Arthur D Little

Opportunities for Micropower and Fuel Cell/Gas Turbine Hybrid Systems in Industrial Applications

Volume II: Appendices

Subcontract No. 85X-TA009V

Notice:

Final Report to Lockheed Martin Energy Research Corporation and the DOE Office of Industrial Technologies

January 2000

Arthur D. Little, Inc.
Acorn Park
Cambridge, Massachusetts
02140-2390 U.S.A.

Reference 38410

Table of Contents

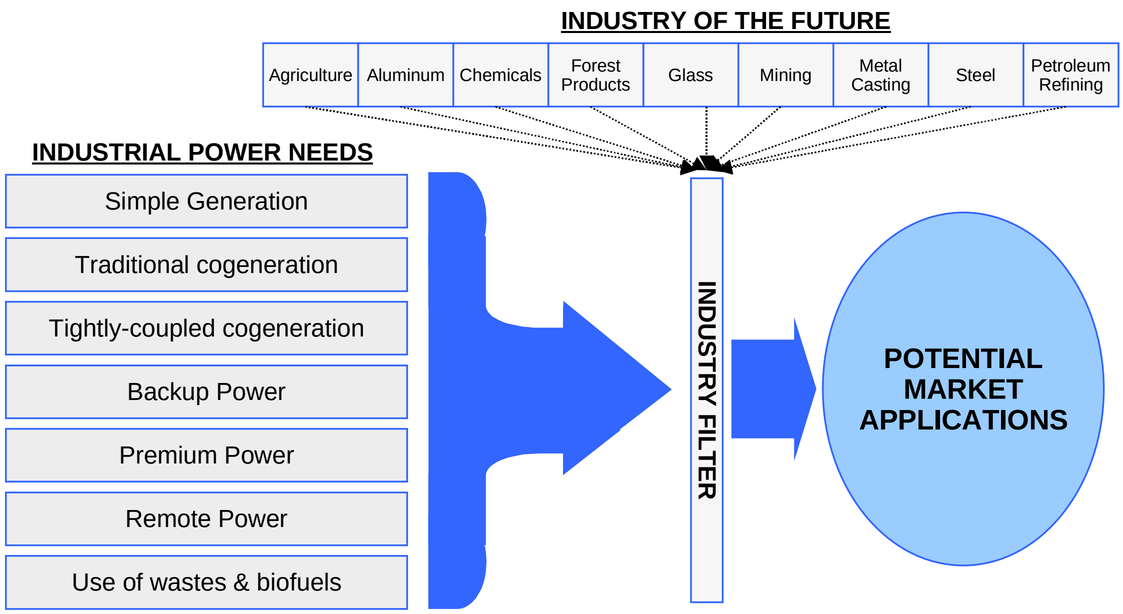
List of Tables

List of Figures

Appendix A: Approach

Quantification of the total market for onsite power generation within the *Industries of the Future* has been estimated through a series of "filters". In the first filter, the market size represented by each of the seven industrial power needs within each industry has been calculated as described in Figure 1.

Figure 1: Analytical Approach Used to Estimate Market Opportunity of Each Industrial Application



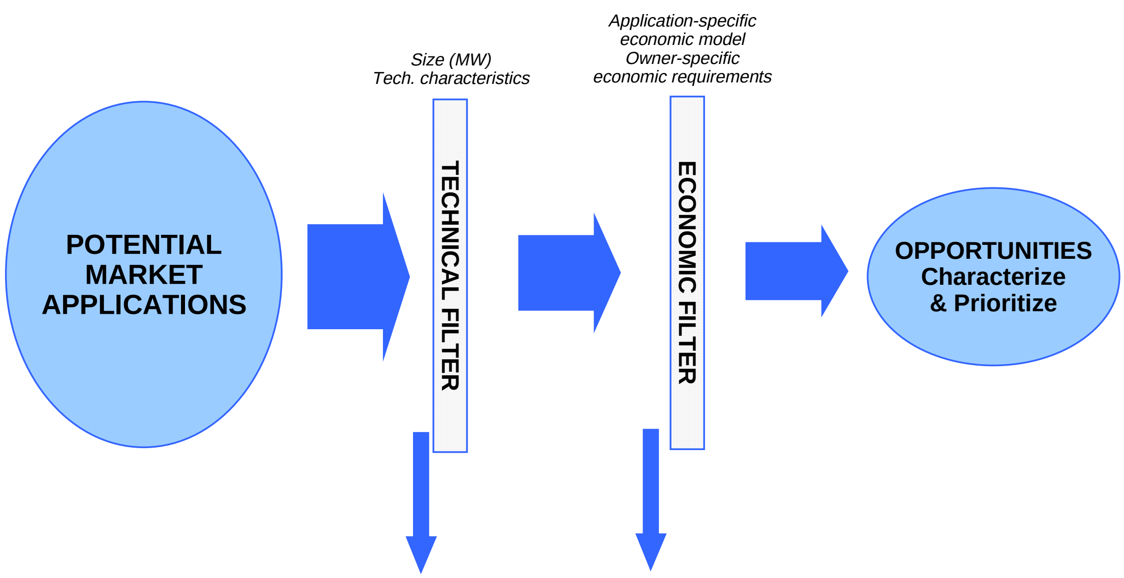
Having estimated these technology-independent market sizes, the market was then passed through a second filter to identify the size of the market that may be met with each of the technologies considered (Figure 2). These technologies are:

- Small reciprocating engines (50 – 300 kW)
- Large reciprocating engines (300 kW – 1 MW)
- Recuperated microturbines (25 kW – 1 MW)
- Unrecuperated microturbines (25 kW – 1 MW)
- Low-temperature fuel cells (PEMFC, PAFC) (50 – 250 kW)
- High-temperature fuel cells (MCFC, SOFC) (250 kW – 1 MW)
- Fuel cell/gas turbine hybrids (250 kW – 20 MW)

This filter is based both upon the technology characteristics and anticipated product sizes (in kW). Market size is reduced at this filter by one of two mechanisms:

- The technology does not meet all the technical requirements of a given industrial application. For example, while the need for cogeneration in the chemicals industry is large, a low-temperature fuel cell with offgas temperatures of 200°C will only be able to meet a small fraction of that need.
- The technology will not be available in a size that meets the full range of facility sizes in which a particular industrial need is expressed. For example, the need for simple generation of power in the aluminum industry is large, but many of these facilities have on-site power demands of over 100 MW, suggesting that micropower technologies under 1 MW will be attractive only in a small fraction of facilities.

Figure 2: Analytical Approach to Determining a Technology-Specific Market Opportunity



The market that remains after this screening is passed through the economic filter. The market that remains represents the maximum *addressable* market that could be served by a particular technology within a particular industry, for a particular application. The technology is capable of meeting both the technical and economic requirements imposed by this market. It should be noted that the *capturable* market that will ultimately be realized by the technology would be further reduced as competing technologies capture market share.

Industries Considered

This analysis considered the nine *Industries of the Future*. However, some of these industries represent broad ranges of SIC codes that in some cases have dramatically different power needs, facility sizes, and/or load profiles.[1] Where these differences were pronounced, Arthur D. Little further segmented the market into multiple industries, as shown in Table 1.

Table 1: Industries Considered in this Study

Industry of the Future	Industry Segments Considered
Agriculture	Food Products
	Textiles
Aluminum	Primary Aluminum
	Aluminum Products
Chemicals	Large Chemicals (top 6 energy consuming industries in SIC code 28)
	Small Chemicals (remaining industries in SIC code 28)
Forest Products	Pulp and Paper mills
	Wood products
Glass	Flat and Blown glass products
Metal Casting	All foundries and die-cast products
Mining	Mineral and coal mining (referred to hereafter as Mining)
	Oil and Gas Exploration/Production
Petroleum	Petroleum Refineries
	Other petroleum (primarily Asphalt)
Steel	Steel Mills
	Steel products

Note that Textiles and Oil and Gas E&P have been added to the list of industries commonly considered as part of the nine *Industries of the Future*. Detailed descriptions of the SIC codes used to define each of these industries are provided in Appendix E.

Additional Parameters Included in the Analysis

In addition to the variability in industrial energy needs suggested by distinct industries, technologies and applications (as described in the following section), four additional parameters have been considered in this analysis. These have been included by virtue of their potential impact on the overall attractiveness of a given technology/industry/ application combination.

1. Year of introduction. Of all of the power generation technologies considered herein only reciprocating engines are mature technology. As such, one may expect there to be significant improvements in cost and performance as the emerging technologies are introduced into the market.

