Assessment of Distributed Generation Technology Applications

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Executive Summary

Introduction. Distributed generation (DG) technologies can provide energy solutions to some customers that are more cost-effective, more environmentally friendly, or provide higher power quality or reliability than conventional solutions. Understanding the wide variety of DG options available in today's changing electric markets can be daunting. Some of these DG technologies offer high efficiency, resulting in low fuel costs, but emit a fair amount of pollutants (CO and NO_x); others are environmentally clean but are not currently cost-effective. Still others are well suited for peaking applications but lack durability for continuous output. With so much to consider, it is often difficult for decision makers to determine which technology is best suited to meet their specific energy needs.

Contents. This report explores DG technology applications and compares and contrasts them with one another. With this overview, current users and potential consumers of these energy products will better understand potential DG technology solutions. These applications include:

- Continuous Power (where DG is operated at least 6,000 hours per year);
- Combined Heat and Power (CHP) (where DG waste heat is used for heating and or cooling);
- Peaking Power (where DG is operated between 200-3000 hours per year during periods of high electricity price or high site demand);
- Green Power (where DG is operated by a facility to help reduce environmental emissions from its power supply);
- Premium Power (where DG provides a higher level of reliability and/or power quality than typically available from the grid);
- Transmission and Distribution Deferral (where DG is used to delay the purchase of new transmission or distribution systems); and
- Ancillary Service Power (where DG is used to provide ancillary service at a transmission or distribution level; includes spinning/ non-spinning reserves, reactive power, voltage control, and local area security).

This report also provides a broad overview of currently available DG technologies in the 5 kW to 5 MW size range, including their history and current status, operation, emission control technologies, potential applications, representative manufacturers, and important issues surrounding their development. These DG technologies include:

- Reciprocating engines - This DG technology was developed more than a century ago, and is still widely utilized in a broad array of applications. The engines range in size from less than 5 to over 5,000 kW, and use either diesel, natural gas, or waste gas as their fuel source. Development efforts remain focused on improving efficiency and on reducing emission levels. Reciprocating engines are being used primarily for backup power, peaking power, and in cogeneration applications.

- Microturbines - A new and emerging technology, microturbines are currently only available from a few manufacturers. Other manufacturers are looking to enter this emerging market, with models ranging from 30 to 200 kW. Microturbines promise low emission levels, but the units are currently relatively expensive. Obtaining reasonable costs and demonstrating reliability will be major hurdles for manufacturers. Microturbines are just entering the marketplace, and most installations are for the purpose of testing the technology. Unit sales are expected to increase in 2001 and beyond.

- Industrial combustion turbines - A mature technology, combustion turbines range from 1 MW to over 5 MW. They have low capital cost, low emission levels, but also usually low electric efficiency ratings. Development efforts are focused on increasing efficiency levels for this widely available technology. Industrial combustion turbines are being used primarily for peaking power and in cogeneration applications.

- Fuel cells - Although the first fuel cell was developed more than one hundred fifty years ago, this technology remains in the development stage. Currently, fuel cells are commercially available from only one manufacturer, with several others developing units in the 5 to 1000+ kW size range to enter the market in the next year or two. Fuel cell emission levels are quite low, but cost and demonstrated reliability remain major problems for the market penetration of this technology. The few fuel cells currently being used provide premium power or are in applications subsidized by the government or gas utilities.

- Photovoltaics - Commonly known as solar panels, photovoltaic (PV) panels are widely available for both commercial and domestic use. Panels range from less than 5 kW and units can be combined to form a system of any size. They produce no emissions, and require minimal maintenance. However, they can be quite costly. Less expensive components and advancements in the manufacturing process are required to eliminate the economic barriers now impeding wide-spread use of PV systems. Photovoltaics are currently being used primarily in remote locations without grid connections and also to generate green power.

- Wind turbine systems - Wind turbines are currently available from many manufacturers and range in size from less than 5 to over 1,000 kW. They provide a relatively inexpensive (compared to other renewables) way to produce electricity, but as they rely upon the variable and somewhat unpredictable wind, are unsuitable for continuous power needs. Development efforts look to pair wind turbines with battery storage systems that can provide power in those times when the turbine is not turning. Wind turbines are being used primarily in remote locations not connected to the grid and by energy companies to provide green power.

DG technologies are currently being used for the niche applications described later in this report. Many reports and studies predict that the market for DG technologies will continue to grow as their price and performance improves and energy markets deregulate.

In an atmosphere of changing customer energy needs, DG technologies, alone or in combination, may offer superior economics or a better overall energy solution for some energy customers. The following table summarizes the DG technologies reviewed in this report.

		Size Range (kW)	Efficiency (%)		Emissions (g/kWh unless otherwise noted)	Packaged Cost ($/kW)[1]	Installation Cost ($/kW)[2]	Electric-Only Cost-to-Generate (cents/kWh)[3]	Cogeneration Cost-to-Generate (cents/kWh)[4]	Applications				
			Electric	Overall						Cont.	CHP	Peak	Green	Prem.
Reciprocating Engines														
Spark Ignition		30-5,000	31-42	80-89	NO_x: 0.7-42 CO: 0.8-27	300-700	150-600	7.6-13.0	6.1-10.7	●	◒	●	○	◒
Diesel		30-5,000	26-43	85-90	NO_x: 6-22 CO: 1-8	200-700	150-600	7.1-14.2	5.6-10.8	●	◒	●	○	◒
Dual Fuel		100-5,000	37-42	80-85	NO_x: 2-12 CO: 2-7	250-550	150-450	7.4-10.7	6.0-9.1	●	◒	●	○	◒
Turbines														
Microturbines	Non-Recup.	30-200	14-20	75-85	NO_x: 9-125ppm CO: 9-125ppm	700-1,000	250-600	14.9-22.5	10.1-15.9	○	●	◒	○	◒
	Recup.		20-30	60-75		900-1,300		11.9-18.9	10.0-16.8	◒	◒	◒	○	◒
Industrial Turbines		1,000-5,000	20-40	70-95	NO_x: 25-200ppm CO: 7-200ppm	200-850	150-250	8.7-15.8	5.8-12.2	◒	●	◒	○	◒
Fuel Cells														
PEM		5-10	36-50	50-75	NO_x: 0.007 CO: 0.01	4,000-5,000	400-1,000	21.9-33.3	20.7-33.3	●	○	○	●	●
Phosphoric Acid		200	40	84	NO_x: 0.007 CO: 0.01	3,000-4,000	360	18.6-22.8	17.0-21.2	●	●	○	●	●
Renewable														
Photovoltaic		5-5,000	-	-	-	5,000-10,000	150-300	18.0-36.3	N/A	◒	○	○	●	○
Wind		5-1,000	-	-	-	1,000-3,600	500-4,000	6.2-28.5	N/A	○	○	○	●	○

[1]Packaged costs include the prime mover, generator, inverter (if needed), and ancillary equipment. Costs can vary based on size, duty cycle, and fuel.

[2]Installation costs can vary with utility interconnection requirements, labor rates, ease of installation, and other site-specific factors.

[3]Cost-to-Generate assuming a 50% load factor and 1999 Maine average price of natural gas to the commercial sector and no thermal utilization. Cost-to-generate includes fuel and O&M expenses as well as amortized capital charges.

[4]Cost-to-Generate assuming a 50% load factor and 1999 Maine average price of natural gas to the commercial sector, 75% utilization of thermal output, and cogeneration equipment adder of $100/kW for reciprocating engines, $150/kW for turbines, and $75/kW for fuel cells. Cost-to-generate includes fuel and O&M expenses as well as amortized capital charges.

Key:
- ● Good fit
- ◒ Moderate fit
- ○ Poor Fit

<u>Applications</u>

- Cont. = Continuous Power
- CHP = Combined Heat and Power
- Peak = Peaking Power
- Green = Green Power
- Prem. = Premium Power

Introduction

The term “distributed generation,” or DG, refers to the small scale generation of electric power by a unit sited close to the load being served. DG technologies range in size from 5 kW to 30+ MW, and include both fully commercial systems, such as reciprocating engines, and others that are primarily in the laboratory, such as fuel cells. This report provides a comprehensive assessment of the strengths and weaknesses of commercial and near-commercial DG technologies in the 5 kW to 5 MW[1] size range. The technologies profiled are reciprocating engines, microturbines, industrial combustion turbines, phosphoric acid and proton exchange membrane fuel cells, photovoltaics, and wind turbine systems.

DG technologies can meet the needs of a wide range of users, with applications in the residential, commercial, and industrial sectors. Decision makers at all levels need to be aware of the potential benefits DG can offer. In some instances, DG technologies can be more cost effective than conventional solutions. Among other things, DG can be used by utilities to both enhance existing systems and to delay the purchase of transmission and distribution equipment. In addition, DG units can help meet the changing demands of end users for premium, reliable or “green” power.

