

Chapter 5B

Distributed Generation and Technologies Matrix

Table 1: Fuel Cell Technology Comparisons

Phosphoric Acid Fuel Cell – Uses liquid phosphoric acid as the electrolyte. Electrodes are made of carbon paper coated with a finely-dispersed platinum catalyst. The catalyst strips electrons off hydrogen-rich fuel at the anode. Positively charged hydrogen ions then migrate through the electrolyte from the anode to the cathode. Electrons generated at the anode travel through an external circuit, providing direct current electric power, and return to the cathode. There, electrons, hydrogen ions and oxygen form clean water, which is discharged from the cell.

Molten Carbonate Fuel Cell – Uses an electrolyte made of lithium-potassium carbonate salts heated to about 1,200°F (650°C). At these temperatures, the salts remain in a molten state that can conduct charged particles, called ions, between two porous electrodes.

Molten carbonate fuel cells eliminate the external fuel processors that lower temperature fuel cells need to extract hydrogen from the fuel. When natural gas is the fuel, methane (the main ingredient of natural gas) and steam are converted into a hydrogen-rich gas inside the fuel cell stack (a process called "internal reforming"). At the anode, hydrogen reacts with the carbonate ions to produce water, carbon dioxide, and electrons. The electrons travel through an external circuit, creating electricity, and return to the cathode. There, oxygen from the air and carbon dioxide recycled from the anode react with the electrons to form carbonate ions that replenish the electrolyte and provide ionic conduction through the electrolyte, completing the circuit.

Solid Oxide Fuel Cell – Composed of all-solid-state materials, the anode, cathode and electrolyte are all made from ceramic substances. Because of the all-ceramic make-up, the cells can operate at temperatures as high as 1,800°F (1000°C). These cells can be configured as either rolled tubes or flat plates, and are manufactured using many of the techniques currently employed in the electronics industry.

Although a variety of oxide combinations have been used for SOFC electrolytes, the most common has been doping zirconia with yttria, which facilitates the transport of oxygen ions. Formed as a crystal lattice, the hard ceramic electrolyte is coated on both sides with specialized porous electrode materials.

At the high operating temperatures, oxygen ions are formed at the "air electrode" (the cathode). When a fuel gas containing hydrogen is passed over the "fuel electrode" (the anode), the oxygen ions migrate through the crystal lattice to oxidize the fuel. Electrons generated at the anode move out through an external circuit, creating electricity. Reforming natural gas or other hydrocarbon fuels to extract the necessary hydrogen can be accomplished within the fuel cell, eliminating the need for an external reformer.

Alkaline Fuel Cell – Alkaline Fuel Cells (AFC) use a solution of potassium hydroxide in water as the electrolyte and can use a variety of non-precious metals as a catalyst at the anode and cathode.

AFCs' high performance is due to the rate at which chemical reactions take place in the cell.

The disadvantage of this fuel cell type is that it is easily poisoned by carbon dioxide (CO₂). In fact, even the small amount of CO₂ in the air can affect this cell's operation, making it necessary to purify both the hydrogen and oxygen used in the cell.

Other disadvantages are the costs and material durability issues. Cost is less of a factor for remote locations such as space or under the sea. However, to effectively in most mainstream commercial markets, these fuel cells will have to become more cost-effective. To be economically viable in large-scale utility applications, fuel cells need to reach operating times exceeding 40,000 hours, something that has not yet been achieved due to material durability issues.

Proton Exchange Membrane Fuel Cell – Polymer electrolyte membrane (PEM) fuel cells—also called proton exchange membrane fuel cells—deliver high power density and offer the advantages of low weight and volume, compared to other fuel cells. PEM fuel cells use a solid polymer as an electrolyte and porous carbon electrodes containing a platinum catalyst. They need only hydrogen, oxygen from the air, and water to operate and do not require corrosive fluids like some fuel cells. They are typically fueled with pure hydrogen supplied from storage tanks or onboard reformers.

Polymer electrolyte membrane fuel cells operate at relatively low temperatures, around 80°C (176°F). Low temperature operation allows them to start quickly (less warm-up time) and results in less wear on system components, resulting in better durability. However, it requires that a noble-metal catalyst (typically platinum) be used to separate the hydrogen's electrons and protons, adding to system cost. The platinum catalyst is also extremely sensitive to CO poisoning, making it necessary to employ an additional reactor to reduce CO in the fuel gas if the hydrogen is derived from an alcohol or hydrocarbon fuel. This also adds cost. Developers are currently exploring platinum/ruthenium catalysts that are more resistant to CO.

PEM fuel cells are used primarily for transportation applications and some stationary applications. Due to their fast startup time, low sensitivity to orientation, and favorable power-to-weight ratio, PEM fuel cells are particularly suitable for use in passenger vehicles, such as cars and buses.

A significant barrier to using these fuel cells in vehicles is hydrogen storage. Most fuel cell vehicles (FCVs) powered by pure hydrogen must store the hydrogen onboard as a compressed gas in pressurized tanks. Due to the low energy density of hydrogen, it is difficult to store enough hydrogen onboard to allow vehicles to travel the same distance as gasoline-powered vehicles before refueling, typically 300-400 miles. Higher-density liquid fuels such as methanol, ethanol, natural gas, liquefied petroleum gas, and gasoline can be used for fuel, but the vehicles must have an onboard fuel processor to reform the methanol to hydrogen. This increases costs and maintenance requirements. The reformer also releases carbon dioxide (a greenhouse gas), though less than that emitted from current gasoline-powered

Direct Methanol Fuel Cell – Most fuel cells are powered by hydrogen, which can be fed to the fuel cell system directly or can be generated within the fuel cell system by reforming hydrogen-rich fuels such as methanol, ethanol, and hydrocarbon fuels. Direct methanol fuel cells (DMFCs), however, are powered by pure methanol, which is mixed with steam and fed directly to the fuel cell anode.

