Reciprocating Engines

Reciprocating internal combustion engines are a mature technology used for power generation, transportation, and many other purposes. Worldwide production of reciprocating internal combustion engines exceeds 200 million units per year.[1] For CHP installations, reciprocating engines have capacities that range from 10 kW to 10 MW. Multiple engines can be integrated to deliver capacities exceeding 10 MW in a single plant. Several manufacturers offer reciprocating engines for distributed power generation, and these engines, which are most often fueled with natural gas, are well suited for CHP service (see **Table 1** for summary of attributes).

Applications

Reciprocating engines are well suited to a variety of distributed generation applications and are used throughout industrial, commercial, and institutional facilities for power generation and CHP. There are nearly 2,400 reciprocating engine CHP installations in the U.S., representing 54% of the entire population of installed CHP systems.[2] These reciprocating engines have a combined capacity of nearly 2.4 gigawatts (GW), with spark ignited engines fueled by natural gas and other gas fuels accounting for 83% of this capacity. Thermal loads most amenable to engine-driven CHP systems in commercial/institutional buildings are space heating and hot water requirements. The primary applications for CHP in the commercial/institutional and residential sectors are those with relatively high and coincident electric and hot water demand. Common applications for reciprocating engine CHP systems include universities, hospitals, water treatment facilities, industrial facilities, commercial buildings, and multi-family dwellings.

Reciprocating engine CHP installation at an industrial facility.
Photo courtesy of Caterpillar.

Table 1. Summary of Reciprocating Engine Attributes

Size range	Reciprocating engines for CHP are available in sizes from 10 kW to 10 MW. Multiple engines can be combined to deliver higher capacities. The majority of CHP installations with reciprocating engine are below 5 MW.[2]
Thermal output	Thermal energy can be recovered from the engine exhaust, cooling water, and lubricating oil, and then used to produce hot water, low pressure steam, or chilled water (with an absorption chiller).
Part-load operation	Reciprocating engines perform well at part-load and are well suited for both baseload and load following applications.
Fuel	Reciprocating engines can be operated with a wide range of gas and liquid fuels. For CHP, natural gas is the most common fuel.
Reliability	Reciprocating engines are a mature technology with high reliability.
Other	Reciprocating engines have relatively low installed costs and are widely used in CHP applications. Reciprocating engines start quickly and operate on typical natural gas delivery pressures with no additional gas compression required.

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1   Power Systems Research, EnginLink™ , 2013.

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

Technology Description

There are two primary reciprocating engine designs relevant to stationary power generation applications – the spark ignition Otto-cycle engine and the compression ignition Diesel-cycle engine. The essential mechanical components of the Otto-cycle and Diesel-cycle are the same. Both use a cylindrical combustion chamber in which a close fitting piston travels the length of the cylinder. The piston connects to a crankshaft that transforms the linear motion of the piston into the rotary motion of the crankshaft. Most engines have multiple cylinders that power a single crankshaft.

The main difference between the two cycles is the method of igniting the fuel. Spark ignition engines (Otto-cycle) use a spark plug to ignite a pre-mixed air fuel mixture introduced into the cylinder. Compression ignition engines (Diesel-cycle) compress the air introduced into the cylinder to a high pressure, raising its temperature to the auto-ignition temperature of the fuel that is injected at high pressure. For CHP, most installations utilize 4-stroke spark ignition engines (see **Figure 1**).

Reciprocating engines are characterized as either rich-burn or lean-burn. Rich-burn engines are operated near the stoichiometric air/fuel ratio, which means the air and fuel quantities are matched for complete combustion, with little or no excess air. In contrast, lean-burn engines are operated at air levels significantly higher than the stoichiometric ratio. In lean-burn engines, engine-out NOx emissions are reduced as a result of lower combustion chamber temperatures compared to rich-burn engines. Most spark ignition and diesel engines relevant to stationary power generation applications complete a power cycle in four strokes of the piston within the cylinder, as shown in Figure 1:

1. Intake stroke - introduction of air (diesel) or air-fuel mixture (spark ignition) into the cylinder.

2. Compression stroke - compression of air or an air-fuel mixture within the cylinder. In diesel engines, the fuel is injected at or near the end of the compression stroke (top dead center, or TDC) and ignited by the elevated temperature of the compressed air in the cylinder. In spark ignition engines, the compressed air-fuel mixture is ignited by an ignition source at or near TDC.