This report is organized into four sections:

1. **Distributed Generation Applications**. This section summarizes different applications for DG technologies, including those located at customer sites and those used by utilities. A table comparing DG application types and their important characteristics is included.
2. **Distributed Generation Technology Summaries**. This section provides a summary of each DG technology, including its history, current status, operation, development, emission controls and application characteristics. Also included are lists of representative manufacturers and technology system diagrams.
3. **Distributed Generation Matrix Assessment**. Price and performance parameters for each commercial and near-commercial DG technology are presented here. The matrix is organized into three tables: a general overview, siting and operation.
4. **Glossary of Distributed Generation Terminology**. This glossary defines the terms used in this report. *Note*: in the remainder of the report, words in italics are defined in the glossary.

[1] Although electric loads vary among users, a typical residential household load is approximately 1-15 kW, a small convenience store or fast-food restaurant is about 30-75 kW, a supermarket is around 400-750 kW, and large institutional or industrial loads can be in the tens of megawatts.

1. Distributed Generation Applications

Distributed generation (DG) is currently being used by some customers to provide some or all of their electricity needs. There are many different potential applications for DG technologies. For example, some customers use DG to reduce demand charges imposed by their electric utility, while others use it to provide premium power or reduce environmental emissions. DG can also be used by electric utilities to enhance their distribution systems. Many other applications for DG solutions exist. The following is a list of those of potential interest to electric utilities and their customers.

Continuous Power - In this application, the DG technology is operated at least 6,000 hours a year to allow a facility to generate some or all of its power on a relatively continuous basis. Important DG characteristics for continuous power include:

- High *electric efficiency,*
- Low variable maintenance costs, and
- Low emissions.

Currently, DG is being utilized most often in a continuous power capacity for industrial applications such as food manufacturing, plastics, rubber, metals and chemical production. Commercial sector usage, while a fraction of total industrial usage, includes sectors such as grocery stores and hospitals.

Combined Heat and Power (CHP) - Also referred to as Cooling, Heating, and Power or cogeneration, this DG technology is operated at least 6,000 hours per year to allow a facility to generate some or all of its power. A portion of the DG waste heat is used for water heating, space heating, steam generation or other thermal needs. In some instances this thermal energy can also be used to operate special cooling equipment. Important DG characteristics for combined heat and power include:

- High useable thermal output (leading to high overall efficiency),
- Low variable maintenance costs, and
- Low emissions.

CHP characteristics are similar to those of Continuous Power, and thus the two applications have almost identical customer profiles, though the high thermal demand necessary here is not a requisite for Continuous Power applications. As with Continuous Power, CHP is most commonly used by industry clients, with a small portion of overall installations in the commercial sector.

Peaking Power - In a peaking power application, DG is operated between 200-3000 hours per year to reduce overall electricity costs. Units can be operated to reduce the utility's demand charges, to defer buying electricity during high-price periods, or to allow for lower rates from power providers by smoothing site demand. Important DG characteristics for peaking power include:

- Low installed cost,
- Quick startup, and
- Low fixed maintenance costs.

Peaking power applications can be offered by energy companies to clients who want to reduce the cost of buying electricity during high-price periods. Currently DG peaking units are being used mostly in the commercial sector, as load factors in the industrial sector are relatively flat. The most common applications are in educational facilities, lodging, miscellaneous retail sites and some industrial facilities with peaky load profiles.

Green Power - DG units can be operated by a facility to reduce environmental emissions from generating its power supply. Important DG characteristics for green power applications include:

- Low emissions,
- High efficiency, and
- Low variable maintenance costs.

Green power could also be used by energy companies to supply customers who want to purchase power generated with low emissions.

Premium Power - DG is used to provide electricity service at a higher level of reliability and/or power quality than typically available from the grid. The growing premium power market presents utilities with an opportunity to provide a value-added service to their clients. Customers typically demand uninterrupted power for a variety of applications, and for this reason, premium power is broken down into three further categories:

> **Emergency Power System -** This is an independent system that automatically provides electricity within a specified time frame to replace the normal source if it fails. The system is used to power critical devices whose failure would result in property damage and/or threatened health and safety. Customers include apartment, office and commercial buildings, hotels, schools, and a wide range of public gathering places.
>
> **Standby Power System -** This independent system provides electricity to replace the normal source if it fails and thus allows the customer's entire facility to continue to operate satisfactorily. Such a system is critical for clients like airports, fire and police stations, military bases, prisons, water supply and sewage treatment plants, natural gas transmission and distribution systems and dairy farms.
>
> **True Premium Power System -** Clients who demand uninterrupted power, free of all power quality problems such as frequency variations, voltage transients, dips, and surges, use this system. Power of this quality is not available directly from the grid – it requires both auxiliary power conditioning equipment and either emergency or standby power. Alternatively, a DG technology can be used as the primary power source and the grid can be used as a backup. This technology is used by mission critical systems like airlines, banks, insurance companies, communications stations, hospitals and nursing homes.

Important DG characteristics for premium power (emergency and standby) include:

- Quick startup,
- Low installed cost, and
- Low fixed maintenance costs.

Transmission and Distribution Deferral - In some cases, placing DG units in strategic locations can help delay the purchase of new transmission or distribution systems and equipment such as distribution lines and substations. A thorough analysis of the life-cycle costs of the various alternatives is critical and contractual issues relating to equipment deferrals must also be examined closely. Important DG characteristics for transmission and distribution deferral (when used as a "peak deferral") include:

- Low installed cost, and
- Low fixed maintenance costs.

Transmission and distribution DG applications in the U.S. are rare and are not discussed in the main sections of this report.

Ancillary Service Power - DG is used by an electric utility to provide ancillary services (interconnected operations necessary to effect the transfer of electricity between purchaser and seller) at the transmission or distribution level. The market for ancillary services is still unfolding in the U.S., but in markets where the electric industry has been deregulated and ancillary services unbundled (in the United Kingdom, for example), DG applications offer advantages over currently employed technologies. Ancillary services include spinning reserves (unloaded generation, which is synchronized and ready to serve additional demand) and non-spinning, or supplemental, reserves (operating reserve is not connected to the system but is capable of serving demand within a specific time or interruptible demand that can be removed from the system within a specified time). Other potential services range from transmission market reactive supply and voltage control, which uses generating facilities to maintain a proper transmission line voltage, to distribution level local area security, which provides back up power to end users in the case of a system fault. The characteristics that may influence the adoption of DG technologies for ancillary service applications will vary according to the service performed and the ultimate shape of the ancillary service market. Ancillary service DG applications in the U.S. are rare and are not discussed in the main sections of this report.

Summary

The following table shows DG application types and important characteristics of each.

Application	Low Cost	High Efficiency	Thermal Output	Emissions	Start-Up Time	Fixed Maint.	Variable Maint.
Continuous Power	◒	●	○	◒	○	◒	●
CHP	◒	●	●	◒	○	◒	●
Peaking	●	◒	○	○	◒	●	◒
Green	◒	◒	◒	●	○	◒	◒
Emergency	●	○	○	○	●	●	○
Standby	●	○	○	○	◒	●	○
True Premium	◒	◒	○	◒	●	◒	◒
Peaking T&D Deferral	●	○	○	○	◒	●	○
Baseload T&D Deferral	◒	●	◒	◒	○	◒	●
Spinning/ Non Spinning Reserve	◒	◒	○	○	●	◒	◒
Reactive Power	◒	◒	○	◒	◒	◒	◒
Voltage Control	◒	◒	○	◒	◒	◒	◒
Local Area Security	●	○	○	○	◒	●	○

Key: ● Important Characteristic
◒ Moderately Important / Important in Certain Applications
○ Relatively Unimportant

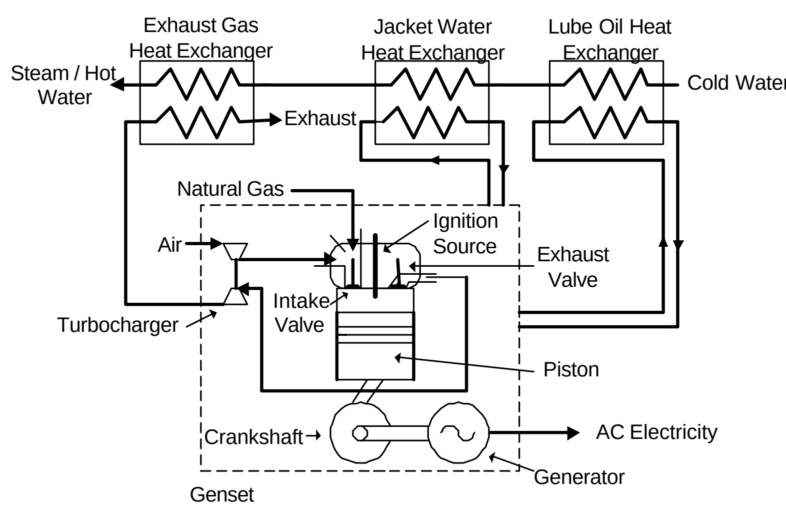
2. Distributed Generation Technology Summaries

A summary of each commercial and near-commercial DG technology is provided below. Included are the technology's history and current status, operational process, emission control technologies, manufacturers, development issues, and application types.