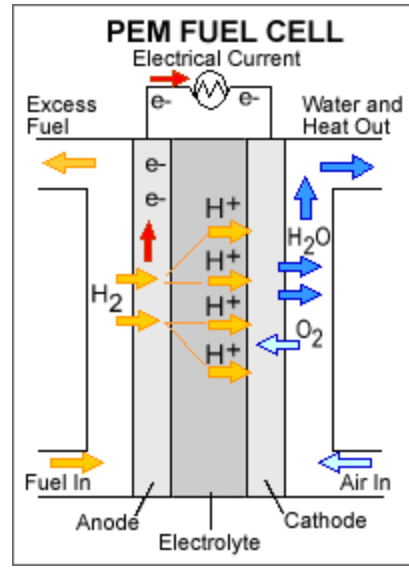
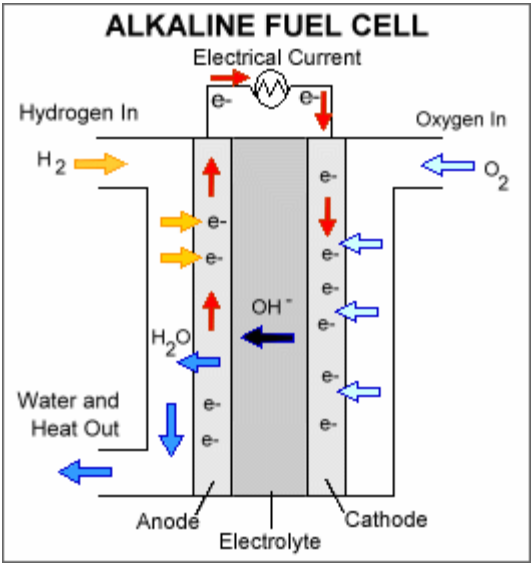
Direct methanol fuel cells do not have many of the fuel storage problems typical of some fuel cells since methanol has a higher energy density than hydrogen—though less than gasoline or diesel fuel. Methanol is also easier to transport and supply to the public using our current infrastructure since it is a liquid, like gasoline.

Direct methanol fuel cell technology is relatively new compared to that of fuel cells powered by pure hydrogen, and DMFC research and development are roughly 3-4 years behind that for other fuel cell types.

Sources: http://www.fossil.energy.gov/programs/powersystems/fuelcells/fuelscells_phosacid.html
http://www.fossil.energy.gov/programs/powersystems/fuelcells/fuelcells_moltencarb.html
http://www.fossil.energy.gov/programs/powersystems/fuelcells/fuelcells_solidoxide.html
http://www.eere.energy.gov/hydrogenandfuelcells/fuelcells/fc_types.html

Gas-Fired Distributed Energy Resource Technology Characterization, NREL/TP-620-34783, November, 2003
http://www.fuelcelltoday.com/FuelCellToday/FCTFiles/FCTArticleFiles/Article_640_SmallStatSurvey0703.pdf
<http://www.fuelcells.org/>

Performance and Cost Trajectories of Clean Distributed Generation Technologies, Nexus Energy Group, May 29, 2002
http://www.eere.energy.gov/hydrogenandfuelcells/fuelcells/fc_types.html



**Table 1: Fuel Cell Technology Comparisons
(Part 1 of 4)**

Technology Type	Fuel Type(s)	Unit Capacity (kW)	Current Status			
			Installed Cost (\$/kW) ¹	Electrical Efficiency (% HHV/LHV) ²	Heat Rate (BTU/kWh)	Net Efficiency (% Electrical + Thermal)
Phosphoric Acid	Hydrogen (external reforming)	50 kW – 1 MW (200 kW typical)	\$4,000/kW – \$4,500/kW	36% – 42%	8,000 – 9,500 BTU/kWh	80% – 85%
Molten Carbonate	Natural gas, propane, LPG, syngas (internal reforming)	<1 kW – 1 MW (250 kW typical)	>\$5,000/kW	50% – 60%	5,700 – 6,800 BTU/kWh	85%
Solid Oxide Fuel Cell	Natural gas, propane, LPG, syngas (internal reforming)	5 kW – 3 MW	\$3,500/kW – \$4,000/kW	50% – 70%	4,900 – 6,800 BTU/kWh	80% – 85%
Alkaline	Hydrogen (external reforming)	10 kW – 100 kW		60% – 70%	4,900 – 5,700 BTU/kWh	NA
Proton Exchange	Hydrogen (external reforming)	<1 kW – 250 kW	\$3,000/kW - \$3,500/kW	50% – 60%	4,900 – 6,800 BTU/kWh	NA
Direct Methanol Fuel Cell	Methanol (internal reforming)	< 1 W – 100 W	NA	NA	NA	NA

Notes: ¹ Installed Costs are “Overnight costs”, and do not include financing costs.
² HHV (higher heating value) is the maximum potential energy released during complete oxidation of a unit of fuel and LHV (lower heating value) is the net energy released during oxidation of a unit of fuel. LHV= HHV- 21.998 (H) - 2.444 (W).

