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

Combined Heat and Power Technology Fact Sheet Series

CHP Technologies: Reciprocating Engines

Reciprocating internal combustion engines are a mature technology used for power generation, transportation, and many other purposes. For distributed generation applications, including combined heat and power (CHP), reciprocating engines are available from multiple manufacturers across a wide range of sizes.

Reciprocating Engines for CHP

Reciprocating engine systems have electric output capacities in the range of 1 kW to 10 MW, and can operate on various fuels, including natural gas, biogas, renewable natural gas (RNG), and hydrogen. Thermal energy from reciprocating engines can be recovered and converted to hot water, steam, chilled water, or chilled thermal fluid, making reciprocating engines well suited for a variety of CHP applications. See Table 1 for a summary of reciprocating engine attributes.

Applications

Reciprocating engines are widely used for CHP in industrial applications (e.g., food processing, manufacturing, wastewater treatment), and major building sectors including multifamily residential, commercial (e.g., nursing homes, hotels), and institutional (e.g., universities, hospitals). Reciprocating engines sized 1 MW or larger are more likely to be found in industrial and institutional CHP applications, while smaller reciprocating engines are more commonly used in the multifamily and commercial sectors. The majority (75%) of reciprocating engine CHP systems are sized under 1 MW.[5]

CHP Reciprocating Engine at an Industrial Facility.
Photo courtesy of Caterpillar

Table 1. Summary of Reciprocating Engine Attributes for CHP Applications

Attribute	Description of Reciprocating Engine Attribute
Size Range	Reciprocating engines for CHP are available in sizes from 1 kW to 10 MW. Multiple engines can be combined to deliver higher capacities. Most reciprocating engine CHP systems are below 5 MW.
Thermal Output	Thermal energy can be recovered from engine exhaust, cooling water, lubricating oil, and intercooler/aftercooler fluid. The recovered thermal energy can be used to produce hot water or steam (<125 psi). With an absorption chiller, thermal energy can be used to produce chilled water or chilled thermal fluid.
Start-Up	Reciprocating engines start quickly and typically reach full power within 3-5 minutes.[1] Some new engines can reach full capacity in under 1 minute.[2]
Part-Load Operation	Reciprocating engines maintain efficient operation at part-load and are well suited for both baseload and load following applications. The minimum part-load operation for CHP reciprocating engines is typically near 25% of full-load.[3]
Fuel	CHP reciprocating engine installations operate on a range of fuels, including natural gas, biogas (e.g., digester gas and landfill gas), RNG, and hydrogen. Natural gas is currently the most common fuel used in reciprocating engine CHP applications.
Reliability	Reciprocating engines are a mature technology and are highly reliable. The minimum availability[4] of reciprocating engines in the Department of Energy's (DOE) Packaged CHP eCatalog is 92%, but it can be higher in practice.
Other	Reciprocating engines have relatively low installed costs and are widely used in CHP applications. Reciprocating engines operate on typical natural gas delivery pressures with no additional gas compression required.

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[1] Power-Gen International, 2017, Mid-Sized New Generation: Reciprocating Internal Combustion Engines or Combustion Turbine? Link

[2] Jenbacher, 2019, INNIO Launches Fast-Start 3-Megawatt Natural Gas Generator Solution for Data Centers. Link

[3] Power-Gen International, 2017, Mid-Sized New Generation: Reciprocating Internal Combustion Engines or Combustion Turbine? Link

[4] Availability is the percentage of time a reciprocating engine is running or available to run. Availability less than 100% reflects downtime for scheduled maintenance and unplanned outages.

[5] Department of Energy (DOE) Combined Heat and Power Installation Database, June 2022, Link