Reciprocating Engines

History and Status Reciprocating engines, developed more than 100 years ago, were the first of the fossil fuel-driven DG technologies. Both Otto (spark ignition) and Diesel cycle (compression ignition) engines have gained widespread acceptance in almost every sector of the economy and are in applications ranging from fractional horsepower units powering small hand-held tools to 60 MW baseload electric power plants. Reciprocating engines are ones in which pistons move back and forth in cylinders. Reciprocating engines are a subset of internal combustion engines, which also include rotary engines. Smaller engines are primarily designed for transportation and can be converted to power generation with little modification. Larger engines are, in general, designed for power generation, mechanical drive, or marine propulsion. Reciprocating engines are currently available from many manufacturers in all DG size ranges. For DG applications, reciprocating engines offer low costs and good efficiency, but maintenance requirements are high, and diesel-fueled units have high emissions.

Operation Almost all engines used for power generation are four-stroke and operate in four cycles (intake, compression, combustion, and exhaust). The process begins with fuel and air being mixed. Some engines are *turbocharged* or *supercharged* to increase engine output, meaning that the intake air is compressed by a small compressor in the intake system. The fuel/air mixture is introduced into the combustion cylinder, then compressed as the piston moves toward the top of the cylinder. In diesel units, the air and fuel are introduced separately with fuel being injected after the air is compressed by the piston in the engine. As the piston nears the top of its movement, a spark is produced that ignites the mixture (in most diesel engines, the mixture is ignited by the compression alone). Dual fuel engines use a small amount of diesel pilot fuel in lieu of a spark to initiate combustion of the primarily natural gas fuel. The pressure of the hot, combusted gases drives the piston down the cylinder. Energy in the moving piston is translated to rotational energy by a crankshaft. As the piston reaches the bottom of its stroke the exhaust valve opens and the exhaust is expelled from the cylinder by the rising piston. Cogeneration configurations are available with heat recovery from the gaseous exhaust and water and oil jackets.



Emission Control Technologies The combustion process produces *NO_x* and, as a result of improper fuel/air mixtures and excessive cylinder cooling, carbon monoxide, hydrocarbon, and particulate emissions. While diesel engines are widely used, tightening emission regulations have made it increasingly difficult to site diesel generators. Control technologies like *Selective Catalytic Reduction (SCR)* are expensive and, as a result, diesels are primarily being used for emergency or standby applications where their low installed equipment cost, performance track record, and availability of trained mechanics make them the technology of choice.

Dual fuel engines offer an alternative that combines the efficiency and reliability of a diesel engine with the emission benefits of natural gas. These engines tend to be both more efficient and produce fewer NO_x and particular emissions than diesel engines. Further reductions in emissions can be obtained through the use of a pre-ignition chamber that lowers the amount of diesel fuel required for ignition. Newer natural gas units focus on lean-burn technology that uses a higher ratio of air to fuel than traditional units. The lean-burn engines have higher efficiencies and lower NO_x emissions, but a lower power output. This can be compensated for by the incorporation of turbocharging to increase power density.

Installed costs and annual expenses for reciprocating engines differ greatly depending upon the emission control regulations in the region where they are sited. As can be seen in the chart below, the installed cost in a LAER - Lowest Achievable Emissions Rate (strict emission control regulations) region is much higher that in a non-LAER (some control) area, although this gap in pricing decreases as the unit size increases.

Capital and Operating Cost Impacts of Emissions Control Technologies

	Size (MW)	Non LAER (some control)		LAER (strict control)		
		Emission control	Installed Cost ($/kW)	Emission control	Installed Cost ($/kW)	Annual Expense ($/kW)
Reciprocating Engine	.2 - 1	Lean-burn	30	LB + SCR	230	36
	1 - 5	Lean-burn	30	LB + SCR	130	10
	5 - 10	Lean-burn	30	LB + SCR	105	5

Add-on emission reducing controls can be incorporated on diesels, dual fuel units and rich-burn natural gas engines, but siting remains difficult in severe or extreme ozone *nonattainment areas*. In addition, particulate traps may be required to control particulate matter emission from diesel engines. Newer lean-burn engines are superior for NO_x control, and often include modifications that allow for further reductions of emission levels.

Applications Reciprocating engines can be utilized in a wide range of DG applications.

Application	Fit	Notes
Continuous	●	High efficiencies lead to low fuel costs. Emissions regulations may make siting diesel units difficult.
CHP	◒	Heat recovery from three streams: exhaust, coolant, and oil. Heat output is generally of lower quality (160-600 °C) than the output from turbines or advanced solid oxide fuel cells.
Peaking	●	Diesel units designed for peaking have the lowest installed cost of all DG technologies. Quick start-time is also a plus.
Green	○	Spark ignited (SI) units (natural gas-fueled) offer favorable emissions compared to other engines, but generally have more CO and NO_x emissions than turbines. However, higher efficiencies lead to lower CO_2 emissions, compared to turbines.
Premium	◒	Good for backup applications, but power quality is not as high as for inverter-based technologies such as fuel cells and microturbines.

Key: ● Good fit ◒ Moderate fit ○ Poor Fit

Manufacturers Reciprocating engines are manufactured by a large group of companies throughout the world in a wide size range. Current development trends seem to be focused on efficiency and emission issues and on reducing costs. In addition, several manufacturers have signed joint venture, marketing and distribution agreements with one another. With these agreements, they can share the costs associated with research and development and breaking into new global markets. A representative group of manufacturers is listed below, along with some available models and current projects.

Manufacturer	Model	Notes
Caterpillar	Compact, modular generator set packages to 4040 kW.	Focus on combustion, air-intake, exhaust sensors and engine design to increase efficiency and reduce emissions.
Waukesha Engine	Natural gas and fuel flexible engines; lean-burn versions	Developing a new gaseous-fueled engine with improved air handling, exhaust treatment, combustion & system integration
Cummins Engine Co.	Diesel and gas engines: 5 kW to 2000 kW	Developing high-pressure natural gas engine systems. Standby, prime power and load management applications.
Jenbacher AG	Cogeneration units; electrical output from 70 kW to 2,700 kW.	GE Power Systems and the Jenbacher Group have expanded their current distribution agreement.
Wartsila Corp.	Diesel, lean-burn, dual-fuel and gas-diesel engines. 1 MW to 300 MW.	Announced joint venture with Cummins Power Generation

Development Issues

Technology

- Dual fuel engines have low levels of emissions because they use primarily natural gas, have good economics, and have the efficiency and reliability of diesels. Micro-pilot ignition has been developed which significantly reduces the amount of diesel fuel that must be used, thereby reducing emissions.
- Achieving higher *power density* may be key to reducing per kW cost, but this may require more durable (higher strength and temperature resistant) engine components. More durable (although expensive) components should also lead to a decrease in maintenance expense.
- Improved cooling of components such as turbochargers, valve seats, and the area around the spark plug can also lead to a longer life for components.

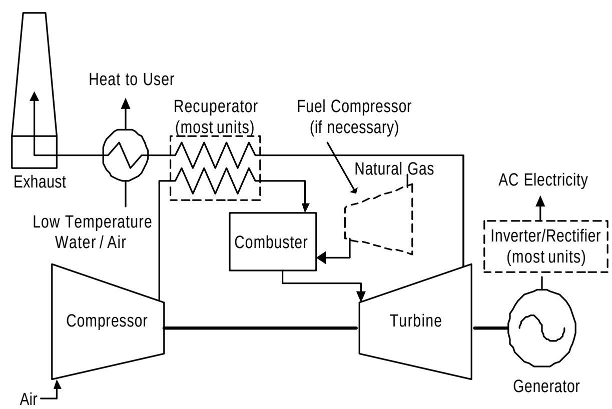
Efficiency

- Combustion chamber design is important not only to the efficient and complete combustion of fuels but also the reduction of NO_x emissions.
- How and when fuel is injected in the cycle plays an important role in how the fuel is combusted, and thus influences power, efficiency, and emissions. High efficiency engines will operate at higher pressure levels that will require high-energy spark ignition systems with durable components. Laser ignition has the potential to improve fuel efficiency and lower emissions by improving ignition timing and placement, increasing reliability, and reducing maintenance requirements.
- Effective turbocharging is key to increasing *Brake Mean Effective Pressure (BMEP)* which leads to increased efficiency. Turbocharged engines can achieve greater power density, allowing units to be placed in a smaller area and/or lessen foundation reinforcement requirements.