**Table 1: Fuel Cell Technology Comparisons
(Part 2 of 4)**

Technology Type	Current Status					
	Operating Temperature (°Centigrade)	Quantity/Quality of Waste Heat (e.g., lbs./hr steam, at what temperature)	Reactive Power ¹ (Y/N)	In-Rush Capability (kW?)	Fuel Cost (\$/kWh)	Levelized Cost (\$/kWh)
Phosphoric Acid	100 - 200 °C (~ 300 - 400 °F)	Can be converted to steam for space and water heating.	Y ²	Y ³	\$0.035/kWh	NA
Molten Carbonate	600 - 700 °C (1112 - 1292 °F)	Can be used in CHP applications and CC electric power plants.	Y ²	Y ³	\$0.03/kWh	\$0.130/kWh - \$0.173/kWh
Solid Oxide	650 to 1000 °C (1202 to 1832 degrees F)	Can be used in CHP applications and CC electric power plants	Y ²	Y ³	\$0.03/kWh	NA
Alkaline	High temp: 100 - 250°C (212 - 482°F). Low temp: 23 - 70°C (74 -158°F)	NA	Y ²	Y ³	NA	NA
Proton Exchange	50 to 100 °C (122 - 212 °F)	NA	Y ²	Y ³	\$0.04/kWh	\$0.133/kWh - \$0.186/kWh
Direct Methanol	60 to 90 °C	NA	Y ²	Y ³	NA	NA

Notes: ¹ "Reactive Power" is the extent to which this facility type might produce (and/or require) ancillary services, such as Reactive Power.
² In order to provide reactive, power, fuel cells must be integrated with power inverters (that is, devices that convert power from direct current to alternating current), which can be made capable of providing reactive power management functions.
³ In order to provide in-rush capability, fuel cells must be integrated with energy storage (e.g., batteries) of sufficient capacity.

**Table 1: Fuel Cell Technology Comparisons
(Part 3 of 4)**

Technology Type	Projected 2010 ¹			Projected 2024 ¹		
	Installed Cost (\$/kW)	Electrical Efficiency (% LHV)	Levelized Cost (\$/kWh)	Installed Cost (\$/kW)	Electrical Efficiency (% LHV)	Levelized Cost (\$/kWh)
Phosphoric Acid	3,200 – 3,600	36% – 42%	NA	2,500 – 3,000	36% – 42%	NA
Molten Carbonate	> 5,000	50% – 60%	0.097 - 0.115	>5,000	50% – 60%	0.075 - 0.093
Solid Oxide	3,000 – 3,500	50% – 70%	0.096	2,500 –3,000	50% – 70%	0.081
Alkaline	NA	60% – 70%	NA	NA	60% – 70%	NA
Proton Exchange	2,500 - 3,000	50% – 60%	0.101 - 0.138	1,500 - 2,000	50% – 60%	0.076 - 0.096
Direct Methanol	NA	NA	NA	NA	NA	NA

**Table 1: Fuel Cell Technology Comparisons
(Part 4 of 4)**

Technology Type	Applications¹	Technology & Market Challenges¹	Commercial Status / # of Units Deployed¹	Leading Manufacturers¹	Manufacturing Locations¹	Other Comments¹
Phosphoric Acid Fuel Cell	Electric utility support	-Requires expensive (platinum) catalysts -Low current and low power -Large size/footprint -Heavy	Commercial >250 globally	United Technologies (IFC)	Connecticut	None
Molten Carbonate Fuel Cell	-Electric utility support -Large-scale distributed generation -Baseload power	-Durability of cell components is low due to high temperature of operation -Complex electrolyte management -Slow start-up -Poor cycling	Pre-Commercial >50 globally	Fuel Cell Energy	NA	NA
Solid Oxide Fuel Cell	-Auxiliary power -Electric utility support -Large-scale distributed generation Baseload power	-Durability of cell components is low due to high temperature of operation -Slow start-up -Poor cycling	Pre-Commercial >250 globally	-Acumentrics -Fuel Cell Technologies -Siemens -Quantum Fuel Systems (Global Thermoelectric) -Sulzer Hexis -Ceramic Fuel Cells Ltd (CFC) -Solid Oxide Fuel Cell, Company (SOFCo) -Rolls Royce Fuel Cell	Switzerland Australia Ohio Massachusetts	None

Technology Type	Applications¹	Technology & Market Challenges¹	Commercial Status / # of Units Deployed¹	Leading Manufacturers¹	Manufacturing Locations¹	Other Comments¹
Alkaline Fuel Cell	Niche transportation applications, including spacecraft, motorbikes, forklift trucks, marine and submarine applications.	-Operating times not yet maximized due to material durability issues. -Susceptibility to CO ₂ poisoning decreases lifetime. -Low cost effectiveness in commercial markets.	Commercial <50 globally	-Eneco -Apollo Energy Systems -Astris Energi -Hydrocell -Industrial Research -NASA	NA	NA
Proton Exchange Fuel Cell	-Back-up power: telecom, data centers -Portable applications – cell phones, laptops, etc. -Small-scale distributed generation -Vehicles	Hydrogen storage issues.	Commercial >750 globally	-PlugPower -Avista Labs -Ballard -IdaTech -Intelligent Energy -Mitsubishi Heavy Industries -Nuvera -Teledyne -United Technologies (IFC) -Distributed Energy Systems (Proton Energy) -Hydrogenics,	New York Washington Vancouver U.K. Connecticut Ontario Idaho	None
Direct Methanol Fuel Cell	Portable applications – cell phones, laptops, etc.	NA	Not commercial	NA	NA	NA

Table 2: Reciprocating Engine Technology Comparisons

Reciprocating Engines – Most commonly found in cars, trucks, light planes, or even trains. Annual North American production tops 35 million units for cars, trucks, heavy equipment, and a wide variety of power generation applications, from small backup power systems to utility-size units. For power generation, internal combustion (IC) engines benefit from having the lowest first cost, by being easy to start, and by being reliable when properly maintained. IC engines are well suited for standby, peaking, and intermediate power applications, as well as for combined heat and power in commercial, institutional, and light industrial applications of less than 10 MW. These units are also used as Baseload applications at land-fill gas sites. Two main IC engine types are used for power generation – the four-cycle, spark-ignition engine, and the compression-ignition reciprocating engine. To date, reciprocating engines and combined heat and power (CHP) represent the distributed generation (DG) options that have experienced the most significant commercial adoption.