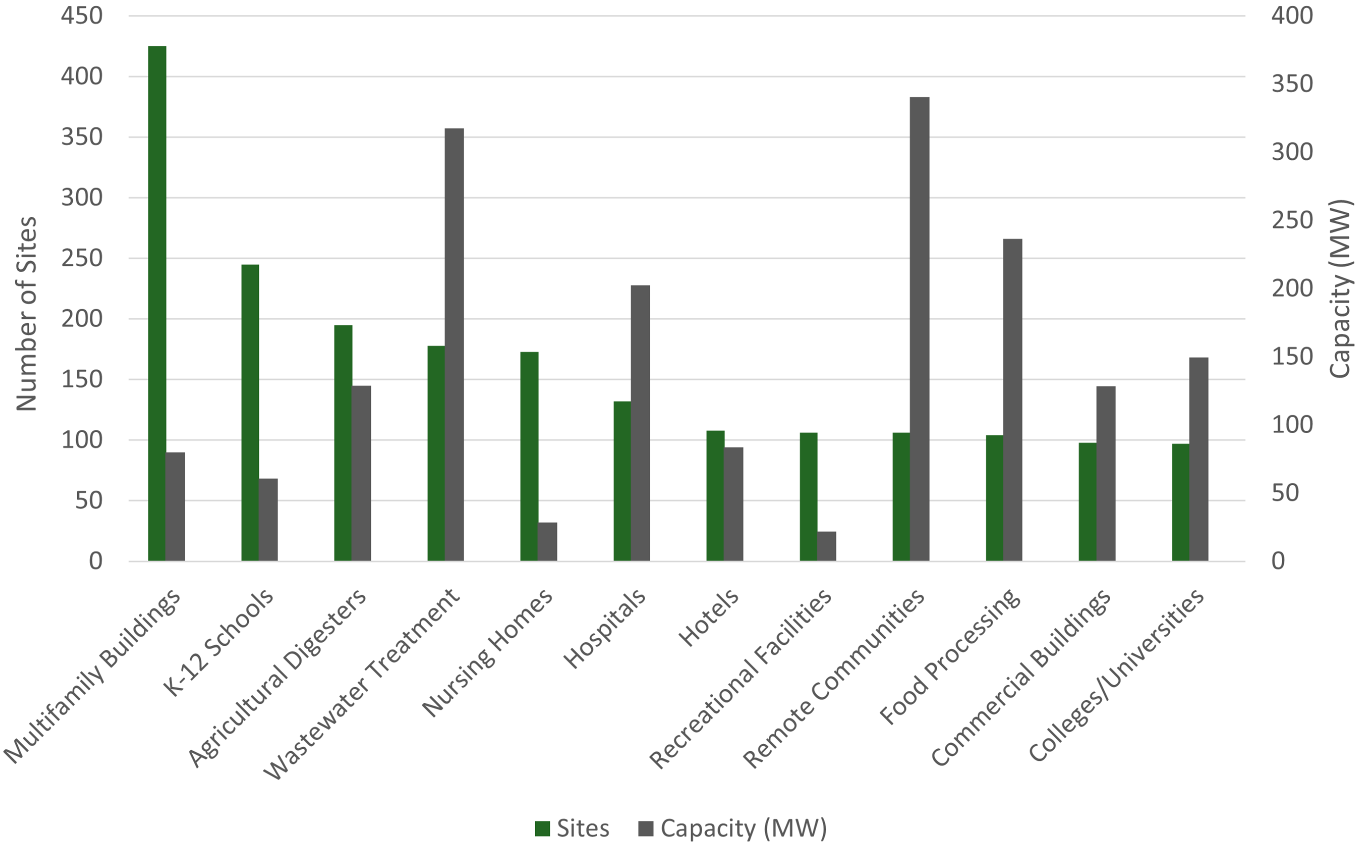

Figure 1. Number of CHP Reciprocating Engine System Installations and Total Capacity by Application.

There are over 2,700 sites with reciprocating engine CHP systems in the United States, representing 58% of all sites with CHP installed.[6] Figure 1 shows the number of sites using reciprocating engine CHP systems in the most common market sectors, including the total installed capacity for each sector.[7] Multifamily buildings are the most common application, while the most capacity for reciprocating engine CHP systems is found in remote communities and wastewater treatment plants.

Reciprocating engine CHP systems have an aggregate installed capacity of nearly 2.9 gigawatts (GW), with systems fueled by natural gas, biogas, and other gaseous fuels accounting for over 82% of this capacity. Reciprocating engine CHP systems fueled by diesel, biodiesel, or fuel oil account for the remaining capacity. These fuels are typically used in remote applications. Thermal output from reciprocating engines can be used for hot water, steam, space heating, dehumidification, and/or cooling (with an absorption chiller).

Technology Description

Engine Types

Two thermodynamic cycles used for reciprocating engines are the spark ignition engine (Otto-cycle), using gaseous fuels, and the compression ignition engine (Diesel-cycle), using liquid fuels. The mechanical components of Otto-cycle and Diesel-cycle engines are essentially the same. The main difference between the two cycles is the method of igniting the fuel. Spark ignition engines use a spark plug to ignite a pre-mixed air/fuel mixture introduced into the engine cylinders. Compression ignition engines inject compressed air into the engine cylinders at or above the auto-ignition temperature of the fuel, which is injected at high pressure into the cylinders. Most reciprocating engine CHP systems are spark ignition, using gaseous fuels such as natural gas and biogas.

