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

Combined Heat
and Power
Technology Fact
Sheet Series

CHP Technologies:
Gas Turbines

Gas turbines, also called combustion turbines, are used in diverse applications including propulsion (e.g., aircraft, ships, and trains), direct drive (e.g., pumps and compressors), and electricity generation. Gas turbines produce large volumes of high-temperature waste heat, which can be used in combined heat and power (CHP) applications, especially sites that require steam. Gas turbines are available from several manufacturers and can be operated on a wide range of fuels, including natural gas and hydrogen.

Gas Turbine Installation at a University.

Photo courtesy of Solar Turbines

Gas Turbines for CHP

Gas turbines are a mature technology and have been used for decades to generate electricity at power plants and industrial facilities. Simple cycle gas turbines can reach capacities up to 400 MW and can be integrated with steam turbines to achieve even higher capacities in combined cycle power plants.[1] Gas turbines have exhaust temperatures of 800°F or higher, which makes the technology well suited for CHP installations. Depending on site requirements, thermal energy from gas turbine exhaust can be used to produce steam, hot water, chilled water, or used for direct process heating or drying. Table 1 provides a summary of gas turbine attributes.

Gas turbines smaller than 1 MW are often referred to as microturbines. While gas turbines and microturbines operate with similar thermodynamic principles, there are design and operating characteristics that separate the two technologies. Microturbines are discussed in a separate fact sheet.[2]

Table 1. Summary of Gas Turbine Attributes for CHP Applications

Attribute	Description
Size Range	Simple cycle gas turbines for CHP are available in sizes from approximately 2 to 400 MW.
Thermal Output	Gas turbine exhaust is 800°F or higher and can be used to produce steam, hot water, or chilled water (with an absorption chiller), or used for direct process heating or drying.
Start-Up	Large gas turbines and combined cycle systems have longer start-up times than smaller aeroderivative gas turbines, which can reach full capacity in 10 minutes.
Part-Load Operation	The electrical generation efficiency of gas turbines declines as the load decreases. Therefore, gas turbines provide the best economic performance in base load applications where systems operate at, or near, full load.
Fuel	Gas turbines can be operated with a wide range of gaseous and liquid fuels. For CHP, natural gas is the most common fuel, although hydrogen is gaining traction as manufacturers introduce gas turbines designed for hydrogen operation.
Reliability	Gas turbines are a mature technology and routinely operate with 95% or higher availability.[a]
Other	Gas turbines have low NOx and CO emissions and can be sited in many locations with no additional emission control hardware.

Notes:

a) Availability based on information provided by solution providers listed in DOE Combined Heat & Power eCatalog, Link.

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[1] In a combined cycle system, exhaust from a gas turbine is used to generate steam, and this steam is then supplied to a steam turbine to produce additional power. Steam exiting the steam turbine can be recovered to meet thermal loads.

[2] Department of Energy (DOE), Combined Heat and Power Technology Fact Sheet Series, CHP Technologies: Microturbines, 2024.