**Table 2: Reciprocating Engine Technology Comparisons
(Part 1 of 6)**

Technology Type - Reciprocating Engine ¹	Unit Capacity (kW)	Current Status					
		Installed Cost (\$/kW) ²	Electrical Efficiency (%, HHV/LHV) ³	Heat Rate (BTU/kWh)	Net Efficiency (%, Electrical + Thermal)	Waste Heat Temperature (degrees Centigrade)	Quantity/Quality of Waste Heat (e.g., lbs./hr steam, at what temperature)
Natural Gas Type 1 Rich Burn 3 Way NSCR (CHP where different)	85 d/	\$1,250 d/	28/31% (29/32%) d/	12,216 (4,704) d/	77% d/	93	Hot Water d/
Natural Gas/Type2 Rich Burn 3 Way NSCR (CHP where different)	100 a/	\$1,126 (\$1,475) ac/	30/33% a/	11,500 (4,879) a/	76% ac/	88 – 99 C a/	Hot Water a/
Natural Gas/Type3 Lean Burn (CHP where different)	1,000	\$787 (1,027) a/	34/38% a/	10,035 (5,394) a/	71a/	88 – 99 C a/	Hot Water a/
Natural Gas/Type4 Lean Burn (CHP where different)	3000 a/	\$776 (1,022) a/	35/39% a/	9,700 (5,599) a/	69% a/	88 – 99 C a/	Hot Water a/
Natural Gas/Type5 Lean Burn (CHP where different)	5000 a/	\$759 (\$973) a/	37/41% a/	9,213 (5,049) a/	73% ac/	88 – 99 C a/	Hot Water a/
Natural Gas/Type6 Lean Burn (CHP where different)	7000	\$750 (\$965) f/	41/45% e/	8,415 (4,839)	74% e/	88 – 99 C e/	Hot Water e/
Notes: ¹ Reciprocating engine generator set (prime power, not standby) ² Installed Costs are “overnight costs” and do not include financing costs. ³ HHV (higher heating value) is the maximum potential energy released during complete oxidation of a unit of fuel and LHV (lower heating value) is the net energy released during oxidation of a unit of fuel. LHV= HHV- 21.998 (H) - 2.444 (W).							

**Table 2: Reciprocating Engine Technology Comparisons
(Part 2 of 6)**

Technology Type - Reciprocating Engine ¹	Current Status					
	Reactive Power (Y/N) ²	Annual Availability (%) ³	Annual Forced Outage Rate ⁴ (%)	Capacity Factor ⁵ (annual average %)	Load Following Capability ⁶	In-Rush Capability (kW?)
Type 1 Rich Burn 3 Way NSCR (CHP where different)	Y/N d/ Synchronous or induction generator models available	92 % d/	4 % d/	92 % b/	Y d/	Y d/
Type 2 Rich Burn 3 Way NSCR (CHP where different)	Y a/	90 – 95% a/	2 – 6 % a/	90 – 95% a/	Y a/	Y a/
Type 3 Lean Burn (CHP where different)	Y a/	90 – 95% a/	2 – 6 % a/	90 – 95% a/	Y a/ But limited d/	Y a/ but limited d/
Type 4 Lean Burn (CHP where different)	Y a/	90 – 95% a/	2 – 6 % a/	90 – 95% a/	Y a/	Y a/
Type 5 Lean Burn (CHP where different)	Y a/	90 – 95% a/	2 – 6 % a/	90 – 95% a/	Y a/	Y a/
Type 6 Lean Burn (CHP where different)	Y e/	92% e/	4 % e/	92% e/	Y e/	Y e/

Notes: 1. Reciprocating engine generator set (prime power, not standby)
2. "Reactive Power" is the extent to which this facility type might produce (and/or require) ancillary services, such as Reactive Power. If other ancillary services are important for this technology, either because it is capable of producing them or it requires them, please describe.
3. Percent of time unit is available, not considering planned outages.
4. Percent of time unit is unavailable due to unplanned outages.
5. Percent of time unit is available due to resource limitations (wind, solar)
6. Can these units follow load increases/decreases.