Spark ignition reciprocating engines are characterized as either rich burn or lean burn. Rich burn engines operate near the stoichiometric air/fuel ratio, which is a ratio where the amount of air is sufficient to burn all the fuel with no excess air. Rich burn engines use a simple three-way catalyst (TWC), similar to the catalyst used in gasoline passenger cars, to reduce nitrogen oxide (NOx), carbon monoxide (CO), and hydrocarbon (HC) emissions, all in one after-treatment system. In contrast to rich burn engines, lean burn engines use a lot of excess air; up to twice the amount needed for complete fuel combustion. In a lean burn engine, the high amount of excess air reduces the peak combustion temperature, thereby reducing NOx production, which results in low engine-out emissions without the need for an after-treatment system in many applications. Compared to rich burn engines, lean burn engines are less prone to knock (detonation),

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[6] Department of Energy (DOE) Combined Heat and Power Installation Database, June 2022, Link

[7] Ibid.

allowing higher brake mean effective pressure levels, which results in higher power density and better fuel efficiency.[8] Lean burn engines may require additional NOx emission controls in the form of selective catalytic reduction (SCR). Site specific factors and application requirements influence the selection of either lean burn or rich burn engines. In general, lean burn combustion is applied to engines over 250 kW in size, while smaller engines are more likely to apply rich burn technologies.

Generators

In most power generation applications, reciprocating engines drive synchronous generators at constant speed to produce alternating current (AC) power. A reciprocating engine with a synchronous generator can be designed to black start (i.e., start without grid power) in the event of a grid outage. Some reciprocating engine systems use induction generators to produce AC power. Induction generators are not capable of black start, and in the event of a grid outage a reciprocating engine with an induction generator will not operate. In contrast to AC generators (either synchronous or induction), some reciprocating engine systems generate direct current (DC) electricity, using an inverter to convert from DC to AC electricity. Reciprocating engine CHP systems with inverters have black start capability and contribute the least to network fault levels, which facilitates interconnection.

Heat Recovery

Thermal energy can be recovered from multiple sources in reciprocating engines as shown in Table 2. Engine exhaust temperatures typically range from 700 to 1,000°F, while temperatures from other thermal energy streams are under 300°F. Engine exhaust, which represents roughly half of recoverable waste heat, can be used to produce either hot water or steam, while the lower temperature streams are limited to hot water production (<200°F). The recovered thermal energy can be used to meet onsite heating or drying requirements and, with the integration of an absorption chiller, space cooling or refrigeration needs.

Table 2. Heat Recovery from Reciprocating Engines

Source	Type of Recovered Thermal Energy
Engine Exhaust	Steam or hot water
Cooling Water Circulated Through Engine Jacket	Hot water
Engine Lubricating Oil	Hot water
Turbocharger Intercooler/ Aftercooler Fluid	Hot water

Performance Characteristics

Performance characteristics for eight representative natural gas reciprocating engine systems used in CHP applications are summarized in Table 3. The eight systems range from 35 kW to 4.5 MW, covering the range of most reciprocating engine CHP installations. Three of the reciprocating engines in Table 3 are rich burn (250 kW and below), and five are lean burn (500 kW and above). CHP systems using lean burn engines typically have higher electric efficiencies compared to rich burn engines. For both engine types, electric efficiencies tend to increase along with increasing engine size. Electric efficiencies (HHV) for the eight systems represented range from slightly below 28% (35 kW) to over 40% (2 MW and above).

Table 3 shows thermal efficiency values for reciprocating engine CHP systems configured to produce hot water or a combination of steam and hot water. Hot water thermal efficiencies[9] for the eight systems range from approximately 38% (2 MW and above) to 54% (35 kW). There is a tradeoff between thermal efficiency and electric efficiency. As electric efficiency increases, there is less energy available for thermal recovery, which typically translates to lower thermal efficiency. For the representative lean burn engines shown in Table 3, steam generation efficiencies range from approximately 18% (500 kW) to 11% (4.5 MW). The combined hot water and steam efficiencies range from approximately 35% (2 MW and above) to 41% (500 kW). CHP efficiencies (electric plus thermal) are near 80% for all eight systems in Table 3 based on recovering hot water. CHP efficiencies are a few percentage points lower for the five lean burn engines that produce both hot water and steam compared to the same engines with only hot water recovery.

The power to heat ratio indicates the balance between electricity production and thermal energy recovered, with values above one indicating that more electric energy is generated compared to thermal energy recovered. The power to heat ratios for the eight systems in Table 3 that recover only hot water range from 0.52 (35 kW) to over one (2 MW and above).

