EPA COMBINED HEAT AND POWER PARTNERSHIP

Catalog of CHP Technologies

Section 5. Technology Characterization – Microturbines

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Section 5. Technology Characterization – Microturbines

5.1 Introduction

Microturbines, as the name implies, are small combustion turbines that burn gaseous or liquid fuels to drive an electrical generator, and have been commercially available for more than a decade. Today's microturbine technology is the result of development work in small stationary and automotive gas turbines, auxiliary power equipment, and turbochargers, much of which took place in the automotive industry beginning in the 1950s. The development of microturbine systems was accelerated by the similarity of design to large engine turbochargers, and that provided the basis for the engineering and manufacturing technology of microturbine components.

During the 1990s several companies developed competing microturbine products and entered, or planned to enter, the market. As the market matured, the industry underwent a consolidation phase during which companies merged, changed hands, or dropped out of the market. In the United States today, this has led to two main manufacturers of stationary microturbine products – Capstone Turbine Corporation and FlexEnergy.

Table 5-1 provides a summary of microturbine attributes. Microturbines range in size from 30 to 330 kilowatts (kW). Integrated packages consisting of multiple microturbine generators are available up to 1,000 kW, and such multiple units are commonly installed at sites to achieve larger power outputs. Microturbines are able to operate on a variety of fuels, including natural gas, sour gas (high sulfur, low Btu content), and liquid petroleum fuels (e.g., gasoline, kerosene, diesel fuel, and heating oil).

Table 5-1. Summary of Microturbine Attributes

Electrical Output	Available from 30 to 330 kW with integrated modular packages up to 1,000 kW.
Thermal Output	Exhaust temperatures in the range of 500 to 600 °F, suitable for supplying a variety of site thermal needs, including hot water, steam, and chilled water (using an absorption chiller).
Fuel Flexibility	Can utilize a number of different fuels, including natural gas, sour gas (high sulfur, low Btu content), and liquid fuels (e.g., gasoline, kerosene, diesel fuel, and heating oil).
Reliability and life	Design life is estimated to be 40,000 to 80,000 hours with overhaul.
Emissions	Low NO_x combustion when operating on natural gas; capable of meeting stringent California standards with carbon monoxide/volatile organic compound (CO/VOC) oxidation catalyst.
Modularity	Units may be connected in parallel to serve larger loads and to provide power reliability.
Part-load Operation	Units can be operated to follow load with some efficiency penalties.
Dimensions	Compact and light weight, 2.3-2.7 cubic feet (cf) and 40-50 pounds per kW.

5.2 Applications

Microturbines are ideally suited for distributed generation applications due to their flexibility in connection methods, their ability to be stacked in parallel to serve larger loads, their ability to provide stable and reliable power, and their low emissions compared to reciprocating engines. Important applications and functions are described below:

- **Combined heat and power (CHP)** – microturbines are well suited to be used in CHP applications because the exhaust heat can either be recovered in a heat recovery boiler, or the hot exhaust gases can be used directly. Typical natural gas fueled CHP markets include:
    - Commercial – hotels, nursing homes, health clubs
    - Institutional – public buildings
    - Industrial – small operations needing hot water or low pressure steam for wash water as in the food and manufacturing sectors

- **Combined cooling heating and power (CCHP)** – The temperature available for microturbine exhaust allows effective use with absorption cooling equipment that is driven either by low pressure steam or by the exhaust heat directly. Cooling can be added to CHP in a variety of commercial/institutional applications to provide both cooling and heating.
- **Resource recovery** – the ability of microturbines to burn a variety of fuels make it useful for resource recovery applications including landfill gas, digester gas, oil and gas field pumping and power applications, and coal mine methane use.
- **Peak shaving and base load power** (grid parallel).
- **Thermal oxidation of very low Btu fuel or waste streams** – Microturbine systems have been designed to provide thermal oxidation for applications needing methane or volatile organic compound destruction such as for landfill gas or other waste gases.
- **Premium power and power quality** – due to the inverter based generators, power quality functionality can be added to CHP, and power-only applications allowing the system to be part of an overall uninterruptible power supply (UPS) system providing black start capability and back-up power capability to provide power when the electrical grid is down. The system can also provide voltage and other power quality support. Such functions are useful for applications with high outage costs and sensitive power needs including small data centers, hospitals, nursing homes, and a variety of other applications that have critical service requirements.
- **Power only applications** – microturbines can be used for stand-alone power in remote applications where grid power is either unavailable or very high cost. The systems can also run as back-up power or in peak-shaving mode, though such use is limited.
- **Microgrid** – Microturbines are inverter based generation, and are therefore well-suited for application in utility microgrids, providing grid support and grid communication functions. This area of use is in a development and demonstration phase by electric power companies.

5.3 Technology Description

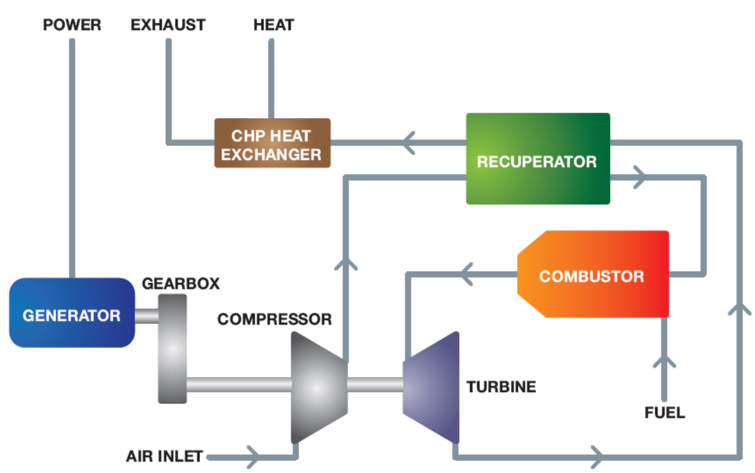
5.3.1 Basic Process

Microturbines operate on the same thermodynamic cycle (Brayton Cycle) as larger gas turbines and share many of the same basic components. In this cycle, atmospheric air is compressed, heated (usually by introducing and burning fuel), and then these hot gases drive an expansion turbine that drives both the inlet compressor and a drive shaft capable of providing mechanical or electrical power. Other than the size difference, microturbines differ from larger gas turbines in that they typically have lower compression ratios and operate at lower combustion temperatures. In order to increase efficiency, microturbines recover a portion of the exhaust heat in a heat exchanger called a recuperator, to increase the energy of the gases entering the expansion turbine thereby boosting efficiency. Microturbines operate at high rotational speeds of up to 60,000 revolutions per minute. Of the two primary players in the domestic industry, Capstone couples this shaft output directly to a high speed generator and uses power electronics to produce 60 Hz electricity. FlexEnergy uses a gearbox to reduce the drive speed to 3600 rpm to power a synchronous electric generator.

