across technology types. One of the key features of CHP is that inefficiencies in electricity generation increase the amount of heat that can be utilized for thermal processes. Therefore, the combined electric and thermal energy efficiency remains in a range of 65-80 percent. The overall efficiency is dependent on the quality of the heat delivered. Gas turbines that deliver high pressure steam for process use have lower overall efficiencies than microturbines, reciprocating engines, and fuel cells that are assumed, in this comparison, to deliver hot water.
- **Installed capital costs** include the equipment (prime mover, heat recovery and cooling systems, fuel system, controls, electrical, and interconnect) installation, project management, engineering, and interest during construction for a simple installation with minimal need for site preparation or additional utilities. The costs are for an average U.S. location; high cost areas would cost more. The lowest unit capital costs are for the established mature technologies (reciprocating engines, gas turbines, steam turbines) and the highest costs are for the two small capacity, newer technologies (microturbines and fuel cells.) Also, larger capacity CHP systems within a given technology class have lower installed costs than smaller capacity systems.
- **Non-fuel O&M costs** include routine inspections, scheduled overhauls, preventive maintenance, and operating labor. As with capital costs, there is a strong trend for unit O&M costs to decline as systems get larger. Among technology classes gas turbines and microturbines have lower O&M costs than comparably sized reciprocating engines. Fuel cells have shown high O&M costs in practice, due in large part to the need for periodic replacement of the expensive stack assembly.
- **Start-up times** for the five CHP technologies described in this Guide can vary significantly. Reciprocating engines have the fastest start-up capability, which allows for timely resumption of the system following a maintenance procedure. In peaking or emergency power applications, reciprocating engines can most quickly supply electricity on demand. Microturbines and gas turbines have a somewhat longer start-up time to “spool-up” the turbine to operating speed. Heat recovery considerations may constrain start-up times for these systems. Steam turbines, on the other hand, require long warm-up periods in order to obtain reliable service and prevent excessive thermal expansion, stress and wear. Fuel cells also have relatively long start-up times (especially for those systems using a high temperature electrolyte.). The longer start-up times for steam turbines and fuel cells make them less attractive for start-stop or load following operation.
- **Availability** indicates the amount of time a unit can be used for electricity and/or steam production. Availability generally depends on the operational conditions of the unit. Measurements of systems in the field have shown that availabilities for gas turbines, steam turbines, and reciprocating engines are typically 95 percent and higher. Early fuel cell and

microturbine installations experienced availability problems; however, commercial units put in service today should also show availabilities over 95 percent.

1.2 CHP Efficiency Compared to Separate Heat and Power

Many of the benefits of CHP stem from the relatively high efficiency of CHP systems compared to other systems. Because CHP systems simultaneously produce electricity and useful thermal energy, CHP efficiency is measured and expressed in a number of different ways.[3] A brief discussion of these measures is provided below, while Appendix A provides a more detailed discussion.

The efficiency of electricity generation in power-only systems is determined by the relationship between net electrical output and the amount of fuel used for the power generation. **Heat rate**, the term often used to express efficiency in such power generation systems, is represented in terms of Btus of fuel consumed per kWh of electricity generated. However, CHP plants produce useful heat as well as electricity. In CHP systems, the **total CHP efficiency** seeks to capture the energy content of both electricity and usable steam and is the net electrical output plus the net useful thermal output of the CHP system divided by the fuel consumed in the production of electricity and steam. While total CHP efficiency provides a measure for capturing the energy content of electricity and steam produced it does not adequately reflect the fact that electricity and steam have different qualities. The quality and value of electrical output is higher relative to heat output and is evidenced by the fact that electricity can be transmitted over long distances and can be converted to other forms of energy. To account for these differences in quality, the Public Utilities Regulatory Policies Act of 1978 (PURPA) discounts half of the thermal energy in its calculation of the efficiency standard ($\mathrm{Eff}_{\mathrm{FERC}}$). The $\mathrm{EFF}_{\mathrm{FERC}}$ is represented as the ratio of net electric output plus half of the net thermal output to the total fuel used in the CHP system.

