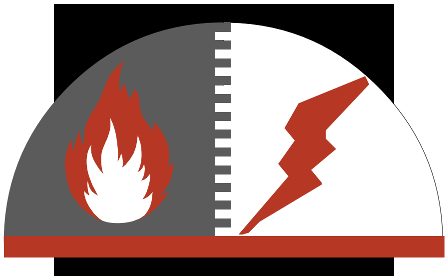
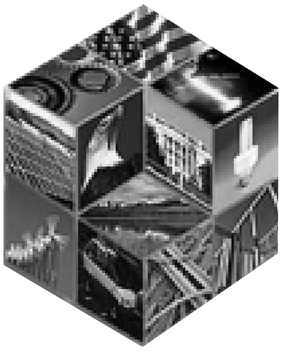
Review of Combined Heat and Power Technologies





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1.0 Combined Heat and Power Technologies

Introduction

Combined heat and power (CHP) technologies produce electricity or mechanical power and recover waste heat for process use. Conventional centralized power systems average less than 33% delivered efficiency for electricity in the U.S.; CHP systems can deliver energy with efficiencies exceeding 90%[1], while significantly reducing emissions per delivered MWh. CHP systems can provide cost savings for industrial and commercial users and substantial emissions reductions for the State of California. This report describes the leading CHP technologies, their efficiency, size, cost to install and maintain, fuels and emission characteristics.

The technologies included in this report include diesel engines, natural gas engines, steam turbines, gas turbines, micro-turbines and fuel cells. Most CHP technologies are commercially available for on-site generation and combined heat and power applications. Several barriers, including utility interconnection costs and issues, environmental regulations and technology costs have kept these technologies from gaining wider acceptance. Many of the technologies are undergoing incremental improvements to decrease costs and emissions while increasing efficiency. The business environment is witnessing dramatic changes with utility restructuring and increased customer choice. As a result of these changes, CHP is gaining wider acceptance in the market.

Selecting a CHP technology for a specific application depends on many factors, including the amount of power needed, the duty cycle, space constraints, thermal needs, emission regulations, fuel availability, utility prices and interconnection issues. Table 1 summarizes the characteristics of each CHP technology. The table shows that CHP covers a wide capacity range from 25 kW micro-turbines to 250 MW gas turbines. Estimated costs per installed kW range from $500-$1000/kW for all the technologies except fuel cells.

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[1] T. Casten, *CHP – Policy Implications for Climate Change and Electric Deregulation*, May 1998, p2.

Table 1 : Comparison of CHP Technologies

	Diesel Engine	**Natural Gas Engine**	**Steam Turbine**	**Gas Turbine**	**Micro-turbine**	**Fuel Cells**
Electric Efficiency (LHV)	30-50%	25-45%	30-42%	25-40% (simple)40-60% (combined)	20-30%	40-70%
Size (MW)	0.05-5	0.05-5	Any	3-200	0.025-0.25	0.2-2
Footprint (sqft/kW)	0.22	0.22-0.31	<0.1	0.02-0.61	0.15-1.5	0.6-4
CHP installed cost ($/kW)	800-1500	800-1500	800-1000	700-900	500-1300	>3000
O&M Cost ($/kWh)	0.005-0.008	0.007-0.015	0.004	0.002-0.008	0.002-0.01	0.003-0.015
Availability	90-95%	92-97%	Near 100%	90-98%	90-98%	>95%
Hours between overhauls	25,000-30,000	24,000-60,000	>50,000	30,000-50,000	5,000-40,000	10,000-40,000
Start-up Time	10 sec	10 sec	1 hr-1 day	10 min –1 hr	60 sec	3 hrs-2 days
Fuel pressure (psi)	<5	1-45	n/a	120-500 (may require compressor)	40-100 (may require compressor)	0.5-45
Fuels	diesel and residual oil	natural gas, biogas, propane	all	natural gas, biogas, propane, distillate oil	natural gas, biogas, propane, distillate oil	hydrogen, natural gas, propane
Noise	moderate to high (requires building enclosure)	moderate to high (requires building enclosure)	moderate to high (requires building enclosure)	moderate (enclosure supplied with unit)	moderate (enclosure supplied with unit)	low (no enclosure required)
NO_x Emissions(lb/MWhr)	3-33	2.2-28	1.8	0.3-4	0.4-2.2	<0.02
Uses for Heat Recovery	hot water, LP steam, district heating	hot water, LP steam, district heating	LP-HP steam, district heating	direct heat, hot water, LP-HP steam, district heating	direct heat, hot water, LP steam	hot water, LP-HP steam
CHP Output (Btu/kWh)	3,400	1,000-5,000	n/a	3,400-12,000	4,000-15,000	500-3,700
Useable Temp for CHP (F)	180-900	300-500	n/a	500-1,100	400-650	140-700

2.0 Reciprocating Engines

Introduction

Among the most widely used and most efficient prime movers are reciprocating (or internal combustion) engines. Electric efficiencies of 25-50% make reciprocating engines an economic CHP option in many applications. Several types of reciprocating engines are commercially available, however, two designs are of most significance to stationary power applications and include four cycle- spark-ignited (Otto cycle) and compression-ignited (diesel cycle) engines. They can range in size from small fractional portable gasoline engines to large 50,000 HP diesels for ship propulsion. In addition to CHP applications, diesel engines are widely used to provide standby or emergency power to hospitals, and commercial and industrial facilities for critical power requirements.

2.1 Technology Description

The essential mechanical parts of Otto-cycle and diesel engines are the same. Both use a cylindrical combustion chamber in which a close fitting piston travels the length of the cylinder. The piston is connected to a crankshaft which transforms the linear motion of the piston within the cylinder into the rotary motion of the crankshaft. Most engines have multiple cylinders that power a single crankshaft. Both Otto-cycle and diesel four stroke engines complete a power cycle in four strokes of the piston within the cylinder. Strokes include: 1) introduction of air (or air-fuel mixture) into the cylinder, 2) compression with combustion of fuel, 3) acceleration of the piston by the force of combustion (power stroke) and 4) expulsion of combustion products from the cylinder.

The primary difference between Otto and diesel cycles is the method of fuel combustion. An Otto cycle uses a spark plug to ignite a pre-mixed fuel-air mixture introduced to the cylinder. A diesel engine compresses the air introduced in the cylinder to a high pressure, raising its temperature to the ignition temperature of the fuel which is injected at high pressure.

A variation of the diesel is the dual fuel engine. Up to 80-90% of the diesel fuel is substituted with gasoline or natural gas while maintaining power output and achieving substantial emission reductions.

Large modern diesel engines can attain electric efficiencies near 50% and operate on a variety of fuels including diesel fuel, heavy fuel oil or crude oil. Diesel engines develop higher part load efficiencies than an Otto cycle because of leaner fuel-air ratios at reduced load.

