White Paper on

"Distributed Generation"

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Table of Contents

Photovoltaic Systems

Photovoltaic energy is a technology that converts sunlight directly into electrical energy. The output is direct current (DC), which can be used directly, converted to alternating current (AC), or stored for later used. Major components of PV systems are the PV array, batteries, inverters, and charge controllers. The components other than the array are generally referred to as balance of systems components.

Figure 1.1: Photovoltaics systems

PV arrays

PV electrical characteristics are specified by a current-voltage diagram. The IV curve characterizes important operational parameters of the cell, among which are the short-circuit current, the open-circuit voltage, and the current and voltage at the maximum power point [1]. The power rating or the maximum power point of a panel is based on measurements performed at Standard Reporting Conditions or SRC, also known as Standard Test Conditions or STC, which are: (i) illumination of 1 kW/m2 at spectral distribution of AM 1.5; and (ii) cell temperature of 25°C.

Manufacturers usually provide IV curve specifications at different levels of irradiation and temperature as shown for BP-SX-60, and BP820, 60-W and 20-W panel from BP respectively (Figures 1.2 and 1.3). From the figures, operating temperature and solar irradiation are seen to have well-defined effects on IV-curve characteristics: the open-circuit voltage decreases with the increasing temperature, whereas the short-circuit current increases slightly. On the other hand, with the decrease in irradiation, output power of the panel decreases significantly.

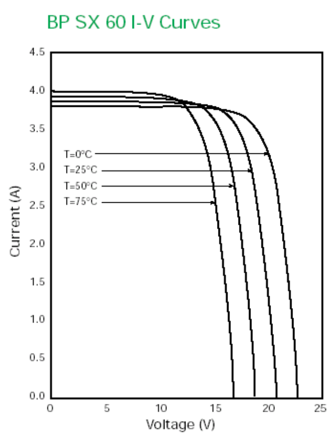


Figure 1.2: IV curve of BP SX 60

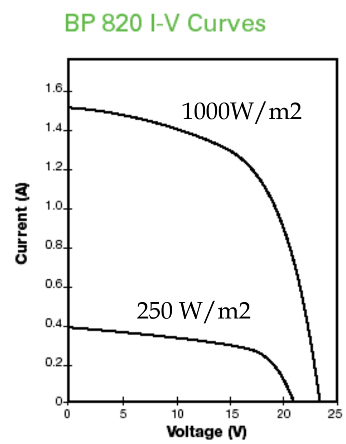


Figure 1.3: IV curve of BP820

Source: BP Solar, Inc.

Batteries:

Batteries are electro-chemical devices. The most common type of battery in both utility and nonutility applications is the lead-acid battery. However, it must be operated within strict boundaries since it is susceptible to damage under certain conditions, such as overcharging, undercharging or remaining for long periods in a low state of charge. The most popular type of battery in distributed power applications is the valve-regulated lead-acid battery (VRLA). VRLA batteries are sealed and need no topping off with water, and thus require less maintenance than regular lead-acid batteries.

Inverters:

Inverters are solid-state components used to convert DC power into AC power. Inverters are vital when a stand-alone PV system is used to operate AC loads. The rule of thumb for inverters is to size them according to the maximum required continuous power output.

Charge Controllers:

A charge controller is usually required on a system utilizing a battery. It is used to control and regulate the charging of the battery, thus providing greater system reliability, longer battery life and overall lower cost to the system owner. Its main functions are top-of-charge regulation to prevent overcharging and load-disconnection to prevent excessive discharging. Moreover, it can give a boost charge from time to time to avoid stratification of the battery. As a rule, the size of battery charger can be defined in terms of its DC output power.

Table 1.1: Photovoltaics System Characteristics

	PV array	Battery	Inverter	Charge controller
Capacity	3W – 300W	12.2AH@12V - 1440AH@2V	125W – 5.5kW	4.5A – 60A
Initial costs	$5/Wp	$1.705/AH	$0.831/W	$5.878/Amp
O&M costs	Typically, PV operating costs are approximately $0.001-0.004/kWh.			
Efficiency	12-25% Depend on type	90%	96% at high power levels	95%
Physical	BP-SX-55U (55W) 1110mmx502mm 7.2 kg	PVX-340T (12V 33AH) 196mmx132mmx175mm 11.4 kg	-	-
Life	20 - 25years	3-8 years	10 – 20 years	10 – 20 years
Emission	Emission during construction (CO_2, SO_2 and NO_x)	-	-	-
Applications	Remote applications, grid-connected application, utility scale application			

Capacity Range:

- PV panels are available in wide variety of ratings from 3 watt to 300 watts.
- Individual batteries are available in capacities ranging from 2.2 AH @12V to 1440AH @2V.
- Inverters are available in power rating ranging from 125W to 5.5kW. Most inverters are capable of handling three to six times more power than their rated size for short periods of time.
- Charge controllers are available in current ratings ranging from 4.5A to 60A.

Costs of PV Systems:

Currently PV systems cost between $6,000-$10,000/kW installed. The cost of a PV system depends on the system size, equipment options and labor costs. Prices vary depending on other factors as well, such as the PV provider, the PV manufacturer and subsidy/incentive programs. In California, small systems funded through California's Buy-Down Program have been averaging $7.00/ watt, after rebates. The average factory price of PV modules is about $4/watt, excluding balance-of-system (BOS) costs. BOS costs increase the factory costs by 30-100% [2]. Typically PV operating costs are approximately $0.001-0.004/kWh [3].

PV Array Initial Costs:

PV panels are available in a wide variety of sizes from 1 Watt to 300 Watts and types, i.e. thin film/Amorphous, polycrystalline, and mono-crystalline. PV initial costs reflect the economy of scale, similar to the utility-scale power plants; that is, the smaller the size of PV panel, the higher the average cost per watt, as shown in Figure 1.4. Thus, the most economic panel size to meet power requirements is the largest available size. However, scale economies cannot be applied to PV systems above a limiting PV system capacity since systems above that size are typically composed of several of smaller panels.