Another definition of CHP efficiency is **effective electrical efficiency**, also known as **fuel utilization effectiveness (FUE)**. This measure expresses CHP efficiency as the ratio of net electrical output to net fuel consumption, where net fuel consumption excludes the portion of fuel that goes to producing useful heat output. FUE captures the value of both the electrical and thermal outputs of CHP plants and it specifically measures the efficiency of generating power through the incremental fuel consumption of the CHP system.

EPA considers fuel savings as the appropriate term to use when discussing CHP benefits relative to separate heat and power (SHP) operations. Fuel savings compares the fuel used by the CHP system to a separate heat and power system (i.e. boiler and electric-only generation). Positive values represent fuel savings while negative values indicate that the CHP system in question is using more fuel than separate heat and power generation.

Figure 1-1 shows the efficiency advantage of CHP compared with conventional central station power generation and onsite boilers. When considering both thermal and electrical processes together, CHP typically requires only ¾ the primary energy separate heat and power systems require. CHP systems

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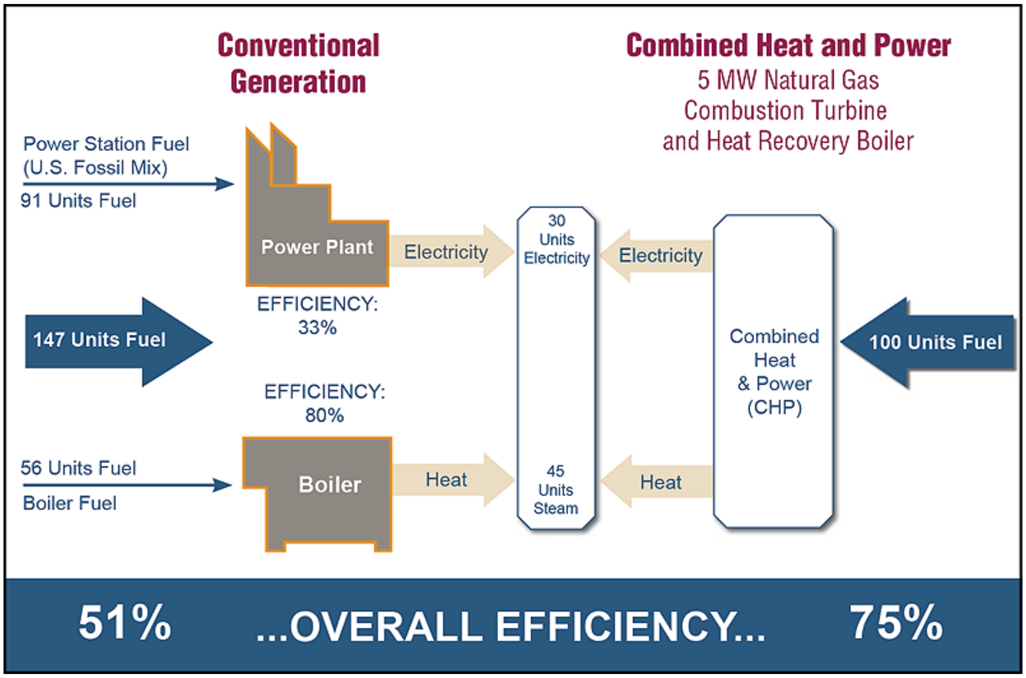
[3] Measures of efficiency are denoted either as lower heating value (LHV) or higher heating value (HHV). HHV includes the heat of condensation of the water vapor in the products. Unless otherwise noted, all efficiency measures in this section are reported on an HHV basis.

utilize less fuel than separate heat and power generation, resulting for the same level of output, resulting in fewer emissions.

Figure 1-1. CHP versus Separate Heat and Power (SHP) Production[4]



Another important concept related to CHP efficiency is the **power-to-heat ratio**. The power-to-heat ratio indicates the proportion of power (electrical or mechanical energy) to heat energy (steam or hot water) produced in the CHP system. Because the efficiencies of power generation and steam generation are likely to be considerably different, the power-to-heat ratio has an important bearing on how the total CHP system efficiency might compare to that of a separate power-and-heat system. **Figure 1-2** illustrates this point. The figure shows how the overall efficiency might change under alternate power-to-heat ratios for a separate power-and-heat system and a CHP system.