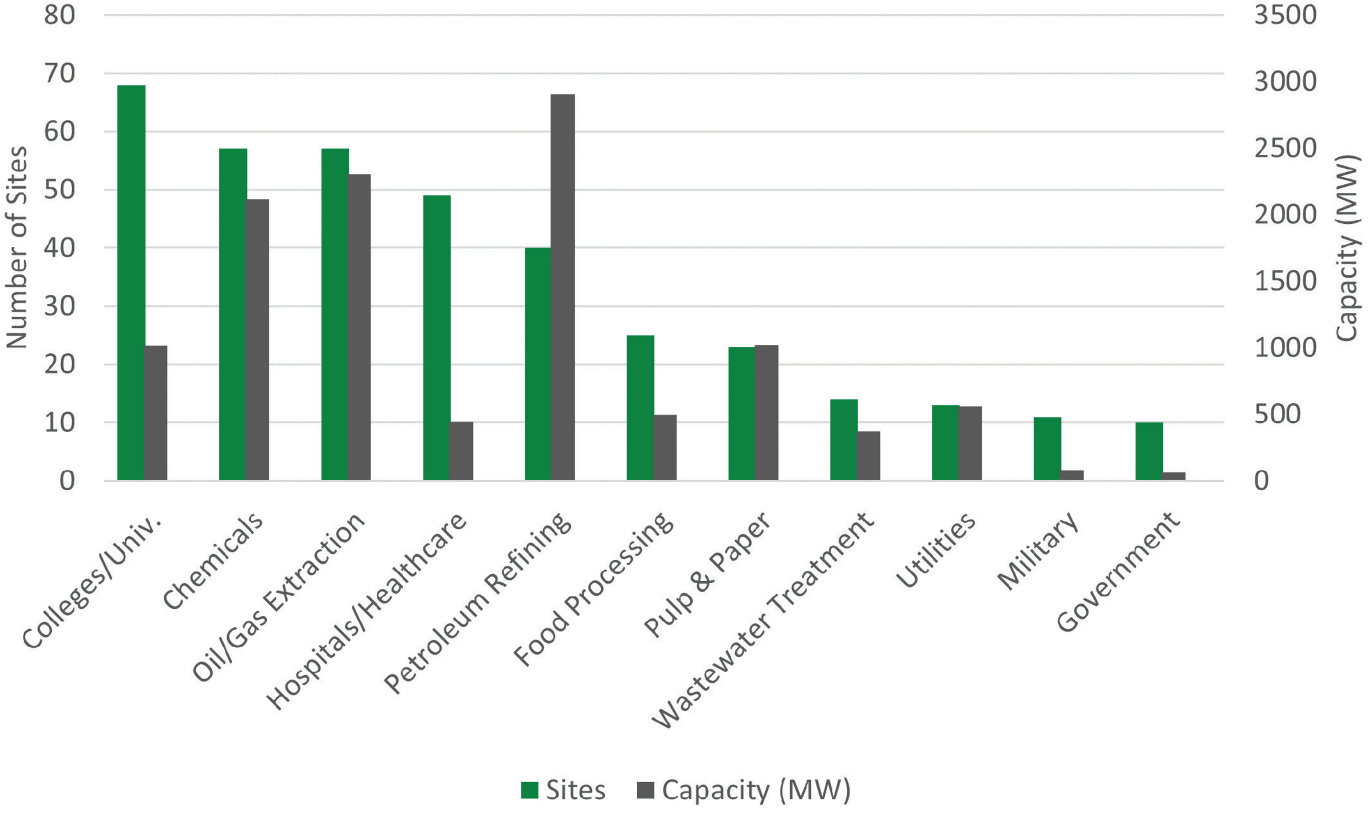

Figure 1. Number of CHP Gas Turbine Installations and Total Capacity by Application

Applications

Gas turbines, including combined cycle systems, account for 56 GW of installed CHP capacity in the United States, representing 70% of the total installed CHP capacity.[3] More than 75% of this gas turbine CHP capacity is in large combined cycle systems. The remaining gas turbine CHP capacity (14 GW) is made up of simple cycle gas turbine CHP systems, typically less than 40 MW in size. Although combined cycle turbines represent a larger share of capacity, simple cycle gas turbines are installed at over twice as many sites across the United States, primarily in the industrial sector.

Gas turbines are ideally suited for industrial CHP applications because high-temperature turbine exhaust can be used to generate steam at conditions up to, or beyond, 1,200 psig and 900°F. In addition to producing steam, gas turbine exhaust can be used directly for industrial process heating or drying. Gas turbines are used to produce power and meet thermal loads across the industrial and commercial sectors, including refineries, chemical plants, pulp and paper, food processing, universities, hospitals, military bases, and a variety of other commercial/institutional sites. Figure 1 shows common applications for simple cycle gas turbine CHP systems, including the number of existing sites and total capacity.

Gas turbines can operate on a wide variety of liquid and gaseous fuels. For CHP applications, natural gas is the most common fuel currently used, although many sites use renewable fuels, such as anaerobic digester gas, which is produced at wastewater treatment plants, agriculture and dairy operations, and certain chemical and food processing plants. CHP systems in refineries and petrochemical plants often operate on process off-gases that contain relatively high levels of hydrogen. Hydrogen fuel, especially hydrogen produced using renewable electricity, offers another pathway to reduce or eliminate carbon emissions. Most turbine manufacturers currently have systems that operate on varying levels of hydrogen blends, and the major companies are developing gas turbines optimized for 100% hydrogen for commercial introduction by 2030. Many of these offerings will include field retrofit solutions that upgrade in-service gas turbines for operation on high hydrogen blends and/or 100% hydrogen fuel.