5.3.2 Components

Figure 5-1 shows a schematic diagram of the basic microturbine components, which include the combined compressor/turbine unit, generator, recuperator, combustor, and CHP heat exchanger. Each of these primary components is described further below.

Figure 5-1. Microturbine-based CHP System Schematic



Source: FlexEnergy

5.3.2.1 Turbine & Compressor

The heart of the microturbine is the compressor-turbine package (or turbocompressor), which is commonly mounted on a single shaft along with the electric generator. The shaft, rotating at upwards of 60,000 rpm, is supported on either air bearings or conventional lubricated bearings. The single moving part of the one-shaft design has the potential for reducing maintenance needs and enhancing overall reliability.

Microturbine turbomachinery is based on single-stage radial flow compressors and turbines, unlike larger turbines that use multi-stage axial flow designs. Radial design turbomachinery handles the small volumetric flows of air and combustion products with reasonably high component efficiency.[84] Large-

[1] With axial flow turbomachinery, blade height would be too small to be practical.

size axial flow turbines and compressors are typically more efficient than radial flow components. However, in the size range for microturbines – 0.5 to 5 lbs/second of air/gas flow – radial flow components offer minimum surface and end wall losses thereby improving efficiency.

As mentioned earlier, microturbines operate on either oil-lubricated or air bearings, which support the shaft. *Oil-lubricated bearings* are mechanical bearings and come in three main forms – high-speed metal roller, floating sleeve, and ceramic surface. Ceramic surface bearings typically offer the most attractive benefits in terms of life, operating temperature, and lubricant flow. While they are a well-established technology, they require an oil pump, oil filtering system, and liquid cooling that add to microturbine cost and maintenance. In addition, the exhaust from machines featuring oil-lubricated bearings may not be useable for direct space heating in cogeneration configurations due to the potential for air contamination.

Air bearings allow the turbine to spin on a thin layer of air, so friction is low and rpm is high. They have been in service on airplane cabin cooling systems for many years. No oil or oil pump is needed. Air bearings offer simplicity of operation without the cost, reliability concerns, maintenance requirements, or power drain of an oil supply and filtering system.

5.3.2.2 Generator

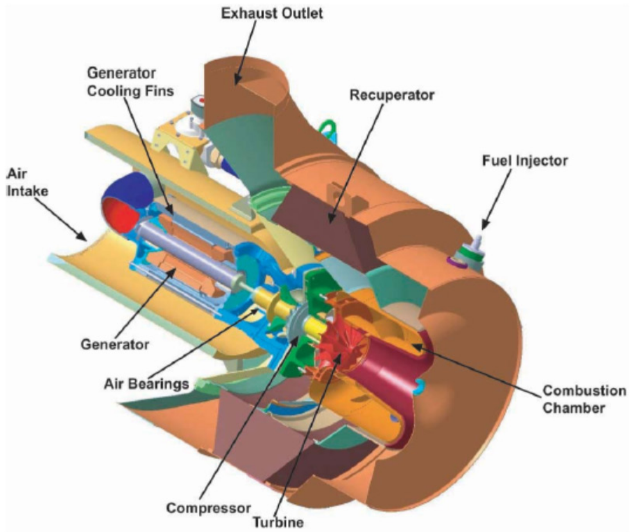
The microturbine produces electrical power either via a high-speed generator turning on the single turbo-compressor shaft or through a speed reduction gearbox driving a conventional 3,600 rpm generator. The high-speed generator single-shaft design employs a permanent magnet, and an air-cooled generator producing variable voltage and high-frequency AC power. This high frequency AC output (about 1,600 Hz for a 30 kW machine) is converted to constant 60 Hz power output in a power conditioning unit. Power conditioning involves rectifying the high frequency AC to DC, and then inverting the DC to 60 Hz AC. However, power conversion comes with an efficiency penalty (approximately 5 percent). In addition to the digital power controllers converting the high frequency AC power into usable electricity, they also filter to reduce harmonic distortion in the output. The power conditioning unit is a critical component in the single-shaft microturbine design and represents significant design challenges, specifically in matching turbine output to the required load. To accommodate transients and voltage spikes, power electronic units are generally designed to handle seven times the nominal voltage. Most microturbine power electronics generate three-phase electricity.

To start-up a single shaft design, the generator acts as a motor turning the turbo-compressor shaft until sufficient rpm is reached to start the combustor. If the system is operating independent of the grid (black starting), a power storage unit (typically a battery) is used to power the generator for start-up.

Electronic components also direct all of the operating and startup functions. Microturbines are generally equipped with controls that allow the unit to be operated in parallel or independent of the grid, and internally incorporate many of the grid and system protection features required for interconnection. The controls also allow for remote monitoring and operation.

Figure 5-2 provides an example of the compact design of the basic microturbine components (in this case, for the Capstone model C200 (200 kW)). The turbocompressor section, riding on air bearings, drives the high speed, air cooled generator. The entire assembly is surrounded by a can-like structure housing the recuperator and the combustion chamber.

Figure 5-2. Compact Microturbine Design



Source: Capstone Turbines, C200

5.3.2.3 Recuperator & Combustor

The recuperator is a heat exchanger that uses the hot turbine exhaust gas (typically around 1,200ºF) to preheat the compressed air (typically around 300ºF) going into the combustor, thereby reducing the fuel needed to heat the compressed air to the required turbine inlet temperature. Depending on microturbine operating parameters, recuperators can more than double machine efficiency. However, since there is increased pressure drop on both the compressed air and turbine exhaust sides of the recuperator, this increased efficiency comes at the expense of about a 10-15 percent drop in power output.

5.3.2.4 CHP Heat Exchanger

In CHP operation, microturbines offer an additional heat exchanger package, integrated with the basic system, that extracts much of the remaining energy in the turbine exhaust, which exits the recuperator at about 500-600^{o} F. Exhaust heat can be used for a number of different applications, including potable water heating, space heating, thermally activated cooling and dehumidification systems (absorption chillers, desiccant dehumidification). Because microturbine exhaust is clean and has a high percentage (15 percent) of oxygen, it can also be used directly for process applications such as driving a double-effect absorption chiller or providing preheat combustion air for a boiler or process heat application.