Microturbines

History and Status The technology used in microturbines is derived from aircraft auxiliary power systems, diesel engine turbochargers, and automotive designs. A number of companies are currently field testing demonstration units for small-scale distributed power generation in the 30-500 kW size range. Although several units are available commercially, most are slated to enter the market in 2001 and 2002.

Operation Simple microturbines consist of a compressor, combustor, turbine, and generator. The compressors and turbines are typically radial-flow designs, and resemble automotive engine turbochargers. Most designs are single-shaft and use a high-speed permanent magnet generator producing variable voltage, variable frequency alternating current (AC) power. An inverter is employed to produce 60 Hz AC power. Most microturbine units are currently designed for continuous-duty operation and are *recuperated* to obtain higher electric efficiencies.



Emission Control Technologies In general, microturbine emissions are comparable with those of larger turbines. For example, NO_x levels are reported as <9 ppm for the Capstone MicroTurbine (30 kW) and 50 ppm for the Honeywell Parallon75 (75 kW). It is difficult to state exact emission levels as most microturbine emission data is based on manufacturer projections and claims, and must be confirmed by field testing. Emission control technologies in microturbines tend to focus on combustor design and flame control rather than technologies used in larger industrial turbines such as water/steam injection. However, because of their small size, these units tend to fall below most compliance requirement triggers. As a result, many microturbine installations have been exempt from emission regulations.

Applications Microturbines can be utilized in a wide range of DG applications.

Application	Fit	Notes
Continuous	◒	Although capital costs may eventually be lower than those of existing technologies, low efficiencies mean higher fuel costs. Maximum output degrades at high ambient temperatures.
CHP	◒	Heat recovery is all from one stream (exhaust) making utilization simple. However the recuperation necessary for high electric efficiencies limits the quality of thermal output since much of the heat output is used for inlet air preheating. Overall system efficiency tends to decrease as the extent of recuperation increases.
Peaking	◒	Lower hours of operation help offset the efficiency disadvantage, and the low costs of non-recuperated units make them well-suited for many peaking applications. However, reciprocating engines are usually cheaper and thus better suited for these applications.
Green	○	Turbines are generally cleaner than engines (lower NO_x and CO emissions), but not as clean as fuel cells or renewable options. Lower efficiency also leads to higher CO_2 emissions.
Premium	◒	Inverter-based generators offer high power quality.

Key: ● Good fit ◒ Moderate fit ○ Poor Fit

Manufacturers While several potential entrants are examining the market, there is currently only a small group of companies with commercially available microturbine units. These manufacturers have worked to solidify their position in the emerging microturbine market through a series of distribution and marketing agreements with larger and established companies. In this fashion, they hope to decrease costs and open new markets for their products. Current customers and test facilities include small to medium sized commercial and industrial customers, municipal facilities producing waste gases, and distributors such as Chicago-based utility Peoples Energy, American Energy Savings Inc. (AES), and Allegheny Energy Solutions.

Manufacturer	**Model**	**Notes**
Capstone Turbine Corporation	MicroTurbine power systems	Shipped its 1,000th microturbine unit this fall. Prototype 30 kW commercial model rated at 28% efficiency (LHV)
Honeywell Power Systems	Parallon 75 microturbine	Currently being acquired by GE
Elliot Energy Systems	Microturbine engines from 35 to 500 kilowatts.	Recuperated one-shaft design with lubricated oil bearings and 50/60 Hz solid state inverter. Prototype 45 kW commercial model rated at 30% efficiency (LHV).
Ingersoll-Rand	PowerWorks microturbine	Slated to be commercially available in mid 2001.
DTE Energy	EnergyNow microturbine products ENT-400	Commercial units are expected to be available in early 2002.

Development Issues

Technology

- Most microturbines use a single shaft with a high-speed permanent magnet generator that produces very high-frequency AC power. Using an *inverter*, this power must then be converted to 60 Hz. An advantage is that single-shaft units have a simpler design and construction than two-shaft configurations, and therefore may require less maintenance. However, two-shaft configurations include a reduction gearbox and an induction generator that directly produce 60 Hz power, so an inverter is not required. Also, split shaft design is necessary for mechanical drive applications.

- Microturbines rotate at high-speeds (40,000+ rpm) and therefore require high-reliability bearing systems. Two configurations are currently being used: air bearings with a compliant foil system, and a pressurized lube-oil system with a pump. Systems with air bearings eliminate the oil system and are simpler, require less maintenance, and have no parasitic oil pump load. However, oil bearings generally last longer.
- Lowering costs will be a major hurdle for microturbine manufacturers. The cost of electronics for power conditioning and grid connections is high. However, standard interconnections or higher production volumes may help reduce these costs.

Efficiency

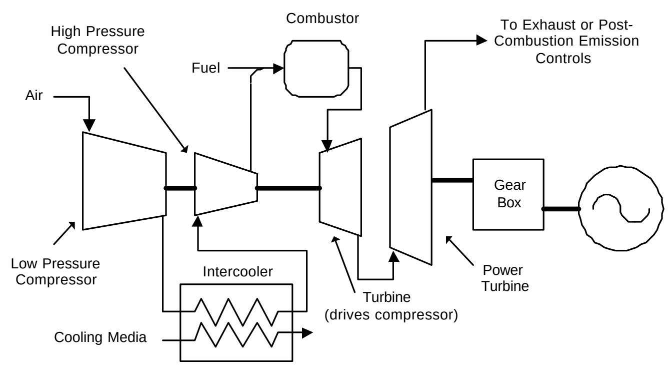
- Recuperators (air-to-air heat exchangers that use exhaust gases to preheat the combustor inlet air) can improve microturbine efficiency to between 20-30% versus the 14-20% efficiency rates of typical non-recuperated units. Obtaining higher efficiency may require higher engine temperatures necessitating improvements in recuperator materials (such as ceramics).
- Microturbine efficiency is impacted by the available natural gas pressure level. Units that are supplied high pressure gas (50-60 psig) are 1-4% more efficient than those using low pressure gas because of the parasitic requirements of the fuel compressor.
- Several manufacturers are developing power generation systems that combine fuel cells with microturbines. These systems typically run the hot gas produced by certain types of fuel cells (primarily Solid Oxide Fuel Cells/SOFC) through a microturbine to generate additional electricity. Commercial hybrid systems are expected to have exceptionally high electric efficiencies (60%+).

Applications

- Gasifiers that produce gaseous fuel from solids (such as coal and biomass) could help turbines gain wider acceptance, especially in international markets and wherever natural gas supplies are scarce. However, such gasifiers would be complex and use fuel with impurities and/or contaminants, and therefore require expensive fuel introduction systems and gas cleanup that can severely compromise efficiency and increase initial costs.
- Manufacturers are designing units that can utilize low-Btu landfill and digestor gas.
- Manufacturers are developing non-recuperated microturbines for backup power and CHP applications that require higher temperatures.
- The starting time for microturbines is longer than for reciprocating engines, a fact which may limit their use as backup systems.

Industrial Combustion Turbines

History and Status Combustion turbines have been used for power generation for decades and range in size from simple cycle units starting at about 1 MW to over a hundred MW. Units from 1-15 MW are generally referred to as industrial turbines, a term which differentiates them from larger utility grade turbines and smaller microturbines. Combustion turbines have relatively low installation costs, low emissions, heat recovery through steam and infrequent maintenance requirements, but low electric efficiency. With these traits, combustion turbines are typically used for cogeneration DG when a continuous supply of steam or hot water and power is desired, as peakers, and in combined cycle configurations.



Operation Historically, industrial turbines have been developed as aero derivatives using jet propulsion engines as a design base. Some, however, have been designed specifically for stationary power generation or for compression applications in the oil and gas industries. A combustion turbine is a device in which air is compressed and a gaseous or liquid fuel ignited and the combustion products expanded directly through the blades in a turbine to drive an electric generator. The compressor and turbine usually have multiple stages and axial blading. This differentiates them from smaller microturbines that have radial blades and are single staged. The intercooler shown in the figure is generally reserved for larger units that can economically incorporate this improvement.

Emission Control Technologies Unlike in reciprocating engines, in combustion turbines combustion occurs outside of the turbine area rather than inside the cylinder. This allows for greater flexibility in reducing NO_x emissions. Typically, emissions control of combustion turbines are controlled in the combustion process. Wet controls, which use water or steam injection to reduce the combustion temperature, which reduces NO_x levels, have been used for years. Usage of this control type is constrained by availability of a water supply and space for storage tanks. Dry Low NO_x (DLN), conceptually similar to lean burn technology for reciprocating engines, creates a lean, homogeneous mixture of air and fuel that then enters the combustor. This minimizes hot spots and reduces the combustion temperature, which leads to lower NO_x levels. DLN has become the standard for NO_x control in combustion turbines.