The performance characteristics in Table 3 are based on reciprocating engine systems fueled with natural gas. Fuels other than natural gas can be used, although performance characteristics can potentially be impacted. Engines fueled with biogas typically have similar gross power output levels compared to natural gas operation. There can be a modest (1-2%) net power reduction, however, if power is required to operate biogas fuel cleaning equipment. Reciprocating engine manufacturers are introducing products that operate on blended hydrogen and, in a few cases, 100% hydrogen.

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[8] EPA CHP Catalog of Technologies, Reciprocating Engines, updated March 2015, accessed June 2022, Link

[9] Hot water assumptions: 180°F supply temperature, 140°F return temperature.

Table 3. Reciprocating Engine Performance Characteristics (Natural Gas Fuel)

Characteristic	CHP Reciprocating Engine (Stoichiometry and Gross Power)[a]							
	Rich Burn			Lean Burn				
	35 kW	100 kW	250 kW	500 kW	1 MW	2 MW	3 MW	4.5 MW
Net Power (kW)[b]	34.7	99.0	247.5	495	990	1,980	2,970	4,455
Fuel Input (MMBtu/hr, HHV)[c]	0.43	1.14	2.58	4.65	9.18	16.80	25.10	37.40
Electric Efficiency (%, HHV, net power basis)	27.7%	29.7%	32.7%	36.3%	36.8%	40.2%	40.4%	40.6%
Thermal Recovery Based on 180°F Hot Water (HW)								
HW Capacity (MMBtu/hr)	0.23	0.57	1.21	1.95	3.85	6.45	9.65	14.40
HW Thermal Efficiency (%, HHV)	54.0%	50.0%	47.0%	41.9%	41.9%	38.4%	38.4%	38.5%
HW Power to Heat Ratio	0.52	0.60	0.70	0.87	0.89	1.06	1.06	1.07
CHP Efficiency (%, HHV)[d]	81.7%	79.7%	79.7%	78.2%	78.7%	78.6%	78.8%	79.1%
Thermal Recovery Based on Steam (125 psig sat) and Hot Water (180°F)								
Jacket Cooling HW Capacity (MMBtu/hr)	Steam recovery is less common in rich burn engines compared to lean burn engines.			1.05	2.15	3.70	5.48	8.85
Exhaust Steam Capacity (MMBtu/hr)				0.85	1.42	2.16	3.27	4.20
HW Efficiency (%, HHV)				22.6%	23.4%	22.0%	21.8%	23.7%
Steam Efficiency (%, HHV)				18.3%	15.5%	12.9%	13.0%	11.2%
Steam + HW Efficiency (%, HHV)				40.9%	38.9%	34.9%	34.9%	34.9%
CHP Efficiency (%, HHV)[e]				77.2%	75.7%	75.1%	75.3%	75.5%

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. Net power equals gross power minus parasitic power.

c) All calculations are based on higher heating value (HHV) of fuel.

d) Overall efficiency is sum of electric and hot water efficiency. Sum may differ due to rounding.

e) Overall efficiency is sum of electric, hot water, and steam efficiency. Sum may differ due to rounding.

Capital and O&M Costs

Table 4 shows representative capital costs and non-fuel operation and maintenance (O&M) costs for natural gas reciprocating engines used in CHP applications. The equipment costs in Table 4 include all hardware for a complete CHP package, including the engine generator set, heat recovery hardware, equipment enclosure, grid interconnection hardware, and control panel. The equipment costs assume that a TWC is included for rich burn engines and an oxidation catalyst is included for lean burn engines. Additional costs for SCR are also provided in the table for lean burn engines. The installation costs in Table 4 include labor and material costs associated with engineering, permitting, civil work, electrical wiring, piping, and all other tasks required to prepare a CHP facility for operation. The installation costs shown in Table 4 reflect a typical CHP reciprocating engine installation, but it is important to recognize that installation costs can be heavily influenced by site-specific requirements. Figure 2 shows the typical range of total installed costs for the eight representative reciprocating engine systems.