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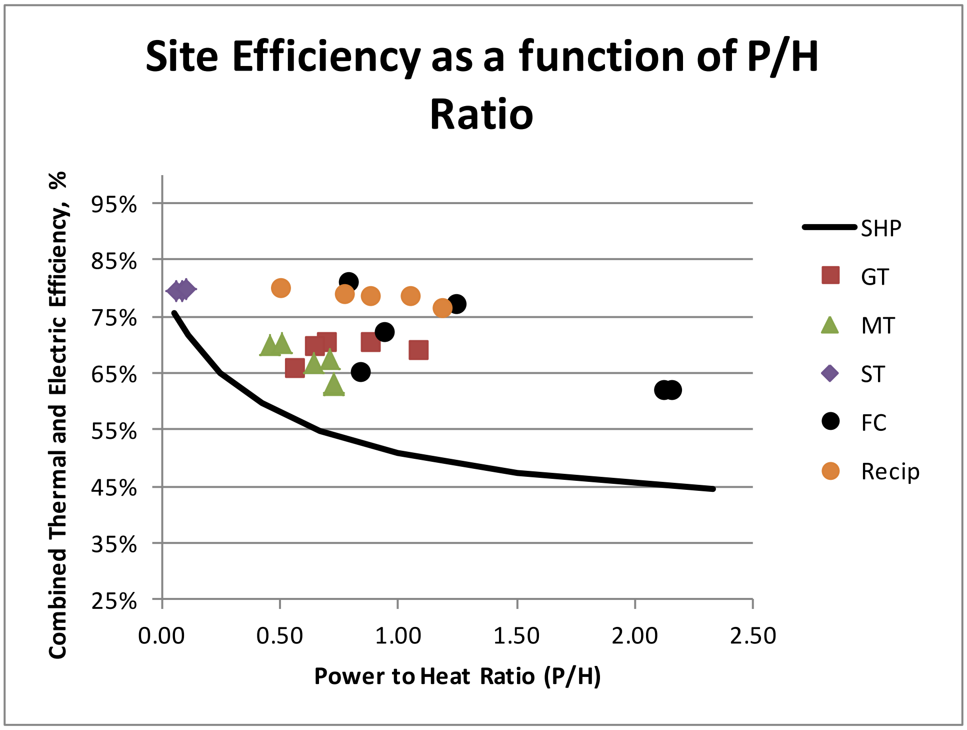
[4] In this example of a typical CHP system, to produce 75 units of useful energy, the conventional generation or separate heat and power systems use 147 units of energy—91 for electricity production and 56 to produce heat—resulting in an overall efficiency of 51 percent. However, the CHP system needs only 100 units of energy to produce the 75 units of useful energy from a single fuel source, resulting in a total system efficiency of 75 percent.

Figure 1-2. Equivalent Separate Heat and Power Efficiency



SHP assumes 35.7 percent efficient electric and 80 percent efficient thermal generation

CHP overall thermal and electric efficiencies are higher than corresponding efficiencies for SHP across the range of power-to-heat ratios. However, as shown the SHP efficiency varies as a function of how much of the lower efficiency electricity is supplied versus the higher efficiency thermal energy. At very low power-to-heat ratios, as is typical for steam turbine systems, CHP is above the SHP line, but only by a few percentage points. As electric efficiencies of the CHP systems get higher (and corresponding p/h ratios increase), the relative improvement of CHP compared to SHP increases dramatically.

1.3 Emissions

In addition to cost savings, CHP technologies offer significantly lower emissions rates compared to separate heat and power systems. The primary pollutants from gas turbines are oxides of nitrogen (NO_x), carbon monoxide (CO), and volatile organic compounds (VOCs) (unburned, non-methane hydrocarbons). Other pollutants such as oxides of sulfur (SO_x) and particulate matter (PM) are primarily dependent on the fuel used. Similarly, emissions of carbon dioxide are also dependent on the fuel used. Many gas turbines burning gaseous fuels (mainly natural gas) feature lean premixed burners (also called dry low-NO_x burners) that produce NO_x emissions ranging between 0.17 to 0.25 lbs/MWh[5] with no post-combustion emissions control. Typically commercially available gas turbines have CO emissions rates ranging between 0.23 lbs/MWh and 0.28 lbs/MWh. Selective catalytic reduction (SCR) or catalytic combustion can further help to reduce NO_x emissions by 80 percent to 90 percent from the gas turbine

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[5] The NO_x emissions reported in this section in lb/MWh are based on the total electric and thermal energy provided by the CHP system in MWh.

exhaust and carbon-monoxide oxidation catalysts can help to reduce CO by approximately 90 percent. Many gas turbines sited in locales with stringent emission regulations use SCR after-treatment to achieve extremely low NO_x emissions.