**Table 2: Reciprocating Engine Technology Comparisons
(Part 3 of 6)**

Technology Type - Reciprocating Engine ¹	Current Status					
	Fuel Cost (\$/kWh)	Fixed O&M Cost (\$/kWh)	Variable O&M Cost (\$/kWh)	Levelized Cost (\$/kWh)	Lead Time: order to install (Months)	Longevity/ Durability (Months)
Type 1 Rich Burn 3 Way NSCR (CHP where different)	\$0.0855 (0.033) d/	\$0.0044 d/	\$0.0110 d/	\$0.111 (0.059) d/	6 months d/	180 months d/
Type 2 Rich Burn 3 Way NSCR (CHP where different)	\$0.081 (0.034) ac/	\$0.003 a/	\$0.017 a/	\$0.109-0.115 (\$0.066 to .073) a/	6 months d/	180 months
Type 3 Lean Burn (CHP where different)	\$0.07 (0.038)ac/	\$0.001 a/	\$0.009 a/	\$0.086-0.090 (\$0.056 to .061) a/	6 to 12 months d/	180 months
Type 4 Lean Burn (CHP where different)	\$0.068(0.039) a/	\$0.0014 a/	\$0.0085 a/	\$0.084 (0.057) a/	12 to 18	180 months d/
Type 5 Lean Burn (CHP where different)	\$0.064 (0.035) ac/	\$0.0011 a/	\$0.0076 a/	\$0.080 (\$0.052) a/	12 to 18	180 months
Type 6 Lean Burn (CHP where different)	\$0.059 (0.034) ec/	\$0.0009 e/	\$0.0066 e/	\$0.073 (\$0.049)e/	12 to 18	180 months
Notes: ¹ Reciprocating engine generator set (prime power, not standby)						

**Table 2: Reciprocating Engine Technology Comparisons
(Part 4 of 6)**

Technology Type - Reciprocating Engine ¹	Current Status – Criteria Emissions (lb/MWh)							
	CO	NO _x	SO _x	PM	PM 10	PM 2.5	Pb	VOCs (non methane)
Type 1 Rich Burn 3 Way NSCR (CHP where different)	Able to meet SCAQMD 2006 ² standards of							
	1.77	0.44	Nil	NA	NA	NA	Nil	.44
Type 2 Rich Burn 3 Way NSCR (CHP where different)	Able to meet SCAQMD 2006 standards of							
	1.77	0.44	Nil	NA	NA	NA	Nil	.44
Type 3 Lean Burn (CHP where different)	Without SCR or oxidation catalyst							
	5.91	2.95	Nil	NA	NA	NA	Nil	2.95
Type 4 Lean Burn (CHP where different)	Without SCR or oxidation catalyst							
	7.38	2.07	Nil	NA	NA	NA	Nil	3.84
Type 5 Lean Burn (CHP where different)	Without SCR or oxidation catalyst							
	7.09	1.48	Nil	NA	NA	NA	Nil	1.48
Type 6 Lean Burn (CHP where different)	Without SCR or oxidation catalyst							
	7.09	1.48	Nil	NA	NA	NA	Nil	1.48
Notes: ¹ Reciprocating engine generator set (prime power, not standby)								
² SCAQMD 2006 – South Coast Air Quality Management District Rule 2006								

**Table 2: Reciprocating Engine Technology Comparisons
(Part 5 of 6)**

Technology Type - Reciprocating Engine ¹	Projected 2010 ¹				Projected 2024 ¹			
	Installed Cost (\$/kW)	Electrical Efficiency (%, LHV)	Availability (%)	Levelized Cost (\$/kWh)	Installed Cost (\$/kW)	Electrical Efficiency (%, LHV)	Availability (%)	Levelized Cost (\$/kWh)
Type 1 Rich Burn 3 Way NSCR (CHP where different)	NA	NA	NA	NA	NA	NA	NA	NA
Type 2 Rich Burn 3 Way NSCR (CHP where different)	\$917	35%	92%	\$0.098	\$834	36%	92%	\$0.094
Type 3 Lean Burn (CHP where different)	\$737	42%	92%	\$0.079	\$703	44%	92%	\$0.075
Type 4 Lean Burn (CHP where different)	\$722	43%	92%	\$0.076	\$689	45%	92%	\$0.073
Type 5 Lean Burn (CHP where different)	\$696	45%	92%	\$0.073	\$649	50%	92%	\$0.067
Type 6 Lean Burn (CHP where different)	NA	NA	NA	NA	NA	NA	NA	NA
Notes: ¹ Reciprocating engine generator set (prime power, not standby)								

**Table 2: Reciprocating Engine Technology Comparisons
(Part 6 of 6)**

Technology Type – Reciprocating Engine ¹	Applications	Technology & Market Challenges	Commercial Status / # of Units Deployed	Leading Manufacturers	Manufacturing Locations	Other Comments
<p>Type 1 Rich Burn 3 Way NSCR (CHP where different)</p>	<p>Most economical in base load CHP application where thermal energy is fully utilized. Hot water output ideal for laundry, washing applications, boiler feedwater heating, and absorption chiller.</p> <p>Multiple units can be teamed together for very high reliability and availability.</p>	<p>Technology is proven. Longer valve life and lower maintenance costs are being developed. Interconnection to utility frequently a hindrance. End users generally prefer to invest in items core to their business instead of power generation.</p>	<p>Commercial About 15 units in the field.</p>	<p>IPower Energy Systems</p>	<p>Indiana</p>	<p>In the future air emissions for these units will be much less than shown above.</p>
<p>Type 2 Rich Burn 3 Way NSCR (CHP where different)</p>	<p>Most economical in base load CHP application where thermal energy is fully utilized. Hot water output ideal for laundry, washing applications, boiler feedwater heating, and absorption chiller.</p> <p>Multiple units can be teamed together for very high reliability and availability.</p>	<p>Technology is proven. Longer valve life and lower maintenance costs are being developed. Interconnection to utility frequently a hindrance. End users generally prefer to invest in items core to their business instead of power generation.</p>	<p>Commercial. Many units in the 60– 120 kW range, primarily CHP applications in the field</p>	<p>Tecogen, IPower Energy Systems, Coast Intelligen</p>	<p>New Jersey, Indiana, Nevada</p>	<p>In the future air emissions for these units will be much less than shown above.</p>