5.4 Performance Characteristics

Table 5-2 summarizes cost and performance characteristics for typical microturbine CHP systems ranging in size from 30 kW to 1 MW. Heat rates and efficiencies are based on manufacturers' specifications for systems operating on natural gas, the predominant fuel choice in CHP applications. The table assumes that natural gas is delivered at typical low delivery pressures which require a booster compressor to raise the gas pressure to the point at which it can be introduced into the compressed inlet air-stream. Electrical efficiencies and heat rates shown are net of power losses from the gas booster compressor. Customers that have, or can gain access to, high pressure gas from their local gas utility can avoid the capacity and efficiency losses due to fuel gas compression. Capital costs, described in more detail in a later section, are based on assumptions of a basic grid connect installation. Installation costs can vary widely depending on site conditions and regional differences in material, labor, and site costs. Available thermal energy is calculated based on manufacturer specifications on turbine exhaust flows and temperatures. CHP thermal recovery estimates are based on producing hot water for process or space heating applications. All performance specifications are at full load International Organization for Standards (ISO) conditions (59 ^{o}F, 60 percent RH, 14.7 psia).

The data in the table show that electrical efficiency generally increases as the microturbine becomes larger. Microturbines have lower electrical efficiencies than reciprocating engines and fuel cells, but are capable of high overall CHP efficiencies. The low power to heat ratios (P/H) of microturbines (which implies relatively more heat production), makes it important for both overall efficiency and for economics to be sited and sized for applications that allow full utilization of the available thermal energy.

As shown, microturbines typically require 50 to 140 psig fuel supply pressure. Local distribution gas pressures usually range from 30 to 130 psig in feeder lines and from 1 to 50 psig in final distribution lines. If available, sites that install microturbines will generally opt for high pressure gas delivery rather than adding the cost of a booster compressor with its accompanying efficiency and capacity losses.

Estimated installed capital costs range from $4,300/kW for the 30 kW system down to $2,500/kW for the 1,000 kW system – described in more detail in Section *Capital Cost.*

Table 5-2. Microturbine Cost and Performance Characteristics

Microturbine Characteristics [1]	System					
	1	2	3	4	5	6
Nominal Electricity Capacity (kW)	30	65	200	250	333	1000
Compressor Parasitic Power (kW)	2	4	10	10	13	50
Net Electricity Capacity (kW)	28	61	190	240	320	950
Fuel Input (MMBtu/hr), HHV	0.434	0.876	2.431	3.139	3.894	12.155
Required Fuel Gas Pressure (psig)	55-60	75-80	75-80	80-140	90-140	75-80
Electric Heat Rate (Btu/kWh), LHV [2]	13,995	12,966	11,553	11,809	10,987	11,553
Electric Efficiency (%), LHV [3]	24.4%	26.3%	29.5%	28.9%	31.1%	29.5%
Electric Heat Rate (Btu/kWh), HHV	15,535	14,393	12,824	13,110	12,198	12,824
Electric Efficiency (%), HHV	21.9%	23.7%	26.6%	26.0%	28.0%	26.6%
CHP Characteristics						
Exhaust Flow (lbs/sec)	0.68	1.13	2.93	4.7	5.3	14.7
Exhaust Temp (^{o}F)	530	592	535	493	512	535
Heat Exchanger Exhaust Temp (^{o}F)	190	190	200	190	190	200
Heat Output (MMBtu/hr)	0.21	0.41	0.88	1.28	1.54	4.43

Table 5-2. Microturbine Cost and Performance Characteristics

Microturbine Characteristics [1]	System					
	1	2	3	4	5	6
Heat Output (kW equivalent)	61.0	119.8	258.9	375.6	450.2	1,299.0
Total CHP Efficiency (%), HHV [4]	70.0%	70.4%	63.0%	66.9%	67.5%	63.1%
Total CHP Efficiency (%), LHV	77.3%	77.8%	69.6%	73.9%	74.6%	69.8%
Power/Heat Ratio [5]	0.46	0.51	0.73	0.64	0.71	0.73
Net Heat Rate (Btu/kWh) [6]	6,211	5,983	6,983	6,405	6,170	6,963
Effective Electric Eff. (%), HHV [7]	54.9%	57.0%	48.9%	53.3%	55.3%	49.0%
Cost						
CHP Package Cost ($/kW) [8]	$2,690	$2,120	$2,120	$1,840	$1,770	$1,710
Total Installed Cost ($/kW) [9]	$4,300	$3,220	$3,150	$2,720	$2,580	$2,500

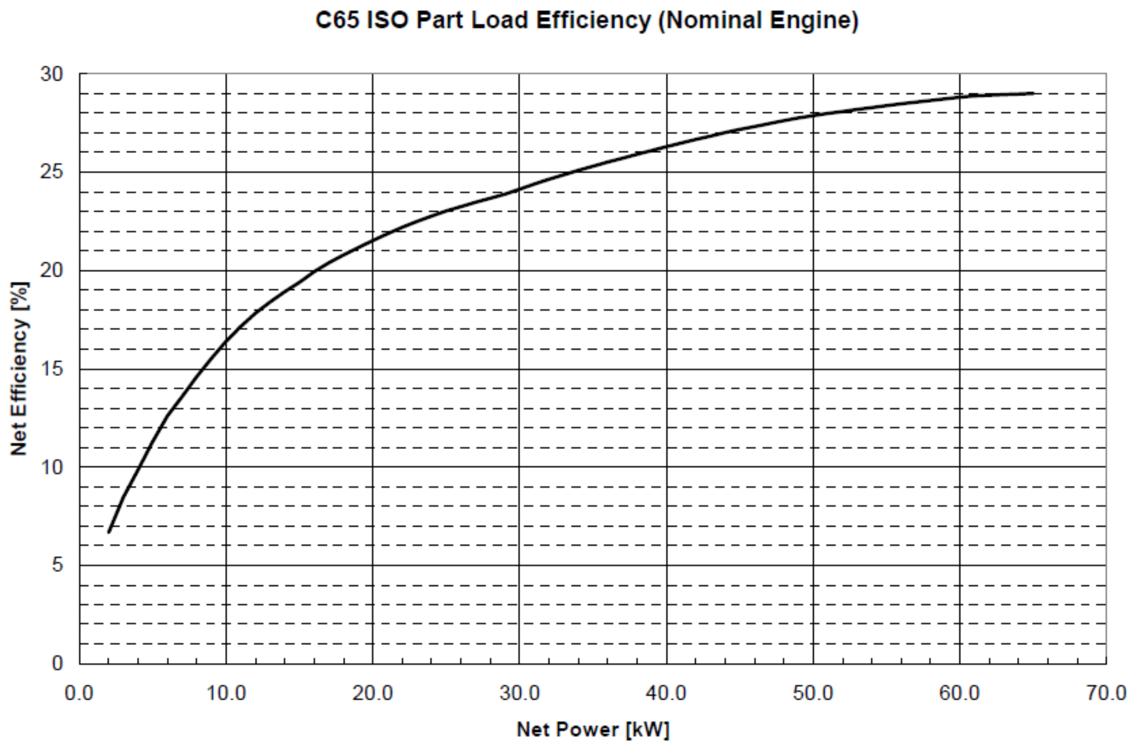
Notes:

1. Characteristics presented are representative of commercially available microturbine systems. Table data are based from smallest to largest: Capstone C30,; Capstone C65 CARB, Capstone C200 CARB, FlexEnergy MT250, FlexEnergy MT330, Capstone C1000-LE
2. Turbine and engine manufacturers quote heat rates in terms of the lower heating value (LHV) of the fuel. Gas utilities typically report the energy content on a higher heating value (HHV) basis. In addition, electric utilities measure power plant heat rates in terms of HHV. For natural gas, the average heat content is near 1,030 Btu/scf on an HHV basis and about 930 Btu/scf on an LHV basis – a ratio of approximately 0.9 (LHV / HHV).
3. Electrical efficiencies are net of parasitic and conversion losses. Fuel gas compressor needs based on 1 psi inlet supply.
4. Total Efficiency = (net electricity generated + net heat produced for thermal needs)/total system fuel input
5. Power/Heat Ratio = CHP electrical power output (Btu)/ useful heat output (Btu)
6. Net Heat Rate = (total fuel input to the CHP system - the fuel that would be normally used to generate the same amount of thermal output as the CHP system output assuming an efficiency of 80 percent)/CHP electric output (kW).
7. Effective Electrical Efficiency = (CHP electric power output) / (total fuel into CHP system – total heat recovered/0.8).
8. Equipment cost only. The cost for all units, except the 30 kW size, includes integral heat recovery water heater. All units include a fuel gas booster compressor.
9. Installed costs based on CHP system producing hot water from exhaust heat recovery in a basic installation in grid connect mode.

5.4.1 Part-Load Performance

Microturbines that are in applications that require electric load following must operate during some periods at part load. Although, operationally, most installations are designed to operate at a constant output without load-following or frequent starts and stops. Multiple unit installations can achieve load following through sequentially turning on more units requiring less need for part load operation. When less than full electrical power is required from a microturbine, the output is reduced by a combination of mass flow reduction (achieved by decreasing the compressor speed) and turbine inlet temperature reduction. In addition to reducing power, this change in operating conditions also reduces efficiency. **Figure 5-3** shows a sample part-load efficiency curve for the Capstone C65. At 50 percent power output, the electrical efficiency drops by about 15 percent (decline from approximately 30 percent to 25 percent). However, at 50 percent power output, the thermal output of the unit only drops 41 percent resulting in a net loss of CHP efficiency of only 5 percent.

Figure 5-3. Part Load Efficiency at ISO Conditions, Capstone C65



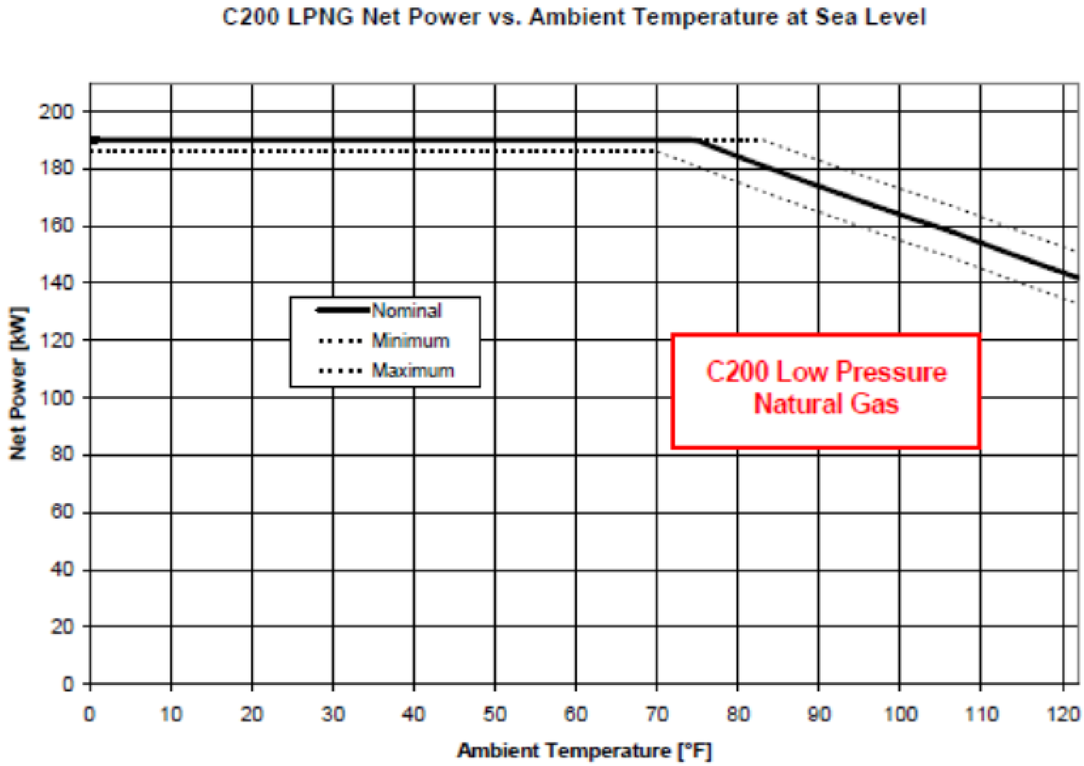
Source: Capstone, C65 Technical Reference

5.4.2 Effects of Ambient Conditions on Performance

The ambient conditions (temperature and air pressure) under which a microturbine operates have a noticeable effect on both the power output and efficiency. This section provides a better understanding of the changes observed due to changes in temperature and air pressure. At elevated inlet air temperatures, both the power and efficiency decrease. The power decreases due to the decreased mass flow rate of air (since the density of air declines as temperature increases), and the efficiency decreases because the compressor requires more power to compress air that is less dense. Conversely, the power and efficiency increase with reduced inlet air temperature.