Microturbines have the potential for low emissions. All microturbines operating on gaseous fuels feature lean premixed (dry low NO_x, or DLN) combustor technology. The primary pollutants from microturbines include NO_x, CO, and unburned hydrocarbons. They also produce a negligible amount of SO_2. Microturbines are designed to achieve low emissions at full load and emissions are often higher when operating at part load. Typical NO_x emissions for microturbine systems range between 4 ppmv and 9 ppmv or 0.08 lbs/MWh and 0.20 lbs/MWh. Additional NO_x emissions removal from catalytic combustion in microturbines is unlikely to be pursued in the near term because of the dry low NO_x technology and the low turbine inlet temperature. CO emissions rates for microturbines typically range between 0.06 lbs/MWh and 0.54 lbs/MWh.

Exhaust emissions are the primary environmental concern with reciprocating engines. The primary pollutants from reciprocating engines are NO_x, CO, and VOCs. Other pollutants such as SO_x and PM are primarily dependent on the fuel used. The sulfur content of the fuel determines emissions of sulfur compounds, primarily SO_2. NO_x emissions from small “rich burn” reciprocating engines with integral 3-way catalyst exhaust treatment can be as low as 0.06 lbs/MWh. Larger lean burn engines have values of around 0.8 lbs/MWh without any exhaust treatment; however, these engines can utilize SCR for NO_x reduction.

Emissions from steam turbines depend on the fuel used in the boiler or other steam sources, boiler furnace combustion section design, operation, and exhaust cleanup systems. Boiler emissions include NO_x, SO_x, PM, and CO. Typical boiler emissions rates for NO_x range between 0.3 lbs/MMBtu and 1.24 lbs/MMBtu for coal, 0.2 lbs/MMBtu and 0.5 lbs/MMBtu for wood, and 0.1 lbs/MMBtu and 0.2 lbs/MMBtu for natural gas. Uncontrolled CO emissions rates range between 0.02 lbs/MMBtu and 0.7 lbs/MMBtu for coal, approximately 0.06 lbs/MMBtu for wood, and 0.08 lbs/MMBtu for natural gas. A variety of commercially available combustion and post-combustion NO_x reduction techniques exist with selective catalytic reductions achieving reductions as high as 90 percent.

Fuel cell systems have inherently low emissions profiles because the primary power generation process does not involve combustion. The fuel processing subsystem is the only significant source of emissions as it converts fuel into hydrogen and a low energy hydrogen exhaust stream. The hydrogen exhaust stream is combusted in the fuel processor to provide heat, achieving emissions signatures of less than 0.019 lbs/MWh of CO, less than 0.016 lbs/MWh of NO_x and negligible SO_x without any after-treatment for emissions. Fuel cells are not expected to require any emissions control devices to meet current and projected regulations.

Other pollutants such as SO_x and PM are primarily dependent on the fuel used. CHP technologies that could use fuels other than natural gas, including reciprocating engines and steam turbines, could also incur other emissions from its fuel choice. For example, the sulfur content of the fuel determines emissions of sulfur compounds, primarily SO_2.

SO$_2$ emissions from steam turbines depend largely on the sulfur content of the fuel used in the combustion process. SO$_2$ comprises about 95 percent of the emitted sulfur and the remaining 5 percent is emitted as sulfur tri-oxide (SO$_3$). Flue gas desulphurization (FGD) is the most commonly used post-combustion SO$_2$ removal technology and is applicable to a broad range of different uses. FGD can provide up to 95 percent SO$_2$ removal.