Technology Description

Gas turbines are constant pressure open cycle heat engines that follow the Brayton thermodynamic cycle. In a gas turbine (see Figure 2), air is compressed and then mixed with fuel in a combustion chamber. Fuel is supplied at high pressure (e.g., 200–400 psig) to the combustion chamber, with the required

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[3] DOE Combined Heat and Power Installation Database, November 2023, Link.

pressure determined by the number of compressor stages and pressure ratio. If the fuel supply pressure at the site is not sufficient, a fuel gas compressor is used to boost the fuel pressure. Hot combustion gas flows from the combustion chamber through a turbine, which rotates a mechanical shaft. The rotating shaft drives an electrical generator and the air compressor. For CHP applications, a common heat recovery configuration is to direct the exhaust from the turbine through a heat recovery steam generator (HSRG). Steam from the HRSG is then used to meet thermal loads.

Gas turbines operate at high excess air levels, resulting in high oxygen concentrations in the exhaust (e.g., 15%). This oxygen, which is at a high temperature (800°F or higher), can be used as preheated combustion air for a duct burner located at the HRSG inlet (see Figure 2). A duct burner—an optional addition to a gas turbine installation—can be incorporated if more steam output is desired from the HRSG. The elevated temperature of the gas turbine exhaust enables a duct burner to produce steam at a higher efficiency than a conventional boiler.

Gas turbine CHP systems are typically custom engineered and assembled onsite, although some gas turbine manufacturers have recently started offering packaged systems. The DOE Packaged CHP eCatalog includes gas turbine systems with electric capacities ranging from 5 to 16 MW.[4] These packaged gas turbine systems are typically delivered to the construction site in two or three pre-assembled modules (e.g., gas turbine generator set; heat recovery, exhaust stack, and exhaust clean-up hardware; and fuel equipment skids).

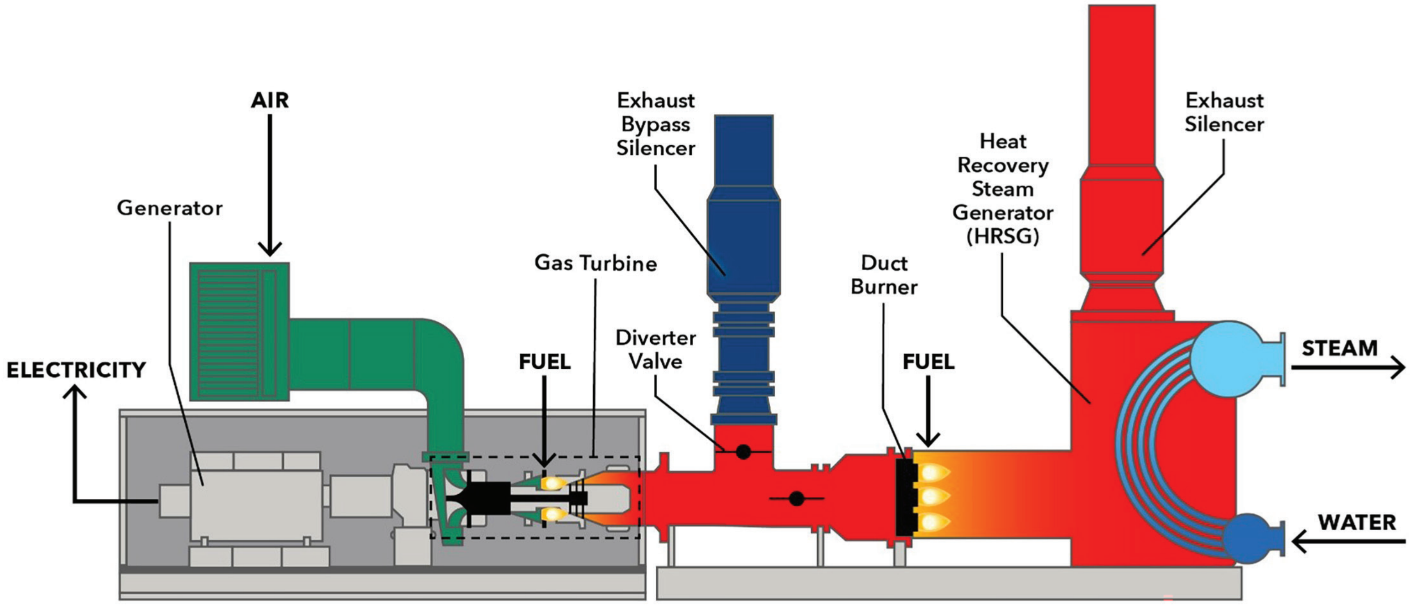

Figure 2. Simple Cycle Gas Turbine with Duct Burner and HRSG

Performance Characteristics

Table 2 shows typical technical performance characteristics for commercially available gas turbines in the range of 2 to 25 MW, all operating on natural gas at ISO[5] conditions. Performance will vary for non-ISO conditions and for turbines with different design features, such as number of compressor stages, pressure ratios, and operating temperatures. As indicated in Table 2, CHP efficiencies (sum of electric and thermal efficiency) for gas turbines without duct burners range from 63% to 71% (higher heating value [HHV], net power basis). CHP efficiencies can be higher for systems with duct burners due to high steam generation efficiencies achieved with duct burners (72% to 78% based on duct burner fired at 1,500°F).