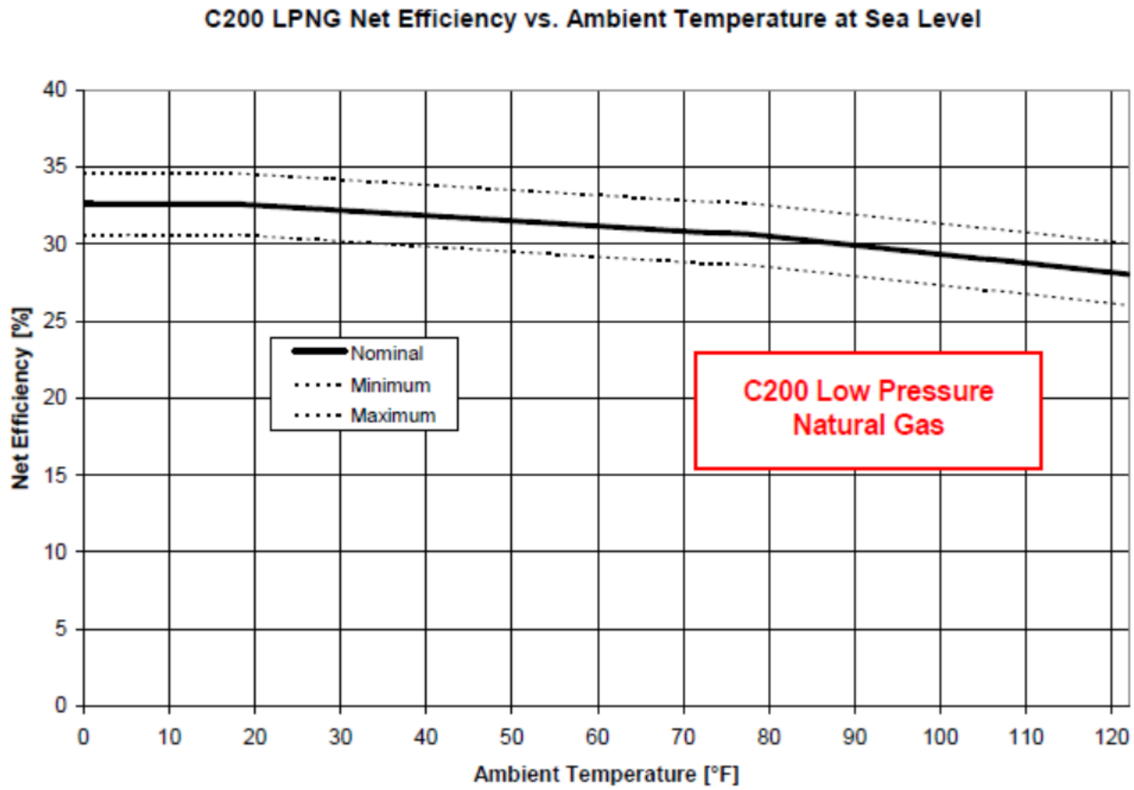
Figure 5-5 shows the variation in power and efficiency for a microturbine as a function of ambient temperature compared to the reference International Organization for Standards (ISO) condition of sea level and 59°F. The density of air decreases at altitudes above sea level. Consequently, power output decreases. **Figure 5-4** shows the effect of temperature on output, and **Figure 5-5** shows the effect on efficiency for the Capstone C200. The Capstone unit maintains a steady output up to 70-80 ^{o}F due to a limit on the generator output. However, the efficiency declines more uniformly as ambient temperature increases. **Figure 5-6** shows a combined power and efficiency curve for the FlexEnergy MT250. For this model, both power output and efficiency change more or less uniformly above and below the ISO rating point.

Figure 5-4. Temperature Effect on Power, Capstone C200-LP



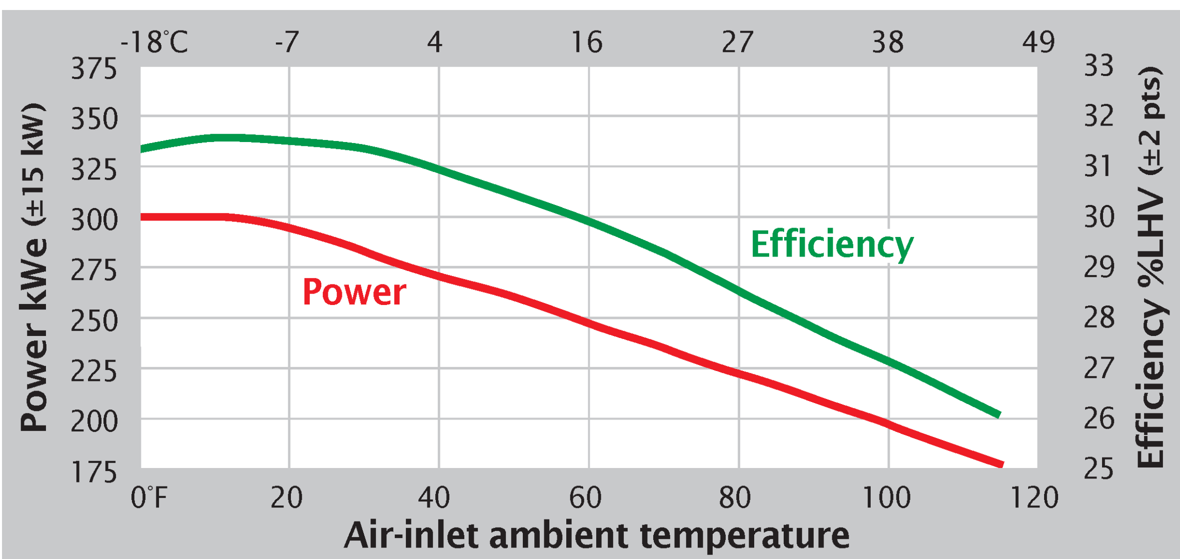
Source: Capstone Turbines

Figure 5-5. Temperature Effect on Efficiency, Capstone C200-LP



Source: Capstone Turbines

Figure 5-6. Temperature Effect on Power and Efficiency, FlexEnergy MT250



Source: FlexEnergy

Inlet air cooling can mitigate the decreased power and efficiency resulting from high ambient air temperatures. While inlet air cooling is not a feature on today's microturbines, cooling techniques now entering the market, or being employed, on large gas turbines may work their way into next generation microturbine products.