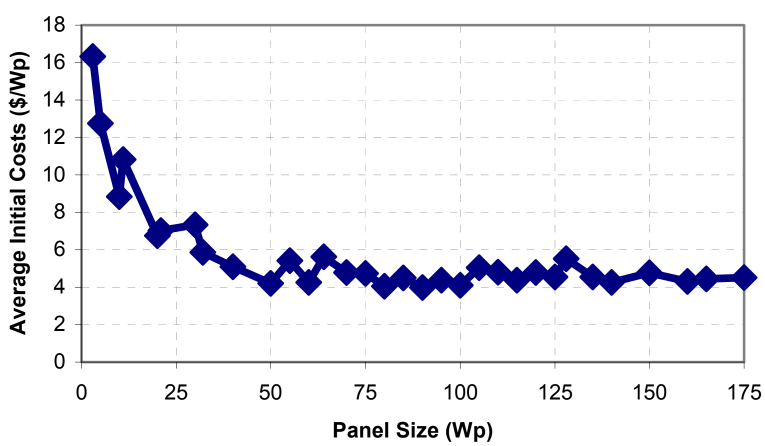


Figure 1.4: Economy of Scale of PV panels

The information, shown in Figure 1.4, is collected from various manufacturers: BP Solarex; Uni-Solar; ASE; Sunwize; Siemens; Astropower; Kyocera; Matrix Solar; and Sharp. Since several manufacturers provide PV panels in similar sizes, the above figure averages the costs per watt of PV panels from various manufacturers and various types of PV material: amorphous, single crystalline and polycrystalline. For instance, the cost per watt of a 75-W panel is calculated from the average of costs per watt of four 75-watt panels from BP, Siemens and Matrix (BP-270, PW750-75, SX-75TU and BP-275), without consideration for their construction materials.

Initial Cost of Battery:

The average initial cost of a 12-V battery per amp hour from various manufacturers – Concorde, MK Battery and Surrette – is $1.705/AH, as of December 2002.

Initial Cost of Inverter:

Based on the data from Solarbuzz Inc. [4], the initial cost is based on prices per continuous watt – which is a measure of the output power of inverters. The average initial inverter cost per watt in year 2002, used in this study, is $0.831/W.

Initial Cost of Charge Controller:

Based on the data from Solarbuzz Inc. [4], the average initial cost of a charge controller per ampere in year 2002, used in this study, is $5.878/Amp.

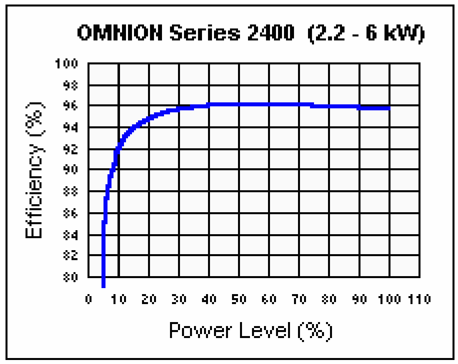
Efficiency:

Efficiency of PV panels depends on type of material as follows:

Thick crystalline materials:	
Single-crystalline silicon	23%
Poly-crystalline silicon	18%
Edge-defined film-fed growth ribbons	14%
Dendritic web	15%
Gallium Arsenide (GaAs)	25%
Thin-Film materials:	
Cadmium Telluride (CdTe)	15.8%
Copper Indium Diselenide (CuInSe2 or CIS)	12-13%
Amorphous Silicon	12%

Source [1]

The default battery efficiency is 90% [5]. Inverter efficiency is generally low at low power levels and good, roughly 96%, at high power levels depending on the inverter type. The following figure shows an example inverter efficiency curves. On the other hand, the default controller efficiency is 95%.



Source: [6]

Figure 1.5: Inverter efficiency versus power level (%)

Physical Characteristics:

For solar panel, BP-SX-55U (55W PV panel)

Dimensions	=	1110mm x 502mm
Weight	=	7.2 kg

For battery, PVX-340T (12V 33AH)

Dimensions	=	196mmx132mmx175mm
Weight	=	11.4 kg

Life:

PV panel life is typically 20 to 25 years.

Battery life is measured in both number of cycle life and floating use. The cycle life of a battery indicates the number of cycles to a specified depth of discharge until the battery's end of life is reached. In other words, a deeper the depth of discharge shortens the battery's life owing to larger internal stresses resulting from a more complete utilization of active materials. On the other hand, the float life is very dependent on the temperature at which the battery is float charged. The float life is very long at low temperature (10-20°C) but at high temperature the float life is shortened. As a general rule, the battery float life will be reduced by half every 10°C increase in average ambient temperature. A typical life of a lead-acid battery is roughly 6-8 years at 25°C and 3-5 years at 36°C.

Inverter and charge controller have typical working lives of 10-20 years.

Emissions:

During normal operation, photovoltaic (PV) power systems do not emit substances harmful to human health or the environment. There are, however, several indirect environmental impacts related to PV power systems that should be noted. Current production processes for PV power systems are relatively energy intensive, and involve the use of large quantities of materials and smaller quantities of substances that are scarce and/or toxic. Finally, at the end of their useful lifetime PV power systems have to be decommissioned, and the resulting waste streams have to be managed. The primary emissions in PV systems are from manufacturing, as shown in the following table.

Table 1.2: Emissions from Photovoltaic Panel

Parameter	Value (kg/kWp)	Value (kg/TJ)
Emission factor - CO2 (kg/TJ)	0	0
Emission factor - SO2 (kg/TJ)	0	0
Emission factor - NOx (kg/TJ)	0	0
Emission factor - Particulates (kg/TJ)	0	0
Emission factor - VOCs (kg / TJ)	0	0
Emissions during construction - CO2	432 - 2138	4,000 - 20,000
Emissions during construction - SO2	5.47 - 6.76	75 - 95
Emissions during construction - NOx	4.52 - 6.07	61 - 83

Source: [7]

Applications:

For rural and remote applications, solar electricity can cost less than any other means of producing electricity. Typical applications: remote communications outposts high in the mountains; lighting; keeping medicines cold; and pumping water in rural areas.

For household, grid-connected systems to provide supplemental power to homes and commercial buildings in cities, e.g. boosting electricity output during times of high demand, and saving money on energy bills by feeding any excess power into the utility grid.

For utilities, large-scale solar electric power plants can help meet demand for new power generation, avoiding or deferring the need for costly line upgrades.

References

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[6] Grid Connected Photovoltaics in Buildings, Department of Mechanical Engineering, the University of Strathclyde in Glasgow, website: www.esru.strath.ac.uk/EandE/Web_sites/98-9/grid_connected_pv/index.htm.

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Wind Turbines

Wind turbine technology has been used for centuries as a source of mechanical energy for mankind. Wind turbines use the wind energy to produce electrical power. Wind energy is in fact a form of solar energy produced by uneven heating of the Earth's surface. Wind energy is less predictable and more influenced by terrain and other factors than solar energy, thus making it much more site specific. Wind energy follows seasonal patterns that provide the best performance in the winter months and the lowest performance in the summer months, which is the opposite of solar energy. Thus, solar systems, together with wind systems, provide a more consistent year-round output than either wind-only or PV-only systems.