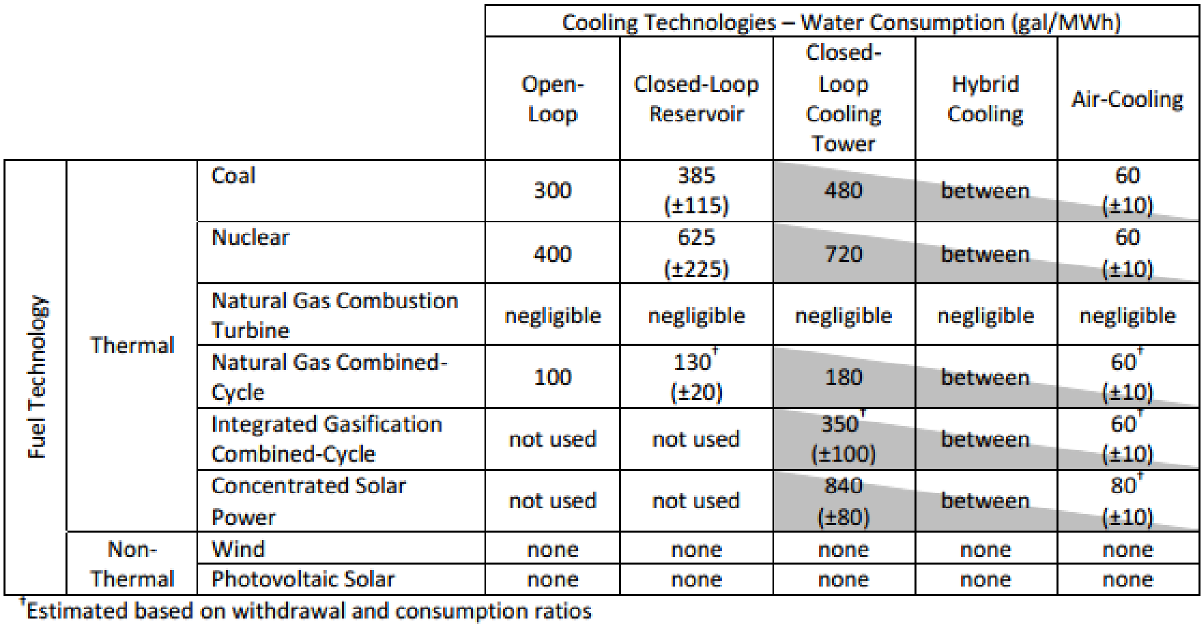
CO$_2$ emissions result from the use the fossil fuel-based CHP technologies. The amount of CO$_2$ emitted in any of the CHP technologies discussed above depends on the fuel carbon content and the system efficiency. The fuel carbon content of natural gas is 34 lbs carbon/MMBtu; oil is 48 lbs of carbon/MMBtu and ash-free coal is 66 lbs of carbon/MMBtu.

1.4 Comparison of Water Usage for CHP compared to SHP

Water is critical in all stages of energy production, from drilling for oil and gas to electricity production. As water supply levels are being challenged by continuing and severe droughts, especially in the Southeast and Western regions of the U.S., as well as increasing demand and regulations, water requirements and usage are becoming important considerations in energy production.

According to the U.S. Geological Survey (USGS), thermoelectric power, which uses water for cooling steam turbines, accounts for the largest share of water withdrawal in the U.S., at 49 percent in 2005 (latest year data are available). **Table 1-4** shows the water consumption (gal/MWh) by SHP technology and cooling technology.

Table 1-4. Water Consumption by SHP Technology, Cooling Technology[6]



			Cooling Technologies – Water Consumption (gal/MWh)				
			Open-Loop	Closed-Loop Reservoir	Closed-Loop Cooling Tower	Hybrid Cooling	Air-Cooling
Fuel Technology	Thermal	Coal	300	385 (±115)	480	between	60 (±10)
		Nuclear	400	625 (±225)	720	between	60 (±10)
		Natural Gas Combustion Turbine	negligible	negligible	negligible	negligible	negligible
		Natural Gas Combined-Cycle	100	130† (±20)	180	between	60† (±10)
		Integrated Gasification Combined-Cycle	not used	not used	350† (±100)	between	60† (±10)
		Concentrated Solar Power	not used	not used	840 (±80)	between	80† (±10)
	Non-Thermal	Wind	none	none	none	none	none
		Photovoltaic Solar	none	none	none	none	none

†Estimated based on withdrawal and consumption ratios

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[6] Stillwell, Ashlynn S., et al, Energy-Water Nexus in Texas, The University of Texas at Austin and Environmental Defense Fund, April 2009.