2.2 Design Characteristics

The features that have made reciprocating engines a leading prime mover for CHP include:

Economical size range:	Reciprocating engines are available in sizes that match the electric demand of many end-users (institutional, commercial and industrial).
Fast start-up:	Fast start-up allows timely resumption of the system following a maintenance procedure. In peaking or emergency power applications, reciprocating engines can quickly supply electricity on demand.
Black-start capability:	In the event of a electric utility outage, reciprocating engines can be started with minimal auxiliary power requirements, generally only batteries are required.
Excellent availability:	Reciprocating engines have typically demonstrated availability in excess of 95%.
Good part load operation:	In electric load following applications, the high part load efficiency of reciprocating engines maintain economical operation.
Reliable and long life:	Reciprocating engines, particularly diesel and industrial block engines have provided many years of satisfactory service given proper maintenance.

2.3 Performance Characteristics

Efficiency
Reciprocating engines have electric efficiencies of 25-50% (LHV) and are among the most efficient of any commercially available prime mover. The smaller stoichiometric engines that require 3-way catalyst after-treatment operate at the lower end of the efficiency scale while the larger diesel and lean burn natural gas engines operate at the higher end of the efficiency range.

Capital Cost
CHP projects using reciprocating engines are typically installed between $800-$1500/kW. The high end of this range is typical for small capacity projects that are sensitive to other costs associated with constructing a facility, such as fuel supply, engine enclosures, engineering costs, and permitting fees.

Availability
Reciprocating engines have proven performance and reliability. With proper maintenance and a good preventative maintenance program, availability is over 95%. Improper maintenance can have major impacts on availability and reliability.

Maintenance

Engine maintenance is comprised of routine inspections/adjustments and periodic replacement of engine oil, coolant and spark plugs every 500-2,000 hours. An oil analysis is an excellent method to determine the condition of engine wear. The time interval for overhauls is recommended by the manufacturer but is generally between 12,000-15,000 hours of operation for a top-end overhaul and 24,000-30,000 for a major overhaul. A top-end overhaul entails a cylinder head and turbo-charger rebuild. A major overhaul involves piston/ring replacement and crankshaft bearings and seals. Typical maintenance costs including an allowance for overhauls is 0.01 - 0.015$/kWhr.

Heat Recovery

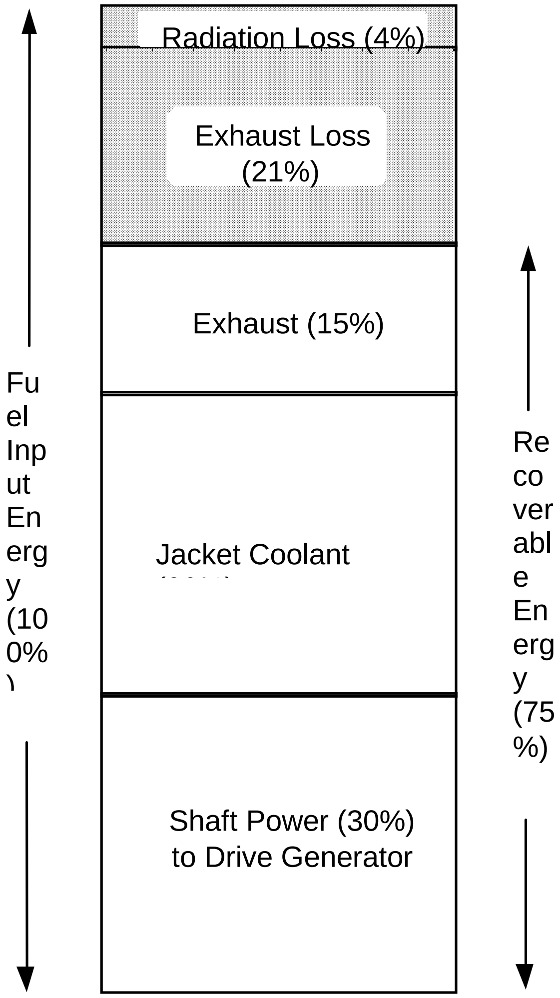
Energy in the fuel is released during combustion and is converted to shaft work and heat. Shaft work drives the generator while heat is liberated from the engine through coolant, exhaust gas and surface radiation. Approximately 60-70% of the total energy input is converted to heat that can be recovered from the engine exhaust and jacket coolant, while smaller amounts are also available from the lube oil cooler and the turbocharger's intercooler and aftercooler (if so equipped). Steam or hot water can be generated from recovered heat that is typically used for space heating, reheat, domestic hot water and absorption cooling.

Heat in the engine jacket coolant accounts for up to 30% of the energy input and is capable of producing 200°F hot water. Some engines, such as those with high pressure or ebullient cooling systems, can operate with water jacket temperatures up to 265°.

Engine exhaust heat is 10-30% of the fuel input energy. Exhaust temperatures of 850°-1200°F are typical. Only a portion of the exhaust heat can be recovered since exhaust gas temperatures are generally kept above condensation thresholds. Most heat recovery units are designed for a 300°-350°F exhaust outlet temperature to avoid the corrosive effects of condensation in the exhaust piping. Exhaust heat is typically used to generate hot water to about 230°F or low-pressure steam (15 psig).

By recovering heat in the jacket water and exhaust, approximately 70-80% of the fuel's energy can be effectively utilized as shown in Figure 1 for a typical spark-ignited engine.

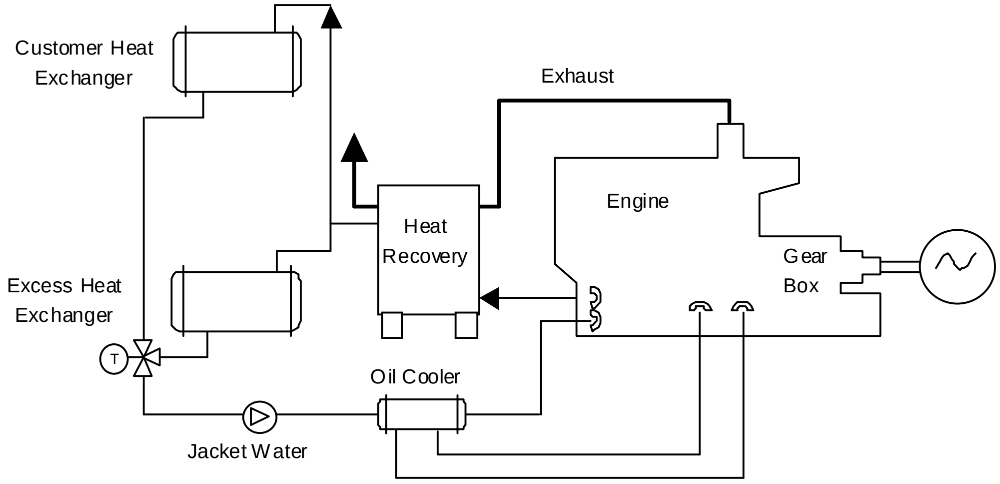
Figure 1 : Energy Balance for a Reciprocating Engine



Closed-Loop Hot Water Cooling Systems

The most common method of recovering engine heat is the closed-loop cooling system as shown in Figure 2. These systems are designed to cool the engine by forced circulation of a coolant through engine passages and an external heat exchanger. An excess heat exchanger transfers engine heat to a cooling tower or radiator when there is excess heat generated. Closed-loop water cooling systems can operate at coolant temperatures between 190°-250°F.