Figure 2.1: Wind Turbine

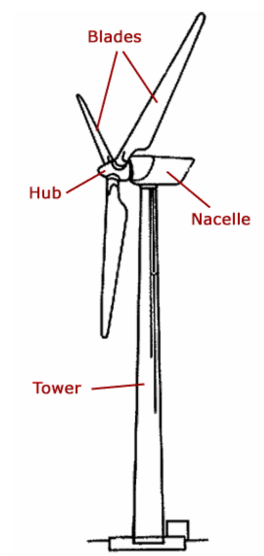


Figure 2.2: Major Components of the Wind

As shown in Figure 2.1, wind turbines have fan blades, which are placed at the top of a tall tower. The tower must be tall enough to harness energy from the wind, without any obstacles, e.g. trees, hills and buildings. As the turbine rotates in the wind, it captures the kinetic energy of the wind and converts it into rotary motion to drive the generator, producing electrical power. A single wind turbine can range in size from a few kW (5-15 kW) for residential applications to more than 5 MW for utility applications [1]. However, wind turbines with rated outputs of 300W to 1kW are also available for applications like remote homes, water-pumping, and battery-charging applications.

Major components of the wind turbines, shown in Figure 2.2, are the nacelle, rotor assembly and tower. The nacelle is the structure that houses the gearbox, generator and associated control equipment of the wind turbine. The rotor assembly consists of the blades, the hub assembly and the pitch-change mechanism. Each blade is attached to the hub through a cylindrical roller bearing that permits the full pitch of the blade from the power position 0 degree to the feather position 90 degree. Blade pitch is controlled by hydraulic actuators to feather the blades at an average rate of 8 deg/sec. Lastly the tower, on which the nacelle is mounted, is the supporting structure of wind turbine systems. A wind turbine must have unrestricted access to the wind to perform efficiently. As a general rule of thumb, a wind turbine should be installed on a tower at least 30 ft above any obstacles within 300 ft. Smaller turbines typically go on shorter towers than larger turbines. A 300-watt turbine is often, for example, installed on a 30-50 ft tower, while a 10 kW turbine will usually need a tower of 80-120 ft.

Table 2.1: Wind Turbine Characteristics

Features	Characteristics	
Capacity	Several W to several MW	
Initial costs	As high as $8/W at 50W; as low as $0.7/kW at 600 kW	
O&M costs	0.8 – 1.0 cents/kWh	
Efficiency	Capacity factor 20-45% approximately	
Physical	400-Watt Turbine Rotor diameter: 1.15 meters Weight: 5.85 kg	2000-kW Turbine Rotor Diameter: 80 meters Weight: 231,000 kg
Life	20 – 25 years	
Emission	No emission	
Applications	Residential, utility-scale applications	

Commercially available wind turbines:

Wind turbines are available in size from as low as several watts to as high as several megawatts. Generally, individual wind turbines are grouped into wind farms containing several turbines. Residential wind turbine systems are 5-15kW; the larger wind farms are often connected to sub-transmission lines for utility-scale applications [1].

Costs:

The majority of costs associated with wind energy systems are the capital costs. The equipment costs for utility scale wind turbines, including all subsystems, such as turbine, rotor, tower, control system, nacelle components and primary step-up transformer, cost between $700 and $750 per kW [2].

For the smaller wind energy systems, wind turbines can be an attractive alternative to photovoltaics systems. Unlike PVs, which are basically the same cost per watt independent of array size, wind turbines get less expensive with increasing system size. At the 50 watt size level, for example, a small wind turbine would cost about $8.00/watt compared to approximately $5.00/watt for a PV module. At 300 watts the wind turbine costs are down to $2.50/watt and $1.50/watt in the case of the Southwest Windpower Air 403 [3], while the PV costs are still at $4.00/watt [4].

Beyond the equipment costs, installation of the wind energy systems requires design work, permit acquisition, lease acquisition and construction labor. This includes excavating the foundations and underground collection array, forming and pouring the concrete, erecting the towers, positioning the turbines, assembling the rotors and performing system tests. As an industry average, the cost of installation is $250 per kW for utility scale systems [5].

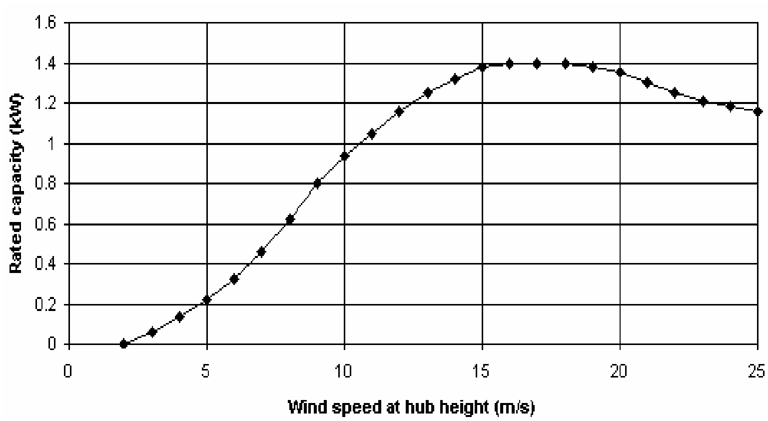
Recurring costs in operating wind energy systems include: O&M costs, insurance charges, land lease, and property taxes. According to the California Energy Commission, maintenance is required at 6-month intervals. As quoted by wind developers, O&M costs are approximately 0.8-1.0 cents/kWh. Insurance is estimated at 6.57 cents/$1000 of system valuation [5]. Land lease and property taxes are very site-specific.

Efficiency:

Wind turbine efficiency is routinely measured in terms of capacity factor (CF), a widely used terminology in the electric utility industry. It refers to the overall performance of a power plant over a month, season or a year. Depending on wind speed and type of turbine, the capacity factor for a single turbine can vary greatly from 20-40% over one year. The relationship between wind speed, power curve and capacity factor is explained in the following paragraph.

Figure 2.3 shows the power curve of a 1.4-kW wind turbine manufactured by Fortis [5]. In contrast to large wind turbines having a cut-in speed[1] of 4-5 meters/sec., cut-in speed for small wind turbines can be as low as 3 meters/sec. The wind turbine produces variable power between the cut-in and rated speeds. When the rated wind speed is attained roughly 15 meters/sec, the turbine produces full power. At speeds are higher than the rated speed, the mechanical and electrical components may be damaged unless the rotor blades are faired and secured.

Figure 2.3: Power Curve of 1.4-kW Wind Turbine



Physical Characteristics:

In order to appreciate the dimensions and weights of various wind turbine sizes, relevant characteristics of two wind turbine systems are presented – one very large unit for utility-scale applications and the other a small unit for residential applications. Table 1 gives the specifications for the AIR 430 (400-W turbine) and Vestas V80 (2MW turbine).

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[1] A certain amount of wind speed necessary for the wind turbine to overcome the mechanical inertia and provide enough rotational motion for the generator to start producing electrical power.