[1] For example, the forest products industry includes 529 pulp and paper mills with an estimated average power demand of 38 MW each, as well as 38,617 wood products facilities (sawmills, furniture factories, etc) with an estimated average size of just 0.2 MW each.

2. Range of Technology Performance. There is some degree of uncertainty in the performance and cost metrics used that represents both manufacturers' range of estimates for future technology performance, and the range of products expected to be available in the market. For each of the three years considered, this range has been used to define the upper and lower bounds of performance and cost.

3. Deregulation of Energy Markets. The ongoing deregulation of domestic electricity and natural gas markets introduces another degree of uncertainty into the analysis. While the pace of deregulation is difficult to predict, the end result will almost certainly be a reduction in energy costs, especially to industrial users. In general, a reduction in electricity costs will decrease the attractiveness of on-site power generation, as purchased grid-power becomes more attractive, while a reduction in gas prices has the opposite effect. The Energy Information Administration's projected electricity and gas prices[2] in a deregulated market have been applied to generate a deregulated scenario for each of the three years in question, assuming the most optimistic technology performance and cost.

4. Ownership. The use of financial models to quantify the economic attractiveness of any particular technology raises the question of who will own the technology, and what will be their payback (or rate of return) expectations. In almost all cases, industrial owners will likely see power generation as beyond their core business, and therefore are likely to have substantially shorter payback horizons than energy services companies, independent power producers, or other dedicated electricity producers that are emerging in the marketplace. Where payback models have been applied, they have been applied over 3 (industrial) and 7 (third-party) year periods to represent each type of potential owner.

Industrial Power Needs and Drivers for Onsite Generation

Unlike the commercial or residential sectors, the industrial need for on-site power generation is often shaped by factors that are much more complex than the potential savings over grid electricity alone. Table 2 shows the 7 dominant industrial needs for onsite power generation, as they have been defined in this study.

[2] From the 1998 Annual Energy Outlook.

Table 2: Industrial Power Applications Considered

Industrial Power Application	Description
Simple Generation	Generation of power only as a substitute for grid power
Traditional Cogeneration	Simultaneous generation of power and heat as steam or hot water
Tightly-Coupled Cogeneration	Simultaneous generation of power and heat as direct process heat
Backup Power	Standby generation capacity used to backup grid power in the event of an outage
Remote Power	Generation of power only at sites that are not connected to the power grid
Premium Power	Generation of power that is of higher quality and/or reliability than grid power
Generation Using Wastes & Biofuels	Generation of power using byproducts of industrial processes that have fuel value

Note: Cogeneration is also called *combined heat and power.* These terms can generally be used interchangeably.

Facility Size Distribution

Census data for some industrial statistics are broken out both by geographic region and over 10 distinct employee size distributions.[3] However, energy consumption is listed only for the industry *in toto*. In order to estimate the distribution of this power demand, the following assumptions have been made:

- Electricity consumption correlates directly with value added by manufacturing. While it is common practice to assume that there is a consistent MW/employee that can be extrapolated across a given industry, there is a danger in such an approach of under-estimating the power demands of highly automated facilities. Value added (which is reported for each employee-size classification) is believed to be a more accurate indicator of the power consumption of a given facility relative to the entire industry.
- All size estimates were assumed to be dispersed uniformly across all states in which a particular industry has facilities.
- All facilities within a given state were assumed to have access to natural gas and electricity at the industrial average rate for that state.

[3] By employee count, the facility data is broken into the following segments: 1-4, 5-9, 10-19, 20-49, 50-99, 100-249, 250-499, 500-999, 1000-2499 and >2500.

Appendix B: Calculation of Economic Fit

For each application, the economic fit of a particular technology has been defined as the percentage of facilities that will find it economically beneficial to use the technology in the specified application. For all applications other than remote power and backup power, this percentage has been defined as the fraction of facilities located in states where the natural gas and electricity rate structures make a given technology/application pairing more attractive than the local grid. For remote power and backup power, the percent of the market that can be captured by a particular technology has been estimated based on competitive cost-of-electricity and capital cost prices respectively.

Fuel and Electric Rates

For all applications except for remote power and generation using wastes & biofuels, the 1998 average industrial fuel and electricity rates were used for all economic models, on a state-specific basis. Regional fuel (natural gas) prices were taken from the DOE/EIA July 1998 *Natural Gas Monthly*, and regional electricity rates were taken from the EIA's form EIA-826, "Monthly Electric Sales and Revenue Report".[4]

Framework for Economic Analysis

Each industrial power application will face a distinct economic hurdle below which it becomes attractive to a particular owner. These needs can be dramatically different, as displayed in Table 3, which summarizes the criteria employed in this study.

Economic Fit

For the bulk of these applications, the economic fit is calculated as the percentage of facilities that are located in states where the local industrial grid-electric price is high enough to justify on-site power production from fuel at local industrial gas prices. As an example, Figure 3 shows recuperated microturbines applied in simple generation within the food products industry, assuming optimistic 2005 technical performance.

In this plot, notice that the number of states with economically attractive energy prices increases as the payback requirement increases from 3 years (industry ownership) to 7 years (third-party ownership). The location and slope of a line of constant payback is a function of the industry-specific load factor[5], and the technology-specific economics (capital cost, efficiency and O&M costs). A given technology can therefore produce power at a price below the price of grid-power in any state located to the *right* of a line of constant-payback.

---

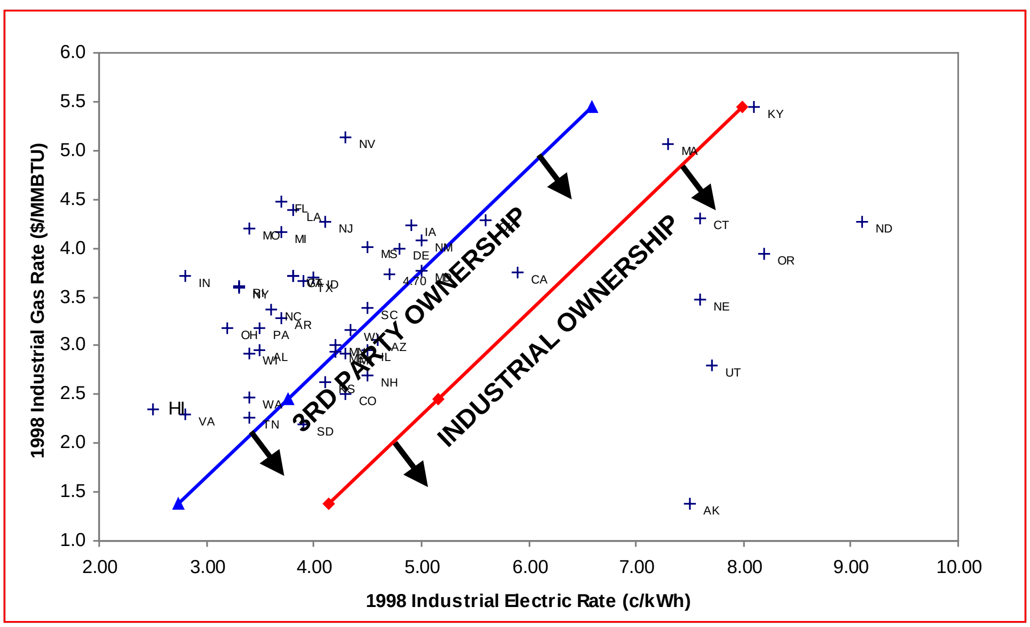
[4] Data on this report is maintained on the Internet at http://www.eia.doe.gov/oiaf/forecasting.html and is updated periodically to estimate the year end average electricity rates before the year has ended. Data used in this study was taken from the site in November of 1998.

[5] Electric load factors were assumed to be the same as plant capacity factors, as reported in the 1994 *Survey of Plant Capacity* (U.S. Census Bureau). For industries including multiple SIC codes, the load factor was calculated as the weighted average of plant capacity factors, weighted by the number of facilities within a particular code.

