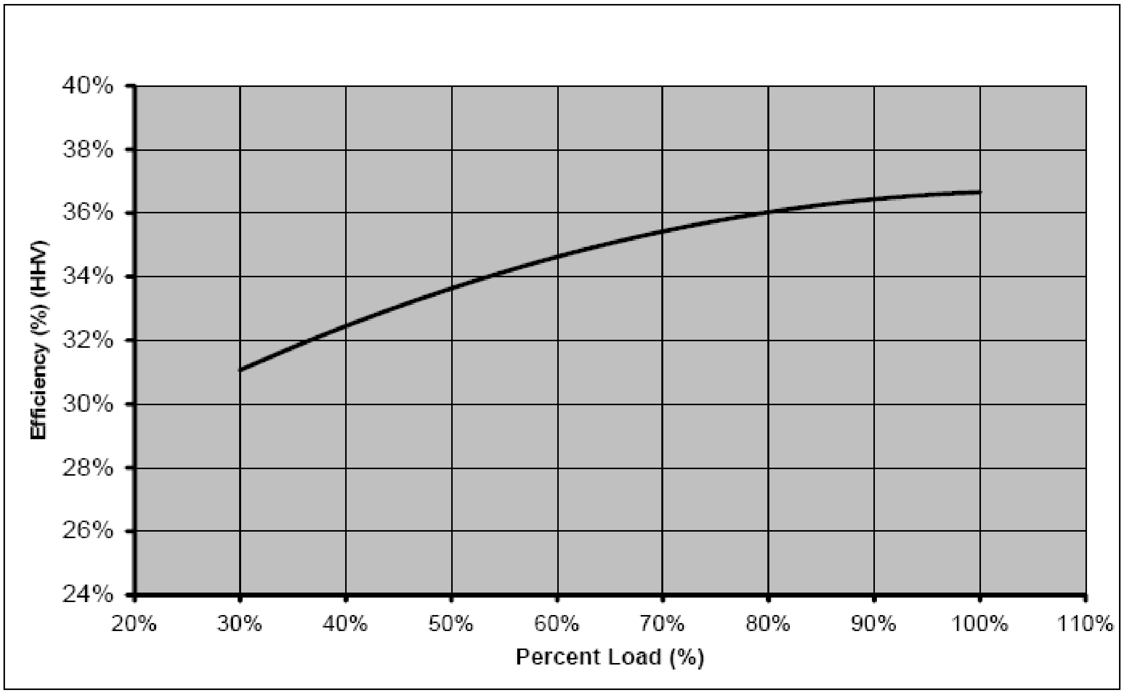
Reciprocating Engines:

Why they are used for CHP:

Reciprocating engines are more commonly known as internal combustion engines. The two major types of reciprocating engines are spark ignited ("Otto Cycle") and diesel. Engines can achieve electrical efficiencies of 25 to 50%, thus making them viable CHP options. Furthermore, engines come in a variety of sizes (from small portable engines to engines large enough to power large ships, and from 50 KW to 5,000 KW). Furthermore, engines have reliability and are typically online for 95% of the year. Similarly, engine technology is proven to provide acceptable performance for many years. Other attractive features of engines include quick start up times. Just like a car engine, a reciprocating engine only requires a few seconds to run at full power. In addition to being a CHP option, engines are options for spinning reserves or back up power for facilities such as hospitals because the unit can go from cold to hot very quickly, thus allowing for near continuous power and operation during blackouts.

One of the most attractive features of a reciprocating engine is its high part load efficiency. As the load of an engine drops, the efficiency does not significantly drop until very low loads are reached. The below figure illustrates engine part load efficiencies:

Figure 1: Spark ignition engine efficiency versus load (taken from NREL)