Figure 2: Closed-Loop Heat Recovery System



Ebullient Cooling Systems

Ebullient cooling systems cool the engine by natural circulation of a boiling coolant through the engine. This type of cooling system is typically used in conjunction with exhaust heat recovery for production of low-pressure steam. Cooling water is introduced at the bottom of the engine where the transferred heat begins to boil the coolant generating two-phase flow. The formation of bubbles lowers the density of the coolant, causing a natural circulation to the top of the engine.

The coolant at the engine outlet is maintained at saturated steam conditions and is usually limited to 250°F and a maximum of 15 psig. Inlet cooling water is also near saturation conditions and is generally 2°- 3°F below the outlet temperature. The uniform temperature throughout the coolant circuit extends engine life, contributes to improved combustion efficiencies and reduces friction in the engine.

2.4 Emissions

The two primary methods of lowering emissions in Otto cycle engines is lean burn (combustion control) and rich burn with a catalytic after-treatment.

Lean burn engine technology was developed during the 1980's in response to the need for cleaner burning engines. Most lean burn engines use turbocharging to supply excess air to the engine and produce lean fuel-air ratios. Lean burn engines consume 50-100% excess air (above stoichiometric) to reduce temperatures in the combustion chamber and limit creation of nitrogen oxides (NO_x,) carbon dioxide (CO) and non-methane hydrocarbons (NMHC.) The typical NO_x emission rate for lean burn engines is between 0.5–2.0 grams/hphr. Emission levels can be reduced to less than 0.15gm/hphr with selective catalytic reduction (SCR) where ammonia is injected into the exhaust gas in the presence of a catalyst. SCR adds a significant cost burden to the installation cost and increases the O&M on the engine. This approach is typically used on large capacity engines.

Catalytic converters are used with rich burn (i.e. stoichiometric) Otto cycles. A reducing catalyst converts NO_x to N_2 and oxidizes some of the CO to CO_2. A catalytic converter can contain both reducing and oxidizing catalytic material in a single bed. Electronic fuel–air ratio controls are typically needed to hold individual emission rates to within a very close tolerance. Also referred to as a three-way catalyst, hydrocarbon, NO_x and CO are simultaneously controlled. Typical NO_x emission rates for rich burn engines are approximately 9 grams/hphr. Catalytic converters have proven to be the most effective after treatment of exhaust gas with control efficiencies of 90-99%+, reducing NO_x emissions to 0.15gm/hphr. A stoichiometric engine with a catalytic convertor operates with an efficiency of approximately 30%. Maintenance costs can increase by 25% for catalyst replacement.

Diesel engines operate at much higher air-fuel ratios than Otto cycle engines. The high excess air (lean condition) causes relatively low exhaust temperatures such that conventional catalytic converters for NO_x reduction are not effective. Lean NO_x catalytic converters are currently under development. Some diesel applications employ SCR to reduce emissions.

A major emission impact of a diesel engine is particulates. Particulate traps physically capture fine particulate matter generated by the combustion of diesel fuel and are typically 90% effective. Some filters are coated with a catalyst that must be regenerated for proper operation and long life. In some areas of California, such as areas under the jurisdiction of the South Coast Air Quality Management District (SCAQMD), diesel engines are very difficult to permit for continuous operation. Some exceptions apply for emergency generators.

2.5 Applications

Reciprocating engines are typically used in CHP applications where there is a substantial hot water or low pressure steam demand. When cooling is required, the thermal output of a reciprocating engine can be used in a single-effect absorption chiller. Reciprocating engines are available in a broad size range of approximately 50kW to 5,000kW suitable for a wide variety of commercial, institutional and small industrial facilities. Reciprocating engines are frequently used in load following applications where engine power output is regulated based on the electric demand of the facility. Thermal output varies accordingly. Thermal balance is achieved through supplemental heat sources such as boilers.

2.6 Technology Advancements

Advances in electronics, controls and remote monitoring capability should increase the reliability and availability of engines. Maintenance intervals are being extended through development of longer life spark plugs, improved air and fuel filters, synthetic lubricating oil and larger engine oil sumps.

Reciprocating engines have been commercially available for decades. A global network of manufacturers, dealers and distributors is well established.

3.0 Steam Turbines

Introduction

Steam turbines are one of the most versatile and oldest prime mover technologies used to drive a generator or mechanical machinery. Steam turbines are widely used for CHP applications in the U.S. and Europe where special designs have been developed to maximize efficient steam utilization.

Most of the electricity in the United States is generated by conventional steam turbine power plants. The capacity of steam turbines can range from a fractional horsepower to more than 1,300 MW for large utility power plants.

A steam turbine is captive to a separate heat source and does not directly convert a fuel source to electric energy. Steam turbines require a source of high pressure steam that is produced in a boiler or heat recovery steam generator (HRSG). Boiler fuels can include fossil fuels such as coal, oil and natural gas or renewable fuels like wood or municipal waste.

Steam turbines offer a wide array of designs and complexity to match the desired application and/or performance specifications. In utility applications, maximizing efficiency of the power plant is crucial for economic reasons. Steam turbines for utility service may have several pressure casings and elaborate design features. For industrial applications, steam turbines are generally of single casing design, single or multi-staged and less complicated for reliability and cost reasons. CHP can be adapted to both utility and industrial steam turbine designs.

3.1 Technology Description

The thermodynamic cycle for the steam turbine is the Rankine cycle. The cycle is the basis for conventional power generating stations and consists of a heat source (boiler) that converts water to high pressure steam. The steam flows through the turbine to produce power. The steam exiting the turbine is condensed and returned to the boiler to repeat the process.

A steam turbine consists of a stationary set of blades (called nozzles) and a moving set of adjacent blades (called buckets or rotor blades) installed within a casing. The two sets of blades work together such that the steam turns the shaft of the turbine and the connected load. A steam turbine converts pressure energy into velocity energy as it passes through the blades.

The primary type of turbine used for central power generation is the *condensing* turbine. Steam exhausts from the turbine at sub-atmospheric pressures, maximizing the heat extracted from the steam to produce useful work.

Steam turbines used for CHP can be classified into two main types:

The *non-condensing turbine* (also referred to as a back-pressure turbine) exhausts steam at a pressure suitable for a downstream process requirement. The term refers to turbines that exhaust steam at atmospheric pressures and above. The discharge pressure is established by the specific CHP application.

The *extraction turbine* has opening(s) in its casing for extraction of steam either for process or feedwater heating. The extraction pressure may or may not be automatically regulated depending on the turbine design. Regulated extraction permits more steam to flow through the turbine to generate additional electricity during periods of low thermal demand by the CHP system. In utility type steam turbines, there may be several extraction points each at a different pressure.

3.2 Design Characteristics

Custom design:	Steam turbines can be designed to match CHP design pressure and temperature requirements. The steam turbine can be designed to maximize electric efficiency while providing the desired thermal output.
High thermal quality:	Steam turbines are capable of operating over the broadest available steam pressure range from subatmospheric to supercritical and can be custom designed to deliver the thermal requirements of the CHP application.
Fuel flexibility:	Steam turbines offer the best fuel flexibility using a variety of fuel sources including nuclear, coal, oil, natural gas, wood and waste products.

3.3 Performance Characteristics

Efficiency

Modern large condensing steam turbine plants have efficiencies approaching 40-45%, however, efficiencies of smaller industrial or backpressure turbines can range from 15-35%.