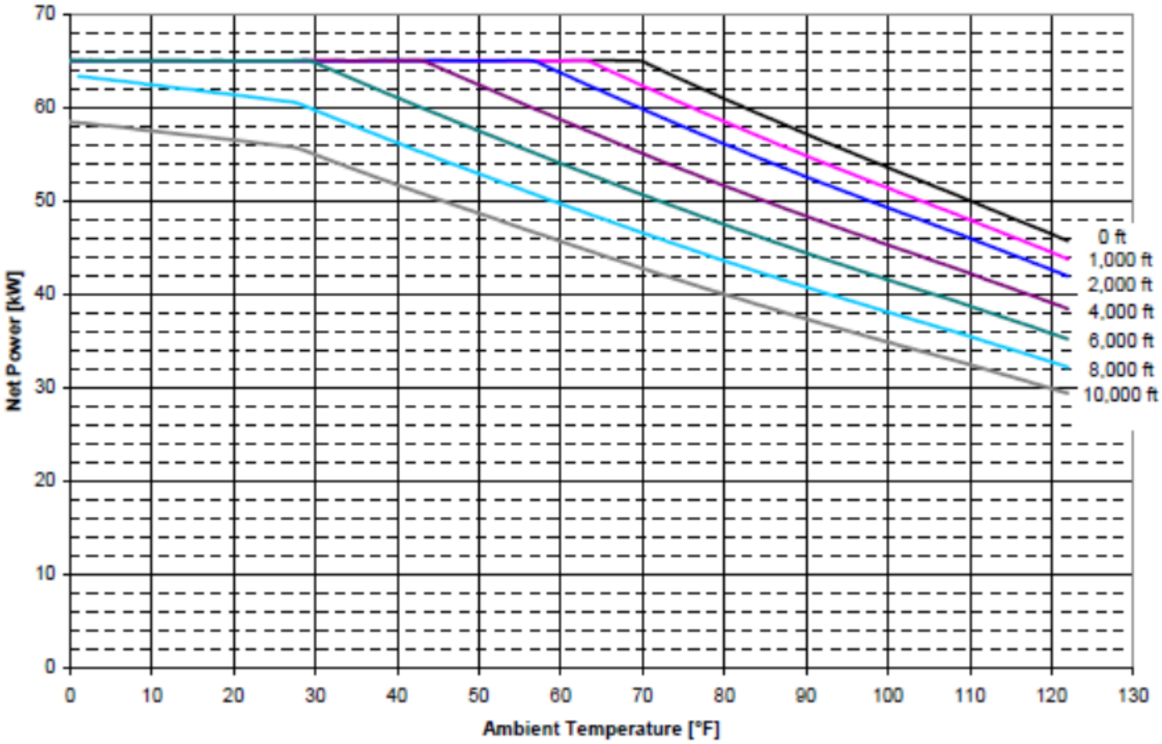
Evaporative cooling, a relatively low capital cost technique, is the most likely inlet air cooling technology to be applied to microturbines. It uses a very fine spray of water directly into the inlet air stream. Evaporation of the water reduces the temperature of the air. Since cooling is limited to the wet bulb air temperature, evaporative cooling is most effective when the wet bulb temperature is significantly below the dry bulb temperature. In most locales with high daytime dry bulb temperatures, the wet bulb temperature is often 20ºF lower. This temperature difference affords an opportunity for substantial evaporative cooling. However, evaporative cooling can consume large quantities of water, making it difficult to operate in arid climates.

Refrigeration cooling in microturbines is also technically feasible. In refrigeration cooling, a compression-driven or thermally activated (absorption) refrigeration cycle cools the inlet air through a heat exchanger. The heat exchanger in the inlet air stream causes an additional pressure drop in the air entering the compressor, thereby slightly lowering cycle power and efficiency. However, as the inlet air is now substantially cooler than the ambient air, there is a significant net gain in power and efficiency. Electric motor driven refrigeration results in a substantial amount of parasitic power loss. Thermally activated absorption cooling can use waste heat from the microturbine, reducing the direct parasitic loss. The relative complexity and cost of these approaches, in comparison with evaporative cooling, render them less likely.

Finally, it is also technically feasible to use thermal energy storage systems – typically ice, chilled water, or low-temperature fluids – to cool inlet air. These systems eliminate most parasitic losses from the augmented power capacity. Thermal energy storage is a viable option if on-peak power pricing only occurs a few hours a day. In that case, the shorter time of energy storage discharge and longer time for daily charging allow for a smaller and less expensive thermal energy storage system.

The density of air also decreases with increasing altitude. The effect of altitude derating on the Capstone C65 is shown in **Figure 5-7**. An installation in the mile high city of Denver would have a capacity of only 56 kW – a 14 percent drop in capacity. Unlike the effects of temperature rise, an increase in altitude at a given temperature does not have much impact on energy efficiency. The units operate at nearly the same efficiency, though at a lower output.

Figure 5-7. Ambient Elevation vs. Temperature Derating, Capstone C65



Source: Capstone Turbines

Gas turbine and microturbine performance is also affected by inlet and exhaust back-pressure. ISO ratings are at zero inlet pressure with no exhaust back-pressure. Adding the additional CHP heat exchanger definitely produces some increase in exhaust back pressure. Pressure drops on the inlet side from air filters also reduces the system output and efficiency. For the C65 shown in the previous figure, every 1" pressure drop on the inlet side produces roughly a 0.6 percent drop in power and a 0.2 percent drop in efficiency. A 1" pressure drop on the exhaust side produces about a 0.35 percent drop in power and a 0.25 percent drop in efficiency.

It is important when evaluating microturbine performance at a given site to consider all of the derating factors that are relevant: site altitude, average temperature and seasonal temperature swings, and pressure loss derating resulting from filters and the CHP heat recovery system. The combination of these factors can have a significant impact on both capacity and efficiency. Reduction in capacity also impacts the unit costs of the equipment because the same costs are being spread over fewer kilowatts.

5.4.3 Capital Cost

This section provides study estimates of capital costs for basic microturbine CHP installations. It is assumed that the thermal energy extracted from the microturbine exhaust is used for producing hot water for use on-site. Equipment-only and installed costs are estimated for each representative microturbine system. It should be emphasized that installed costs can vary significantly depending on the scope of the plant equipment, geographical area, competitive market conditions, special site requirements, emissions control requirements, prevailing labor rates, and whether the system is a new or a retrofit application.

Table 5-3 provides cost estimates for combined heat and power applications, assuming that the CHP system produces hot water and that there is no fuel pretreatment. Thermal recovery in the form of cooling can be accomplished with the addition of an absorption chiller – not included in this comparison. The basic microturbine package consists of the microturbine and power electronics. All of the commercial and near-commercial units offer basic interconnection and paralleling functionality as part of the package cost. All but one of the systems offers an integrated heat exchanger heat recovery system for CHP within the package.

There is little additional equipment that is required for these integrated systems. A heat recovery system has been added where needed, and additional controls and remote monitoring equipment have been added. The total plant cost consists of total equipment cost plus installation labor and materials (including site work), engineering, project management (including licensing, insurance, commissioning and startup), and financial carrying costs during a typical 3-month construction period.

The basic equipment costs represent material on the loading dock, ready to ship. It includes the cost of the generator package, the heat recovery, the flue gas compression and interconnection equipment cost. As shown in the table, the cost to a customer for installing a microturbine-based CHP system includes a number of other factors that increase the total costs by 70-80 percent.

Labor/materials represent the labor cost for the civil, mechanical, and electrical work and materials such as ductwork, piping, and wiring. A number of other costs are also incurred. These costs are often referred to as *soft costs* and they vary widely by installation, by development channel and by approach to project management. Engineering costs are required to design the system and integrate it functionally with the application's electrical and mechanical systems. In this characterization, environmental permitting fees are included. Project and construction management also includes general contractor markup, and bonding and performance guarantees. Contingency is assumed to be 5 percent of the total equipment cost in all cases. An estimated financial interest of 5 percent during a 3-month construction period is also included.