Technology Type – Reciprocating Engine ¹	Applications	Technology & Market Challenges	Commercial Status / # of Units Deployed	Leading Manufacturers	Manufacturing Locations	Other Comments
Type 3 Lean Burn (CHP where different)	Most economical in base load CHP application where thermal energy is fully utilized. Hot water output ideal for laundry, washing applications, boiler feedwater heating, and absorption chiller.	Technology is proven. Interconnection to utility frequently a hindrance. End users generally prefer to invest in items core to their business instead of power generation.	Commercial. Many units in the field.	Northern Power, Jenbacher, Caterpillar, Cummins, Waukesha, Deutz, Major engine/generators or distributors		Urea and ammonia SCR systems for further control of emissions are unwieldy for this size system.
Notes: ¹ Reciprocating engine generator set (prime power, not standby)						

Sources:

- a) L. Goldstein, B. Hedman, D. Knowles, S. I. Freedman, R. Woods., and T. Schweizer, “Gas-Fired Distributed Energy Resource Technology Characterizations”. National Renewable Energy Laboratory, Golden, Colorado. November 2003. (TP-620-34783). Cost data in 2003 dollars escalated to 2006 dollars by 3 percent inflation for three years.
- b) DTE Energy Technologies, Inc. internal data.
- c) Calculated from other data and using natural gas price assumption of \$7.00 per MCF (1,030,000 BTU HHV)
- d) Vendor (IPower Energy Systems, LLC - Anderson, Indiana) provided data.
- e) Wartsila technical specifications (www.wartsila.com), April 2006.
- f) Cost data extrapolated to larger sizes from L. Goldstein, B. Hedman, D. Knowles, S. I. Freedman, R. Woods., and T. Schweizer, “Gas-Fired Distributed Energy Resource Technology Characterizations”. National Renewable Energy Laboratory, Golden, Colorado. November 2003.
- g) Expect data for 7 MW Wartsila Model 34 SG to be similar to 5 MW Wartsila Model 34 SG included in L. Goldstein, B. Hedman, D. Knowles, S. I. Freedman, R. Woods., and T. Schweizer, “Gas-Fired Distributed Energy Resource Technology Characterizations”. National Renewable Energy Laboratory, Golden, Colorado. November 2003. Wartsila technical specifications (www.wartsila.com), April 2006.

Table 3: Stirling Engine Technology Comparisons

Stirling Engine: Stirling engine is typically associated with external combustion piston engines, whose heat-exchange process allows for near-ideal efficiency in conversion of heat into mechanical movement. This occurs by following the Carnot cycle as closely as is practical with given materials. Coupled with an electric generator, a Stirling engine can convert heat into electrical power. Intended applications include use with renewable fuels and to serve distributed stationary power generation applications.

Any temperature difference will power a Stirling engine, so the term "external combustion engine" often applied to it is misleading. A heat source may be the result of combustion but can also be solar, geothermal, or nuclear or even biological. Likewise a "cold source" below the ambient temperature can be used as the temperature difference. A cold source may be the result of a cryogenic fluid or iced water. Since small differential temperatures require large mass flows, parasitic losses in pumping the heating or cooling fluids rise and tend to reduce the efficiency of the cycle.

Because a heat exchanger separates the working gas from the heat source, a wide range of combustion fuels can be used, or the engine can be adapted to run on waste heat from some other process. Since the combustion products do not contact the internal moving parts of the engine, a Stirling engine can run on landfill gas containing siloxanes without the accumulation of silica that damages internal combustion engines running on this fuel. The life of lubricating oil is longer than for internal-combustion engines.

The U.S. Department of Energy in Washington, NASA Glenn Research Center in Cleveland, and Stirling Technology Co. of Kennewick, Wash., are developing a free-piston Stirling converter for a Stirling Radioisotope Generator. This device would use a plutonium source to supply heat.

The potential also exists for nuclear powered Stirling engines in electric power generation plants. Replacing the steam turbines of nuclear power plants with Stirling engines would greatly simplify the plant, yield greater efficiency, and provide a much greater margin of safety, while reducing radioactive by-products.

Some Stirling engine designs require both input and output heat exchangers, which must contain the pressure of the working fluid, and which must resist any corrosive effects due to the heat source. These increase the cost of the engine, especially when they are designed to the high level of "effectiveness" (heat exchanger efficiency) needed for optimizing fuel economy. Fuel economy may not be an issue considering the advantages of using unlimited but unusual fuel sources that are available for a Stirling engine.

Due to heat exchangers, Stirling engines that run on small temperature differentials are quite large for the amount of power that they produce. Increasing the temperature differential allows for smaller Stirling engines that produce more power.

Dissipation of waste heat is especially complicated because the coolant temperature is kept as low as possible to maximize thermal efficiency. This drives up the size of the radiators markedly, which can make packaging difficult. This has been one of the factors limiting the adoption of Stirling engines as automotive prime movers. (Conversely, it is convenient for domestic or business heating systems where combined heat and power (CHP) systems show promise.

A "pure" Stirling engine cannot start instantly; it literally needs to "warm up". This is true of all external combustion engines, but the warm up time may be shorter for Stirlings than for others of this type, such as steam engines. Stirling engines are best used as constant run, constant speed engines. Power output of a Stirling is constant and hard to change rapidly from one level to another. Typically, changes in output are achieved by varying the displacement of the engine (often through use of a swashplate crankshaft arrangement) or by changing the mass of entrained working fluid (generally helium or hydrogen). This property is less of a drawback in hybrid electric propulsion or base load utility generation where a constant power output is actually desirable.