Capital Cost

Boiler/ steam turbines installation costs are between $800-$1000/kW or greater depending on environmental requirements. The incremental cost of adding a steam turbine to an existing boiler system or to a combined cycle plant is approximately$400-$800/kW.

Availability

A steam turbine is generally considered to have 99%+ availability with longer than a year between shutdowns for maintenance and inspections. This high level of availability applies only for the steam turbine and does not include the heat source.

Maintenance

A maintenance issue with steam turbines is solids carry over from the boiler that deposit on turbine nozzles and degrades power output. The oil lubrication system must be clean and at the correct operating temperature and level to maintain proper performance. Other items include inspecting auxiliaries such as lubricating-oil pumps, coolers and oil strainers and check safety devices such as the operation of overspeed trips. Steam turbine maintenance costs are typically less than $0.004 per kWhr.

3.4 Heat Recovery

Heat recovery methods from a steam turbine use exhaust or extraction steam. Heat recovery from a steam turbine is somewhat misleading since waste heat is generally associated with the heat source, in this case a boiler either with an economizer or air preheater.

A steam turbine can be defined as a heat recovery device. Producing electricity in a steam turbine from the exhaust heat of a gas turbine (combined cycle) is a form of heat recovery.

The amount and quality of the recovered heat is a function of the entering steam conditions and the design of the steam turbine. Exhaust steam from the turbine can be used directly in a process or for district heating. Or it can be converted to other forms of thermal energy including hot water or chilled water. Steam discharged or extracted from a steam turbine can be used in a single or double-effect absorption chiller. A steam turbine can also be used as a mechanical drive for a centrifugal chiller.

3.5 Emissions

Emissions associated with a steam turbine are dependent on the source of the steam. Steam turbines can be used with a boiler firing a large variety of fuel sources or it can be used with a gas turbine in a combined cycle. Boiler emissions can vary depending on environmental conditions. In the SCAQMD jurisdiction, large boilers use SCR to reduce NO_x emissions to single digit levels.

3.6 Applications

Steam Turbines for Industrial and CHP Applications
In industrial applications, steam turbines may drive an electric generator or equipment such as boiler feedwater pumps, process pumps, air compressors and refrigeration chillers. Turbines as industrial drivers are almost always a single casing machine, either single stage or multistage, condensing or non-condensing depending on steam conditions and the value of the steam. Steam turbines can operate at a single speed to drive an electric generator or operate over a speed range to drive a refrigeration compressor.

For non-condensing applications, steam is exhausted from the turbine at a pressure and temperature sufficient for the CHP heating application. Back pressure turbines can operate over a wide pressure range depending on the process requirements and exhaust steam at typically between 5 psig to 150 psig. Back pressure turbines are less efficient than condensing turbines, however, they are less expensive and do not require a surface condenser.

Combined Cycle Power Plants
The trend in power plant design is the combined cycle which incorporates a steam turbine in a bottoming cycle with a gas turbine. Steam generated in the heat recovery steam generator (HRSG) of the gas turbine is used to drive a steam turbine to yield additional electricity and improve cycle efficiency. The steam turbine is usually an extraction-condensing type and can be designed for CHP applications.

3.7 Technology Advancements

Steam turbines have been commercially available for decades. Advancements will more likely occur in gas turbine technology.

4.0 Gas Turbines

Introduction

Over the last two decades, the gas turbine has seen tremendous development and market expansion. Whereas gas turbines represented only 20% of the power generation market twenty years ago, they now claim approximately 40% of new capacity additions. Gas turbines have been long used by utilities for peaking capacity, however, with changes in the power industry and increased efficiency, the gas turbine is now being used for base load power. Much of this growth can be accredited to large (>50 MW) combined cycle plants that exhibit low capital cost (less than $550/kW) and high thermal efficiency. Manufacturers are offering new and larger capacity machines that operate at higher efficiencies. Some forecasts predict that gas turbines may furnish more than 80% of all new U.S. generation capacity in coming decades.[2]

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[2] U.S. DOE Energy Information Administration

Gas turbine development accelerated in the 1930's as a means of propulsion for jet aircraft. It was not until the early 1980's that the efficiency and reliability of gas turbines had progressed sufficiently to be widely adopted for stationary power applications. Gas turbines range in size from 30 kW (microturbines) to 250 MW (industrial frames).

4.1 Technology Description

The thermodynamic cycle associated with the majority of gas turbine systems is the Brayton cycle, that passes atmospheric air, the working fluid, through the turbine only once. The thermodynamic steps of the Brayton cycle include compression of atmospheric air, introduction and ignition of fuel, and expansion of the heated combustion gases through the gas producing and power turbines. The developed power is used to drive the compressor and the electric generator. Primary components of a gas turbine are shown in Figure 3.

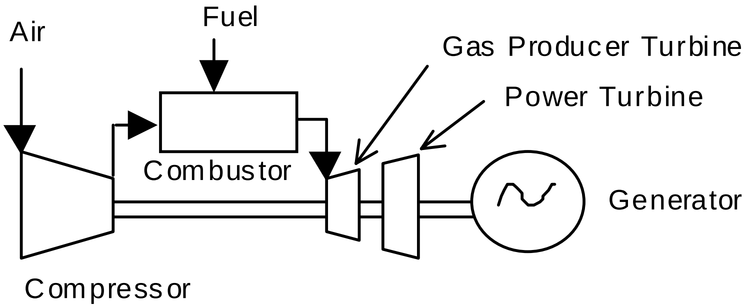


Figure 3: Components of a Gas Turbine

Aeroderivative gas turbines for stationary power are adapted from their jet engine counterpart. These turbines are light weight and thermally efficient, however, are limited in capacity. The largest aeroderivitives are approximately 40 MW in capacity today. Many aeroderivative gas turbines for stationary use operate with compression ratios up to 30:1 requiring an external fuel gas compressor. With advanced system developments, aeroderivitives are approaching 45% simple cycle efficiencies.

Industrial or frame gas turbines are available between 1 MW to 250 MW. They are more rugged, can operate longer between overhauls, and are more suited for continuous base-load operation. However, they are less efficient and much heavier than the aeroderivative. Industrial gas turbines generally have more modest compression ratios up to 16:1 and often do not require an external compressor. Industrial gas turbines are approaching simple cycle efficiencies of approximately 40% and in combined cycles are approaching 60%.

Small industrial gas turbines are being successfully used in industry for onsite power generation and as mechanical drivers. Turbine sizes are typically between 1–10 MW for these applications. Small gas turbines drive compressors along natural gas pipelines for cross country transport. In the petroleum industry they drive gas compressors to maintain well pressures. In the steel industry they drive air compressors used for blast furnaces. With the coming competitive electricity market, many experts believe that installation of small industrial gas turbines will proliferate as a cost effective alternative to grid power.

4.2 Design Characteristics

Quality thermal output:	Gas turbines produce a high quality thermal output suitable for most CHP applications.
Cost effectiveness:	Gas turbines are among the lowest cost power generation technologies on a $/kW basis, especially in combined cycle.
Fuel flexibility:	Gas turbines operate on natural gas, synthetic gas and fuel oils. Plants are often designed to operate on gaseous fuel with a stored liquid fuel for backup.
Reliable and long life:	Modern gas turbines have proven to be reliable power generation devices, given proper maintenance.
Economical size range:	Gas turbines are available in sizes that match the electric demand of many end-users (institutional, commercial and industrial).