Table 3: Economic Criteria Applied to Each Application of On-site Power Generation

Operating Mode	Dominant Economic Driver
Simple Generation	Technology must meet criteria imposed by owner-specific payback requirements
Traditional Cogeneration	Technology must meet criteria imposed by owner-specific payback requirements, with revenues based on both thermal and electric energy savings
Tightly-Coupled Cogeneration	Technology must meet criteria imposed by owner-specific payback requirements, with revenues based on both thermal and electric energy savings
Backup Power	Lowest first cost among competing technologies
Premium Power	Technology must meet criteria imposed by owner-specific payback requirements, with produced electricity valued at a 25% premium (the assumed premium for this study)
Remote Power	Lowest levelized cost of electricity among competing technologies (function of fuel costs, capital cost, O&M cost and lifetime)
Generation Using Wastes & Biofuel	Technology must meet criteria imposed by owner-specific payback requirements assuming zero fuel cost

Figure 3: Graphical Representation of Economic Fit Calculation[6]



[6] Gas rates in this plot are from the Energy Information Administration's *Natural Gas Monthly* (July 1998). Electricity rates are from the EIA's *Annual Energy Outlook.*

This analysis assumes that all the facilities in a given state are served by electricity and gas at the rates described in the above figure. By comparing the above plot to the distribution of facilities within a given industry[7], the economic fit of a technology to an application within a particular industry is calculated as the fraction:

$$\frac{\text{Number of facilities in Economically Attractive States}}{\text{Total facilities in the industry}}$$

It should be noted that with smaller facility sizes, electricity and gas prices tend to be considerably higher – often closer to commercial rate structures. Independent of other factors, this tends to improve the economics of a given technology, but one must keep in mind that this is often coupled with a dramatic decrease in load factor.[8] At a load factor of 66%, almost no technologies are competitive by the above analysis. However, if the OIT can identify facilities with commercial rate structures but high load factors, these will be particularly attractive spots for the roll-out of advanced micropower and fuel cell hybrid technologies. Fuel cell hybrids, modeled in this study in unit sizes up to 20MW, would also be able to address the needs of much larger facilities.

Industrial facilities were assumed to be uniformly distributed throughout the country, such that the above percentage can be used interchangeably as the percent of facilities in economically attractive locations *or* the percent of megawatts in economically attractive locations.

This tool was used to calculate the economic viability of technologies used in simple generation, traditional cogeneration, tightly-coupled cogeneration, generation using wastes & biofuels, and premium power applications, as described below.

Simple Generation

The economic fit was calculated as described above.

Traditional Cogeneration

The economic fit was calculated as described above, but the additional cost and value of cogeneration was taken into account. Additional capital costs were assumed to be $150/kW for reciprocating engines (based upon the approximate difference between current, commercially available cogeneration and power-only units), 30% of the base capital cost for microturbines, and $0/kW for all fuel cell technologies.

---

[7] As given by the 1992 Census of Manufacturers (U.S. Census Bureau)

[8] The average load factor used in this analysis is 84%, when weighted by facility size (as measured in kWh). If one assumes that facilities with access to commercial rate structures work only 1-2 shifts per day, then the effective load factor would drop to 33 – 66%.

The 30% multiplier for microturbines was based upon communications with microturbine manufacturers external to this analysis. Note that the implication of cheaper cogeneration systems for unrecuperated engines (which have a lower capital cost) is consistent with the higher temperatures available, which lead to smaller heat exchanger surface areas.

No incremental capital cost was assumed for fuel cell technologies as the production of steam is integral to the operation of all fuel cell packages, which must produce steam in order to reform methane into hydrogen.

In all cases, the fuel savings attributed to cogeneration were calculated with the assumption that the steam generator operates at 80% efficiency (steam energy out/offgas energy in). Within a particular industry, a technology was given credit for cogeneration only if the temperature of the offgases was greater than or equal to temperatures required for industrial processes.[9] (e.g., the high hot water needs of the textiles industry afforded cogeneration opportunities for all technologies, but the high temperature needs of the glass industry afforded none.)

Tightly-Coupled Cogeneration

The economics of tightly-coupled cogeneration were calculated in the same manner as traditional cogeneration. However, no additional capital cost was assumed for this application nor was any efficiency penalty assessed, since offgases can be fed directly into processes.

As with traditional cogeneration, tightly-coupled cogeneration was considered to have an economic benefit only in those industries with needs for direct heating at temperatures that could be provided by the micropower of fuel cell hybrid systems.

Premium Power

Premium power was evaluated in the same manner as simple generation, but the break-even electricity price at which an application was assumed to be economic was assumed to be 25% higher than the price charged by the local grid. This value represents an estimate of the average value that the *Industries of the Future* with premium power needs would place on high quality power.

Generation Using Wastes & Biofuels

The use of wastes and biofuels for power generation occurs in any industry where waste products are produced that may either be sent to a landfill or converted into energy to meet the facility's heat and power needs. (Note that this does not necessarily include all waste production, as some have zero- or low-energy contents, while others are too dirty to justify the legally required exhaust cleanup that would result from incineration.) In

---

[9] As quantified in SERI Report TR-790 (1974).

some industries, there will be a small, non-zero cost associated with this fuel, while in others it may actually have a negative cost, by virtue of avoided tipping fees. In this analysis, the fuel produced was assumed to have zero cost, and applications were considered to be economic only if the cost of power production with a zero-cost fuel was less than the price of grid-electricity.

In the case of liquid and gaseous fuels found in the chemicals, steel mills and some (75%) of the petroleum refining industry, no additional capital cost or efficiency penalty was assessed on the conversion of this fuel into power. For the solid fuels found in the wood products, pulp and paper, textiles, agriculture and some (25%) of the petroleum refining industries, it was assumed that gasification technologies would be required for the conversion of this fuel into power. When used, gasifiers were given a cold gas efficiency of 80%, a capital cost of \$360/kW_{fuel}[10], and an O&M cost of 1 ¢/kWh.

Remote Power

By definition, there is no source of grid-power available in remote locations, so the economic framework used in the other applications cannot be applied here. In general, facilities will opt to generate power on-site if the cost of power production is lower than the cost of a grid extension, which in turn will be a function of the remoteness of the facility. Since this will vary dramatically from one facility to another, this analysis has simply assumed that facilities will opt for the technology that can deliver the lowest levelized cost of electricity.

In each industry with remote power needs (oil and gas E&P, mining, wood products and pulp and paper), industry-specific load factors have been used to calculate the cost of power production given expected technology lifetimes, at a 15% pretax internal rate of return. All fuel cell technologies have been assumed to have a 15-year life, while microturbines and reciprocating engines have been assumed to have a 5-year life in the year 2000, and a 10-year life in years 2005 and 2010. Particularly in the oil and gas E&P industry, small (1-10 MW) gas turbines currently play a dominant role in the production of remote power, and these have therefore been added to the assessment to determine the lowest cost technology.

For most remote industries, operation in locations where the electricity grid is not available is often accompanied by a lack of access to the natural gas grid. As such, fuel prices will be dictated not by the local gas prices, but by the delivered cost of logistics fuels (commonly diesel or propane). The average U.S. industrial price of #2 diesel fuel oil in 1995 was \$5/MMBtu,[11] which was used as an effective fuel price for remote

---

[10] This value was extrapolated from the DOE Report, *Gasification-Based Biomass*, which gives a near-term cost for a gasification system of \$2000/kW_{elec}, with approximately one-half of that cost attributable to the gasifier. At a gross system efficiency of 36%, this equates to a gasifier cost of \$360/kW_{fuel}, or \$12/MMBtu/year.

[11] From the November 1998 Petroleum Marketing Monthly (Energy Information Administration)

power generation in the mining, pulp and paper and wood products industries. In the oil and gas E&P industry, low cost flare gas is commonly available, and the fuel costs were therefore assumed to be just $0.50/MMBtu for remote power generation in this industry.

For reciprocating engines, the use of diesel fuel was assumed to go hand-in-hand with the use of reciprocating engines that are designed for diesel fuel. These engines will conform to a slightly different set of performance metrics, as shown in Table 4.

Table 4: Performance Characteristics for Natural Gas and Diesel Reciprocating Engines

			Installed Cost $/kW		Non-Fuel O&M ¢/kWh		Electric Efficiency LHV	
			High	Low	High	Low	Low	High
NATURAL GAS OPERATION	Large Recips	ca. 2000	600	400	1.5	0.7	28%	37%
		ca. 2005	550	375	1.3	0.6	29%	41%
		ca. 2010	500	350	1.0	0.5	30%	47%
	Small Recips	ca. 2000	750	500	2	1.5	24%	33%
		ca. 2005	700	450	1.7	1.3	25%	35%
		ca. 2010	650	400	1.3	1.0	26%	37%
DIESEL OPERATION	Large Recips	ca. 2000	450	300	2	1.5	34%	42%
		ca. 2005	445	295	1.7	1.3	35%	43%
		ca. 2010	440	290	1.3	1.0	36%	44%
	Small Recips	ca. 2000	600	375	2.5	2.0	27%	39%
		ca. 2005	595	370	2.0	1.7	28%	41%
		ca. 2010	590	365	1.6	1.3	29%	43%

Once the technology costs of electricity have all been identified, the maximum possible market share is defined as:

- All technologies within 5-10% of the lowest cost of electricity are assumed to evenly share 25% of the market.
- All technologies within 5% of the lowest cost of electricity share the remainder of the market.