Table 4. Reciprocating Engine Capital and O&M Costs (Typical)

Cost Element	CHP Reciprocating Engine (Stoichiometry and Gross Power)							
	Rich Burn			Lean Burn				
	35 kW	100 kW	250 kW	500 kW	1 MW	2 MW	3 MW	4.5 MW
CHP Equipment Cost ($/kW)	$2,250	$1,900	$1,700	$1,500	$1,300	$1,150	$1,050	$900
Installation Cost ($/kW)	$2,000	$1,800	$1,750	$1,650	$1,500	$1,400	$1,300	$1,100
Total Installed Cost ($/kW)	$4,250	$3,700	$3,450	$3,150	$2,800	$2,550	$2,350	$2,000
Non-Fuel O&M (¢/kWh)	3.0	2.5	2.2	2.0	1.7	1.5	1.4	1.3
Total Installed Cost for SCR ($/kW)	NA	NA	NA	$375	$300	$230	$180	$130
O&M Costs for SCR (¢/kWh)	NA	NA	NA	0.25	0.25	0.25	0.25	0.25

Notes: *Costs are compiled from multiple sources and reported in 2020 US$. Equipment costs are based on hot water thermal recovery.*

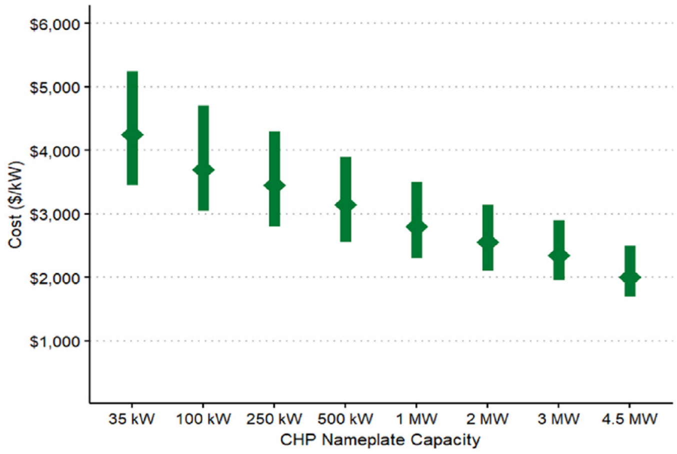

Figure 2. Total Installed Costs for Reciprocating Engine CHP Systems.

Emissions

Engine-Out and After-Treatment Emissions

Because rich and lean burn engines have different combustion characteristics, these engines produce different amounts of NOx, CO, and HC emissions. Catalysts are used with both rich and lean burn engines to reduce emissions. Natural gas rich burn engines have typical engine-out NOx emissions of 10 g/bhp-hr or higher.[10] Rich burn engines utilize TWC systems to simultaneously reduce NOx, CO, and HC emissions. TWC systems are also referred to as non-selective catalytic reduction (NSCR), and can reduce NOx emissions by 99% or higher, resulting in after-treatment NOx emissions of 0.1 g/bhp-hr or lower. All rich burn engines currently sold for CHP applications include TWC systems for emissions control. Lean burn engines, which have lower combustion temperatures compared to rich burn engines, have lower engine out NOx emissions, typically in the range of 0.5 to 1.0 g/bhp-hr. In lean burn engines, an oxidation catalyst is normally used to control the concentration of CO and HC emissions. SCR can be added to reduce NOx emissions for lean burn engines by 90-95%.

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 natural gas rich burn (with TWC) and lean burn engines (with oxidation catalyst). For non-attainment areas, rich burn reciprocating engines using natural gas (with TWC) can generally be sited without restrictions, although some local air quality management districts may have more stringent standards that require advanced emissions control hardware or control strategies. In non-attainment areas, lean burn reciprocating engines may require SCR, along with an oxidation catalyst, to meet local air district requirements.

CO_2 Emissions

Table 5 shows CO_2 emissions for reciprocating engine 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.[11] As indicated in Table 5, effective CO_2 emissions for CHP reciprocating engines using natural gas range from 468 lbs/MWh (35 kW) to 523 lbs/MWh (500 kW). 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.[12] 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 5. Reciprocating Engine CO_2 Emissions (Natural Gas-Fueled)

Description	CHP Reciprocating Engine (Stoichiometry and Gross Power)							
	Rich Burn			Lean Burn				
	35 kW	100 kW	250 kW	500 kW	1 MW	2 MW	3 MW	4.5 MW
Total CO_2 Emissions (lbs/MWh)[a]	1,439	1,343	1,221	1,098	1,084	992	988	981
CHP Effective Electric CO_2 Emissions (lbs/MWh)[b,c]	468	504	504	523	516	516	513	509

Notes:

a) *CO_2 emissions are calculated on net power, where net power is gross power minus parasitic power. Parasitic power is assumed to be 1% of gross power.*

b) *Values may differ due to rounding.*

c) *Effective Electric Emissions subtracts avoided boiler emissions, assuming thermal energy from CHP displaces natural gas boilers (80% efficient).*

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For more information, visit: energy.gov/chp

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[10] GE Energy, 2012, Lean-burn or rich-burn? Link

[11] 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

[12] 2022 AVERT Uniform EE marginal emissions factor, Link