Table 2.2: Physical Characteristics of AIR403 and Vestas V80

Features	AIR 403	Vestas V80
Power Output	400 W	2000 kW
Operating Voltage	12, 24, 48 VDC	690V
Rotor Diameter	1.15 meters	80 meters
Hub height	-	60 - 67 - 78 meters
Weight	5.85 kg	231,000 kg

Life, emissions and applications:

A typical life for a wind turbine is 20-25 years. Wind power provides wide-ranging applications for distributed generation. Farms can be sized for either small- or large-scale power generation. For small applications, wind generators can be used for battery charging, and direct motor drive for water pumping. For utility-scale applications, wind generators are used for providing electricity for the electricity grid. Although wind turbines have no harmful emissions, they introduce several impacts on the intermediate surroundings, e.g. noise, wildlife impact and aesthetic concerns in higher population density areas.

References:

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[3] Southwest Windpower, website www.windenergy.com.

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[5] National Wind Coordinating Committee, Wind Energy Costs, Wind Energy Series no.11, January, 1997, website http://www.nationalwind.org

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Reciprocating Engines

A reciprocating engine is a widespread and well-know technology. In developing countries, reciprocating engines have been used for many decades and play a very important role in providing power for rural applications. They are commercially available in most towns and cities in developing countries in a range of size for various applications. Also called the internal combustion (IC) engine, the reciprocating engine requires fuel, air, compression and a combustion source to function. Reciprocating engines generally fall into two categories depending upon the ignition sources, i.e. [1]

Figure 3.1: Reciprocating Engine
Source: DOE

(a) Spark ignited engines: fueled by gasoline or natural gas

The four-stroke, spark-ignited reciprocating engine has an intake, compression, power and exhaust cycle. In the intake phase, as the piston moves downward in its cylinder, the intake valve opens and the upper portion of the cylinder fills with fuel and air. When the piston returns upward in the compression cycle, the spark plug emits a spark to ignite the fuel/air mix. This controlled reaction, or "burn", forces the piston down thereby turning the crankshaft and producing power. In the exhaust phase, the piston moves back up to its original position and the spent mixture is expelled through the open exhaust valve. Gasoline/petrol generators are available in very small sizes and are most suitable when loads are small and only seldom powered.

(b) Compression-ignited engines: fueled by diesel oil

The compression-ignition engine operates in the same manner. In compression-ignited engines, air alone is drawn into the cylinder and is compressed to a much smaller volume, resulting in heated air. A controlled quantity of diesel fuel is injected into the cylinder while the valves are closed. The fuel ignites spontaneously and the piston is forced downwards by the combustion gases. Compared to gasoline generators, diesel generators are more expensive, longer-lived, cheaper to maintain, and consume less fuel.

Table 3.1: Reciprocating Engine Characteristics

	Small Reciprocating Engine			Large Reciprocating Engine		
	Present	2005	2010	Present	2005	2010
Capacity	50 – 300kW	50 – 300kW	50 – 300kW	0.3 – 6.5 MW	0.3 – 6.5 MW	0.3 – 6.5 MW
Initial costs ($/kW)	500-750	450-700	400-650	400-600	375-550	350-500
Non-fuel O&M costs (c/kWh)	1.5-2	1.3-1.7	1.0-1.3	0.7-1.5	0.6-1.3	0.5-1.0
Efficiency	24-33%	26-35%	26-37%	28-37%	29-41%	30-47%
Physical	250 kW diesel engine: Dimensions: 134 x 50 x 64 in, Weight: 6,090 lb			1 MW diesel engine: Dimensions: 180 x 78 x 103 in, Weight: 16,202 lb		
Life	20-25 years					
Emission	NO_X: 21.8 lb/MWh; SO_2: 0.454 lb/MWh; CO_2: 1,432 lb/MWh; PM-10: 0.78 lb/MWh Target NO_X: 0.29 lb/MWh by 2010					
Applications	Remote power; portable power; transportation; base load; grid support; premium power; peak-shaving devices and cogeneration applications					

Commercially available reciprocating engines:

Reciprocating generating sets come in a wide range of commercially available sizes from several kW to several MW.

Costs:

Installed capacity costs of reciprocating engines are roughly $400-750/kW; non-fuel operating and maintenance costs are generally $0.007-$0.020/kWh [2]. According to the California Energy Commission, the target for bus bar energy costs, including operating and maintenance costs, is 10% less than current state-of-the-art engine systems while meeting projected environmental requirements.

Efficiency:

The efficiency of an engine depends on various factors, e.g. load factor, engine size and engine type. Efficiency of the engine (>50kW) is approximately 24-37% [2] as shown in Table 1. By 2010, the fuel-to-electricity efficiency (low heating value) is projected to improve to 47%.

Dimensions and Weights:

To get an idea about the physical characteristics of typical reciprocating engines, dimensions and weights of 250 kW and 1 MW diesel generator sets [3] are shown as examples below.

250kW – diesel generator set - liquid cooled - four cycle - Cumming engines:

L x W x H = 134 x 50 x 64 in
Weight = 6,090 lb

1 MW - diesel generator set - liquid cooled - four cycle - Cumming engines:

L x W x H = 180 x 78 x 103 in
Weight = 16,202 lb

Typical lifetime:

Very small diesel engines (<5kW) tend to have a very short life span of 25,000-30,000 operating hours; however, larger engines may last 20-25 years.

Emissions:

Emission rates (NO_X, SO_2, PM-10, CO_2, and CO) for particular types and size ranges of engines vary from manufacturer to manufacturer due to differences in fuel/air ratio, combustion technique, and ignition timing. It is important to note that the uncontrolled NOx emissions from the engines are the highest among distributed energy technologies. Representative emission levels for reciprocating engines are listed below:

Table 2.2: Emissions from Reciprocating Engines

Emission Rates	Uncontrolled Gas-Fired Lean Burn IC Engine	3-way Catalyst Gas-Fired Rich Burn IC Engine	Uncontrolled Diesel Engine	SCR Controlled Diesel Engine
NO_X (lb/MWh)	2.2	0.5	21.8	4.7
SO_2 (lb/MWh)	0.006	0.007	0.454	0.454
PM-10 (lb/MWh)	0.03	0.03	0.78	0.78
CO_2 (lb/MWh)	1,108	1,376	1,432	1,432
CO (lb/MWh)	5.0	4.0	6.2	6.2

Source: [4]

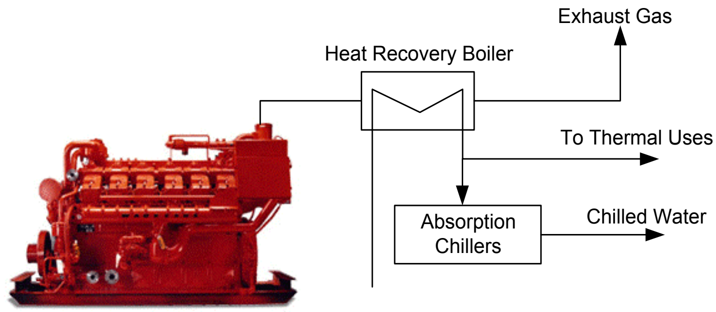
Note:

(a) Three-Way Catalyst (TWC) Systems - reduce NOx, CO and unburned hydrocarbons by 90% or more. TWC systems are widely used for automotive applications.