This splitting of the market was done twice, once for all technologies that will be made in sizes below 250 kW (microturbines, small reciprocating engines and low-temperature fuel cells), and once for all technologies that will be made in sizes above 250 kW (all technologies). The final economic fit was then defined as the total projected market share over all size ranges.

Backup Power

For backup (stand-by) power generation, the low load factors dictate that first cost alone will drive the economic attractiveness of a given technology. The economic fit of a particular technology has been correlated to the installed capital cost of the devices, in the same manner as was used for cost-of-electricity comparisons in remote power applications:

- All technologies within 5-10% of the lowest capital cost are assumed to evenly share 25% of the market.
- All technologies within 5% of the lowest capital cost share the remainder of the market.

As with remote power, this splitting of the market was done twice, once for all technologies that will be made in sizes below 250 kW (microturbines, small reciprocating engines and low-temperature fuel cells), and once for all technologies that will be made in sizes above 250 kW (all technologies). The final economic fit was then defined as the total projected market share over all size ranges.

Appendix C: Calculation of Techno-Economic Fit

Technology Performance

The attractiveness of a given micropower technology in each application for on-site power generation is based upon the ability of the technology to meet the needs imposed by each of these applications. Figure 4, Figure 5, and Figure 6 show how the expected performance of each technology compares to the requirements of each application in 2000, 2005 and 2010.[12]

Figure 4: Technology Performance Characteristics and Technical Fit, year 2000

Technology Operating Requirements	Simple Gen.	Trad. Cogen	Tightly Coupled Cogen	Backup Power	Remote Power	Wastes / Biofuels	Premium Power	M-turbines	Recips	Low T FCs	High T FCs	FC/GT
Rapid Startup	○			●	○			●	●	◒	N/A	N/A
Proven Reliability	●	○	○	●	●	○	●	◒	◒	◒	N/A	N/A
Operation on diesel, propane				●	●			●	●	◒	N/A	N/A
Low O&M requirements	●	○	○	○	○	○	○	●	◒	◒	N/A	N/A
High Temp waste heat		●	●					◒	◒	○	N/A	N/A
Power quality							●	◒	○	◒	N/A	N/A
Production of clean offgas			●					●	◒	●	N/A	N/A
Control over T/E		●	●					◒	◒	◒	N/A	N/A
Operation with Δ fuel comp.						●		●	●	○	N/A	N/A
Operation with dirty fuel						●		●	●	○	N/A	N/A
Operation on solid fuels						●		○	◒	○	N/A	N/A
Operation on low-BTU fuels						●		●	●	◒	N/A	N/A
High turndown***	○				○			◒	●	●	N/A	N/A
Low emissions	●	●	●		○	●	●	◒	○	●	N/A	N/A

● Primary Driver
○ Secondary Driver

● High fit
◒ Moderate fit
○ Low fit

** Includes use of multiple units

---

[12] In the subsequent figures, the requirements of given applications are assumed to be constant over the 2000-2010 timeframe, except for emissions requirements which are assumed to become increasingly strict.

Figure 5: Technology Performance Characteristics and Technical Fit, year 2005

	Simple Gen.	Trad. Cogen	Tightly Coupled Cogen	Backup Power	Remote Power	Wastes / Biofuels	Premium Power	M-turbines	Recips	Low T FCs	High T FCs	FC/GT
Rapid Startup	○			●	○			●	●	◒	○	○
Proven reliability	●	○	○	●	●	○	●	●	◒	●	◒	◒
Operation on diesel, propane				●	●			●	●	◒	◒	◒
Low O&M requirements	●	○	○	○	○	○	○	●	◒	●	◒	○
High Temp waste heat		●	●					◒	◒	○	●	○
Power quality*							●	●	●	●	●	●
Production of clean offgas			●					●	◒	●	●	●
Control over T/E		●	●					◒	◒	◒	◒	●
Operation with Δ fuel comp.						●		●	●	○	◒	◒
Operation with dirty fuel						●		●	●	○	○	○
Operation on solid fuels**						●		◒	◒	◒	◒	◒
Operation on low-BTU fuels						●		●	●	◒	●	●
High turndown***	○				○			◒	●	●	●	●
Low emissions	●	●	●	○	○	●	●	◒	○	●	●	●

● Primary Driver
○ Secondary Driver

● High fit
◒ Moderate fit
○ Low fit

As power electronics costs fall, reciprocating engines may be retrofitted to produce high quality power
* The development of gasification technologies may make all technologies amenable to operation on solid fuels
** Includes use of multiple units

Figure 6: Technology Performance Characteristics and Technical Fit, year 2010

	Simple Gen.	Trad. Cogen	Tightly Coupled Cogen	Backup Power	Remote Power	Wastes / Biofuels	Premium Power	M-turbines	Recips	Low T FCs	High T FCs	FC/GT
Rapid Startup	○			●	○			●	●	◒	○	○
Proven reliability	●	○	○	●	●	○	●	●	◒	●	●	●
Operation on diesel, propane				●	●			●	●	●	●	●
Low O&M requirements	●	○	○	○	○	○	○	●	◒	●	●	◒
High Temp waste heat		●	●					◒	◒	○	●	○
Power quality *							●	●	●	●	●	●
Production of clean offgas			●					●	◒	●	●	●
Control over T/E		●	●					◒	◒	◒	◒	●
Operation with Δ fuel comp.						●		●	●	◒	◒	◒
Operation with dirty fuel						●		●	●	◒	◒	◒
Operation on solid fuels**						●		●	●	●	●	●
Operation on low-BTU fuels						●		●	●	◒	●	●
High turndown***	○				○			◒	●	●	●	●
Low emissions	●	●	●	○	○	●	●	◒	○	●	●	●

● Primary Driver
○ Secondary Driver

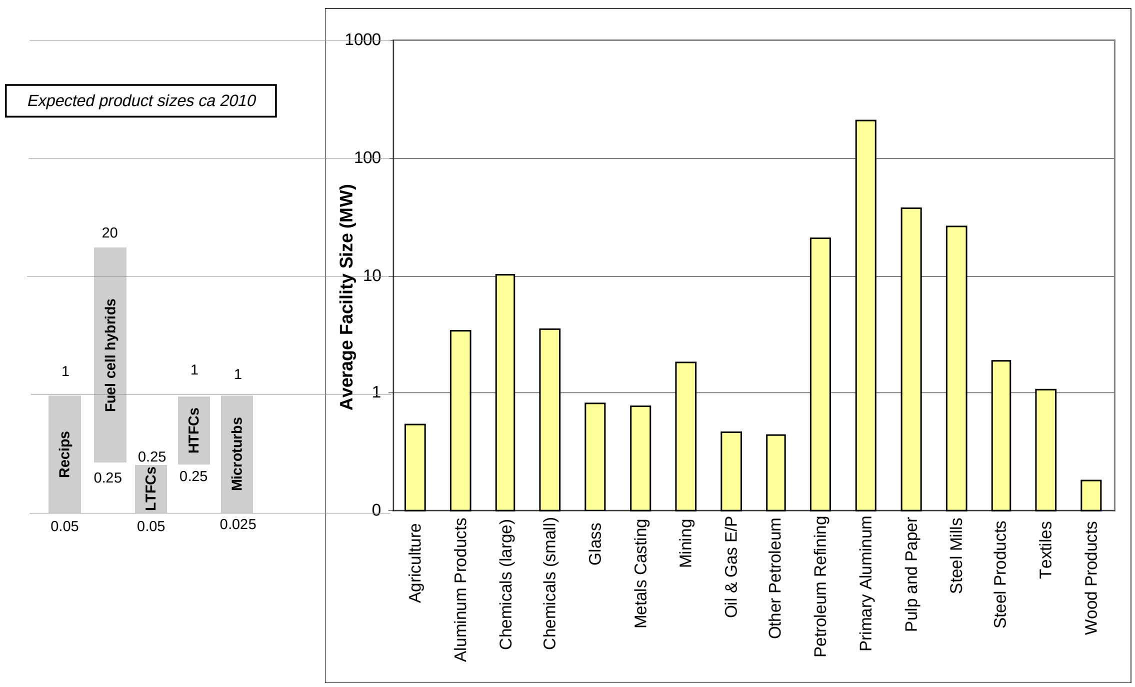
● High fit
◒ Moderate fit
○ Low fit

As power electronics costs fall, reciprocating engines may be retrofitted to produce high quality power
* The development of gasification technologies may make all technologies amenable to operation on solid fuels
** Includes use of multiple units

Technology Sizes

By definition, all the micropower technologies considered within this analysis will be available in unit sizes of 1 MW or less.[13] However, manufacturers are expected to bundle some technologies into multi-unit packages. The implication of this packaging on industrial applications is significant, as it dramatically increases the number of facilities with power needs that match the output of micropower-based systems. Figure 7 shows the range of facility sizes, and how that compares to the single-unit sizes for each technology in year 2010.