The cost estimates shown represent a basic installation. In the California Self-Generation incentive Program (SGIP) the average installation cost for 116 non-renewable fuel microturbine systems between 2001-2008 was $3,150/kW. For 26 renewable fueled systems over the same time period, the average installed cost was $3,970/kW.[85]

Table 5-3. Equipment and Installation Costs

	System					
	1	2	3	4	5	6
Electric Capacity						
Nominal Capacity (kW)	30	65	200	250	333	1000
Net Capacity (kW)	28	61	190	240	320	950

[85] *CPUC Self-Generation Incentive Program: Cost Effectiveness of Distributed Generation Technologies*, ITRON, Inc., 2011.

Table 5-3. Equipment and Installation Costs

	System					
	1	2	3	4	5	6
Equipment Costs						
Gen Set Package	$53,100	$112,900	$359,300	$441,200	$566,400	$1,188,600
Heat Recovery	$13,500	$0	$0	$0	$0	$275,000
Fuel Gas Compression	$8,700	$16,400	$42,600	$0	$0	$164,000
Interconnection	$0	$0	$0	$0	$0	$0
Total Equipment ($)	***$75,300***	***$129,300***	***$401,900***	***$441,200***	***$566,400***	***$1,627,600***
($/kW)	***$2,689***	***$2,120***	***$2,120***	***$1,840***	***$1,770***	***$1,710***
Installation Costs						
Labor/Materials	$22,600	$28,400	$80,400	$83,800	$101,900	$293,000
Project & Construction Mgmt	$9,000	$15,500	$48,200	$52,900	$68,000	$195,300
Engineering and Fees	$9,000	$15,500	$44,200	$48,500	$56,600	$162,800
Project Contingency	$3,800	$6,500	$20,100	$22,100	$28,300	$81,400
Financing (int. during const.)	$700	$1,200	$3,700	$4,100	$5,100	$14,800
Total Other Costs ($)	*$45,100*	*$67,100*	*$196,600*	*$211,400*	*$259,900*	*$747,300*
($/kW)	*$1,611*	*$1,100*	*$1,035*	*$881*	*$812*	*$787*
Total Installed Cost ($)	**$120,400**	**$196,400**	**$598,500**	**$652,600**	**$826,300**	**$2,374,900**
($/kW)	**$4,300**	**$3,220**	**$3,150**	**$2,720**	**$2,580**	**$2,500**

Source: Microturbine package costs and equipment from the vendors; installation costs developed by ICF.

As the table shows, there are economies of scale as sizes get larger. From 30 to 333 kW capital costs increase as the 0.8 power factor of the capacity increase[86] – a 100 percent increase in size results in an 80 percent increase in capital cost. Similar scale economies also exist for multiple unit installations such as the 1,000 kW unit comprised of five 200-kW units. The unit cost of the larger system is only 80 percent of the cost of the single unit.

5.4.4 Maintenance

Maintenance costs vary with size, fuel type and technology (air versus oil bearings). A typical maintenance schedule is shown in **Table 5-4.**

Table 5-4. Example Service Schedule, Capstone C65

Maintenance Interval	Component	Maintenance Action	Comments
24 months	UCB Battery	Replace	---
4,000 hours	Engine Air Filter	Inspect	Replace if application requires
	Electronics Air Filter	Inspect	Clean if necessary
	Fuel Filter Element (external)	Inspect	Replace if application requires (not required for gas pack)

[86] $(Cost_1/Cost_2) = (Size_1/Size_2)^{0.8}$

Table 5-4. Example Service Schedule, Capstone C65

Maintenance Interval	Component	Maintenance Action	Comments
	Fuel System	Leak Check	---
8,000 hours	Engine Air Filter	Replace	---
	Electronics Air Filter	Clean	---
	Fuel Filter Element (external)	Replace	Not required for gas pack
	Igniter	Replace	---
	ICHP Actuator	Replace	---
20,000 hours or 3 years	Battery Pack	Replace	---
20,000 hours	Injector Assemblies	Replace	---
	TET Thermocouple	Replace	---
	SPV	Replace	Replace with Woodward valve upgrade kit
40,000 hours	Electronic Components: ECM, LCM, & BCM Power Boards, BCM & ECM Fan Filters, Fans, EMI Filter, Frame PM	Replace	Kits available for each major configuration
	Engine	Replace	Remanufactured or new

Source: Adapted from Capstone C65 User's Manual.

Most manufacturers offer service contracts that cover scheduled and unscheduled events. The cost of a full service contract covers the inspections and component replacements outlined in **Table 5-5**, including replacement or rebuild of the main turbocompressor engine components. Full service costs vary according to fuel type and service as shown.

Table 5-5. Maintenance Costs Based on Factory Service Contracts

Maintenance Costs	System					
	1	2	3	4	5	6
Nominal Electricity Capacity (kW)	30	65	200	250	333	1000
Fixed ($/kW/yr)	---	---	---	$9.120	$6.847	---
Variable ($/kWh)	---	---	---	$0.010	$0.007	---
Average @ 6,000 hrs/year operation ($/kWh)	---	$0.013	$0.016	$0.011	$0.009	$0.012

Source: Compiled by ICF from vendor supplied data

Maintenance requirements can be affected by fuel type and site conditions. Waste gas and liquid fuel applications may require more frequent inspections and component replacement than natural gas systems. Microturbines operating in dusty and/or dirty environments require more frequent inspections and filter replacements.

5.4.5 Fuels

Stationary microturbines have been designed to use natural gas as their primary fuel. Microturbines designed for transportation applications typically utilize a liquid fuel such as methanol. As previously noted, microturbines are capable of operating on a variety of fuels including:

- **Liquefied petroleum gas (LPG)** – propane and butane mixtures
- **Sour gas** – unprocessed natural gas as it comes directly from a gas well
- **Biogas** – any of the combustible gases produced from biological degradation of organic wastes, such as landfill gas, sewage digester gas, and animal waste digester gas
- **Industrial waste gases** – flare gases and process off-gases from refineries, chemical plants and steel mills
- **Manufactured gases** – typically low- and medium-Btu gas produced as products of gasification or pyrolysis processes

Some of the elements work as contaminants and are a concern with some waste fuels, specifically the acid gas components (H_2S, halogen acids, HCN, ammonia, salts and metal-containing compounds, halogens, nitrogen compounds, and silicon compounds) and oils. In combustion, halogen and sulfur compounds form halogen acids, SO_2, some SO_3, and possibly H_2SO_4 emissions. The acids can also corrode downstream equipment. Solid particulates must be kept to low concentrations to prevent corrosion and erosion of components. Various fuel scrubbing, droplet separation, and filtration steps are required if fuel contaminant levels exceed manufacturer specifications. Landfill gas in particular often contains chlorine compounds, sulfur compounds, organic acids, and silicon compounds which dictate fuel pretreatment. A particular concern with wastewater treatment and landfill applications is the control of siloxane compounds. Siloxanes are a prevalent manmade organic compound used in a variety of products, and they eventually find their way into landfills and waste water. When siloxanes are exposed to high temperatures inside the combustion and exhaust sections of the turbine, they form hard silicon dioxide deposits that can eventually lead to turbine failure.