(b) Selective Catalytic Reduction (SCR) - SCR is normally used with relatively large (>2 MW) lean-burn reciprocating engines. In SCR, a NOx-reducing agent such as ammonia is injected into the hot exhaust gas before it passes through a catalytic reactor. The NOx can be reduced by about 80-95%.

Applications:

Reciprocating engines are frequently used as a backup power supply in residential, commercial, and industrial applications. When used in combination with a 1-5 minute UPS (uninterruptible power supply), the system is able to supply seamless power during a utility outage. In addition, large IC engine generators may be used as base load, grid support, or peak-shaving devices. Moreover, some models can be used in CHP applications, with resulting overall efficiency as high as 80-85%, as shown in Figure 2.2.



Heat recovery added costs
= $75 - $150/kW

Figure 2.2: Reciprocating Engine in CHP Application

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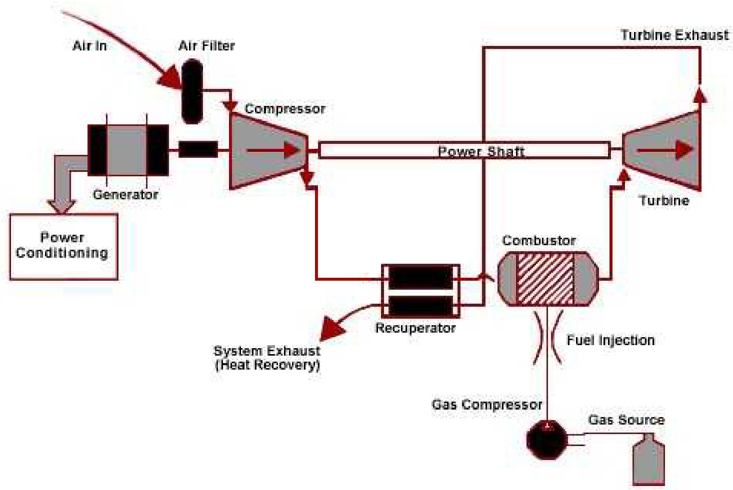
Microturbines

Microturbines are small combustion turbines that produce between 25 kW and 500 kW of power. Microturbines have a common shaft on which is mounted a compressor, turbine, and generator. These components are mounted on air bearings, so no lubrication is required; because friction is eliminated, the cost of maintenance is significantly reduced. Most microturbines are single-stage, radial flow devices with high rotating speeds of 90,000 to 120,000 revolutions per minute. The frequency may vary from 1,300 to 1,600 Hz. This AC power may be converted to DC power and later re-converted via inverters into AC power at 240 or 480V and 50 or 60 Hz [1].



Source: California Energy Commission

Figure 4.1: Recuperated Microturbine Systems

Microturbine generators can be divided into two general classes: (i) Recuperated microturbines, that recover the heat from the exhaust gas to boost the temperature of combustion and increase efficiency; and (ii) Unrecuperated (or simple cycle) microturbines, which have lower efficiencies, but also lower capital costs [2]. While some early product introduced in the market have featured unrecuperated designs, the bulk of developers' efforts are focused on recuperated systems. The recuperator recovers heat from the exhaust gas in order to boost the temperature of the air stream supplied to the combustor. Further exhaust heat recovery can be used in a cogeneration configuration. The figure below illustrates a recuperated microturbine system.

In the recuperated microturbine systems, units are air cooled, with air brought in through an inlet to cool the generator set. The air is then compressed before it is ducted through the regenerator into the combustion chamber. Once the air is compressed, it is sent to the recuperator to raise its temperature, passing to the combustion chamber, and mixing with fuel. Ignition of the mixture creates the combustion gases that enter the turbine, making it rotate. The gases leave the turbine at 1,100°F and return to the recuperator, which transfers a large fraction of the heat to the compressed air before the compressed air enters the combustion chamber. Exhaust gases at 450°F may be sent to a heat exchanger in order to heat water for industrial, commercial, and residential purposes, as well as for the production of steam.

Table 4.1: Microturbine Characteristics

	Recuperated Microturbines			Unrecuperated Microturbines		
	Present	2005	2010	Present	2005	2010
Capacity	25 - 500kW	25 - 500kW	25 - 1000kW	25 - 500kW	25 - 500kW	25 - 1000kW
Initial costs ($/kW)	750-900	500-700	400-600	600-720	400-560	320-480
Non-fuel O&M costs (c/kWh)	0.5-1.0	0.3-0.5	0.1-0.2	0.5-1.0	0.3-0.5	0.1-0.2
Efficiency	30%	33-36%	38-42%	17%	20-23%	23-30%
Physical	50 kW – microturbine L x W x H = 42″ x 32″ x 28″ Weight = 375 lb			250 kW - microturbine L x W x H = 25″ x 40″ x 38″ Weight = 475 lb		
Life	40,000 operating hours					
Emission	NO_X: 0.44 lb/MWh; SO_2: 0.008 lb/MWh; CO_2: 1,596 lb/MWh; PM-10: 0.09 lb/MWh					
Applications	Backup power; premium power; stand-by power; power quality and reliability; peak shaving; and cogeneration applications.					

Commercially available Size:

Microturbines come in a wide range of commercially available sizes from 25kW to 500MW.

Costs:

Presently, capital costs of recuperated microturbines are roughly $750-$900/kW, and $600-$720/kW for unrecuperated turbines. The non-fuel O&M costs are $0.005-$0.010/kW for both types. These costs are expected to be lowered in 2005 and 2010. [3]

Efficiency:

Unrecuperated microturbine efficiency is approximately 17%, in comparison with 30% efficiency for recuperated turbines. Efficiency can be as high as 85% with heat recovery option. [2]

Dimensions and Weights:

To get an idea about the physical characteristics of typical microturbines, dimensions and weights of 50 kW and 250 kW microturbines [1] are shown as examples below.

i.e. 50 kW - microturbine

L x W x H = 42″ x 32″ x 28″

Weight = 375 lb .

i.e. 250 kW - microturbine

L x W x H = 25″ x 40″ x 38″

Weight = 475 lb

Typical lifetime:

Microturbines have a life span of approximately 40,000 operating hours.