The installed costs of combustion turbines differ greatly depending upon the emission control regulations in the region where they are sited. As can be seen in the chart below, the installed cost in a LAER (strict emission control regulations) region is much higher than that in a non-LAER (some control) area, although this gap in pricing decreases as the unit size increases.

Capital and Operating Cost Impacts of Emissions Control Technologies

	Size (MW)	Non LAER (some control)		LAER (strict control)		
		Emission control	Installed Cost ($/kW)	Emission control	Installed Cost ($/kW)	Annual Expense ($/kW)
Turbine	.2 - 1	Dry Low NOx	30	DLN + SCR	230	36
	1 - 5	Dry Low NOx	30	DLN + SCR	130	10
	5 - 10	Dry Low NOx	30	DLN + SCR	105	5
	10-20	Dry Low NOx	30	DLN + SCR	80	3
	20-30	Dry Low NOx	30	DLN + SCR	60	2

Although combustion engines generate lower emissions than other established fossil fuel-driven DG technologies, in many U.S. states units must be installed with additional control technologies to further reduce NO_x emissions. Catalytic combustors, one emerging NO_x control option, fully convert the input fuel and air without the use of a flame. Since in a traditional combustor the majority of NO_x is produced in the high-temperature region near the flame, catalytic systems substantially reduce these emissions. This system is currently under demonstration and is not yet commercially available. $SCONO_x$, another emissions control development, uses a proprietary oxidation/adsorption/regeneration process to reduce NO_x, CO, and total hydrocarbons (THC) to levels below U.S. standards. This technology is currently being developed, and may allow for economic installations of industrial turbines with single digit NO_x emissions.

<u>Application</u> Combustion turbines can be utilized in a wide range of DG applications.

Application	Fit	Notes
Continuous	◒	Low efficiencies lead to high fuel costs but can be considerably mitigated by combined cycle systems. Maximum output degrades at high ambient temperatures.
CHP	●	Heat recovery is all from one stream (exhaust). Output heat quality is generally better than all other options.
Peaking	◒	Lower hours of operation limit the efficiency disadvantage, but reciprocating engines are usually cheaper and more effective for all but the largest applications.
Green	○	Turbines are generally cleaner than engines (lower NO_x and CO emissions) although not as clean as fuel cells or renewable options. Lower efficiency also leads to higher CO_2 emissions.
Premium	◒	Small turbines are used for back-up power in Europe and Japan.

Key: ● Good fit ◒ Moderate fit ○ Poor Fit

<u>Manufacturers</u> Turbines are currently available from numerous manufacturers. The next generation of turbines is under development. Among other projects, the Advanced Turbine System program, sponsored by the U.S. Department of Energy, seeks to increase turbine efficiency and lower NO_x emissions through the use of recuperation and advanced materials.

Manufacturer	Model	Notes
Alstom	Gas turbines to 50 MW, combined cycle from 50 to 265 MW.	Fueled by natural gas, light oil, crude oil or coal gas. A switching facility eliminates dependency on any one fuel.
Kawasaki	Output from 650 kW to 30 MW. CHP, standby and combined-cycle.	Will market and sell the GPB15X generator package with Catalyticas' Xonon™ Cool Combustion system.
Nuovo Pignone	Turbines range from 2 MW to 124 MW.	Nearly 1300 installed with more than 55 million fired hours.
Pratt & Whitney	300 to 5000 kW for Generators, CHP, Auxiliary Power.	Formed New Industrial Gas Turbine Unit P2 Energy, LLC this fall.
Rolls Royce	Units to 150 MW, aeroderivative gas turbines and diesel engines.	Announced business re-organization, will concentrate its Energy business large gas turbine operations in Montreal.
Solar	Units from 1 to 15 MW	Solar has the largest market share in the 1 to 15 MW size range.

<u>Development Issues</u>

Efficiency

- More durable and temperature resistant materials (ceramics, single-crystal superalloys, and directionally solidified material) or advanced cooling schemes (transpiration and vortex) are needed for first stage turbine blades and combustors in order to increase the operating temperature/compression ratio and, therefore, efficiencies of turbines. Such developments will also result in less down-time and lower-cost maintenance.

- Efficiency may be improved through the use of recuperators (air-to-air heat exchangers that use exhaust gases to preheat the compressed combustor inlet air). Although recuperation is not commonly employed for turbines in the >1 MW size range, it is an integral part of the Advanced Turbine System (ATS) program and is already used in microturbines. Intercooling (cooling air between 2 or more compression stages) can increase efficiency by reducing air compression power requirements, and produces lower temperature air for better cooling of turbine parts.
- Ambient effects on efficiency are also important since peak turbine use is normally during high temperature periods when their maximum output is lowest. Current methods to lessen the effects of ambient temperature include evaporative, mechanical, or adsorption inlet air chillers, steam injection into the combustor for higher mass flow or NO_x control, and compressed air storage/injection.

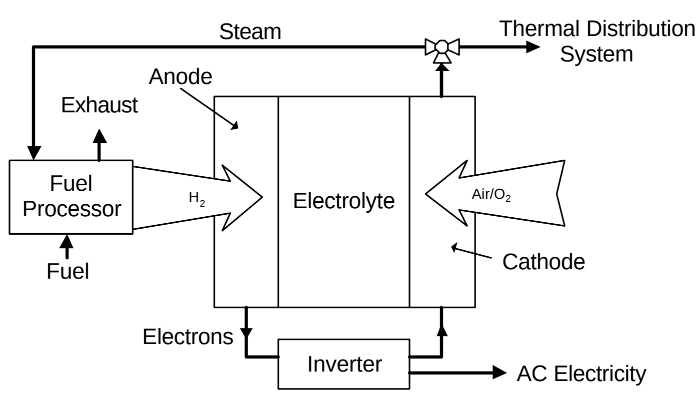
Applications

- Maintenance costs can be reduced through modular construction (designing components within each module to require maintenance at the same time or in multiples of each other) or through advanced monitoring of turbine performance to anticipate maintenance needs.
- Gasifiers that produce gaseous fuel from solids, such as coal and biomass, could help turbines gain wider acceptance, especially in international markets and where no natural gas supply exists. However such gasifiers introduce significant system complexity and costs.

Phosphoric Acid and Proton Exchange Membrane Fuel Cells

<u>History and Status</u> Although the first fuel cell was developed in 1839 by Sir William Grove, the technology was not put to practical use until the 1960's when NASA installed fuel cells to generate electricity on Gemini and Apollo spacecraft. There are many types of fuel cells currently under development, including phosphoric acid, proton exchange membrane, molten carbonate, solid oxide, alkaline, and direct methanol. However, fuel cells are not generally commercially available. A number of companies are currently field testing demonstration units and plan for commercial delivery in the near future.

<u>Operation</u> There are many types of fuel cells, but each uses the same basic principle to generate power. A fuel cell consists of two electrodes (an anode and a cathode) separated by an electrolyte. Hydrogen fuel is fed into the anode, while oxygen (or air) enters the fuel cell through the cathode. With the aid of a catalyst, the hydrogen atom splits



into a proton (H+) and an electron. The proton passes through the electrolyte to the cathode, and the electrons travel through an external circuit connected as a load, creating a DC current. The electrons continue on to the cathode, where they combine with hydrogen and oxygen, producing water and heat.

The main differences between fuel cell types are in their electrolytic material. Each different electrolyte has both benefits and disadvantages, based on materials and manufacturing costs, operating temperature, achievable efficiency, power to volume (or weight) ratio, and other operational considerations. The part of a fuel cell that contains the electrodes and electrolytic material is called the "stack," and is a major component of the cost of the total system. Stack replacement is very costly but becomes necessary when efficiency degrades as stack operating hours accumulate.

Fuel cells require hydrogen for operation. However, it is generally impractical to use hydrogen directly as a fuel source; instead, it is extracted from hydrogen-rich sources such as gasoline, propane, or natural gas using a reformer. Cost effective, efficient fuel reformers that can convert various fuels to hydrogen are necessary to allow fuel cells increased flexibility and commercial feasibility.

Emission Control Technologies Fuel cells have very low levels of NO_x and CO emissions because the power conversion process is an electrochemical rather than a combustion one. For this reason, as emission standards become increasingly stringent, fuel cells will offer a clear advantage, especially in non-attainment zones. To date, fuel cells have been exempt from environmental regulations in most parts of the United States.

Application Fuel cells can be utilized in a wide range of DG applications.