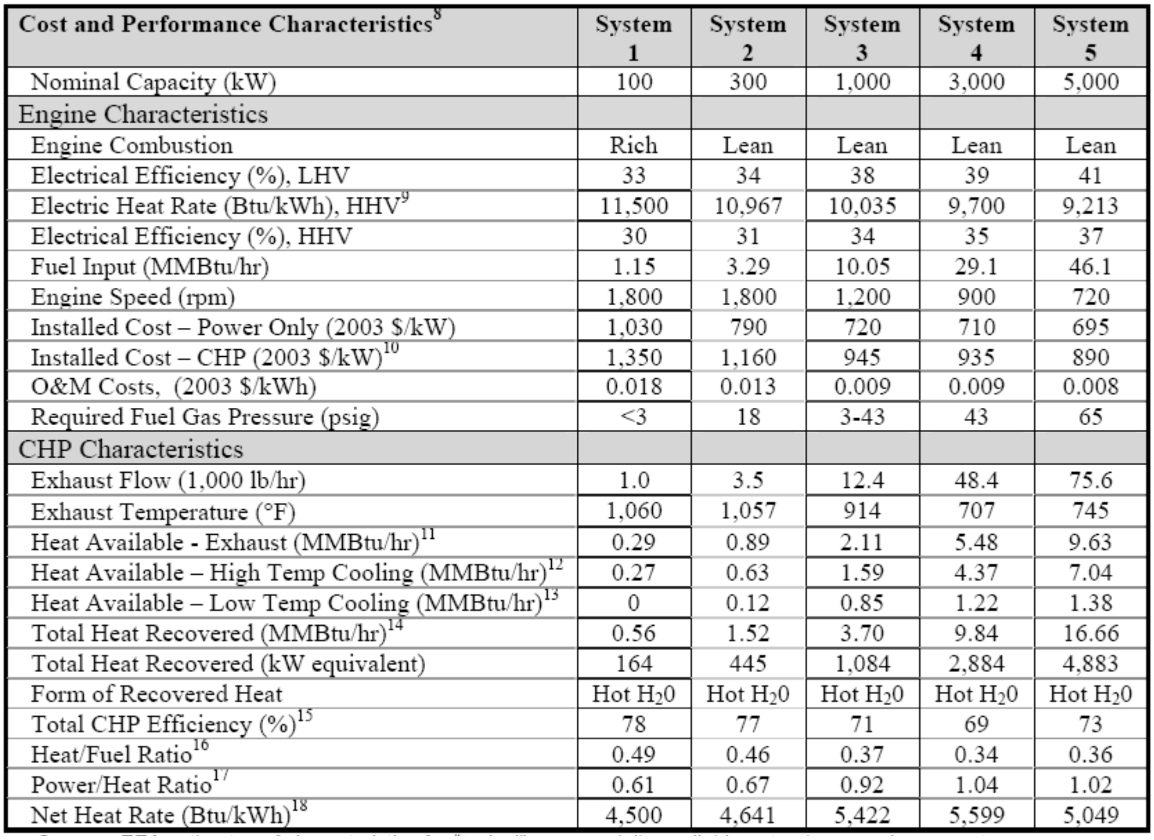
Brief technological description:

As stated, there are two types of engines – diesel and internal combustion – the difference being that the latter requires a spark plug to provide an explosion whereas the former does not and combustion is achieved by pressuring the fuel to its flash point. The engines work exactly the same way as those in your car. Piston-cylinders are connected to a crankshaft. The linear motion of the piston-cylinder transforms to rotational motion on the crankshaft. The rotating shaft then produces electricity by rotating inside a magnetic field. The linear motion of the piston-cylinder is created by a sequence of four strokes: 1) intake, where air/fuel is drawn into the chamber 2) compression, where the air/fuel is compressed 3) power stroke, where either the spark plug or pressurization (depending on the fuel) creates an explosion and 4) exhaust, where the expansion of gasses due to combustion pushes the cylinder down and exhausts the combustion gasses.

An important note should be made at this point about diesel engines. Although called a diesel engine, such engines do not necessarily require diesel fuel. Many can run a mixture of 80-90% natural gas or gasoline and the remainder diesel, and many can run on crude oil or heavy fuel oil. The term diesel engine only indicates that there is no spark plug providing the power stroke.

Waste heat is created in many parts of the engine: exhaust gasses, engine coolant, and surface radiation, lube oil cooler and turbocharger inter and after coolers. The exhaust gasses are ejected at 850 – 1200^0 F, while the engine jacket coolant reaches up to 265^0 F. These waste streams can be used to produce steam or hot water to meet space heating, air reheat, domestic hot water, or absorption cooling needs. After heat recovery, 70 to 80% of the input fuel is used. The chart below shows performance characteristics for various types of reciprocating engines.