Emissions:

Emission rates (NO_X, SO_2, PM-10, CO_2, and CO) for recuperated microturbine are listed below:

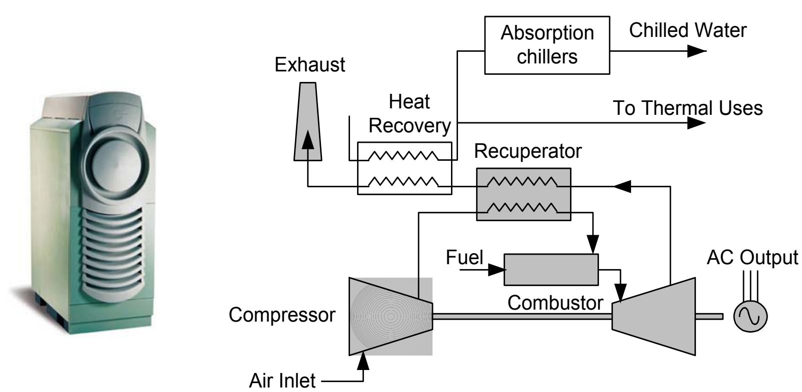
Table 4.2: Emissions from Microturbines

Emission Rates	Recuperated Microturbine
NO_X (lb/MWh)	0.44
SO_2 (lb/MWh)	0.008
PM-10 (lb/MWh)	0.09
CO_2 (lb/MWh)	1,596
CO (lb/MWh)	1.2

Source: [4]

Applications:

Microturbines can be used for stand-by power, power quality and reliability, peak shaving, and cogeneration applications. In addition, because microturbines are being developed to utilize a variety of fuels, they are increasingly used for resource recovery and landfill gas applications. They are well suited for small commercial building establishments such as: restaurants, hotels/motels, small offices, retail stores, and many others. The development of microturbine technology for transportation applications is also in progress. Cogeneration is an option in many cases where a microturbine is located at the point-of-power utilization. The combined thermal electrical efficiency of microturbines in such cogeneration applications can reach as high as 85% depending on the heat process requirements. [1]



Heat recovery added costs = $75 - $350/kW

Figure 4.2: Microturbine in CHP Application

References:

[1] Jorge Gutierrez-Vera, "Mini Cogeneration Schemes in Mexico". Article based on a presentation made during a 2000 IEEE PES Winter Meeting panel session on "Impact of New Technology on Asian Power Generation, Transmission, and Distribution Development in the Twenty-First Century".

[2] California Energy Commission, www.energy.ca.gov/distgen, as of Dec 2002.

[3] Arthur D Little, Opportunities for Micropower and Fuel Cell/Gas Turbine Hybrid Systems in Industrial Applications, Final Report to Lockheed Martin Energy Research Corporation and the DOE Office of Industrial Technologies, January, 2000.

[4] Regulatory Assistance Project (RAP), website: http://www.rapmaine.org/ DGEmissionsMay2001.PDF, as of Dec 2002.

Combustion Turbines

Natural gas-fired combustion turbines are the most widely adopted and very mature technology for grid-connected power generation worldwide. Gas turbines consist of a compressor, combustor, and turbine-generator assembly as shown in Figure 5.1.

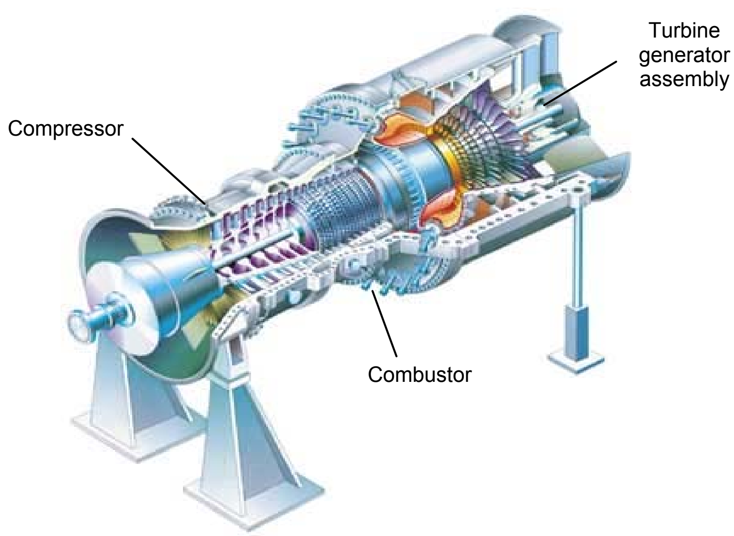


Figure 5.1: Gas Turbine Cross-Section
Ansaldo Energia - V94.3A 260MW Class

The simple-cycle gas turbines are based on the thermodynamics of the Brayton cycle, which works as follow: Air is drawn into the compressor and is compressed to very high pressure. The compressed air is then passed to the combustor, where the compressed air is heated via fuel combustion under constant pressure conditions. The heated air-fuel mixture is allowed to expand through a turbine to perform work, rotating the turbine blades, thus producing electrical power. The exhaust gases subsequently are discharged to the atmosphere. Lower heating value (LHV) efficiencies for this design (compressor, combustor, turbine) range from 18-35% [1]. Like the microturbine, the turbine efficiency can be enhanced with recuperation. The thermal energy from the exhaust gas flow is used to heat the compressed air, thus gaining more work out of the fuel. Table 5.1 summarizes general characteristics of combustion turbines.

Table 5.1: Gas Turbine Characteristics

Feature	Present	Future Development
Capacity	500kW – 25MW	-
Initial costs ($/kW)	$300-$1000/kW add $100-$200/kW with heat recovery	10% reduction in costs
Non-fuel O&M costs (c$/kWh)	$0.005-0.007/kWh	
Efficiency	20 – 45%	Up to 60%
Life	20-25 years	-
Emission	For medium GT: NO_X: 0.61 lb/MWh; SO_2: 0.007 lb/MWh; CO_2: 1,327 lb/MWh; PM-10: 0.07 lb/MWh; it is expected to further reduced NO_X and SO_X emissions.	
Applications	Utility-scale applications, industry, mechanical drives, base load grid-connected power generation, and remote off-grid applications	

Commercially available Gas Turbines:

Combustion Turbines typically range in size from about 500 kW up to 25 MW for distributed generation applications, and up to approximately 250 MW for central power generation.

Costs:

The capital cost of combustion turbines varies from $300 per kW output to $1000 per kW output. It is ultimately to be determined by manufacturers' quotes; however past projects can serve as a guide. Like other technologies, capital cost of combustion turbines reflects economy of scale. Note that Balance of Plant (BOP) equipment costs and other miscellaneous costs can be expected to increase first costs by 30-50%. These costs include control package, fuel supply system, electrical system and attendant power-switching and safety protection features such as grounding, circuit breakers and transfer switches. Adding heat recovery capabilities increases the capital cost by $100-$200/kW. Including other balance-of-plant components, the typical installed cost of a mid-sized gas turbine with a heat recovery unit will be in the $1,000-$1,200/kW range. The DOE Advanced Turbine System (ATS) research and development program is aimed to achieve operating costs of 10-20% lower than conventional power systems in the future.