Without a duct burner, the power to heat ratio shown in Table 2 increases from 0.55 to 1.01 as gas turbine capacity increases. Most gas turbine CHP installations are sized based on a site's thermal load. If thermal loads are relatively high compared to electricity requirements, a duct burner can be added to increase thermal output. As shown in Table 2, a duct burner significantly increases steam production, which is reflected by lower power to heat ratios (range from 0.38 to 0.64).

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[4] DOE Combined Heat & Power eCatalog, accessed October 2023, Link.

[5] ISO (International Organization for Standardization) conditions are 59°F, sea level, and 60% relative humidity.

Table 2. Gas Turbine Performance Characteristics (Natural Gas Fuel)

Description	Gross Electric Power (MW)[a]						
	2.0	3.5	5.0	8.0	10	15	25
Net Electric Power (MW)[b]	1.98	3.47	4.95	7.92	9.90	14.9	24.8
Fuel Input (MMBtu/hr, HHV)[c]	30.2	47.5	64.4	88.2	115	160	243
Electric Efficiency (%, HHV, net power basis)	22.3%	24.9%	26.2%	30.6%	29.4%	31.7%	34.7%
Thermal Recovery Without Duct Burner – 145 psi saturated steam							
Useful Steam Energy (MMBtu/hr)	12.3	19.5	27.5	35.6	46.1	58.5	84.0
Thermal Efficiency (%, HHV)	40.7%	41.1%	42.6%	40.3%	40.2%	36.6%	34.6%
Power to Heat Ratio	0.55	0.61	0.61	0.76	0.73	0.87	1.01
CHP Efficiency (%, HHV, net power basis)[d]	63.0%	66.0%	68.9%	70.9%	69.6%	68.2%	69.3%
Thermal Recovery with Duct Burner – fired to 1,500 °F, 145 psi saturated steam							
Useful Steam Energy (MMBtu/hr)	28.1	49.1	53.9	68.4	97.9	128.2	196.6
Additional Fuel (MMBtu/hr, HHV)	17.8	31.2	27.9	34.8	55.3	73.8	119.4
Duct Burner Efficiency (%, HHV)	88.5%	94.9%	94.4%	94.3%	93.8%	94.4%	94.3%
Thermal Efficiency (%, HHV)	58.4%	62.5%	58.3%	55.6%	57.6%	54.8%	54.2%
Power to Heat Ratio	0.38	0.40	0.45	0.55	0.51	0.58	0.64
CHP Efficiency (%, HHV, net power basis)	72.5%	77.5%	76.6%	77.5%	77.4%	76.5%	77.5%

Notes:

a) Performance characteristics are compiled from multiple sources and do not represent a specific product.

b) Parasitic power is assumed to be 1% of gross power, not including fuel gas compressor. Net power equals gross power minus parasitic power.

c) All calculations are based on HHV of fuel.

d) Overall efficiency is sum of electric and thermal efficiency. Total may differ due to rounding.

Capital and O&M Costs

Table 3 presents estimated installed capital costs for typical gas turbine CHP systems divided into four categories:

- **Gas Turbine** – The gas turbine cost represents a basic system that includes a gas turbine, gearbox, generator, inlet exhaust ducting, inlet air filtration, and starting system. The baseline cost applies to natural gas operation and does not include a fuel gas compressor, dual fuel capability, inlet air cooling, after treatment emission control hardware, or a continuous emission monitoring system.

- **Heat Recovery Steam Generator (HRSG)** – HRSG costs are based on operation without a duct burner. A duct burner, if included, requires a more expensive HRSG designed to operate at higher steam flow rates and/or tolerate higher exhaust temperatures.

- **Balance of Plant (BOP)** – BOP costs include controls, electrical equipment (e.g., pumps and motors), mechanical equipment, and other hardware required to construct an operational CHP system configured with a basic gas turbine as described above.