Table 1: Performance Characteristics for Reciprocating Engines (from NREL)

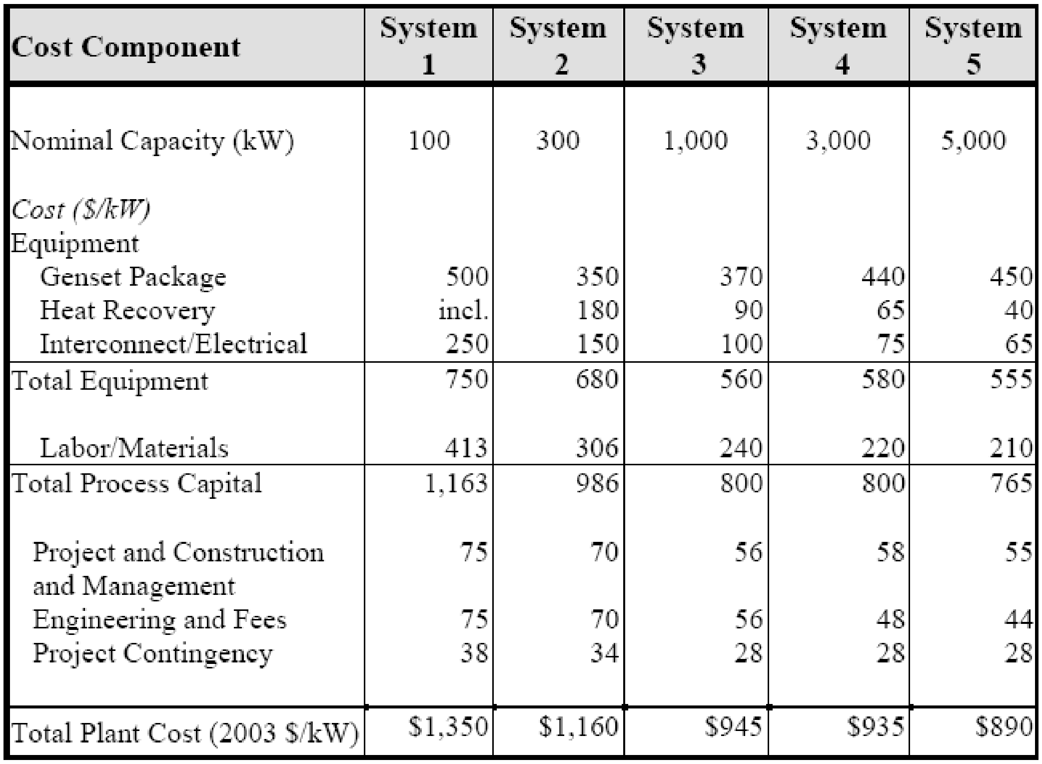


Cost and Performance Characteristics[8]	System 1	System 2	System 3	System 4	System 5
Nominal Capacity (kW)	100	300	1,000	3,000	5,000
Engine Characteristics					
Engine Combustion	Rich	Lean	Lean	Lean	Lean
Electrical Efficiency (%), LHV	33	34	38	39	41
Electric Heat Rate (Btu/kWh), HHV[9]	11,500	10,967	10,035	9,700	9,213
Electrical Efficiency (%), HHV	30	31	34	35	37
Fuel Input (MMBtu/hr)	1.15	3.29	10.05	29.1	46.1
Engine Speed (rpm)	1,800	1,800	1,200	900	720
Installed Cost – Power Only (2003 $/kW)	1,030	790	720	710	695
Installed Cost – CHP (2003 $/kW)[10]	1,350	1,160	945	935	890
O&M Costs, (2003 $/kWh)	0.018	0.013	0.009	0.009	0.008
Required Fuel Gas Pressure (psig)	<3	18	3-43	43	65
CHP Characteristics					
Exhaust Flow (1,000 lb/hr)	1.0	3.5	12.4	48.4	75.6
Exhaust Temperature (°F)	1,060	1,057	914	707	745
Heat Available - Exhaust (MMBtu/hr)[11]	0.29	0.89	2.11	5.48	9.63
Heat Available – High Temp Cooling (MMBtu/hr)[12]	0.27	0.63	1.59	4.37	7.04
Heat Available – Low Temp Cooling (MMBtu/hr)[13]	0	0.12	0.85	1.22	1.38
Total Heat Recovered (MMBtu/hr)[14]	0.56	1.52	3.70	9.84	16.66
Total Heat Recovered (kW equivalent)	164	445	1,084	2,884	4,883
Form of Recovered Heat	Hot H_20	Hot H_20	Hot H_20	Hot H_20	Hot H_20
Total CHP Efficiency (%)[15]	78	77	71	69	73
Heat/Fuel Ratio[16]	0.49	0.46	0.37	0.34	0.36
Power/Heat Ratio[17]	0.61	0.67	0.92	1.04	1.02
Net Heat Rate (Btu/kWh)[18]	4,500	4,641	5,422	5,599	5,049

Costs:

Typical engine costs are between $800 - $1500/KW. Typical maintenance costs for an engine are $0.01 – $0.015/KWH. Spark plugs, engine oil, and coolant should be replaced every 500 – 2000 hours. Top end overhauls (cylinder head and turbocharger) are recommended at 12,000 – 15,000 hours and major overhauls (piston ring, crankshaft bearings and seals replacement) are recommended at 24,000 – 30,000 hours. With proper maintenance, it has been reported that an engine's availability is around 95%.
The table below shows the costs associated with using an engines of different sizes for a CHP system.