4.3 Performance Characteristics

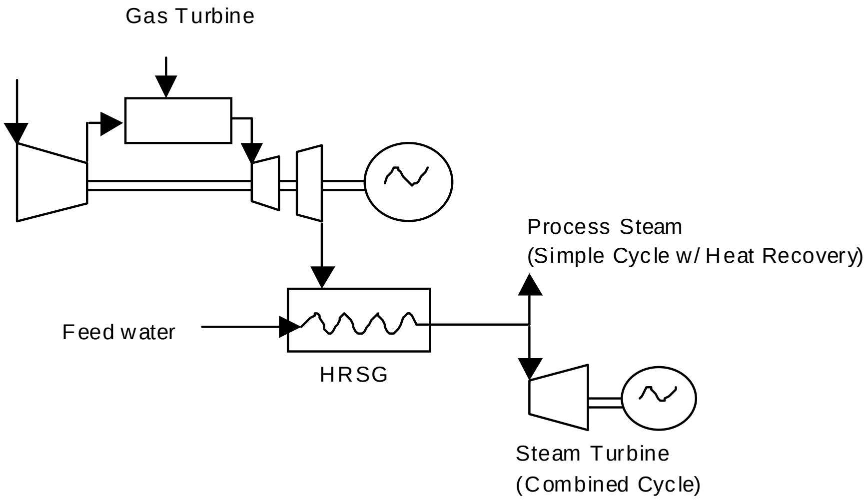
Efficiency
The thermal efficiency of the Brayton cycle is a function of pressure ratio, ambient air temperature, turbine inlet temperature, the efficiency of the compressor and turbine elements and any performance enhancements (i.e. recuperation, reheat, or combined cycle). Efficiency generally increases for higher power outputs and aeroderivative designs. Simple cycle efficiencies can vary between 25-40% lower heating value (LHV). Next generation combined cycles are being advertised with electric efficiencies approaching 60%.

Capital Cost
The capital cost of a gas turbine power plant on a kW basis ($/kW) can vary significantly depending on the capacity of the facility. Typical estimates vary between $300-$900/kW. The lower end applies to large industrial frame turbines in combined cycle.

Availability
Estimated availability of gas turbines operating on clean gaseous fuels like natural gas is in excess of 95%. Use of distillate fuels and other fuels with contaminants require more frequent shutdowns for preventative maintenance that reduce availability.

Maintenance
Although gas turbines can be cycled, maintenance costs can triple for a turbine that is cycled every hour versus a turbine that is operated for intervals of 1000 hours. Operating the turbine over the rated design capacity for significant time periods will also dramatically increase the number of hot path inspections and overhauls. Maintenance costs of a turbine operating on fuel oil can be approximately three times that as compared to natural gas. Typical maintenance costs for a gas turbine fired by natural gas is 0.003-0.005 $/kWhr.

Figure 4: Heat Recovery from a Gas Turbine System



4.4 Heat Recovery

The simple cycle gas turbine is the least efficient arrangement since there is no recovery of heat in the exhaust gas (see Figure 4). Hot exhaust gas can be used directly in a process or by adding a heat recovery steam generator (HRSG), exhaust heat can generate steam or hot water.

For larger gas turbine installations, combined cycles become economical, achieving approximately 60% electric generation efficiencies using the most advanced utility-class gas turbines. The heat recovery options available from a steam turbine used in the combined cycle can be implemented to further improve the overall system efficiency (as discussed previously.)

Since gas turbine exhaust is oxygen rich, it can support additional combustion through supplementary firing. A duct burner is usually fitted within the HRSG to increase the exhaust gas temperature at efficiencies of 90% and greater.

4.5 Emissions

The dominant NO_x control technologies for gas turbines include water/steam injection and lean pre-mix (combustion control) and selective catalytic reduction (post combustion control). Without any controls, gas turbines produce levels of NO_x between 75-200 ppmv. By injecting water or steam into the combustor, NO_x emissions can be reduced to approximately 42 ppmv with water and 25 ppmv with steam. NO_x emissions from distillate-fired turbines can be reduced to about 42-75 ppmv. Water or steam injection requires very purified water to minimize the effects of water-induced corrosion of turbine components.

Lean pre-mix (dry low NO_x) is a combustion modification where a lean mixture of natural gas and air are pre-mixed prior to entering the combustion section of the gas turbine. Pre-mixing avoids "hot spots" in the combustor where NO_x forms. Turbine manufacturers have achieved NO_x emissions of 9-42 ppmv using this technology. This technology is still being developed and early designs have caused turbine damage due to "flashback". Elevated noise levels have also been encountered.

Selective catalytic reduction (SCR) is a post combustion treatment of the turbine's exhaust gas in which ammonia is reacted with NO_x in the presence of a catalyst to produce nitrogen and water. SCR is approximately 80-90% effective in the reduction of upstream NO_x emission levels. Assuming a turbine has NO_x emissions of 25 ppm, SCR can further reduce emissions to 3-5 ppm. SCR is used in series with water/steam injection or lean pre-mix to produce single-digit emission levels. SCR requires an upstream heat recovery device to temper the temperature of the exhaust gas in contact with the catalyst. SCR requires onsite storage of ammonia, a hazardous chemical. In addition ammonia can "slip" through the process unreacted that contributes to air pollution. SCR systems are expensive and significantly impact the economic feasibility of smaller gas turbine projects.

4.6 Applications

Gas turbines are a cost effective CHP alternative for commercial and industrial end-users with a base load electric demand greater than about 5 MW. Although gas turbines can operate satisfactorily at part load, they perform best at full power in base load operation. Gas turbines are frequently used in district steam heating systems since their high quality thermal output can be used for most medium pressure steam systems.

Gas turbines for CHP can be in either a simple cycle or a combined cycle configuration. Simple cycle applications are most prevalent in smaller installations typically less than 25 MW. Waste heat is recovered in a HRSG to generate high or low pressure steam or hot water. The thermal product can be used directly or converted to chilled water with single or double effect absorption chillers.

4.7 Technology Advancements

Advancements in blade design, cooling techniques and combustion modifications including lean premix (dry low NOx) and catalytic combustion are under development to achieve higher thermal efficiencies and single digit emission levels without post combustion treatment. Gas turbine manufacturers have been commercializing their products for decades. A global network of manufacturers, dealers and distributors is well established.