The role of CHP technologies could be critical in water issues, as CHP systems, particularly reciprocating engine, combustion turbine, microturbines, and fuel cells, use almost negligible amounts of water. A boiler/steam turbine CHP system water consumption would be similar to the SHP technology shown in **Table 1-4**.

1.5 Outlook

In the last twenty years, there has been substantial improvement in gas turbine technology with respect to power, efficiency, durability, emissions, and time/cost to market. These improvements have been the combined results of collaborative research efforts by private industry, universities, and the federal government. Public-private partnerships such as the DOE Advanced Turbine Systems Program and the Next Generation Turbine program have advanced gas turbine technology. Current collaborative research is focusing on both large gas turbines and those applicable for distributed generation. Large gas turbine research is focused on improving the efficiency of combined cycle plants to 65 percent (LHV), reducing emission even further, and integrating gas turbines with clean coal gasification and carbon capture. The focus for smaller gas turbines is on improving performance, enhancing fuel flexibility, reducing emissions, reducing life cycle costs, and integration with improved thermal utilization technologies. Continued development of aeroderivative gas turbines for civilian and military propulsion will provide carryover benefits to stationary applications. Long-term research includes the development of hybrid gas turbine fuel cell technology that is capable of 70 percent (LHV) electric efficiency.

Microturbine manufacturers are continuing to develop products with higher electrical efficiencies. Working cooperatively with the Department of Energy, Capstone is developing a 250 kW model with a target efficiency of 35 percent (gross output, LHV) and a 370 kW model with a projected 42 percent efficiency. The C250 will feature an advanced aerodynamic compressor design, engine sealing improvements, improved generator design with longer life magnet, and enhanced cooling. The project will use a modified Capstone C200 turbocompressor assembly as the low-pressure section of a two shaft turbine. This low-pressure section will have an electrical output of 250 kW. A new high-temperature, high-pressure turbocompressor assembly will increase the electrical output to 370 kW. Product development in microturbines over the years has been to achieve efficiency and cost reductions by increasing the capacity of the products. Starting with original products in the 30-50 kW range, microturbine manufacturers have developed and are continuing to develop increasingly larger products that compete more directly with larger reciprocating gas engines and even small simple cycle gas turbines.

Public-private partnerships such as the DOE Advanced Reciprocating Engine System (ARES) funded by DOE and the Advanced Reciprocating Internal Combustion Engine (ARICE) program funded by the California Energy Commission have focused attention on the development of the next generation reciprocating engine. The original goals of the ARES program were to achieve 50 percent brake thermal efficiency (LHV) , NO_x emissions to less than 1 g/bhp-hr (0.3 lb/MWh), and maintenance costs of $0.01/kWh, all while maintaining cost competitiveness. The development focus under ARES includes:

- Combustion chamber design
- Friction reduction
- Combustion of dilute mixtures

- Turbocompounding
- Modified or alternative engine cycles
- Exhaust energy retention
- Exhaust after-treatment – improving SCR and TWC operation and proving the operation of Lean NO_x catalyst (LNC)
- Water injection
- High power density
- Multiple source ignition

The U.S. DOE funds collaborative research and development toward the development of improved ultra-supercritical (USC) steam turbines capable of efficiencies of 55-60 percent that are based on boiler tube materials that can withstand pressures of up to 5,000 psi and temperatures of 1,400 ^{o}F. To achieve these goals, work is ongoing in materials, internal design and construction, steam valve development, and design of high pressure casings. A prototype is targeted for commercial testing by 2025. Research is also underway to restore and improve the performance of existing steam turbines in the field through such measures as improved combustion systems for boilers, heat transfer and aerodynamics to improve turbine blade life and performance, and improved materials to permit longer life and higher operating temperatures for more efficient systems.

The focus on emerging markets such as waste heat recovery and biomass-fueled power and CHP plants is stimulating the demand for small and medium steam turbines. Technology and product development for these markets should bring about future improvements in steam turbine efficiency, longevity, and cost. This could be particularly true for systems below 500 kW that are used in developmental small biomass systems and in waste-heat-to-power systems designed to operate in place of pressure reduction valves in commercial and industrial steam systems operating at multiple pressures.