Hydrogen's low molecular weight makes it the best working gas to use in a Stirling engine. As a tiny molecule, however, it is difficult to keep hydrogen inside the engine and, therefore, auxiliary systems usually need to be added to maintain the proper quantity of working fluid. These systems can be as simple as a gas storage bottle or as complicated as a gas generator. In any event, they add weight, increase cost, and introduce some undesirable complications. Some engines use air as the working fluid which is less thermodynamically efficient but avoids loss problems. Most technically advanced Stirling engines like those developed for United States government labs use helium as the working gas, because it functions close to the efficiency of hydrogen with fewer of the material containment issues.

Market Challenges: 1) Spark spread (i.e. cost of natural gas relative to cost of grid electricity) and 2) Market acceptance of new product.

Sources: Dave Miklosi, STM Power, 7/26/06

<http://www.stmpower.com/>

<http://www.whispergen.com/main/acwhispergen/>

<http://www.sunpower.com/>

<http://www.stirlingenergy.com/>

http://en.wikipedia.org/wiki/Stirling_engine

**Table 3: Stirling Engine Technology Comparisons
(Part 1 of 6)**

Technology Type	Unit Capacity (kW)	Current Status					
		Installed Cost (\$/kW) ¹	Electrical Efficiency (% HHV/LHV) ²	Heat Rate (BTU/kWh)	Net Efficiency (% Electrical + Thermal)	Waste Heat Temperature (degrees Centigrade)	Quantity/Quality of Waste Heat (e.g., lbs./hr steam, at what temperature)
Stirling Engine Natural Gas	55	\$1218/kW	29% (LHV)	11,800	80	58 °C	330,000 BTU/hr
Stirling Engine Bio Gas	55	\$1218/kW	29% (LHV)	12,200	78	58 °C	330,000 BTU/hr

Notes: ¹ Installed Costs are “overnight costs” and do not include financing costs.
² HHV (higher heating value) is the maximum potential energy released during complete oxidation of a unit of fuel and LHV (lower heating value) is the net energy released during oxidation of a unit of fuel. LHV= HHV- 21.998 (H) - 2.444 (W).

**Table 3: Stirling Engine Technology Comparisons
(Part 2 of 6)**

Technology Type	Current Status					
	Reactive Power (Y/N) ¹	Annual Availability (%)	Annual Forced Outage Rate (%)	Capacity Factor (annual average %)	Load Following Capability	In-Rush Capability (kW?)
Stirling Engine Natural Gas	Y	95%	5%	NA	N	Y
Stirling Engine Bio- Gas	Y	95%	5%	NA	N	Y

Notes: ¹ “Reactive Power” is the extent to which this facility type might produce (and/or require) ancillary services, such as Reactive Power.

**Table 3: Stirling Engine Technology Comparisons
(Part 3 of 6)**

Technology Type	Current Status						
	Fuel Cost (\$/kWh)	Fixed O&M Cost (\$/kWh)	Variable O&M Cost (\$/kWh)	Levelized Cost (\$/kWh)	Lead Time – order to install (Months)	Longevity/Durability (Months)	Footprint (ft ² /kW)
Stirling Engine Natural Gas	Dependent on installation, project, and region of globe	\$0.008/kWh	None	NA	3	With regular maintenance, no known limit	0.435
Stirling Engine Bio- Gas	If renewable, fuel is usually “free.”	\$0.008/kWh	None	NA	3	With regular maintenance, no known limit	0.435

**Table 3: Stirling Engine Technology Comparisons
(Part 4 of 6)**

Technology Type	Current Status		
	Criteria Emissions ¹	Toxic Emissions	Solid Wastes
Stirling engine Natural Gas	NOX – 1.0 CO – 6.0	None	NA
Stirling engine Bio- Gas	NOX – 1.5 CO – 1.9	None	NA
Notes: ¹ Report residual air emissions, after installation and operation of all expected pollution control equipment, for the following (expressed in lbs./MWh)			

**Table 3: Stirling Engine Technology Comparisons
(Part 5 of 6)**

Technology Type	Projected 2010				Projected 2024			
	Installed Cost (\$/kW)	Electrical Efficiency (% LHV)	Availability (%)	Levelized Cost (\$/kWh)	Installed Cost (\$/kW)	Electrical Efficiency (% LHV)	Availability (%)	Levelized Cost (\$/kWh)
Stirling engine Natural Gas	\$1000/kW	35%	97%	-	\$900/kW	45%	98%	-
Stirling engine Bio- Gas	\$1000/kW	35%	97%	-	\$900/kW	45%	98%	-

**Table 3: Stirling Engine Technology Comparisons
(Part 6 of 6)**

Technology Type/Application	Technology & Market Challenges	Commercial Status / # of Units Deployed	Leading Manufacturers	Manufacturing Locations	Other Comments
Stirling engine Natural Gas – can be used in any area where natural gas is present; rural or urban, if spark spread is agreeable.	<p>Technology Challenges:</p> <ul style="list-style-type: none"> - high cost needed for optimizing fuel economy via heat exchange efficiency. - dissipation of waste heat requires large radiators so difficult to compactly package - cannot start instantly; needs to "warm up" and best used as constant run, constant speed engines. - power output is constant and hard to change rapidly - if using Hydrogen as working fluid adds weight (for storage system), increase costs, and introduce some undesirable complications. Some engines use air as the working fluid which is less thermodynamically efficient but avoids loss problems. <p>Market Challenges:</p> <ul style="list-style-type: none"> - spark spread (i.e. cost of natural gas relative to cost of grid electricity). - market acceptance of new product. 	<ul style="list-style-type: none"> - STM – 20-30 units total - Whisper Gen and Sunpower - Stirling Energy Systems – 500 - MW "SolarOne" project with Southern California Edison will be completed by 2009. 	<ul style="list-style-type: none"> - STM Power - Whisper Gen - Sunpower - Stirling Energy Systems 	Ann Arbor, MI New Zealand United Kingdom Athens, OH	Reflects ONLY data from STM Power
Stirling engine Bio- Gas					