5.0 Microturbines

Introduction

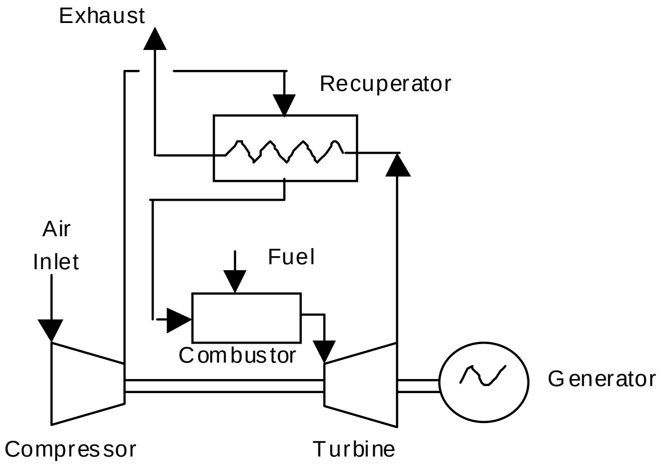
A new class of small gas turbines called microturbines is emerging for the distributed resource market. Several manufacturers are developing competing engines in the 25-250 kW range, however, multiple units can be integrated to produce higher electrical output while providing additional reliability. Most manufacturers are pursuing a single shaft design wherein the compressor, turbine and permanent-magnet generator are mounted on a single shaft supported on lubrication-free air bearings. These turbines operate at speeds of up to 120,000 rpm and are powered by natural gas, gasoline, diesel, and alcohol. The dual shaft design incorporates a power turbine and gear for mechanical drive applications and operate up to speeds of 40,000 rpm. Microturbines are a relatively new entry in the CHP industry and therefore many of the performance characteristics are estimates based on demonstration projects and laboratory testing.

5.1 Technology Description

The operating theory of the microturbine is similar to the gas turbine, except that most designs incorporate a recuperator to recover part of the exhaust heat for preheating the combustion air. As shown in Figure 5, air is drawn through a compressor section, mixed with fuel and ignited to power the turbine section and the generator. The high frequency power that is generated is converted to grid compatible 60HZ through power conditioning electronics. For single shaft machines, a standard induction or synchronous generator can be used without any power conditioning electronics.

Figure 5: Schematic of a Recuperated Microturbine

5.2 Design Characteristics



Compact:	Their compact and lightweight design makes microturbines an attractive option for many light commercial/ industrial applications.
Right-sized:	Microturbine capacity is right sized for many customers with relatively high electric costs.
Lower noise:	Microturbines promise lower noise levels and can be located adjacent to occupied areas.

5.3 Performance Characteristics

Efficiency
Most designs offer a recuperator to maintain high efficiency while operating at combustion temperatures below NO_x formation levels. With recuperation, efficiency is currently in the 20%-30% LHV range.

Capital Cost
Installed prices of $500-1000/kW for CHP applications is estimated when microturbines are mass produced.

Availability
Although field experience is limited, manufacturers claim that availability will be similar to other competing distributed resource technologies, i.e. in the 90->95% range.

Maintenance

Microturbines have substantially fewer moving parts than engines. The single shaft design with air bearings will not require lubricating oil or water, so maintenance costs should be below conventional gas turbines. Microturbines that use lubricating oil should not require frequent oil changes since the oil is isolated from combustion products. Only an annual scheduled maintenance interval is planned for micoturbines. Maintenance costs are being estimated at 0.006-0.01$/kW.

5.4 Heat Recovery

Hot exhaust gas from the turbine section is available for CHP applications. As discussed previously, most designs incorporate a recuperator that limits the amount of heat available for CHP. Recovered heat can be used for hot water heating or low pressure steam applications.

5.5 Emissions

NO_x emissions are targeted below 9 ppm using lean pre-mix technology without any post combustion treatment.

5.6 Applications

Markets for the microturbine include commercial and light industrial facilities. Since these customers often pay more for electricity than larger end-users, microturbines may offer these customers a cost effective alternative to the grid. Their relatively modest heat output may be ideally matched to customers with low pressure steam or hot water requirements. Manufacturers will target several electric generation applications, including standby power, peak shaving and base loaded operation with and without heat recovery.

One manufacturer is offering a two shaft turbine that can drive refrigeration chillers (100-350 tons), air compressors and other prime movers. The system also includes an optional heat recovery package for hot water and steam applications.

5.7 Technology Advancements

Microturbines are being developed in the near term to achieve thermal efficiencies of 30% and NOx emissions less than 10 ppm. It is expected that performance and maintenance requirements will vary among the initial offerings. Longer term goals are to achieve thermal efficiencies between 35-50% and NOx emissions between 2-3 ppm through the use of ceramic components, improved aerodynamic and recuperator designs and catalytic combustion.

Manufacturers are currently releasing prototype systems for demonstration and testing. Commercialization is planned by year 2000 with significant cost reductions expected as manufacturing volume increases.

6.0 Fuel Cells

Introduction

Fuel cells offer the potential for clean, quiet, and very efficient power generation, benefits that have driven their development in the past two decades. Fuel cells offer the ability to operate at electrical efficiencies of 40-60% (LHV) and up to 85% in CHP. Development of fuel cells for commercial use began in earnest in the 1970's for stationary power and transportation applications.

Although several fuel cell designs are under development, only the phosphoric acid fuel cell (PAFC) is commercially available. The price of the most competitive PAFC is still around $3000/kW which is still too high for most industrial and commercial applications. The fuel cell requires continued research and development before it becomes a serious contender in the CHP market.

6.1 Technology Description

Fuel cells are similar to batteries in that they both produce a direct current (DC) through an electrochemical process without direct combustion of a fuel source. However, whereas a battery delivers power from a finite amount of stored energy, fuel cells can operate indefinitely provided that a fuel source is continuously supplied. Two electrodes (a cathode and anode) pass charged ions in an electrolyte to generate electricity and heat. A catalyst is used to enhance the process. Individual fuel cells produce between 0.5-0.9 volts of DC electricity. Fuel cells are combined into "stacks" like a battery to obtain usable voltage and power output.

A fuel cell consists of several major components including a fuel reformer to generate hydrogen-rich gas, a power section where the electrochemical process occurs and a power conditioner to convert the direct current (DC) generated in the fuel cell into alternating current (AC). Fuel reforming "frees" the hydrogen in the fuel and removes other contaminants that would otherwise poison the catalytic electrodes. Fuel processing is usually performed at the point of use eliminating storage of the hydrogen-rich mixture. Depending on the operating temperature of the fuel cell, fuel reforming can occur external or internal the cell.

The general design of most fuel cells is similar except for the type of electrolyte used. The five main types of fuel cells are defined by their electrolyte and include alkaline, proton exchange membrane (PEMFC), phosphoric acid (PAFC), molten carbonate (MCFC) and solid oxide (SOFC) fuel cells. A comparison of fuel cell types is presented in Table 2.

Alkaline fuel cells which are very efficient and have been used successfully in the space program, require very pure hydrogen that is expensive to produce and for this reason are not considered major contenders for the stationary power market.

The PAFC represents the most mature technology and is commercially available today, having been installed in over 80 locations in the U.S., Europe and Japan.

The MCFC which is currently being demonstrated at several sites operates at higher temperature and is more efficient than the commercially available PAFC with efficiencies up to 55% (LHV) estimated. The high exhaust temperature of a MCFC can generate additional electricity in a steam turbine or in a gas turbine combined cycle. The MCFC is expected to target 1-20 MW stationary power applications and should be well suited for industrial CHP.

Many experts believe that the SOFC will be the dominant technology for stationary power applications. The SOFC offers the reliability of all-solid ceramic construction and is expected to have an electric efficiency of up to 50% (LHV). The high exhaust temperature of a SOFC can generate additional electricity in a steam turbine or in a gas turbine combined cycle. Hybrid systems using gas turbines or microturbines could increase electric efficiencies to 60%.