5.4.6 System Availability

Microturbine systems in the field have generally shown a high level of availability.[87] The basic design and low number of moving parts is conducive to high availability; manufacturers have targeted availabilities of 98-99 percent. The use of multiple units or backup units at a site can further increase the availability of the overall facility.

5.5 Emissions

Microturbines are designed to meet State and federal emissions regulations including more stringent State emissions requirements such as in California and other states (e.g., the Northeast). All microturbines operating on gaseous fuels feature lean premixed (dry low NO_x, or DLN) combustor technology. All of the example commercial units have been certified to meet extremely stringent standards in Southern California of less than 4-5 ppmvd of NO_x (15 percent O_2.) After employing a CO/VOC oxidation catalyst, carbon monoxide (CO) and volatile organic compound (VOC) emissions are at

[87] Availability refers to the percentage of time that the system is either operating or available to operate. Conversely, the system is unavailable when it is shut down for maintenance or when there has been a forced outage.

the same level. "Non-California" versions have NO_x emissions of less than 9 ppmvd. The emissions characteristics are shown in **Table 5-6**.

Table 5-6. Microturbine Emissions Characteristics

	System					
	1	2	3	4	5	6
Nominal Electric Capacity (kW)	30	65	200	240	320	1,000
Recovered Thermal Energy (kW)	61.0	119.8	258.9	376	450	1,299.0
Nominal Electrical Efficiency, HHV	23.6%	25.3%	28.1%	27.2%	29.2%	28.1%
NO_x (ppm @ 15% O_2, dry) [1]	9	4	4	5	9	4
NO_x (lb/MWh) [2]	0.49	0.17	0.14	0.23	0.39	0.14
NO_x (lb/MWh with CARB CHP credit)	0.16	0.06	0.06	0.09	0.16	0.06
CO (ppm @ 15% O_2, dry) [1]	40	8	8	5	10	8
CO (lb/MWh) [3]	1.8	0.24	0.2	0.14	0.26	0.2
CO (lb/MWh with CARB CHP credit)	0.59	0.08	0.09	0.06	0.11	0.09
VOC (ppm @ 15% O_2, dry) [1, 4]	9	3	3	5	9	3
VOC (lb/MWh) [5]	0.23	0.05	0.2	0.08	0.13	0.2
VOC (lb/MWh with CARB CHP credit)	0.08	0.02	0.09	0.03	0.06	0.09
CO_2 (lb/MWh electric only) [6]	1,814	1,680	1,497	1,530	1,424	1,497
CO_2 (lb/MWh with CARB CHP credit)	727	700	817	749	722	815

Notes:

1. Vendor estimates for low emission models using natural gas fuel. For systems 1, 2, 3, and 6 the vendor provided both input- (ppmv) and output-based emissions (lb/MWh.) For units 4 and 5, the output emissions were calculated as described below.
2. Output based NO_x emissions (lb/MWh) = (ppm @15% O_2) X 3.413) / ((272 X (% efficiency HHV))
3. Output based CO emissions (lb/MWh) = (ppm @15% O_2) X 3.413) / ((446 X (% efficiency HHV))
4. Volatile organic compounds.
5. Output based VOC emissions (lb/MWh) = (ppm @15% O_2) X 3.413) / ((782 X (% efficiency HHV))
6. Based on 116.39 lbs CO_2 / MMBtu.

The CO_2 emissions estimates with CHP show the potential of microturbines in CHP applications to reduce the emissions of CO_2. Coal fired generation emits about 2,000 lb/MWh, and even state of the art natural gas combined cycle power plants produce CO_2 emissions in the 800-900 lb/MWh range, even before transmission line losses are considered.

5.6 Future Developments

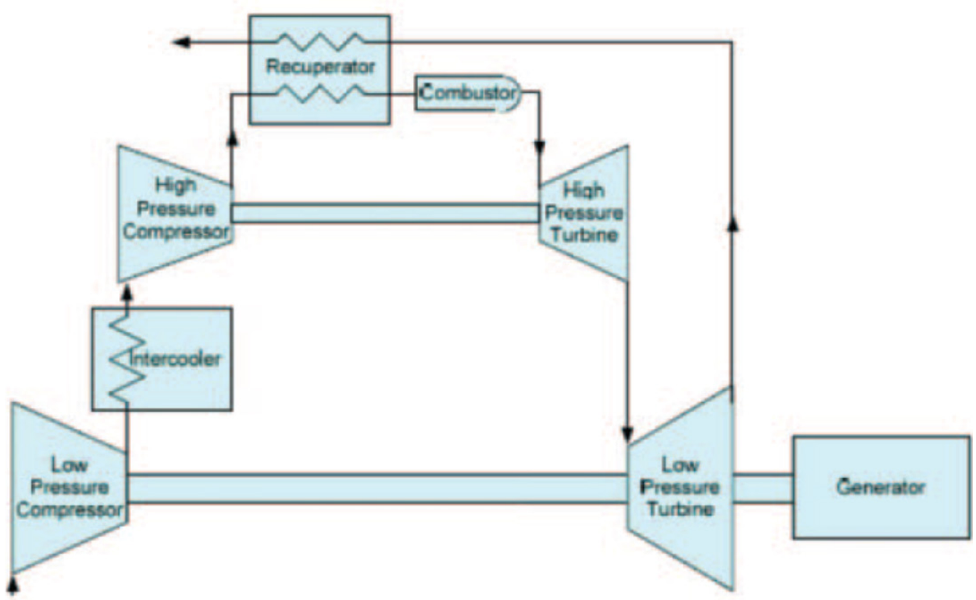
Microturbines first entered the market in the 30-75 kW size range. Of the last several years, microturbine manufacturers have developed larger capacity products to achieve better economics of operation through higher efficiencies and lower capital and maintenance costs.

Manufacturers are continuing to develop products with higher electrical efficiencies. Known developments include a model Capstone is developing, with the Department of Energy, on 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 is intended to feature an advanced aerodynamic compressor design, engine sealing improvements, improved generator design with longer life magnet, and enhanced cooling.

Key technical developments of the C370 model, shown schematically in **Figure 5-8**, include:

- Dual property, high-temperature turbine
- High-pressure compressors (11:1) and recuperator
- Dual generators – both low pressure and high-pressure spool
- Dual spool control development
- High-temperature, low emissions combustor
- Inter-state compressor cooling

Figure 5-8. Capstone C370 Two-shaft High Efficiency Turbine Design



Source: DOE, Energy Efficiency and Renewable Energy Fact Sheet

The C370 model 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.