Table 1: Technology Characterization Matrix

Technology	**Stirling Engine**	**Stirling Engine**
Basic Description	The Stirling engine is a heat engine of the external combustion piston engine type whose heat-exchange process allows for near-ideal efficiency in conversion of heat into mechanical movement by following the Carnot cycle as closely as is practically possible with given materials. Coupled with an electric generator, can convert heat into electrical power. Intended for use with renewable fuels to serve distributed stationary power generation applications. Any temperature difference will power a Stirling engine and 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. There is a potential 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 above all, a much greater margin of safety, while reducing radioactive by-products.	
Fuel Type(s)[1]	Natural Gas	Bio-gas
Unit Electrical Capacity (kW, or range of sizes in kW)	55	55

[1] Depending on operating characteristics, it may be necessary to completely separate Technology Type characterizations for at least some of the indicated categories, for the same basic technology using different types of fuel.

Technology		**Stirling Engine**	**Stirling Engine**
CURRENT	**Installed Cost ($/kW)**[2]	$1218/kW (NOTE: DTE questions whether this is a fully installed cost)	$1218/kW (NOTE: DTE questions whether this is a fully installed cost)
	Electrical Efficiency (in %, HHV/LHV)	29% (LHV)	29% (LHV)
	Heat Rate (BTU/kWh)	11,800	12,200
	Net Efficiency (in %, Electrical + Thermal)	80	78
CURRENT	**Waste Heat Temperature (degrees Centigrade)**	58 deg C	58 deg C
	Quantity/Quality of Waste Heat (e.g., lbs./hr steam, at what temperature)	330,000 BTU/hr	330,000 BTU/hr
	Reactive Power[3] **(Y/N)**	Y (NOTE: DTE questions this, as previous units have utilized induction generators)	Y (NOTE: DTE questions this, as previous units have utilized induction generators)
	Annual Availability (%)[4]	95%	95%
	Annual Forced Outage Rate (%)[5]	5%	5%
	Capacity Factor (annual average %)[6]	NA	NA
	Load Following Capability (Y/N)[7]	N	N
	In-Rush Capability (Y/N) [8]	Y	Y
	Fuel Cost ($/kWh)[9]	Dependent on installation and project, region of globe.	If renewable, fuel is usually "free."

[2] Installed Cost assumes no financing cost.
[3] Does the technology provide Reactive Power.
[4] For dispatchable technologies, % of time unit is available, not considering planned outages.
[5] For dispatchable technologies, % of time unit is unavailable due to unplanned outages.
[6] For non-disptachable technologies, % of time units is available due to resource limitations (wind, solar)
[7] Can these units follow load increases/decreases. If yes, provide the rate of change in kW per minute up or down. Describe operating characteristics under "Applications," below.
[8] Does the technology provide In-Rush Capability.
[9] Include ample description of assumptions regarding fuel type and price. Use a range of fuel cost, if necessary, based on variable fuel units.

Technology		Stirling Engine	Stirling Engine
	Fixed O&M Cost ($/kWh)	$0.008/kWh	$0.008/kWh
	Variable O&M Cost ($/kWh)	None	None
	Levelized Cost ($/kWh)		
	Lead Time – order to install (Months)[10]	3	3
	Longevity/Durability (Months)	With regular maintenance and repair, no known limit	With regular maintenance and repair, no known limit
	Footprint (ft^2/kW)	0.435	0.435
	Criteria Emissions (lb/MWh)[11]	NOX – 1.0 CO – 6.0	NOX – 1.5 CO – 1.9
	Toxic Emissions (lb/MWh)[12]	None	None
	Solid Waste, Water Quality Effects[13]	NA	NA
	Employment Effects[14]		
	Economic Multiplier Effects[15]		
	Accidents/Vulnerabilities[16]		
PROJECTED – 2010	Installed Cost ($/kW)	$1000/kW	$1000/kW
	Electrical Efficiency (LHV)	35%	35%
	Availability (%)	97%	97%
	Levelized Cost ($/kWh)	-	-

[10] Provide ample description of issues such as permitting requirements, interconnection process, manufacturing backlog for equipment, etc.
[11] Air emissions of CO, NOx, SOx, PM, PM10, PM2.5, Pb and VOCs.
[12] Air emissions Hg and other HAPs.
[13] Qualitative description of solid wastes and water quality effects.
[14] Employment effects are being estimated for a research project currently underway by Michigan DEQ and NextEnergy.
[15] Economic multiplier information is expected to be available from the analysis being completed by MDEQ/Next Energy.
[16] Include in qualitative discussion at end, under technical/marketing/etc. issues. The purpose of this proposed variable is to capture additional qualitative information about potential accidents or hazards due to natural disaster, human error, terrorist action, etc.

Technology		Stirling Engine	Stirling Engine
PROJECTED – 2024	**Installed Cost ($/kW)**	$900/kW	$900/kW
	Electrical Efficiency (LHV)	45%	45%
	Availability (%)	98%	98%
	Levelized Cost ($/kWh)	-	-
Applications[17]		Any area where natural gas is present; rural or urban, if spark spread is agreeable.	Any source of methane, to include WWTPs, landfills, industrial and agricultural digesters, gasifiers, flare gas and coal bed methane. Any source of gaseous energy that meets minimal criteria.
Technology and Market Challenges		**<u>Technical Challenges</u>** 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 with the advantages of using unlimited but unusual fuel sources that a Stirling engine can make use of. Stirling engines that run on small temperature differentials are quite large for the amount of power that they produce, due to the heat exchangers. 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	

[17] Qualitative discussion of current and potential applications of the technology.

Technology	Stirling Engine	Stirling Engine
	constant power output is actually desirable. Hydrogen's lowest molecular weight makes it the best working gas to use in a Stirling engine, but as a tiny molecule, it is very hard to keep it inside the engine and auxiliary systems need to be typically 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:** Spark spread (i.e. cost of natural gas relative to cost of grid electricity). Market acceptance of new product.	
Commercial Status / # Units in the Field	STM – 20-30 units total Whisper Gen and Sunpower – NA Stirling Energy Systems – 500 MW "SolarOne" project with Southern California Edison will be completed by 2009.	
Leading Manufacturers	STM Power Whisper Gen Sunpower Stirling Energy Systems	
Manufacturing Locations	Ann Arbor, MI New Zealand United Kingdom Athens, OH	
Comments	Boxes shaded in gray reflect ONLY data from STM Power	

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