Application	Fit	Notes
Continuous	●	High efficiencies lead to low fuel costs. Lack of moving parts increases availability.
CHP	◒	PAFC's produce a high thermal quality output. However, cogeneration options for PEM fuel cells are largely limited to hot water supply due to their lower operating temperatures.
Peaking	○	Due to extremely high capital costs, fuel cells do not typically reduce energy costs unless they operates continuously.
Green	●	Fuel cells have virtually no pollutant emissions. CO_2 emissions are also low due to high efficiency; however, they are no better than an engine with the same efficiency and fuel.
Premium	●	Fuel cells deliver digitally perfect power. However, most power quality problems have less expensive solutions.

Key: ● Good fit ◒ Moderate fit ○ Poor Fit

Manufacturers One company, International Fuel Cells/ONSI, currently manufacturers a 200 kW phosphoric acid fuel cell for use in commercial and industrial applications. A number of other companies are close to commercializing proton exchange membrane (PEM) fuel cells, with marketplace introductions expected in 2001-2002. Although they were originally designed solely for electric generation, many fuel cells have transportation applications as well. Several manufacturers have entered into alliances with automobile manufacturers who can fund the costly R&D work.

Manufacturer	Model	Notes
International Fuel Cells/ONSI	200 kW phosphoric acid fuel cell; commercial/industrial uses.	Supplied the largest commercial fuel cell system in the nation, at the Anchorage Mail Processing Center in Alaska.
DAIS Analytic	Developing 2.5 MW and 10 kW fuel cell power plants .	Products in testing include: an ammonia cracker hydrogen source for small fuel cell power supplies.
Avista Corp.	Modular, cartridge-based, PEM fuel cells.	Selected for the first demonstration unit for a Houston Advanced Research Center (HARC) multi-year project.
Ballard Power Systems	250-kilowatt stationary PEM fuel cell power generator.	Partners include: DaimlerChrysler AG, Ford Motor Company, GPU International Inc., Alstom SA and Ebara.
PlugPower	7 kW residential PEM unit.	Will soon demonstrate the first prototypes of the fuel cell it hopes to market in 2002.
FuelCell Energy, Inc.	Carbonate technology, nominal ratings of 300 kW, 1.5 & 3 MW.	Contract for two additional fuel cell power plants to be installed by Los Angeles Department of Water and Power

Development Issues – Most development work on fuel cells is focused not on refining current models, but rather on getting units to work and demonstrating their effectiveness. Currently, only Phosphoric Acid fuel cells (PAFC) are being produced commercially for power generation. Other fuel cell types have entered the testing and demonstration phases, with Proton Exchange Membrane (PEM) cells receiving a great deal of attention for their transportation applications and for small DG units designed for residential use.

Phosphoric Acid Fuel Cells (PAFC)

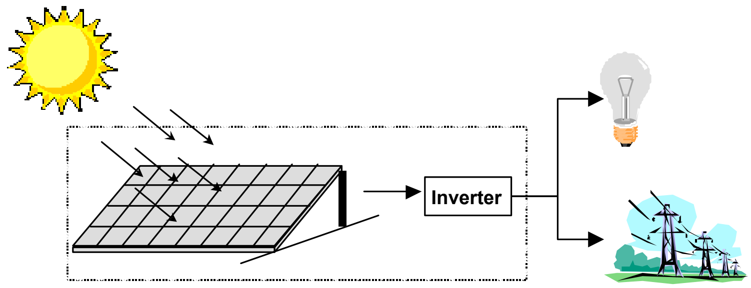
- PAFC's generate electricity at around 40% efficiency, and this increases to nearly 85% if the by-product thermal energy produced by the fuel cell is used for cogeneration. Operating temperatures are in the range of 350^{o}F.
- PAFC's are fed with a hydrogen-rich gas in the anode, where gaseous hydrogen is oxidized to protons and electrons. The protons then travel through a matrix layer, made of Teflon-bonded silicon carbide soaked with phosphoric acid to the cathode where they combine with oxygen and electrons returning from an external circuit to produce water.
- Since a PAFC system operates at a relatively high temperature and uses an external water loop to cool the stack, heat recovery is easier than with other fuel cell technologies.

Proton Exchange Membrane (PEM) Fuel Cells

- PEMs operate at relatively low temperatures (about 200^{o}F), have high power density, and can vary their output quickly to meet shifts in power demand. Most units in development are for small-scale applications common in the transportation and residential energy sectors.
- The PEM fuel cell uses a proton exchange membrane (also known as polymer electrolyte membrane) sandwiched between two electrodes that form the cell. The plastic-like membrane is made of polyperfluorosulfonic acid and is somewhat similar to DuPont Teflon. This material is used in fuel cells because of its ability to conduct hydrogen atoms.
- PEM's operate at lower temperatures than most other fuel cells, and contain no chemicals such as liquid acids or molten bases that would cause materials-of-construction concerns.

Photovoltaic Systems

History and Status In 1839, French physicist Edmund Becquerel discovered that certain materials produced small electric currents when exposed to light. His early experiments were about 1 to 2 percent efficient in converting light into electricity and precipitated research into these photovoltaic effects. The next breakthrough came in the 1940s when material science evolved and the Czochralski process was developed to produce very pure crystalline silicon (The process is named after Jan Czochralski, the Polish scientist credited with inventing it). In 1954, Bell Labs used this process to develop a silicon photovoltaic cell that increased the light to electricity conversion efficiency to 4 percent. Photovoltaic systems, commonly known as solar panels, are currently widely available, produce no emissions, are reliable, and require minimal maintenance to operate. Photovoltaic systems are not used widely because the are one of the most expensive DG technologies to buy, only work while sunlight is available, and have a fairly large *footprint*.



Photovoltaic System

Operation Photovoltaic (PV) solar panels are composed of discrete cells connected together that convert light radiation into electricity. The PV cells produce direct-current (DC) electricity. Since the electricity supplied by the electric utilities and used by most residential end-users is AC electricity, the electricity generated by solar panels cannot be used until it is converted from DC to AC using an inverter. In some instances, additional power conditioning equipment may be required if the solar panel is connected to the electric grid.

Insolation is a term used to describe available solar energy that can be converted to electricity. The factors that affect insolation are the intensity of the light and the operating temperature of the PV cells. Light intensity is dependent on the local latitude and climate and generally increases as the site gets closer to the equator. Another major factor is the position of the solar panel. In order to maximize light intensity, the panel should be positioned to maximize the duration of perpendicular incident light rays. Even with these adjustments, the maximum theoretical efficiency that can be attained by a PV cell is 30 percent.

Emission Control Technologies PV systems produce no emissions.

Applications PV systems can be utilized in a wide range of DG applications, ranging from residential and commercial uses to remote power applications.

Application	Fit	Notes
Continuous	◒	Solar cells can only produce power when there is daylight. Truly continuous applications require battery storage, which some residential systems have.
CHP	○	CHP applications are not expected.
Peaking	○	Since the output of these units cannot be controlled, they are not suited for peaking applications. However, they do produce power during periods of maximum available solar radiation -- the same periods when many commercial and residential buildings have their peak electric usage.
Green	●	PVs do not emit pollutants or CO_2.
Premium	○	The unpredictable nature of power from solar cells prohibits their use for premium applications.

Key: ● Good fit ◒ Moderate fit ○ Poor Fit

Manufacturers Photovoltaic systems are currently available from a number of manufacturers for both residential and commercial applications. Manufacturers continue to reduce installed costs and increase efficiency (which is presently 24% in the lab and 10% in actual use).

Manufacturer	**Model**	**Notes**
ASE America	Modules from 50 watts to the industry's largest 4'x6' module generating 300 watts of power.	Supplying electricity to the grids of several dozen utilities.
Astro Power	Panels designed for on-site peak demand power for commercial and domestic use.	Working with Elkem for final development of a low-cost process for manufacturing solar-grade silicon.
BP Solar (Solarex)	High efficiency crystalline and thin film photovoltaic modules.	Apollo® thin film module achieved record 10.6 percent efficiency with power output of 91.5 Watts.
Siemans Solar	Produce solar cells and modules.	New solar modules ranging from 130 to 150 W.

Development Issues New technologies and processes can help eliminate economic barriers that are impeding the entry of photovoltaic systems into the marketplace.

Technology

- The development of cheaper components will reduce the cost of photovoltaic systems. Currently, the majority of the systems being manufactured are thin plate crystalline silicon. However, manufacturers are exploring alternatives. For example, a thin film crystalline system is now being developed that will produce electricity using a fraction of the silicon required in thin-plate photovoltaic cells.
- Advancements in the manufacturing process would also influence the market penetration of photovoltaic systems. Higher production yields would translate into lower manufacturing costs, since a smaller percentage of photovoltaic cells would need to be discarded due to manufacturing defects and impurities. Since a premium is built into the price of each photovoltaic cell to cover the cells that are discarded, advancements in manufacturing technology would translate into cost savings for customers.