- **Engineering, Construction, and Installation** – Engineering, construction, and installation costs are based on a simple installation with no unique or complicated site-specific requirements. Engineering costs do not include design and engineering time required for inlet air cooling, dual fuel operation, duct burner equipment, or emission control hardware. Construction costs include civil, mechanical, and electrical work for a straightforward installation. Costs are not included for demolition of structures or removal of unwanted equipment at the construction site. Permitting, owner's costs, land costs, taxes, and interest during construction are not included.

As indicated in Table 3, estimated capital costs for simple cycle[6] gas turbine CHP systems range from $5,200/kW for a 2 MW system to $1,700/kW for a 25 MW system. Selective catalytic reduction (SCR) emission control hardware, if required, increases capital costs by $100 to $400/kW.

Operation and maintenance (O&M) costs for basic gas turbine CHP systems are estimated to range from 1.5 to 0.9 cents/kWh (variable and fixed maintenance combined). If SCR equipment is installed, maintenance costs increase by 0.20-0.25 cents/kWh. Maintenance costs can vary significantly depending on adherence to preventive maintenance schedules and operating conditions. Recommended maintenance practices include scheduled maintenance based on run time, predictive maintenance, performance testing, and vibration analysis. Inspections are typically required every 4,000 hours to ensure that the turbine is free of excessive vibration due to worn bearings, aging rotors, or damaged blade tips. A gas turbine overhaul is needed every 25,000 to 50,000

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[6] Combined cycle gas turbine installations include a steam turbine. Steam turbine costs are discussed in a separate fact sheet.

Table 3. Gas Turbine Capital and O&M Costs

Description	Gross Electric Power (MW)[a]						
	2.0	3.5	5.0	8.0	10	15	25
Capital Costs ($/kW)[b]							
Gas Turbine (natural gas fuel, no fuel gas compressor)	$1,500	$1,250	$1,000	$900	$850	$750	$600
HRSG (no duct burner)	$600	$400	$300	$250	$180	$150	$100
BOP	$700	$600	$500	$400	$350	$300	$230
Engineering, Construction, and Installation	$2,400	$1,950	$1,600	$1,300	$1,120	$950	$770
Total Installed Cost	**$5,200**	**$4,200**	**$3,400**	**$2,850**	**$2,500**	**$2,150**	**$1,700**
Operation and Maintenance Costs (¢/kWh)							
Non-Fuel O&M	1.5	1.4	1.4	1.3	1.3	1.1	0.9
Additional Costs for SCR (90% NOx reduction)							
SCR Capital ($/kW)	$400	$300	$250	$200	$180	$140	$100
SCR O&M (¢/kWh)	0.25	0.25	0.25	0.20	0.20	0.20	0.20

Notes:
a) Costs are compiled from multiple sources and do not represent a specific product.
b) Per kW costs based on gross power.

hours, depending on service, and typically includes a complete inspection and rebuild of components to restore the gas turbine to original performance standards. Gas turbine overhaul costs are included in the O&M costs shown in Table 3.

Costs in Table 3 reflect typical, or baseline, CHP gas turbine installations. Project costs can be higher or lower based on a variety of factors including system configuration and site conditions as discussed below and shown in Figure 3:

- **Typical, or baseline, costs** (green circle in Figure 3) – Key cost factors for systems in Table 3 include a baseline gas turbine system: natural gas only (no dual fuel capability), no fuel compressor, no duct burner, no additional emission control hardware; a clean site ready for construction (i.e., no removal of existing structures or hardware); and equipment sited on new outdoor concrete pad or within an existing building.
- **Factors that increase costs** – Costs increase if the project scope expands beyond a baseline system. While these costs can vary considerably, general guidelines for additional cost factors include: fuel compressor (up to 10% of baseline costs); duct burner and corresponding HRSG upgrades (15% to 25% of baseline costs depending on firing temperature); dual fuel capability (up to 5% of baseline costs); SCR (5% to 8% of baseline costs); and/or a complex installation, need for new building, or need to remove existing structures/hardware prior to construction.
- **Factors that reduce costs** – Installation costs can be lower if the following conditions apply: CHP system delivered to site in pre-assembled modules rather than assembled onsite; equipment sited on existing outdoor concrete pad or located in existing building; simplified interconnection process (depends on local utility requirements); and/or location with competitive local labor market and experienced CHP contractors.