The PEMFC is of particular interest to the automotive industry as a future power plant for electric vehicles. Much of the current development effort is to introduce a PEMFC for the stationary power market as an intermediate step towards small and cost effective units for automobiles and buses. The PEMFC has very high power densities and can start-up quickly and meet varying demand.

Table 2 : Comparison of Fuel Cell Types

	Alkaline (AFC)	**Proton Exchange Membrane (PEM)**	**Phosphoric Acid (PAFC)**	**Molten Carbonate (MCFC)**	**Solid Oxide (SOFC)**
Electrolyte	Alkaline lye	Perfluorated sulphonated polymer	Stabilized phosphoric acid	Molten carbonate solution	Ceramic solid electrolyte
Typical Unit Sizes (kW)	<<100	0.1-500	5-200 (plants up to 5,000)	800-2000 (plants up to 100,000)	2.5-100,000
Electric Efficiency	Up to 70%	Up to 50%	40-45%	50-57%	45-50%
Installed Cost ($/kW)		4,000	3,000-3,500	800-2,000	1,300-2,000
Commercial Availability	Not for CHP	R&D	Yes	R&D	R&D
Power Density lbs/kW ft^3/kW		 8-10 ~0.2	 ~25 0.4	 ~60 ~1	 ~40 ~1
Heat Rejection (Btu/kWhr)		1640 @ 0.8 V	1880 @0.74V	850 @0.8V	1780 @0.6V
Electric/ Thermal Energy		~ 1	~ 1	Up to 1.5	Up to 1.5
Oxidation Media	Oxygen	Oxygen from Air	Oxygen from Air	Oxygen from Air	Oxygen from Air
Cooling Medium		Water	Boiling Water	Excess Air	Excess Air
Fuel	H_2	H_2 and reformed H_2	H_2 reformed from natural gas	H_2 and CO reformed from natural gas or coal gas	H_2 and CO reformed from natural gas or coal gas
Operating Temp (F)	160-210	120-210	320-410	1250	1500-1800
Operating Pressure (psig)		14.7-74	14.7-118	14.7-44	14.7->150
Applications	Space and military (today)	Stationary power (1997-2000) Bus, railroad, automotive propulsion (2000-2010)	Stationary power (1998) Railroad propulsion (1999)	Stationary power (2000->2005)	Stationary power and railroad propulsion (1998->2005)

6.2 Design Characteristics

Emissions:	Installation of PAFC has been exempted from air quality permits in some of the strictest districts in the country including South Coast Air Quality Management District in the Los Angeles basin.
Quiet operation:	Much of the appeal of the fuel cell is its quiet operation so that siting and special enclosures are of minimal concern.
Commercial use:	The 200kW PAFC is ideally suited to typical commercial installations.
Thermal quality:	The quality of the thermal product depends on the type of electrolyte. The commercially available PAFC operates at lower temperatures and therefore produces low pressure steam or hot water as a byproduct.

6.3 Performance Characteristics

Efficiency
The electric efficiency of fuel cells are dramatically higher than combustion-based power plants. The current efficiency of PAFC is 40% with a target of 40-60% (LHV) estimated. With the recovery of the thermal byproduct, overall fuel utilization could approach 85%. Fuel cells retain their efficiency at part load.

Capital Cost
The capital cost of fuel cells is currently much higher than competing distributed resources. The commercial PAFC currently costs approximately $3,000/kW. Fuel cell prices are expected to drop to $500-$1500/kW in the next decade with further advancements and increased manufacturing volumes. Substantial cost reductions in the stationary power market are expected from advancements in fuel cells used for transportation.

Availability
Theoretically, fuel cells should have higher availability and reliability than gas turbines or reciprocating engines since they have fewer moving parts. PAFC have run continuously for more than 5,500 hours which is comparable to other power plants. Limited test results for PAFC have demonstrated availability at 96% and 2500 hours between forced outages.

Maintenance
The electrodes within a fuel cell that comprise the “stack” degrade over time reducing the efficiency of the unit. Fuel cells are designed such that the “stack” can be removed. It is

estimated that “stack” replacement is required between four and six years when the fuel cell is operated under continuous conditions. The maintenance cost for PAFC (200 kW) including an allowance for periodic stack replacements has been in the range of $0.02-$5 kWh. Improvements should bring the cost down to $0.015/kWhr over the twenty year life of the unit.

6.4 Heat Recovery

Significant heat is released in a fuel cell during electrical generation. The PAFC and PEMFC operate at lower temperatures and produce lower grades of waste heat generally suitable for commercial and industrial CHP applications. The MCFC and SOFC operate at much higher temperatures and produce heat that is sufficient to generate additional electricity with a steam turbine or a microturbine hybrid gas turbine combined cycle.

6.5 Emissions

Fuel cells have little environmental impact and have been exempted from air permitting requirements by several California Air Quality Management Districts.

6.6 Applications

The type of fuel cell determines the temperature of the heat liberated during the process and its suitability for CHP applications. Low temperature fuel cells generate a thermal product suitable for low pressure steam and hot water CHP applications. High temperature fuel cells produce high pressure steam that can be used in combined cycles and other CHP process applications. Although some fuel cells can operate at part load, other designs do not permit on/off cycling and can only operate under continuous base load conditions.

For stationary power, fuel cells are being developed for small commercial and residential markets and as peak shaving units for commercial and industrial customers.

In a unique innovation, high temperature fuel cells and gas turbines are being integrated to boost electric generating efficiencies. Combined cycle systems are being evaluated for sizes up to 25 MW with electric efficiencies of 60-70% (LHV). The hot exhaust from the fuel cell is combusted and used to drive the gas turbine. Energy recovered from the turbine’s exhaust is used in a recuperator that preheats air from the turbine’s compressor section. The heated air is then directed to the fuel cell and the gas turbine. Any remaining energy from the turbine exhaust can be recovered for CHP.

6.7 Technology Advancements

With the exception of PAFC, fuel cell technology is still being demonstrated in the field or in the laboratory. Significant development and funding will be required over the next 5-10 years to achieve projected performance and cost. Major activities include reformer design, size reduction and improved manufacturing techniques. Collaboration between industry and government has been a important factor in sustaining development efforts.

Development in the mobile market should have a major impact on fuel cell technology. It is anticipated that PEM technology will be demonstrated by the year 2000.

7.0 System Issues

Integrating a CHP technology with a specific application together as a system, requires an understanding of the engineering and site-specific criteria that will provide the most economic solution. The final design must address siting issues like noise abatement and footprint constraints. Engineering information for designing a technically and economically feasible system should include electric and thermal load profiles, capacity factor, fuel type, performance characteristics of the prime mover, etc. CHP by definition implies the simultaneous generation of two or more energy products that function as a system. This chapter of the report reviews some of the primary issues faced by the design engineer in selecting and designing a CHP system.