Efficiency

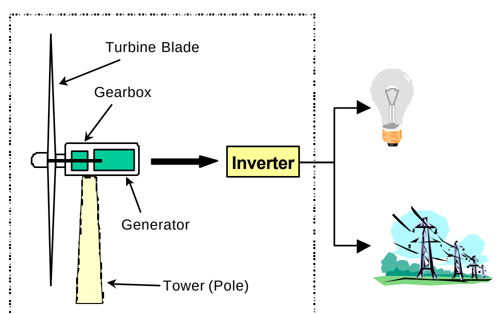
- Today's systems have an energy conversion efficiency that is less than one-half of the efficiency attained in the laboratory. Increasing the efficiency of these systems will not only reduce the costs, but also reduce the footprint of these systems by producing more electricity per unit surface area.

Wind Turbine Systems

History and Status Windmills have been used for many years to harness wind energy for mechanical work such as pumping water. Before the Rural Electrification Act in the 1920's provided funds to extend electric power to outlying areas, farms were using windmills to produce electricity with electric generators. In the US alone, eight million mechanical windmills have been installed.

Wind energy became a significant topic in the 1970s during the energy crisis in the U.S. and the resulting search for potential renewable energy sources. Wind turbines, basically windmills dedicated to producing electricity, were considered the most economically viable choice within the renewable energy portfolio. During this time, subsidies in the form of tax credits and favorable Federal regulations were available for wind turbine projects to encourage the penetration of wind turbines and other renewable energy sources. Today, attention has remained focused on this technology as an environmentally sound and convenient alternative. Wind turbines can produce electricity without requiring additional investments in infrastructure such as new transmission lines, and are thus commonly employed in remote locations. Most wind turbines currently being used are small units (less than 5 kW) designed for the residential sector, or larger units installed by electric companies so they can sell green power to their customers.

Operation Wind turbines are packaged systems that include the rotor, generator, turbine blades, and drive or coupling device. As the wind blows through the blades, the air exerts aerodynamic forces that cause the blades to turn the rotor. Most systems have a gearbox and generator in a single unit behind the turbine blades. The output of the generator is processed by an inverter that changes the electricity from DC to AC so that the electricity can be used.



Wind Turbine System

Most of the turbines in service today have a horizontal axis configuration (as shown in the figure). Wind conditions limit the amount of electricity that wind turbines are able to generate, and the minimum wind speed required for electricity generation determines the turbine rating. Generally, the minimum wind speed threshold is attained more frequently when the turbine is placed higher off of the ground. Also important to consider when siting a wind turbine is the terrain. Coastlines and hills are among the best places to locate a wind turbine, as these areas typically have more wind.

Emission Control Technologies Wind turbines produce no emissions.

Applications Wind turbines can be utilized in the following DG applications.

Application	Fit	Notes
Continuous	○	Wind turbines can only produce power when there is sufficient wind. Truly continuous applications are not likely and would require battery storage, which some residential system have.
CHP	○	CHP applications are not expected.
Peaking	○	Since the output of these units cannot be controlled, they are not suited for peaking applications.
Green	●	Wind turbines do not emit pollutants or CO_2. However, their use in some applications has been criticized for the threat they pose to migratory birds.
Premium	○	The unpredictable nature of power from wind turbines prohibits their use for premium applications.

Key: ● Good fit ◒ Moderate fit ○ Poor Fit

Manufacturers Wind turbines are currently available from many manufacturers and improvements in installed cost and efficiency continue.

Manufacturer	Model	Notes
Atlantic Orient Corporation	15 m rotor, 50 kW AC output industrial-scale wind generator.	10 kW WindLite DC wind generator is in development.
Bergey Windpower	Wind turbines installed in all 50 States and more than 90 countries.	50 kW Advanced Small Wind Turbine Prototype.
Northern Power Systems	Hybrid design solutions; standalone and grid-tied applications.	New 100 kW utility scale wind turbine optimized for distributed generation and village power applications.
Southwest Windpower	Battery charging wind turbines.	9/15/2000 Southwest Windpower became the first company to receive UL approval on a wind turbine.
Wind Turbine Industries Corp.	Wind plants from 10 to 20 kW, rotor sizes from 23 to 29 ft.	Applications include Grid Intertie and Hybrid battery charging (remote battery charging).

Development Issues

- The drawback to using wind turbines is that they rely on a variable and somewhat unpredictable source. If the wind speed is not sufficient to turn the shaft in the generator, electricity will not be produced. However, systems are now being developed that will lower the minimum wind speed threshold.
- To compensate for the unpredictable nature of wind conditions, battery storage systems are being integrated to provide electricity when the turbine is not turning. Voltage regulators have been developed and are being improved so that the turbine can recharge the batteries while simultaneously producing electricity. These should ultimately make wind turbines more affordable.
- Wind turbines provide a relatively inexpensive way to produce electricity compared with PV, the only other truly green technology. Wind turbines are expected to keep this cost advantage in the future.
- One of the major costs associated with a wind turbine system is the tower that the turbine must be placed on. A rule of thumb is to raise the turbine 30 feet above any obstruction within a 300 feet radius.

3. Distributed Generation Matrix Assessment

The following tables present price and performance parameters for each commercial and near-commercial DG technology. These tables provide data on equipment performance, maintenance, siting and environmental issues, economics, and generation costs.

General

	Size Range (kW)	Efficiency (%) Electric	Efficiency (%) Overall	Thermal Output Quantity (Btu/kWh)	Thermal Output Temperature	Packaged Cost ($/kW)[1]	Installation Cost ($/kW)[2]	Fixed O&M ($/kW - yr)	Variable O&M ($/kWh)	Electric-Only Cost-to-Generate (cents/kWh)[3]	Cogeneration Cost-to-Generate (cents/kWh)[4]
Reciprocating Engines											
Spark Ignition	30-5,000	31-42	80-89	1600-5500	320-770°F 160-409°C	300-700	150-600	5-15	0.007-0.01	7.6-13.0	6.1-10.7
Diesel	30-5,000	26-43	85-90	900-6500	880-1110°F 472-600°C	200-700	150-600	10-18	0.005-0.008	7.1-14.2	5.6-10.8
Dual Fuel	100-5,000	37-42	80-85	900-6500	880-1110°F 472-600°C	250-550	150-450	10-18	0.005-0.008	7.4-10.7	6.0-9.1
Turbines											
Microturbines Non-Recup.		14-20	75-85	9000-10000	930-1300°F 500-700°C	700-1000				14.9-22.5	10.1-15.9
Microturbines Recup.	30-200	20-30	60-75	3000-9000	390-570°F 200-300°C	900-1300	250-600	3-10	0.005-0.01	11.9-18.9	10.0-16.8
Industrial Turbines	1,000-5,000	20-33	70-95	3,500-15,000	750-1060°F 400-571°C	200-850	150-250	10-25	0.0025-0.004	8.7-15.8	5.8-12.2
Fuel Cells											
PEM	5-10	27-40	40-75	2000-3200	122-167°F 50-75°C	4,000-5,000	400-1,000	3-10	0.01-0.04	21.9-33.3	20.7-33.3
Phosphoric Acid	200	40	84	3750	122-158°F 50-70°C	3,000-4,000	360	3-10	0.013-0.016	18.6-22.8	17.0-21.2
Renewable											
Photovoltaic	5-5,000	-	-	-	-	5,000-10,000	150-300	-	0.001-0.004	18.0-36.3	N/A
Wind	5-1,000	-	-	-	-	1,000-3,600	500-4,000	-	0.01-0.02	6.2-28.5	N/A

[1]Packaged costs include the prime mover, generator, inverter (if needed), and ancillary equipment. Costs can vary based on size, duty cycle, and fuel. All costs in this table exclude equipment necessary for thermal utilization. In general larger units are less epensive (per kW) than smaller units and units designed for peaking/back-up power are less expensive than units designed for baseload operation.

[2]Installation costs can vary with utility interconnection requirements, labor rates, ease of installation, and other site-specific factors.

[3]Cost-to-Generate assuming a 50% load factor and 1999 Maine average price of natural gas to the commercial sector and no thermal utilization. Cost-to-generate includes fuel and O&M expenses as well as amortized capital charges.

[4]Cost-to-Generate assuming a 50% load factor and 1999 Maine average price of natural gas to the commercial sector, 75% utilization of thermal output, and cogeneration equipment adder of $100/kW for reciprocating engines, $150/kW for turbines, and $75/kW for fuel cells. Cost-to-generate includes fuel and O&M expenses as well as amortized capital charges.