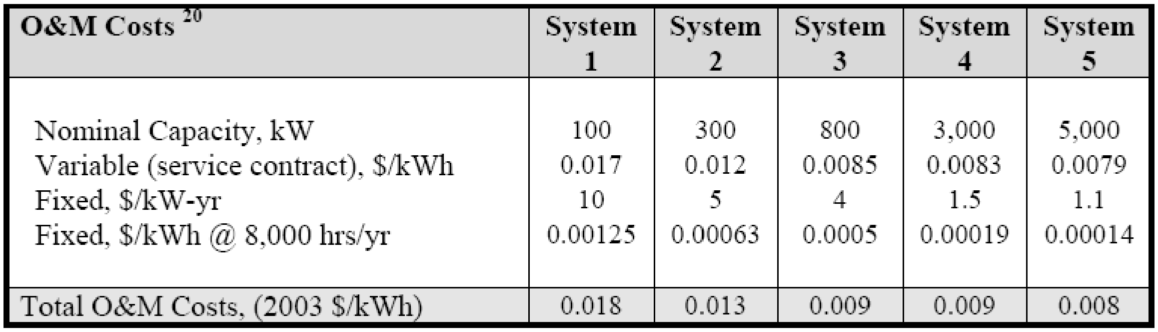
Table 2: Costs associated with using an engine for a CHP system (taken from NREL)



Cost Component	System 1	System 2	System 3	System 4	System 5
Nominal Capacity (kW)	100	300	1,000	3,000	5,000
Cost ($/kW)					
Equipment					
Genset Package	500	350	370	440	450
Heat Recovery	incl.	180	90	65	40
Interconnect/Electrical	250	150	100	75	65
Total Equipment	750	680	560	580	555
Labor/Materials	413	306	240	220	210
Total Process Capital	1,163	986	800	800	765
Project and Construction and Management	75	70	56	58	55
Engineering and Fees	75	70	56	48	44
Project Contingency	38	34	28	28	28
Total Plant Cost (2003 $/kW)	$1,350	$1,160	$945	$935	$890

The table below shows operation and maintenance costs for a natural gas fired engine.

Table 3: O&M Costs for a natural gas engine (taken from NREL)



O&M Costs [20]	System 1	System 2	System 3	System 4	System 5
Nominal Capacity, kW	100	300	800	3,000	5,000
Variable (service contract), $/kWh	0.017	0.012	0.0085	0.0083	0.0079
Fixed, $/kW-yr	10	5	4	1.5	1.1
Fixed, $/kWh @ 8,000 hrs/yr	0.00125	0.00063	0.0005	0.00019	0.00014
Total O&M Costs, (2003 $/kWh)	0.018	0.013	0.009	0.009	0.008

Emissions:

In internal combustion engines one can control emission either by burning lean or by burning rich with a catalytic treatment. In lean burn engines, excess air is drawn into the combustion processes. This lowers the temperature of combustion, thus lowering the amount of NOx, CO, CO_2, and non methane hydrocarbons. Typical NOx levels in lean burn engines are around 0.5 – 2 grams/hphr. With "selective catalytic reduction (SCR)", this figure can drop to 0.15 grams/hphr. Catalytic treatment on rich burn can change NOx to nitrogen gas and change CO to carbon dioxide. NOx emissions can be reduced to .15 grams/hphr. Catalytic treatment will raise maintenance costs as they need to be replaced.

Since diesel engines burn rich, they can burn at lower temperatures. As a result, the NOx levels are much lower than with Otto Cycle engines and catalytic converters are not useful. However, particulates are of concern with diesel engines. Particulate capturing devices can capture up to 90% of the particulates.

Engine manufacturers:

Caterpillar, Inc., www.caterpillar.com

Cooper Energy Systems, www.cooperenergy.com

Coast Intelligen, Inc., www.coastintelligen.com

Cummins Engine Company, www.cummins.com

Fairbanks-Morse Engine Company, www.fairbanksmorse.com

Hess Microgen, Inc., www.hessmicrogen.com

Jenbacher Engines, www.jenbacher.com

Kohler Power Systems, www.kohlerpowersystems.com

Tecogen, Inc., www.tecogen.com

Waukesha Engine Inc., www.waukeshaengine.com

Wartsila NSD North America, Inc., www.wartsilausa.com