Efficiency

Simple cycle turbines have efficiencies generally in the range of 20 - 45%. The heavy frame turbines have slightly lower efficiencies (20 - 34%) than the aero derivative turbines (26 - 45%). The range in efficiency values is generally a result of size; the larger the turbine the better the efficiency. Combined cycle turbines can reach efficiencies of up to 55% (LHV). However, these are generally utilized in central power plant arrangements, rather that distributed generation [2]. In 5 to 10 years, one of the objectives of the ATS program is to bring the high efficiencies of the larger turbines into the smaller industrial sizes and break the 60% barrier in net thermal efficiency.

Emissions:

Emission rates (NO_X, SO_2, PM-10, CO_2, and CO) for combustion turbines depend on a particular type and size ranges of turbines, and they also vary from manufacturer to manufacturer. The emission levels for reciprocating engines are listed below:

Table 5.2: Emissions from Gas Turbines

Emission Rates	Small Gas Turbine	Medium Gas Turbine	Large Gas Turbine	Large Gas Combined Cycle
Typical Capacity (MW)	4.6	12.9	70.1	500
NO_X (lb/MWh)	1.15	0.61	0.59	0.06
SO_2 (lb/MWh)	0.008	0.007	0.007	0.004
PM-10 (lb/MWh)	0.08	0.07	0.07	0.04
CO_2 (lb/MWh)	1,494	1,327	1,281	776
CO (lb/MWh)	0.7	0.6	0.6	0.1

Source: [3]

Applications

Combustion turbines are used primarily for power industry. Nearly all new power plants are combined cycle combustion turbines. Smaller versions can be used for DER. Most independent power producers and cogeneration plants use combustion turbines. Small combustion turbines are found in a broad array of applications including mechanical drives, base load grid-connected power generation, and remote off-grid applications. Some cogeneration units are available, but the cogeneration package must be added to the basic turbine.

References:

[1] Anne-Marie Borbely and Jan F. Kreider, Distributed Generation: The Power Paradigm for the New Millennium, 2001.

[2] California Energy Commission, www.energy.ca.gov/distgen, as of Dec 2002.

[3] Regulatory Assistance Project (RAP), website: http://www.rapmaine.org/DGEmissionsMay2001.PDF, as of Dec 2002.

Fuel cells

A fuel cell is an electrochemical energy conversion device that converts hydrogen and oxygen directly into usable electrical energy - with water and heat byproducts – without combustion. Similar to batteries, fuel cells contain electrodes and electrolytic materials to accomplish the electrochemical production of electricity. The fuel cell consists of two electrodes, an anode and a cathode, separated by an electrolyte. Power is produced by the passing of ions formed at one end of the electrodes to the other end, through the electrolyte. The chemical reaction can be represented as following [1]:

Anode: $H_2 + 2OH^- \rightarrow 2H_2O + 2e^-$

Cathode: $2e^- + \frac{1}{2} O_2 + H_2O \rightarrow 2OH^-$

Net reaction: $H_2 + \frac{1}{2} O_2 \rightarrow H_2O$

A typical fuel cell requires both gaseous fuel and oxidants. Due to its high reactivity, hydrogen is the preferred fuel. Hydrocarbon fuels can be supplied, which typically require conversion to hydrogen prior to entering the fuel cell. On the other hand, oxygen is the preferred oxidant because of its availability in the atmosphere.

Fuel cell technologies are of different types, depending on their electrolyte. Some of the different electrolyte types include phosphoric acid (PAFC), molten carbonate (MCFC), solid oxide (SOFC), and proton exchange membrane (PEMFC). Table 6.1 presents a summary comparison of the four primary fuel cell types under serious consideration for distributed power generation.

Table 6.1: Comparison of Different Fuel Cell Technologies

	PAFC	SOFC	MCFC	PEMFC
Electrolyte	Liquid phosphoric acid soaked in a matrix	Solid zirconium oxide to which small amount of yttrium is added	Liquid solution of lithium, sodium and/or potassium carbonates	Solid organic polymer poly-perflouro-sulfonic acid
Size Range	200-250 kW	1 kW - 1MW	250 kW - 1MW	3-250 kW
Fuel	Natural gas, landfill gas, digester gas, propane	Natural gas, hydrogen, landfill gas, fuel oil	Natural gas, hydrogen	Natural gas, hydrogen, propane, diesel
Efficiency	36-42%	45-60%	45-55%	30-40%
Operating Temperature	200 °C	1,000 °C	650 °C	90°C
Other Features	Cogen (hot water)	Cogen (hot water, LP or HP steam)	Cogen (hot water, LP or HP steam)	Cogen (80°C water)

Fuel cell system:

A fuel cell power plant is composed of three subsystems: a fuel-processing section, a power section and a power conditioning section. The fuel processor typically accomplishes the conversion of hydrocarbon fuels to a mixture of hydrogen-rich gases and subsequent removal of contaminants to provide pure hydrogen. This gas is fed into the power section and reacts with oxygen to produce DC current and heat as a byproduct.

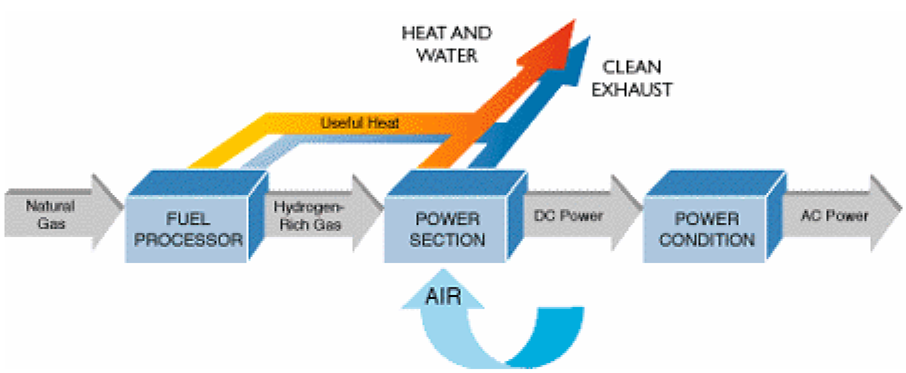


Figure 6.1: Schematic Representation of a Fuel Cell System

In addition to the fuel cell system requirement of a fuel processor for operation on hydrocarbon fuels, a power conditioning or inverter system is needed to convert the DC current to AC current. The power conditioning has two main purposes [2]: adapting the fuel cell output to suit the electrical requirements at the point of power delivery; and providing power to the fuel cell system auxiliaries and controls.

Low-temperature fuel cell technologies such as the phosphoric acid fuel cell (PAFC) and proton exchange membrane fuel cell (PEM) require a fuel-processing unit (reformer) to convert the natural gas into a hydrogen-rich mixture suitable for use in the fuel cell. In contrast, high temperature fuel cells such as the molten carbonate fuel cell (MCFC) or the solid oxide fuel cell (SOFC) do not require a reformer since the high operating temperature of the fuel cell allows for the direct conversion of natural gas to hydrogen.