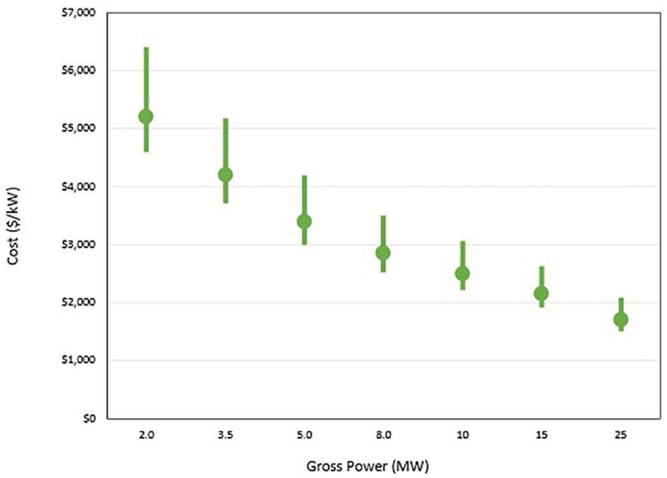

Figure 3. Installed Cost Range for Gas Turbine CHP Systems

Emissions

Gas turbine manufacturers, with support from DOE and other stakeholders, have invested substantial resources in recent decades to improve efficiency and reduce emissions. These extensive development efforts have produced advanced gas turbines with much better fuel economy and significantly lower emissions compared to gas turbines from the 1980s and 1990s. Advancements in combustor design have helped extend lean burn operating limits, improve fuel/air mixing, and reduce combustion zone temperatures. These advancements have resulted in gas turbines with inherently low emissions of nitrogen oxides (NOx), carbon monoxide (CO), and unburned hydrocarbons (UHCs). Without treatment, emission levels for turbines with dry low NOx burners are routinely <15 ppm NOx, <25 ppm CO, and <25 ppm UHC (all measured at 15% oxygen). For some gas turbines, untreated emissions are well below these levels.

Attainment and Non-Attainment Areas

The Environmental Protection Agency (EPA) has established National Ambient Air Quality Standards for six criteria pollutants. Regions that are in compliance with standards set for these pollutants are referred to as attainment areas, and regions that are out of compliance for one or more of the pollutants are designated non-attainment areas. Attainment areas present no air emission challenges for siting gas turbines. Depending on non-attainment area requirements, after treatment can be added to gas turbines to comply with emission limits. With SCR and an oxidation catalyst, gas turbine emissions can be reduced to <2.5 ppm NOx, <5 ppm CO, and <5 ppm UHC (all measured at 15% oxygen).

CO_2 Emissions

Table 4 shows CO_2 emissions for gas turbine CHP systems fueled by natural gas. The CO_2 emissions are calculated based on the assumption that thermal energy supplied by the CHP system offsets thermal energy that would otherwise be produced with an 80% efficient natural gas boiler.[7] As indicated in Table 4, effective CO_2 emissions for CHP gas turbines using natural gas range from 878 lbs/MWh (2 MW size) to 646 lbs/MWh (8 MW size). For comparison, marginal grid emissions, representing avoided emissions from reduced grid demand with consistent CHP operation, are estimated at over 1,400 lbs/MWh on average in the United States.[8] Carbon emissions for CHP installations can be further reduced, or eliminated, by using low or zero carbon fuels such as biogas, renewable natural gas, and hydrogen, especially hydrogen produced using renewable electricity and water electrolysis. ■

Table 4. Gas Turbine Emission Characteristics (Natural Gas)

Description	Gross Electric Power (MW)						
	2.0	3.5	5.0	8.0	10	15	25
Total CO_2 Emissions (lbs/MWh)[a]	1,786	1,601	1,522	1,302	1,356	1,260	1,148
CHP Effective Electric CO_2 Emissions (lbs/MWh)[b]	878	778	710	646	675	684	652

Notes:

a) CO_2 emissions based on natural gas fuel and no duct burner.

b) Effective emissions include credit based on avoided emissions from 80% efficient boiler.

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[7] Effective electric CHP CO_2 emissions is equal to CO_2 emissions from fuel chargeable to power divided by net MWh generated; fuel chargeable to power is equal to total CHP fuel input minus displaced thermal energy fuel from an 80% efficient boiler; emissions factor for natural gas is 116.9 lbs CO_2/MMBtu. For more information on CHP emission reduction calculations, see the recommended methodology from the EPA CHP Partnership, Link.

[8] 2022 AVERT uniform EE marginal emissions factor, Link.

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