Figure 7: Facility Size Variation by Industry



For this analysis, it was assumed that micropower technologies will be packaged in multi-unit systems so long as the resulting package has a lower levelized cost of electricity than comparably sized gas turbines. In years beyond 2000, is was assumed that gas turbine performance will meet the goals of the DOE's Advanced Turbine

[13] This applies to all technologies except fuel cell hybrids. Fuel cell hybrids are expected to be produced in unit sizes up to 20 MW, and have been analyzed accordingly. Both high-temperature fuel cells and reciprocating engines will also be available in larger sizes, but only those units under 1 MW were considered in this analysis.

Systems (ATS) program.[14] Under these assumptions, the likely size ranges of packaged micropower units within each time period are as described in Table 5.

Table 5: Anticipated Technology Package Sizes (MW)

Micropower Technology	2000	2005	2010
Large Recips	0.3 - 10	0.3 – 10	0.3 – 10
Small Recips	0.05 – 1.5	0.05 – 1.5	0.05 – 1.5
Recuperated Microturbines	0.025 – 1	0.025 – 10	0.025 – 10
Unrecuperated Microturbines	0.025 – 1	0.025 – 5	0.025 – 10
Low Temperature Fuel Cells	0.2 – 1	0.05 – 3	0.05 – 10
High Temperature Fuel Cells	Not available	0.25 – 5	0.25 – 10
Fuel Cell Hybrids	Not available	3 – 5	0.25 - 40

Technical Fit

Each technology will have a different technical "fit" within each of the seven industrial power applications identified. The ability of each technology to meet the criteria imposed by a given application is expected to change with time as the technologies mature. The rankings shown in Figure 8 and Figure 9 summarize the technical fits of each technology in each application for the years 2000 and 2010.

[14] The ATS program is targeting a 10% reduction in levelized electricity costs by 2010. Gas turbine costs of electricity have been calculated using data from the 1997 Gas Turbine World Handbook for the year 2000. This value was reduced by 5% in 2005, and by an additional 5% in 2010.

Figure 8: Year 2000 Technology Fits by Application

		Micro-turbines	Recips	Low Temp Fuel Cells	High Temp Fuel Cells	Fuel Cell Hybrids
Simple Generation		High fit	High fit	High fit	NA	NA
Traditional Cogen		Moderate Fit	Moderate Fit	Moderate Fit	NA	NA
Tightly-Coupled Cogen		High fit	Moderate Fit	Low Fit	NA	NA
Backup Power		High fit	High fit	Low Fit	NA	NA
Remote Power		High fit	High fit	Moderate Fit	NA	NA
Generation Using Wastes & Biofuels		Low Fit	Moderate Fit	Low Fit	NA	NA
Premium Power	Power quality	Moderate Fit	Moderate Fit	High fit	NA	NA
Premium Power	Power reliability	High fit	High fit	High fit	NA	NA

High fit | Moderate Fit | Low Fit

Figure 9: Year 2010 Technology Fits by Application

		Micro-turbines	Recips	Low Temp Fuel Cells	High Temp Fuel Cells	Fuel Cell Hybrids
Simple Generation		High fit	High fit	High fit	High fit (orange)	High fit (orange)
Traditional Cogen		High fit (orange)	Moderate Fit	Moderate Fit	High fit (orange)	Moderate Fit (orange)
Tightly-Coupled Cogen		High fit	Moderate Fit	Moderate Fit (orange)	High fit (orange)	Moderate Fit (orange)
Backup Power		High fit	High fit	Moderate Fit (orange)	Low Fit	Low Fit
Remote Power		High fit	High fit	High fit (orange)	High fit (orange)	High fit (orange)
Generation Using Wastes & Biofuels		High fit (orange)	High fit (orange)	Moderate Fit (orange)	Moderate Fit (orange)	Moderate Fit (orange)
Premium Power	Power quality	High fit (orange)	High fit (orange)	High fit	High fit (orange)	High fit (orange)
Premium Power	Power reliability	High fit	High fit	High fit	High fit (orange)	High fit (orange)

High fit | Moderate Fit | Low Fit

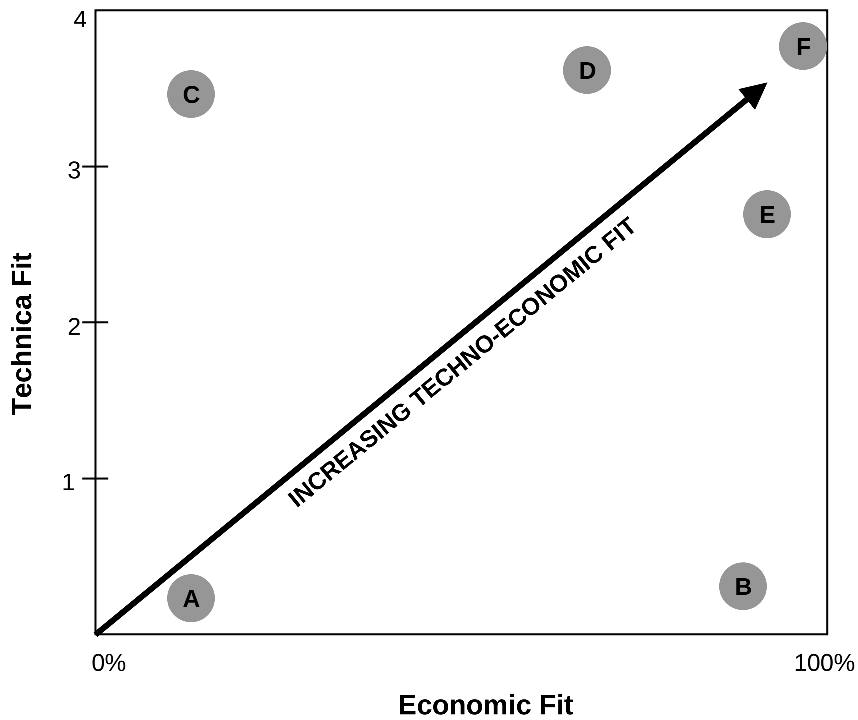
Techno-Economic Fit

Ultimately, the overall fit of a technology in a given application will be a function of both the technical fit and economics within a particularly industry/application. In this analysis, these two metrics have been combined into a single "techno-economic fit", that defines the overall fit of a technology in a particular industrial application. Figure 10 is a simplified example of an industry with six distinct technology/application pairs.

Recognizing the approximate nature of the qualitative technical descriptions, the technical fit is quantified as a simple 1-4 score. The economic fit is also approximate, and is represented as the percentage of the total market for a given application/industry pair that will find a technology economically attractive.

In the example, technology "A" is the least attractive, while technology "F" is most attractive. In contrast, although technologies "B" and "C" each score very high on one axis, they are less attractive than technologies "D" and "E".

Figure 10: Sample Technical-Economic Fit Map



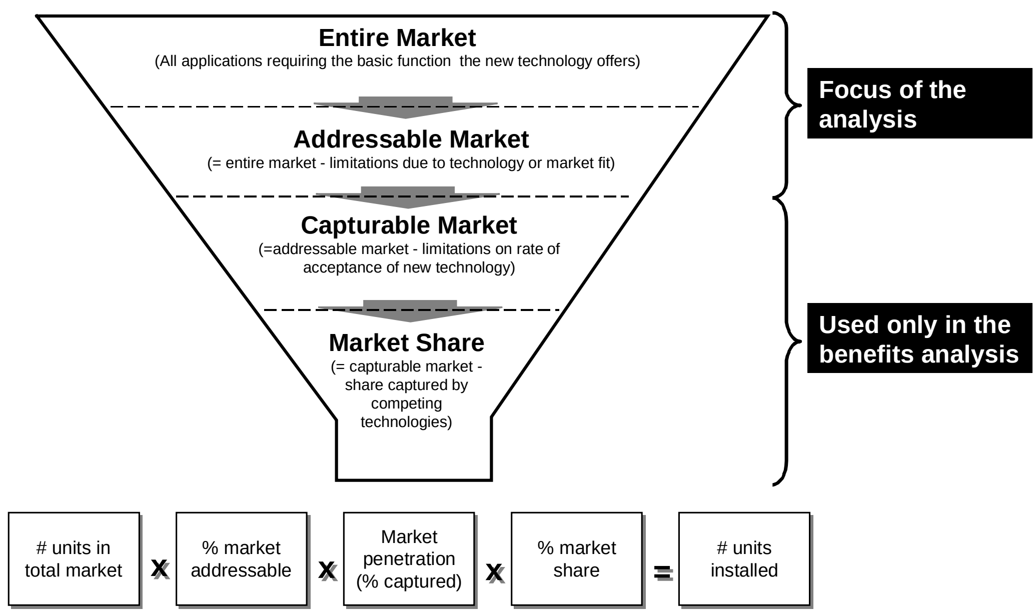
It is somewhat more difficult to discern the attractiveness of "D" relative to "E". While D is more technically attractive, E is more economically attractive, but neither appears to be a clear winner over the other. To address this, this study has defined a *techno-economic fit* that captures both axes of the above plot into a single dimensionless value to describe the overall attractiveness of a given industry/application/technology combination. The techno-economic fit is calculated as the product of the technical and economic fits. While this number has no physical meaning, it provides a useful tool with which to compare competing technologies. In this context, F will still be the most attractive technology, followed by D and E (which will be equivalently attractive), followed by B and C (which will also be equivalently attractive).