Table 4: Battery Storage Technology Comparisons

Lithium Ion and Lithium Polymer Batteries: Lithium batteries (Li) are near maintenance free, have high cycle capability, do not generate hydrogen under normal operating conditions, and are half the weight and size of sealed lead acid batteries. Smaller versions of Li batteries are used in cell phones and laptop computers. Lithium is unstable in air and in many designs this may pose a risk. Currently the service life is about ½ to ¼ of Nickel Metal Hydride. The high cost, lower service life, and safety issues have limited the commercial use of Lithium in larger applications such as uninterrupted power systems (UPS) and Hybrid vehicles.

Nickel Cadmium Batteries (NiCad): NiCad batteries today come in both vented and sealed versions as well as a variety of plate materials and designs. Though NiCad batteries have been widely used, they are more expensive than Lead Acid batteries. NiCad's batteries cycle better than lead acid, withstand higher temperatures, have a higher energy density, are more predictable, and are more reliable than lead acid batteries. NiCad batteries, however, create environmental issues because the batteries contain cadmium. OSHA labels cadmium as "extremely toxic". Fire in a NiCad battery room can be life threatening because of the possibility of inhaled gases. NiCad batteries also have a memory effect that may be a major problem in UPS applications.

Nickel Metal Hydride Batteries (NiMH): NiMH batteries have been in hybrid vehicles for several years. As with Li Ion, NiCad, and other high end technologies, NiMH technology is more expensive than lead acid batteries. NiMH is attractive relative to lead acid batteries because of its superior cycling capability, better ambient temperature performance, safety, weight, and a smaller footprint. NiMH also out performs lead acid in comparable environment, life testing outcomes. Because of its chemistry, NiMH cell failure is much more predicable than lead acid cell failures. NiMH cells are projected to function for ten years or more and failure is normally indicated by a long warning impedance rise; reliability may equal or exceed that of flooded batteries in many applications. NiMH can electrically discharge at full power to well below half nominal voltage without impacting service life, which allows for a smaller battery when associated with a generator. The battery is non-spillable, and does not have an explosive risk like that associated with lead acid or lithium. NiMH can reduce weight and footprint up to 75 percent when compared to sealed lead acid batteries. Because of their recycling ability, NiMH batteries are an excellent choice to pair with renewable generation applications. When cycled in parallel with a generator, battery can discharge well over 2000 times.

Lead Acid (LA): Lead Acid batteries can be found in a variety of formats. The most widely accepted and used types are high rate discharge rectangular plate "sealed" or "flooded" LA batteries. In both cases lead along with Calcium, Antimony or other alloys, make up the bulk of the plates. Concentrated Sulfuric Acid is the common electrolyte. The charge discharge process involves formation of explosive hydrogen. Air conditioning with these batteries is necessary since service life drops dramatically with rising temperatures. Sizing a lead acid battery to 25% more than the applications need is recommended due to heat related capacity loss.

Flooded Lead acid Batteries (FLA): Flooded batteries also known as vented or wet cell batteries, are usually the first choice for large data centers. These batteries are normally very reliable. They typically are sold with a pro rata warranty of 20 years. FLA batteries are subject to service affecting issues such as seal leaks, case cracks, plate growth, and other events which cause the loss of electrolyte. When loss of electrolyte occurs the results are immediate and catastrophic to the battery system as FLA batteries are usually in a single string configuration and offer no redundancy. Extensive maintenance is a necessity in FLA systems.

Sealed Lead Acid Batteries (SLA): Sealed lead acid, sometimes called recombinant, are readily available. Most common are gelled electrolyte and valve regulated with a design life of five years.

Typical useful life is three to five years. More expensive SLA is available with longer design life. SLA batteries are the product choice for small UPS, low bid, and non critical applications. Their first cost is so low that they significantly outsell FLA batteries. They are typically half the size and weight of FLA's. The largest problem with SLA's is dry out, which causes the loss of an entire string with the failure of one cell. It is also difficult to predict failure with this type of battery. Because of the high failure rate and lack of predictability SLA's should be installed in parallel to provide redundancy and to protect critical applications. Failure rates rise significantly in years four and five of typical SLA batteries. Although expensive, a program of monitoring the batteries should be considered to assure that the batteries' operating conditions are maintained and to help predict the batteries' useful service lives.

Ultracapacitors (UCs): Ultracapacitors (also called ultracaps, supercapacitors, or supercaps) have been an emerging technology for some time. Recently, however, they have become less expensive and field tests have been conducted in hybrid vehicles, rail systems and wind systems. As with many emerging technologies, UC's "first cost" is much higher than lead acid batteries. UC's have high cycling ability without impact to service life, but UC's are negatively affected, and their operating life can be shortened, as a result of exposure to high temperatures (> X°F or Y°C). Standard Warranty is only one year for most manufactures. Cell failure is typically projected at five to ten years; the failure mode is open circuit from electrolyte dry-out which, like SLA's, causes the loss of the entire string. For this reason, UC's are not normally considered for critical applications.

Source: http://mydocs.epri.com/docs/CorporateDocuments/EPRI_Journal/2006-Spring/1013289_storage.pdf