Siting

	Footprint (sqft/kW)	Weight (lb/kW)	Noise Levels (dB @ 10ft)	Inter-connection Requirements	Emissions (g/kWh unless otherwise noted)	Emissions Control Technologies Available
Reciprocating Engines						
Spark Ignition	.15-.3	5-22	80-100; requires building enclosure		NO_x: 0.7-42 CO: 0.8-27	Increase the air-fuel ratio (lean-burn, ultra lean-burn) and lower the temperature in the combustion chamber; SCR (lean-burn) or NSCR (rich-burn)
Diesel	.15-.4	5-17	67-92; requires building enclosure		NO_x: 6-22 CO: 1-8	SCR, particulate traps
Dual Fuel	.1-.2	5-17	80-100; requires building enclosure		NO_x: 2-12 CO: 2-7	Pre-ignition chamber to lower the amount of diesel fuel needed.
Turbines						
Microturbines	.2-.5	3-13	<60; enclosure supplied with unit	Inverter-based power	NO_x: 9-125ppm CO: 9-125ppm	None
Industrial Turbines	.04-1	5-30	67-92; enclosure sometimes supplied with unit		NO_x: 25-200ppm CO: 7-200ppm	Water/Steam Injection, Dry-low NOx, SCONOx, Catalytic combustion
Fuel Cells						
PEM	.6-3	100-300	46; no enclosure required	Inverter-based power	NO_x: 0.007 CO: 0.01	None
Phosphoric Acid	1-1.5	200	72; usually no enclosure required	Inverter-based power	NO_x: 0.007 CO: 0.01	None
Renewable						
Photovoltaic	1.5-9.0	1,800-2,200	None	Inverter-based power	-	-
Wind	130-550	175-860	78-84		-	-

Operation

	Loading Options		Fuel Flexibility				Maintenance		
	Duty-Cycles Available	Ability to Operate at Part Load	Types	Pressure (psig)	Availability (%)	Start-up Time (s)	Planned Schedule (hrs)	Expected Maintenance Activities	Time Between Overhauls (hrs)
Reciprocating Engines									
Spark Ignition	CON, CHP, PEK, GRN, PRE	Efficiency degrades ~11-17% to 50%; Operation down to ~25%	NG, P, BG, G	35-60	90-97	5-10	1,000-2,000	Oil, coolant and filter change, examine belts and clearances, timing adjustments, compression checks, replacement of wires and plugs (for SI). Upper head overhaul that includes piston replacement, cylinder liner replacements, valve work, fuel-injectors, etc. at 10,000-20,000 hours. Lower head overhauls include replacement of crankshaft and bearings and are	10,000-24,000
Diesel	CON, CHP, PEK, PRE	Fairly steady efficiency down to 50%; Operation down to ~25%	D	3-14.5	90-97	10	1,000-2,000		10,000-24,000
Dual Fuel	CON, CHP, PEK, GRN, PRE	Fairly steady efficiency down to 50%; Operation down to ~25%	D & NG, D	3-14.5	90-95	10	1,000-2,000		10,000-24,000
Turbines									
Microturbines	CON, CHP, PEK, GRN, PRE	Efficiency degrades ~ 20% at 50% load; Operation down to 5-50%	NG, D, K, N, M, E, A, F, G, P, BG	3-100	92-98	30-60	5,000-8,000	Replace/clean air filter, inspect internal fuel filter, change external fuel filter, replace thermocouple, igniter, and fuel injector. Rotating core and combustor overhaul at ~10,000 hrs. Recuperator replacement at ~40,000 hours	10,000-40,000
Industrial Turbines	CON, CHP, PEK, GRN, PRE	Efficiency degrades ~ 20% at 50% load; Operation down to 5-50%	NG, D, K	100-300	85-98	100-600	2,000-4,000	Quarterly: Washdown, oil change. Annually: Inspection (boroscoping of blades, control troubleshooting, possible bearing roll-out). Rotor replacement at 25,000-40,000 hours.	25,000-40,000
Fuel Cells									
PEM	CON, GRN, PRE	Almost no degradation to 50%; Operation down to 5%	NG, P, M, E, H	.14-.58	90-98	50-100	8,000	Inspection and auxiliary equipment repair. Swap power modules.	10,000-40,000
Phosphoric Acid	CON, CHP, GRN, PRE	Almost no degradation to 50%; Operation down to 5%	NG, P, M, E, H	.14-.58	88-96	10min-12hr (cold)	2,500-8,000	Inspection and auxiliary equipment repair. Stack replacement at ~40,000 hours	40,000
Renewable									
Photovoltaic	GRN	Varies with weather	None	-	100*	-	4,000-8,000	Cleaning	100,000+
Wind	GRN	Varies with weather	None	-	95-99*	-	8,000	Annual inspection	130,000

Duty Cycles: CON - Continuous, Combined Heat and Power - CHP, PEK - Peaking, GRN - Green, PRE - Premium
Fuels: NG - Natural Gas; D - Diesel; K - Kerosene; N - Naphtha; M - Methanol; E - Ethanol; A - Alcohol; F - Flare Gas; P - Propane; BG - Biogas; G - Gasoline; H - Hydrogen
PEM fuel cells and microturbines have not gained enough operating hours to accurately determine maintenance schedules.
Data supplied for these technologies is based on manufacturer supplied data.
*Use of these renewable technologies requires availability of wind/solar radiation which is not accounted for in these values

4. Glossary of Distributed Generation Terminology

Availability – A measure of system reliability. It refers to the number of hours that a power plant is available to produce power divided by the total clock hours in the same time period (usually a year).

Brake Mean Effective Pressure (BMEP) – A measure of how effectively an engine uses its piston displacement to do work.

Capacity Factor – For an electricity generating unit, the total amount of power generated over a period of time divided by the maximum amount of power that could be generated over that period of time. The maximum amount of power that could be generated is defined as the unit's rated output multiplied by the amount of time in the period.

CO – Carbon monoxide. A gaseous pollutant which is a product of incomplete combustion.

Combustor – The part of a combustion turbine in which fuel is burned.

Compressor – The part of a combustion turbine system where intake air is pressurized.

Distributed Generation – Relatively small electricity generating units located close to the loads being served. In general, distributed generation covers units in the 5 kW to 30+ MW size range.

Efficiency, Electric – Net electric output divided by total fuel heat input (Lower Heating Value [LHV]) in like units. LHV assumes the water produced during combustion leaves the process uncondensed, as vapor (essentially wasting the heat required to vaporize the water). Higher Heating Value (HHV) assumes that water leaves the process condensed, recovering the heat of vaporization. Electric efficiency is normally reported in LHV, but natural gas heat content is normally expressed in HHV. A rule-of-thumb for natural gas is that Efficiency (LHV) ≈ Efficiency (HHV) * 1.1 and Heat Content (LHV) ≈ Heat Content (HHV) / 1.1.

Efficiency, Overall – The sum of the electrical and thermal outputs divided by the total fuel heat input (LHV) for a generation unit.

Fixed O&M Costs – The portion of total Operating and Maintenance Costs that are independent of the hours of operation and capacity factor. These costs generally consist of inspection and other annual/semi annual service expenses and those costs that are a function of the number of hours that equipment operates rather than the amount of energy produced.

Footprint – The physical floor space area required by a DG unit.

Interconnection – A link between a generator and the load being served or utility grid.

Insolation – Available solar radiation that is received in the Earth's atmosphere or at its surface and can be converted to electricity.

Installation Cost – Cost necessary to prepare a packaged unit for operation on a site. These costs include engineering studies, permitting, interconnection, and set-up expenses.

Inverter – A device for converting direct current into alternating current.

Load Factor – The average rate of power consumption during some period of time divided by the maximum rate of power consumption during that period.

Nonattainment – Area where air quality does not primary or secondary ambient air quality standards may be designated "nonattainment."

NO_x – The oxides of nitrogen. A gaseous pollutant which is a product of high combustion temperatures.

NSCR – Non Selective Catalytic Reduction. An emission-reducing process employing a three-way catalytic converter such as that employed on automobiles which simultaneously removes NO_x, CO, and hydrocarbons.

Overhaul – A rebuilding or replacement of a major portion of a technology.

Packaged Cost – Cost for all equipment in a complete generator set including the prime mover, generator, and packaging.

Power Density – Power output per unit size.

Radial-flow Design – A compressor or turbine where kinetic energy is added by accelerating the fluid outward from the axis of rotation.

Recuperator – A heat exchanger that transfers heat from gaseous products of combustion to incoming air or fuel.

SCR – Selective Catalytic Reduction. This process reacts ammonia with the NO_x in the exhaust gas to convert the NO_x into molecular nitrogen.

Supercharger – A belt-driven compressor that increases engine intake air density, and combined with additional fuel, allows the engine to produces more power.

Turbocharger - A type of supercharger that uses a turbine to drive a compressor. The turbine, driven by hot gases in the exhaust manifold, spins the compressor. The compressor increases the intake air density, and combined with additional fuel, produces more power.

Variable O&M Costs – Those operating and maintenance costs that are directly proportional to the amount of energy produced. Costs such as worn equipment replacement, consumables, disposal charges, etc. are generally variable.

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