Appendix D: Quantification of the Market Opportunity

The market size estimates used in this analysis were determined first by quantifying the maximum potential market for a given application within a particular industry, the so-called *entire market*. Note that this number may be higher than the actual currently installed capacity for a given application within an industry. This value was then screened down to a maximum *addressable market*, which represents the total number of MW that could be produced by a particular technology. Note that while the *entire market* describes an industry and application only, the *addressable market* describes the portion of the potential market that can be served by a specific technology.

The addressable market value was used to identify the market opportunities associated with each technology/application combination. However, assessing the expected market as calculated in the national benefits analysis required an additional quantification of the actual *market share* that can be *captured* by any given technology in a competitive environment. While this was not the focus of the analysis, it was done to eliminate double counting of benefits. Figure 11 illustrates the relationship between these different market definitions.

Figure 11: Market Size Estimating Methodology



Potential Market Size Estimates

The *entire market* for each application within each industry was evaluated from U.S. Census data along with ADL estimates where necessary. Detailed explanations of the market sizes for each application are described below. The values used in all market penetration estimations were as described below. For national benefits assessments, all markets were assumed to grow (from a 1994 base year) at 2% per year.

Simple Generation

Annual electricity consumption in million kWh was taken from the *1994 Manufactures Consumption of Energy Survey* (MCES). Electric load factors were assumed to be equal to plant capacity factors, as reported in the 1996 *Annual Survey of Manufactures* (ASM), and peak/base load ratios were assumed to be equal to the inverse of the load factor. These values were then used to directly convert kWh into MW of power generation equipment that could potentially be located onsite.

Traditional Cogeneration

For each industry, detailed data from the 1994 MCES on energy consumption by type and end-use (process heating, electricity production, etc.) were compiled to estimate an industry-specific thermal/electric ratio. Data from SERI Report TR-790 was then used to estimate the fraction of heat used in a given industry as steam or hot water. The maximum potential market for cogeneration (measured in electric MW) was then assumed to be the smaller of:

a) The facility-specific MW calculated for simple generation multiplied by the industry T/E ratio, multiplied by the fraction of thermal use as steam or hot water
b) The facility-specific MW as calculated for simple generation

Tightly-Coupled Cogeneration

This was calculated in the same manner as traditional cogeneration , but rather than multiplying by the fraction of heat used as steam or hot water, the (MW_{elec}) x (T/E ratio) was multiplied by the fraction of heat used as direct heat or heated gas.

Backup Power

Very little data is readily available on industrial purchases of power generation equipment for backup power. Conversations with the Electric Power Research Institute have indicated that many utilities are now initiating such studies in response to competitive pressures. In the absence of such data, estimates were made of the fraction of power demand within each industry that is likely to be installed as backup power, is summarized Table 6.

Remote Power

Data on this application are also not widely available. Again estimates of the fraction of the total power demand that can be described as remote power were made based on ADL expertise, as shown in Table 7.

Table 6: Estimated Demand for Backup Power Generation Equipment

Industry	Dominant backup power needs	Assumed backup %
Food Products	Shutdown, maintenance of sterility	5%
Primary Aluminum	Shutdown, extraction processes	30%
Aluminum Products	Shutdown	5%
Chemicals	Shutdown, pumps, compressors	30%
Glass	Shutdown, float glass, maintaining molten glass	10%
Metal Casting	Shutdown	5%
Mining	Shutdown, safety, pumping	10%
Oil and Gas E/P	Redundant equipment for remote power backup	30%
Petroleum refining	Shutdown, pumps, compressors	30%
Other petroleum	Shutdown	5%
Pulp and Paper	Shutdown, pumps, compressors, motors	30%
Steel Mills	Shutdown, pumps	10%
Steel Products	Shutdown	5%
Textiles	Shutdown	5%
Wood Products	Shutdown	5%

Table 7: Estimated Demand for Remote Power Generation Equipment

Industry	Assumed remote %
Food Products	-
Primary Aluminum	-
Aluminum Products	-
ChemicalS	-
Glass	-
Metal Casting	-
Mining	20%
Oil and Gas E/P	90%
Petroleum refining	-
Pulp and Paper	5%
Steel Mills	-
Steel Products	-
Textiles	-
Wood Products	10%

Premium Power

Data on this application are also not widely available. Again, estimates were made based upon ADL expertise, as shown in Table 8.

Table 8: Estimated Demand for Premium Power Generation Equipment

Industry	Dominant premium power needs	Assumed premium %
Food Products		0%
Primary Aluminum	Controls (UPS)	1%
Aluminum Products	Controls (UPS)	5%
Chemicals	Controls (UPS)	1%
Glass	Controls (UPS)	1%
Metal Casting		0%
Mining	Safety	1%
Oil and Gas E/P	Safety	1%
Petroleum refining	Controls (UPS)	1%
Other petroleum		0%
Pulp and Paper	Controls (UPS), DC drives	5%
Steel Mills	Controls (UPS), avoided grid penalties (EAF)	5%
Steel Products	Controls (UPS)	1%
Textiles	Controls (UPS), DC drives	1%
Wood Products		0%

Wastes and Biofuels

Consumption of non-traditional fuels is listed in the MCES report as "Other fuel", "End use not reported". For each industry, the maximum market for electricity generation from these fuels was assumed to be equal to the amount of electricity that could be cogenerated from a system with 70% electrical generating efficiency[15] and 85% boiler efficiency. Output was adjusted accordingly to ensure that neither the thermal nor electrical load exceeded that of the industry. The values used are listed in Table 9.

[15] The efficiency of the most efficient technology considered in this analysis, a fuel cell/gas turbine hybrid.

Table 9: Markets for Power Production from Wastes & Biofuels

	Waste Fuel Use* (trillion Btu/yr)	Estimated Electricity Potential (MW)	Estimated Thermal Potential (MW)
Food Products	136	4,100	1,490
Large Chemicals	449	12,020	4,380
Small Chemicals	0	0	0
Metal Casting	28	60	930
Petroleum Refining	2,161	4,540	60,830
Pulp & Paper	1,343	19,490	22,290
Steel Mills	1,118	2,690	31,890
Steel Products	1	0	0
Textiles	14	420	150
Wood Products	290	870	9,220
Total	**5,540**	**44,190**	**131,210**

* As reported in the *1994 Manufacturing Consumption of Energy Survey (U.S. Census). Consumption of waste fuel for cogeneration extrapolated from industry T/E ratios.*

Addressable Market Estimates

Using the *entire market* as a starting point, the *addressable market* is then defined as that portion of the total market that can be met by a particular technology.

The first step in this calculation is the determination of the fraction of the *entire market* that can be served by a technology of a fixed kW output.[16] For power-only applications, this is based on the distribution of facility sizes within the industry and the assumed maximum package size of the technology. For cogeneration applications, the efficiency of the technology is also taken into account to calculate the power which could be produced by units that are sized appropriately to meet a facility's thermal load.

The final step is a calculation of the percentage of this appropriately sized market that will find it economically attractive to use a particular technology. In this case, the appropriately sized market was multiplied by the economic fit (as defined in Appendix C) to yield the *addressable market*.

[16] This has been defined as a range representing the likely sizes of packaged micropower systems, as described in Appendix C.