3. Power stroke - acceleration of the piston by the expansion of the hot, high pressure combustion gases.
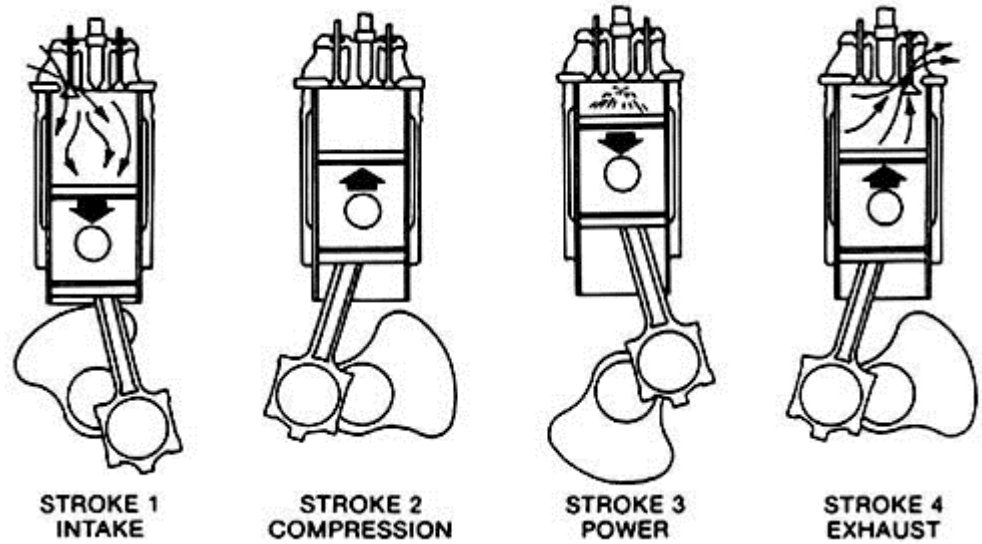

Figure 1. Four-stroke spark ignition reciprocating engine.
Graphic credit IHS Engineering.

4. Exhaust stroke - expulsion of combustion products from the cylinder through the exhaust port.

Performance Characteristics

Performance characteristics for five representative natural gas reciprocating engines used in CHP applications are summarized in **Table 2**.

The five systems shown in **Table 2** range from 100 kW to 9.3 MW, which covers most CHP installations that use reciprocating engines. Electric efficiencies generally increase with size, and the electric efficiencies for the five systems range from approximately 30% (System #1) to 42% (System #5). Overall CHP efficiencies are near 80%, ranging from approximately 77% (System #5) to 83% (System #1). As electrical efficiency increases, the quantity of thermal energy available to produce useful heat decreases per unit of power output, and the power to heat ratio generally increases. A changing ratio of power to heat impacts project economics and may affect the decisions that customers make in terms of CHP acceptance, sizing, and the desirability of selling power. For the representative systems in **Table 2**, the power to heat ratio ranges from 0.56 to 1.20. In power generation and CHP applications, reciprocating engines generally drive synchronous generators at constant speed to produce stead alternating current (AC) power. As load is reduced, the heat rate of spark ignition engines increases and efficiency decreases. While gas engines compare favorably to gas turbines—which typically experience efficiency decreases of 15 to 25 percent at half load conditions—multiple engines may be preferable to a single large unit to avoid efficiency penalties where significant load reductions are expected on a regular basis.

Table 2. Reciprocating Engine Performance Characteristics

Description	System				
	1	2	3	4	5
Net Electric Power (kW)[3]	100	633	1,141	3,325	9,341
Fuel Input (MMBtu/hr, HHV)[4]	1.15	6.26	10.37	27.73	76.06
Useful Thermal (MMBtu/hr)	0.61	2.84	4.46	10.69	26.60
Power to Heat Ratio[5]	0.56	0.76	0.87	1.06	1.20
Electric Efficiency (%, HHV)	29.6%	34.5%	37.6%	40.9%	41.9%
Thermal Efficiency (%, HHV)	53.2%	45.3%	43.0%	38.6%	35.0%
Overall Efficiency (%, HHV)	82.8%	79.8%	80.6%	79.5%	76.9%

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

Capital and O&M Costs

Table 3 shows representative capital costs for natural gas reciprocating engines used in CHP applications. The costs are average values based on data collected from multiple manufacturers. Installed costs can vary significantly depending on the scope of the plant equipment, geographical area, competitive market conditions, special site requirements, emissions control hardware, and prevailing labor rates.

Capital costs for generator set packages shown in **Table 3** include all expenses for a complete CHP system, including heat recovery hardware and emission control equipment. The CHP systems shown in **Table 3** are assumed to produce hot water, although reciprocating engines are also capable of producing low pressure steam. With construction and installation included, installed costs range from $2,900 to $1,430 per kW. As indicated, capital costs decline on a per kW basis as size increases. Non-fuel operation and maintenance (O&M) costs are also shown in **Table 3**. As indicated, these costs range from 2.4 to 0.9 ¢/kWh. Like capital costs, O&M costs decline as capacity increases. Maintenance

costs vary with type, speed, size, and number of cylinders of an engine. These costs typically include:

- Maintenance labor

- Engine parts and materials (e.g., oil filters, air filters, spark plugs, gaskets, valves, piston rings, electronic components, etc.) and consumables, such as oil

- Minor and major overhauls

Maintenance can either be done by in-house personnel or contracted out to manufacturers, distributors, or dealers under service contracts.