Table 6.2: Fuel Cell Characteristics

	High T Fuel Cells (MCFC)			Low T Fuel Cells (PAFC)		
	Present	2005	2010	Present	2005	2010
Capacity	N/A	250kW – 10MW	250kW – 10MW	200-250 kW	50-250 kW	50-250 kW
Initial costs ($/kW)	N/A	1,500-2,000	1,200-1,500	2,000-4,000	1,000-2,000	750-1,000
Non-fuel O&M costs (c/kWh)	N/A	1.0-2.0	0.5-1.5	1.5-2.0	1.0-1.75	0.5-1.5
Efficiency	N/A	45-55%	50-60%	30-40%	32-42%	35-45%
Physical	PC25™ (PAFC from UTC fuel cells) Rated electrical capacity: 200kW/235kVA Power module footprint: 120″ x 120″ x 216″ (weight = 40,000 lb) Cooling module footprint: 48″ x 168″ x 48″ (weight = 1,700 lb)					
Life	PAFC = 9,000 hours					
Emissions	PAFC: NO_X: 0.03 lb/MWh; SO_2: 0.006 lb/MWh; CO_2: 1,078 lb/MWh					
Applications	Automotive, residential, commercial, light industrial (250 kW and below), both with and without cogeneration functionality and portable power (several kW and smaller)					

Fuel Cell Capacity

The 200-kW PAFC from United Technology Corporation (UTC) is currently the only fuel cell technology commercialized as a distributed generation product. Many companies plan to commercialize 100-kW PAFC and 50-kW PAFC by 2010. [3]

Cost:

The first cost of fuel cells is very high compared to those of other technologies. Currently, United Technology Corporation manufactures 200-kW PAFC units at a cost of approximately $4000/kW, which is expected to be $1,000/kW by 2010. However, fuel cells are expected to have minimum maintenance requirements. Maintenance costs of a fuel cell are expected to be comparable to that of a microturbine, ranging from $0.015-$0.020/kWh based on an annual inspection visit to the unit. [3]

Efficiency:

The electrical conversion efficiencies of phosphoric acid fuel cell units have been demonstrated in the range of 30-40% [4]. These efficiencies could increase to the 35-45% level in the 2010 timeframe. For PEMFC, it is estimated that the most likely near-term cost-optimized efficiency will be in the 30 - 33% range. On the other hand, high temperature fuel cells are expected to achieve higher efficiency levels - vendor assessments have projected MCFC and SOFC electrical efficiency (LHV) at around 50%.

Dimensions and Weights:

PAFC from UTC fuel cells - PC25™

Rated electrical capacity:	200kW/235kVA
Power module footprint:	120″ x 120″ x 216″ (weight = 40,000 lb)
Cooling module footprint:	48″ x 168″ x 48″ (weight = 1,700 lb)

Source: [5]

Life:

PAFC is expected to have an operating life of approximately 9,000 hours [3]. On the other hand, PEM fuel cells tend to have a short operating life, approximately 5,000 hours. As a result, they are usually operated only at peak load.

Emissions:

Emission rates (NO_X, SO_2, and CO_2) for PAFC are listed below:

Table 6.3: Emissions from Fuel Cells

Emission Rates	PAFC Fuel Cells
NO_X (lb/MWh)	0.03
SO_2 (lb/MWh)	0.006
CO_2 (lb/MWh)	1,078

Source: [6]

Applications:

PAFC fuel cells have been installed at medical, industrial, and commercial facilities throughout the country and the 200-kW size is a good match for distributed generation applications. The operating temperature is about 400°F, which is suitable for co-generation applications. Concerning high temperature fuel cell, potential applications for MCFCs include: industrial, government facilities, universities, and hospitals. On the other hand, SOFC fuel cells are being considered for a wide variety of applications, such as base-load utility applications, residential cogeneration, small commercial buildings and industrial facilities.

Finally, PEM fuel cell technologies are currently being developed for a broad range of applications including: automotive, residential (<10 kW), commercial (10-250kW), light industrial (<250kW) and portable power. As with all fuel cell technologies, the need to reject system heat (in the form of hot water) makes them particularly attractive for cogeneration, which is included in almost all products currently under development [3]. Figure 6.2 shows how fuel cells can be integrated into CHP application.

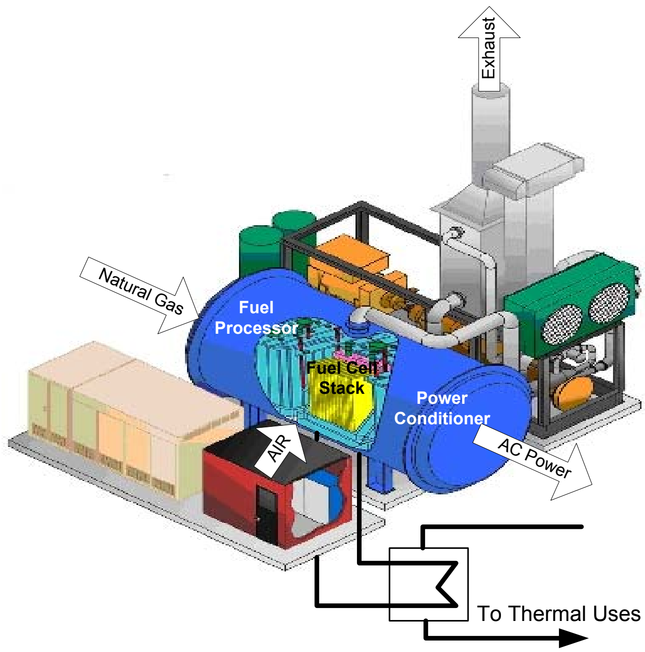


Figure 1: Fuel Cells in CHP Applications

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[1] Anne-Marie Borbely and Jan F. Kreider, Distributed Generation: The Power Paradigm for the New Millennium, 2001.

[2] J.H. Hirschenhofer, D.B. Stauffer, R.R. Engleman, and M.G. Klett, Fuel Cell Handbook, Department of Energy, November 1998.

[3] California Energy Commission, www.energy.ca.gov/distgen, as of Dec 2002.

[4] Arthur D Little, Opportunities for Micropower and Fuel Cell/Gas Turbine Hybrid Systems in Industrial Applications, Final Report to Lockheed Martin Energy Research Corporation and the DOE Office of Industrial Technologies, January, 2000.

[5] UTC Fuel Cells: A United Technologies Company, website: www.utcfuelcells.com/commercial/features.shtml

[6] Regulatory Assistance Project (RAP), website: www.rapmaine.org/DGEmissionsMay2001.PDF, as of Dec 2002.