Market Penetration Estimates

The market that can ultimately be realized will be a still smaller fraction of the addressable market, as the addressable market will be divided amongst all competing technologies. Below are outlined the steps taken by to calculate the ultimate size of the market that may be achieved by a particular technology, as well as an example calculation for a hypothetical market. Note that these calculations result in the maximum potential market for a given industry/application/technology combination, and are not presented as an actual forecast of market penetration. Also note that within an industry, the resulting markets are not additive across applications (although within an application, the totals are additive across industries).

1. For each technology/industry/application combination, the technical fit (1-4) and economic fit (0 – 100%) are calculated as defined previously.
2. From these fits, the techno-economic fit is calculated as described in Appendix C.
3. For all applications other than remote and backup power,[17] any technology/application combination with a techno-economic fit less than 2 is discarded, as it is assumed that below some critical level, a technology will receive none of the available market.
4. Any technologies remaining receive 100% of any available markets in which they have no competition.
5. For markets in which competing technologies exist, the addressable market is apportioned according to the LOGIT[18] function:

$$\text{Market Share for Technology A} = \frac{(1/T_A)^{-\lambda}}{(1/T_A)^{-\lambda} + (1/T_B)^{-\lambda} + \ldots (1/T_N)^{-\lambda}}$$

   for N technologies, where T_X = the techno-economic fit of technology X, and λ is sensitivity variable ranging from 1 – 16. If $\lambda = 1$, then the market penetration for each technology will be based solely upon their relative techno-economic fits, while higher values of λ apply to scenarios where proportionally more of the market goes to “high-fit” technologies. This analysis assumes $\lambda = 3$.
6. For markets in which less than all of the competing technologies have access to a portion of the market, the market penetration of each technology is assumed to be

[17] For these applications, the definition of economic fit implies that even those technologies with techno-economic fits below 2 may have access to some portion of the market.

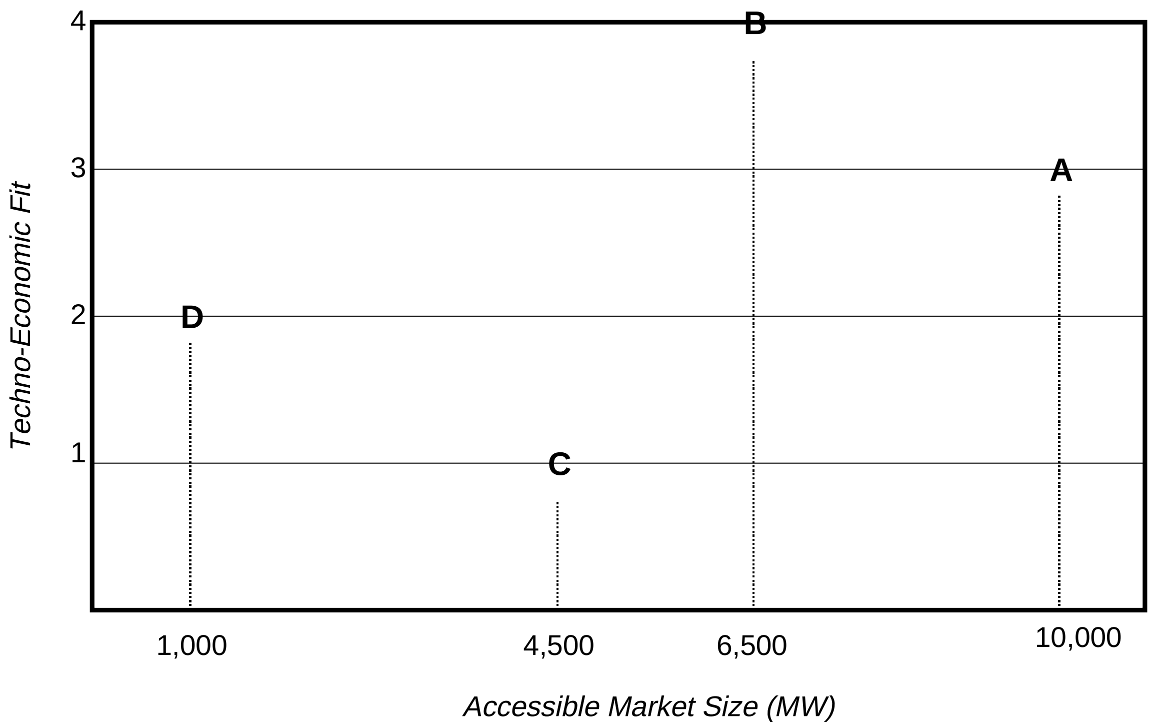
[18] Modified from Gilshannon, *Review of Methods for Forecasting the Market Penetration of New Technologies* (U.S. DOE).

the market share as calculated by the LOGIT function for technology A divided by the market shares for all competing technologies.

Sample Calculation

The following figure represents a hypothetical market/techno-economic fit map for an application other than remote or backup power, with technologies A, B, C and D represented by four discreet points on the map.

Figure 12: Hypothetical Market/Techno-Economic Fit Map for Sample Calculation



Technology C is discarded on the basis that its techno-economic fit is so low as to preclude the likelihood that any facilities would select it. This may be because its economics are so poor, because it is technically not suited to this particular application, or some combination of the two factors.

Technology A has the largest potential market size. This may be due to a broader range of available technology sizes relative to the other technologies (which increases the number of facilities which are appropriately sized for the technology), superior economics (which also increases the number of available facilities), or to some combination of the two factors. Notice that the technology that has the potential to serve the largest market may not necessarily have the highest techno-economic fit. An example of such a technology might be unrecuperated microturbines in traditional cogeneration applications. While their lower efficiency implies that their economics (and thus their techno-economic fit) will always be worse than a comparable recuperated microturbine, the higher temperature of their offgas may help expand the size of the cogeneration market that they can serve.

Of the 10,000 MW potential market for technology A, it is the only technology capable of serving the top 3,500 MW of the market (between A and B), so it gets 100% of that market. Between technologies B and D (a span including 5,500 MW), it must share the market with B. For $\lambda = 3$, the market share of technology A will be:

$$\frac{(1/3)^{-3}}{(1/3)^{-3} + (1/4)^{-3}}$$

or 43% (2,365 MW), while technology B will receive the remaining 57% (3,135 MW) of the market.

At the bottom of the market, technologies A, B and D must all split the available 1,000 MW. Given techno-economic fits of 2, 4 and 3 respectively, technology A will receive 33% of this market (330 MW), technology B will receive 45% (450 MW) and technology D will receive the remaining 22% (220 MW). The total potential market allocated to each of the technologies is therefore:

Technology	Top 3,500 MW	Middle 5,500 MW	Bottom 1,000 MW	Total Potential Market (MW)
A	3,500	2,365	330	6,195
B	0	3,135	450	3,585
C	0	0	0	0
D	0	0	220	220
Total	**3,500**	**5,500**	**1,000**	**10,000**

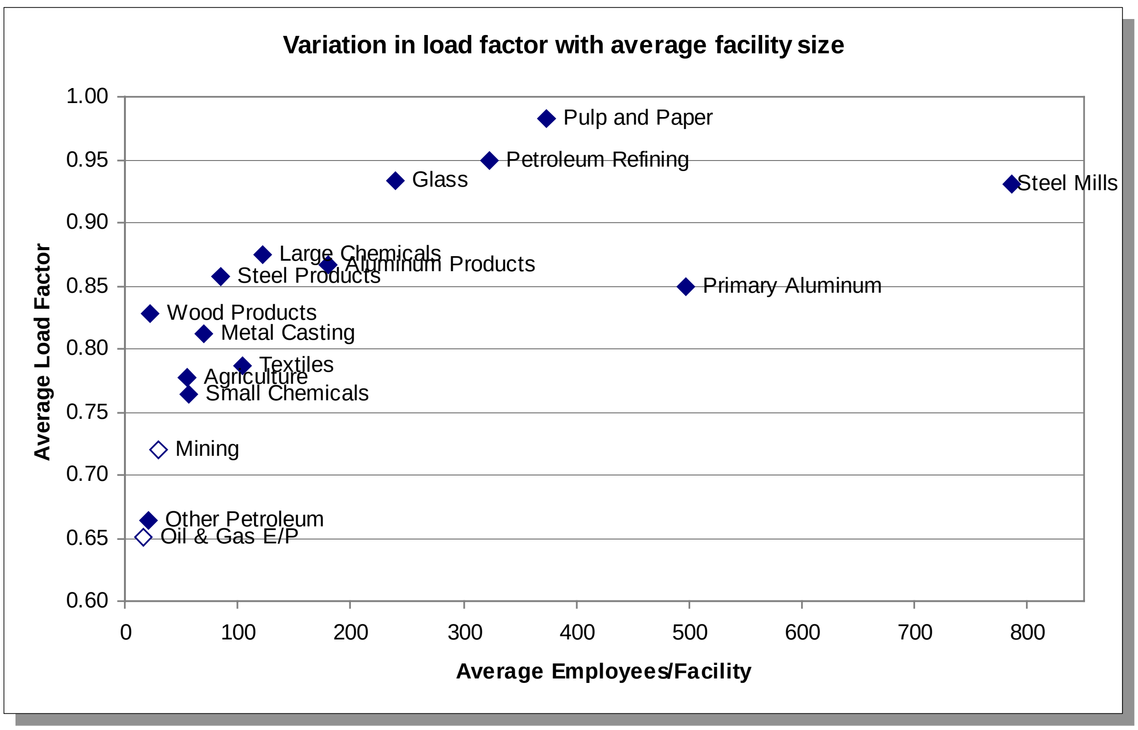
Notice that the total market for all micropower technologies is thus assumed to be equivalent to the largest potential market that can be served by any technology (10,000 MW), and that the technology with the highest techno-economic fit will not necessarily achieve the largest potential market.