Table 3. Reciprocating Engine Capital and O&M Costs

Description	System				
	1	2	3	4	5
Net Electric Power (kW)	100	633	1,141	3,325	9,341
Engine Type	Rich-burn	Lean-burn	Lean-burn	Lean-burn	Lean-burn
Engine and Generator ($/kW, including heat recovery and emission control)	$1,650	$1,650	$1,380	$1,080	$900
Construction and Installation	$1,250	$1,190	$990	$720	$530
Total Installed Cost	$2,900	$2,840	$2,370	$1,800	$1,430
Total O&M Cost (¢/kWh)	2.4	2.1	1.9	1.6	0.9

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

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3 Parasitic electric loads for reciprocating engines are typically small. In this fact sheet, parasitic loads are assumed to be negligible, resulting in no difference between gross and net power.

4 Values in this fact sheet are based on the higher heating value (HHV) of natural gas unless noted otherwise.

5 Power to heat ratio is the electric power output divided by the useful thermal output.

Emissions

Emissions of criteria pollutants —oxides of nitrogen (NOx), carbon monoxide (CO), and volatile organic compounds (unburned, non-methane hydrocarbons, or VOCs)—are the primary environmental concern with reciprocating engines operating on natural gas. **Table 4** shows representative emissions for reciprocating engines operating on natural gas in CHP applications. Emissions can vary significantly between different engine models and manufacturers and can also vary significantly with small changes in operating conditions (e.g., air/fuel ratio). Rich-burn engines have higher uncontrolled NOx emissions compared to lean-burn engines and are almost always supplied with a three-way catalyst to control NOx, CO, and VOC emissions. For lean-burn engines, selective catalytic reduction (SCR) can be used to reduce NOx emissions if needed, and an oxidation catalyst can be used to reduce CO and VOC emissions.

Table 4 shows CO_2 emissions for CHP systems based on the power output of the complete CHP system. For the complete CHP system, CO_2 emissions are calculated with a thermal credit for natural gas fuel that would otherwise be used by an on-site boiler. With this thermal credit, CO_2 emissions range from 452-536 lbs/MWh. For comparison, a typical natural gas combined cycle power plant will have emissions of 800-900 lbs/MWh, and a coal plant will have CO_2 emissions near 2,000 lbs/MWh. ■

Table 4. Reciprocating Engine Emission Characteristics

Description	System				
	1	2	3	4	5
Electric Capacity (kW)	100	633	1,141	3,325	9,341
Engine Combustion	Rich-burn	Lean-burn	Lean-burn	Lean-burn	Lean-burn
Emissions before Exhaust Treatment (g/bhp-hr)[6, 7, 8]					
NOx	N/A[9]	< 1.0	< 1.0	< 1.0	< 1.5
CO		< 1.5	< 1.5	< 1.5	< 1.5
VOC		< 1.0	< 1.0	< 1.0	< 1.0
Emissions after Exhaust Treatment (g/bhp-hr)[10]					
NOx	0.05	0.05	0.05	0.05	0.08
CO	0.14	0.08	0.08	0.08	0.08
VOC	0.07	0.05	0.05	0.05	0.05
Emissions after Exhaust Treatment (lbs/MWh)[11, 12]					
NOx	0.14	0.15	0.15	0.15	0.22
CO	0.41	0.22	0.22	0.22	0.22
VOC	0.20	0.15	0.15	0.15	0.15
CO_2 Emissions (lbs/MWh)					
Electricity only	1,348	1,157	1,062	975	952
CHP with thermal credit[13]	452	502	491	505	536

Note: Emissions are average values and are not intended to represent a specific product.

6 Manufacturers often express an upper limit for emissions performance (e.g., NOx < 1.0 g/bhp-hr). This format is used for emissions data prior to exhaust treatment (also referred to as "engine-out" emissions).

7 CO and VOC emissions for Systems #2, #3, and #4 were not available from product specification sheets, and the values shown are estimates.

8 NOx, CO, and VOC emissions for System #5 were not available from product specification sheets, and the values shown are estimates.

9 Rich-burn engines are typically supplied with a three-way catalyst. Hence, uncontrolled emissions are not reported.

10 For lean-burn engines, exhaust treatment is assumed to reduce emissions by 95%.

11 To convert between g/bhp-hr and lbs/MWh, multiply value in g/bhp-hr by 2.956 to get result in lbs/MWh.

12 NOx, CO, and VOC emissions are based on electric output and do not include a thermal credit.

13 The CHP CO_2 emissions include a thermal credit for avoided fuel that would otherwise be used in an onsite boiler. The boiler is assumed to operate on natural gas with an efficiency of 80%.