7.1 Electric and Thermal Load Profiles

One of the first and most important elements in the analysis of CHP feasibility is obtaining accurate representations of electric and thermal loads. This is particularly true for load following applications where the prime mover must adjust its electric output to match the demand of the end-user while maintaining zero output to the grid. A 30-minute or hourly load profile provides the best results for such an analysis. Thermal load profiles can consist of hot water use, low and high pressure steam consumption and cooling loads. The shape of the electric load profile and the spread between minimum and maximum values will largely dictate the number, size and type of prime mover. It is recommended that electric and thermal loads be monitored if such information is not available.

For base load CHP applications that export power to the grid and meet a minimum thermal load required under PURPA, sizing a CHP facility is largely dictated by capacity requirements in the wholesale energy market. Rather than meeting the demand of an end-user, such plants are dispatched to the grid along with other generating systems as a function of cost of generation.

Capacity factor is a key indicator of how the capacity of the prime mover is utilized during operation. Capacity factor is a useful means of indicating the overall economics of the CHP system. The capacity factor indicates the facility’s proximity to baseload operation. Capacity factor is defined as follows:

$$Capacity\ Factor = \frac{Actual\ Energy\ Consumption}{Peak\ Capacity\ of\ Prime\ Mover\ x\ 8{,}760\ hours}$$

A low capacity factor is indicative of peaking applications that derive economic benefits generally through the avoidance of high demand charges. A high capacity factor is desirable for most CHP applications to obtain the greatest economic benefit. A high capacity factor effectively reduces the fixed unit costs of the system ($/kWh) and to remain competitive with grid supplied power.

Gas turbines are typically selected for applications with relatively constant electric load profiles to minimize cycling the turbine or operating the turbine for a large percentage of hours at part load conditions where efficiency declines rapidly. Gas turbines are ideal for industrial or institutional end-users with 24 hour operations or where export to the grid is intended.

Most commercial end-users have a varying electric load profile, i.e., high peak loads during the day and low loads after business hours at night. Natural gas reciprocating engines are a popular choice for commercial CHP due to good part-load operation, ability to obtain an air quality permit and availability of size ranges that match the load of many commercial and institutional end-users. Reciprocating engines exhibit high electric efficiencies meaning that there is less available rejected heat. This is often compatible with the thermal requirements of the end-user.

Micro-turbines are just emerging as a as a future distributed resource that will be ideally sized to meet the electric load profiles of many commercial and institutional end-users. Exhaust heat can be recovered for hot water or steam loads.

Thermal demand of a commercial or institutional end-user often consists of hot water or low pressure steam demand in the winter and a cooling demand in the summer. Heat from the prime moveris often used in a single-stage steam or hot water absorption chiller. This option allows the CHP system to operate continuously throughout the year while maintaining a good thermal load without the need to reject heat to the environment.

7.2 Quality of Recoverable Heat

The thermal requirements of the end-user may dictate the feasibility of a CHP system or the selection of the prime mover. Gas turbines offer the highest quality heat that is often used to generate power in a steam turbine. Gas turbines reject heat almost exclusively in its exhaust gas stream. The high temperature of this exhaust can be used to generate high pressure steam or lower temperature applications such as low pressure steam or hot water. Larger gas turbines (typically above 25 MW) are frequently used in combined cycles where high pressure steam is produced in the HRSG and is used in a steam turbine to generate additional electricity. The high levels of oxygen present in the exhaust stream allows for supplemental fuel addition to generate additional steam at high efficiency.

Some of the developing fuel cell technologies including molten carbonate fuel cells (MCFC) and solid oxide fuel cells (SOFC) will also provide high quality rejected heat comparable to a gas turbine.

Reciprocating engines and the commercially available phosphoric acid fuel cell (PAFC) produce a lower grade of rejected heat. Heating applications that require low pressure steam (15 psig) or hot water are most suitable, although the exhaust from a reciprocating engine can generate steam up to 100 psig.

Reciprocating engines typically have a higher efficiency than most gas turbines in the same output range and are a good fit where the thermal load is low relative to electric demand. Reciprocating engines can produce low and high pressure steam from its exhaust gas, although low pressure steam or hot water is generally specified. Jacket water temperatures are typically limited to 210F so that jacket heat is usually recovered in the form of hot water. All the jacket heat can be recovered if there is sufficient demand, however, only 40-60% of the exhaust heat can be recovered to prevent condensation of corrosive exhaust products in the stack that will limit equipment life.

7.3 Industrial Heat Recovery

Industrial sites that produce excess heat or steam from a process may offer a CHP opportunity. If the excess thermal energy is continuously available or at a high load factor and is of sufficient quality, this heat can be used in a “bottoming cycle” to generate electricity in a steam turbine. In addition to electrical generation, steam turbines are often used to drive rotating equipment like air compressors or refrigeration compressors. Through a variety of turbine designs, the steam exhausted from the turbine can be used for lower grade heating applications or cooling in a CHP configuration. Excess steam could also be used for reforming natural gas for a fuel cell.

7.4 Noise

Although fuel cells are relatively expensive to install, they are being tested in a number of sites typically where the cost of a power outage is significant to lost revenues or lost productivity and where uninterrupted power is mandatory. Their relatively quiet operation has appeal and these units are being installed in congested commercial areas. Locating a turbine or engine in a residential area usually requires special consideration and design modifications to be acceptable.

Engine and turbine installations are often installed in building enclosures to attenuate noise to surrounding communities. Special exhaust silencers or mufflers are typically required on exhaust stacks. Gas turbines require a high volume of combustion air, causing high velocities and associated noise. Inlet air filters can be fitted with silencers to substantially reduce noise levels.

Gas turbines are more easily confined within a factory supplied enclosure than reciprocating engines. Reciprocating engines require greater ventilation due to radiated heat that makes their installation in a sound-attenuating building often the most practical solution. Gas turbines require much less ventilation and can be concealed within a compact steel enclosure.

7.5 Foot Print

Phosphoric acid fuel cells and micro-turbines offer compact packaging and have an appeal to those end-users that are seeking a non-obtrusive power generation or CHP system. Larger gas turbines and reciprocating engines generally are isolated in either a factory enclosure or a separate building along with ancillary equipment.

7.6 Fuel Supply

A potential system issue for gas turbines is the supply pressure of the natural gas distribution system at the end-user’s property line. Gas turbines need minimum gas pressures of about 120 psig for small turbines with substantially higher pressures for larger turbines. Assuming there is no high pressure gas service, the local gas distribution company would have to construct a high pressure gas line or the end-user must purchase a gas compressor. The economics of constructing a new line must consider the volume of gas sales over the life of the project.

Gas compressors may have reliability problems especially in the smaller size ranges. If "black start" capability is required, then a reciprocating engine may be needed to turn the gas compressor, adding cost and complexity.

Reciprocating engines and fuel cells are more accommodating to the fuel pressure issue, generally requiring under 50 psig. Reciprocating engines operating on diesel fuel storage do not have fuel pressure as an issue, however, there may be special permitting requirements for on-site fuel storage.

Diesel engines should be considered where natural gas is not available or very expensive. Diesel engines have excellent part load operating characteristics and high power densities. In most localities, environmental regulations have largely restricted their use for CHP. In California and elsewhere in the U.S., diesel engines are almost exclusively used for emergency power or where uninterrupted power supply is needed such as in hospitals and critical data operating centers. As emergency generators, diesel engines can be started and achieve full power in a relatively short period of time.