Appendix E: Industry Definitions

This Appendix summarizes the 4-digit SIC codes used to describe each industry. In all cases, the SIC codes used have been those recommended by the OIT to describe the *Industries of the Future*. In some cases these industries have been broken down into sub-industries if there was deemed to be a substantial difference between facility size and power needs.

The load factors applied to each industry have been assumed to be equal to industrial capacity factors, as reported in the 1994 Survey of Plant Capacity (U.S. Census). Where multiple SIC codes are included in a given industry, the industrial load factor has been calculated as the average across all relevant SIC codes, weighted by the number of facilities included within each code. In the mining industries (mining and oil and gas E&P), capacity factors were not available, and were therefore estimated from the average facility size, as per the following figure.

Figure 13: Industrial Capacity Factor as a Function of Average Facility Size



Agriculture – Food Products

The food products industry includes all of SIC code 20 (Table 10).

Table 10: Agriculture – Food Products Industry Definition, by SIC Code

Agriculture – Food Products	
2011 Meat Packing Plants	2062 Cane sugar refining
2013 Sausages and other prepared meats	2063 Beet sugar
2015 Poultry slaughtering and processing	2064 Candy and other confectionery products
2021 Creamery butter	2066 Chocolate and cocoa products
2022 Cheese, natural and processed	2067 Chewing gum
2023 Dry, condensed and evaporated dairy products	2068 Salted and roasted nuts and seeds
2024 Ice cream and frozen deserts	2074 Cottonseed oil mills
2026 Fluid milk	2075 Soybean oil mills
2032 Canned specialties	2076 Vegetable oil mills, n.e.c.
2033 Canned fruits and vegetables	2077 Animal and marine fats and oils
2034 Dehydrated fruits, vegetables and soups	2079 Edible fats and oils, n.e.c.
2035 Pickles, sauces and salad dressings	2082 Malt beverages
2037 Frozen fruits and vegetables	2083 Malt
2038 Frozen specialties, n.e.c.	2084 Wines, brandy and brandy spirits
2041 Flour and other grain mill products	2085 Distilled and blended liquors
2043 Cereal breakfast foods	2086 Bottled and canned soft drinks
2044 Rice milling	2087 Flavoring extracts and syrups, n.e.c.
2045 Prepared flour mixes and doughs	2091 Canned and cured fish and seafoods
2046 Wet corn milling	2092 Fresh or frozen prepared fish
2047 Dog and cat food	2095 Roasted coffee
2048 Prepared feeds, n.e.c.	2096 Potato chips and similar snacks
2051 Bread, cake and related products	2097 Manufactured ice
2052 Cookies and crackers	2098 Macaroni and spaghetti
2053 Frozen bakery products, except bread	2099 Food preparations, n.e.c.
2061 Raw cane sugar	

Aluminum

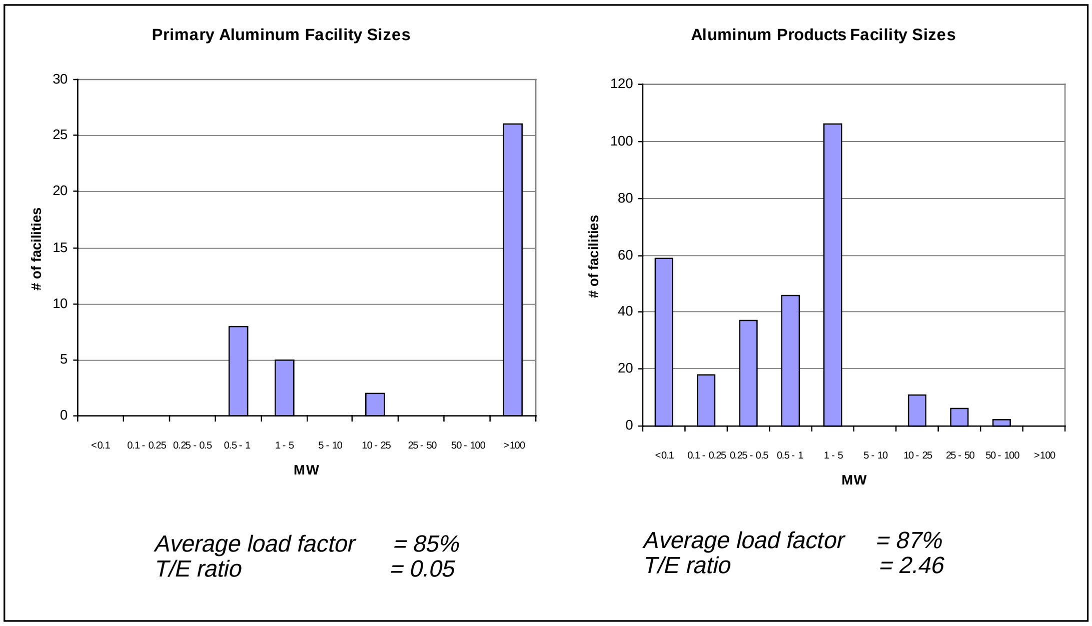
The Aluminum industry has been broken down into two distinct sub-industries, primary aluminum and aluminum products (Table 11).

Table 11: Aluminum Industry Definition, by SIC Code

Primary Aluminum	Aluminum Products
3334 Primary Aluminum	3353 Aluminum sheet, plate and foil 3354 Aluminum extruded products 3355 Aluminum rolling and drawing, n.e.c.

Within the Aluminum industry, the dominant differences between the two sub-industries are facility size and T/E ratio (Figure 14).

Figure 14: Sub-Industry Distinctions within the Aluminum Industry



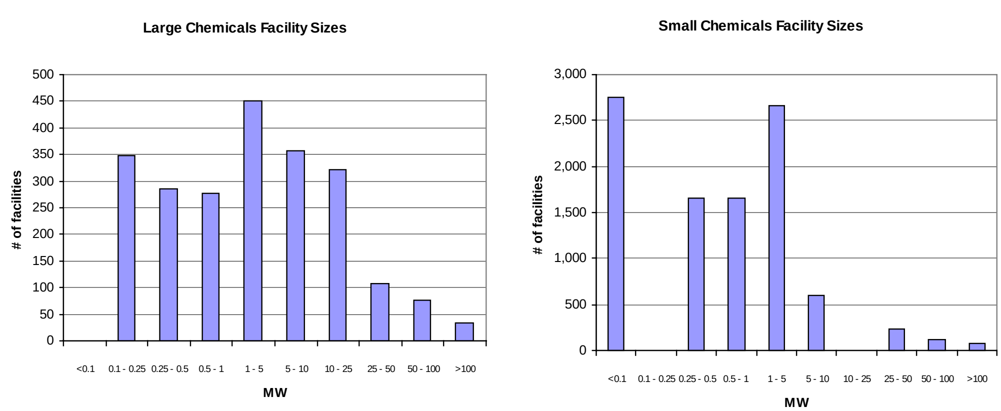
Chemicals

The chemicals industry has been divided into two distinct sub-industries, *large* chemicals and *small* chemicals (Table 12). Those making up the large chemicals sub-industry include the six largest electricity users in the sector. The primary differences between these two sub-industries are the load factor and number of employees per facility (Figure 15).

Table 12: Chemicals Industry Definition, by SIC Code

Small Chemicals	Large Chemicals
2813 Industrial gases 2816 Inorganic pigments 2822 Synthetic rubber 2823 Cellulosic manmade fibers 2824 Organic fibers, noncellulosic 2833 Medicinals and botanicals 2834 Pharmaceutical preparations 2835 Diagnostic substances 2836 Biological products except diagnostics 2841 Soap and detergents 2842 Polishes and sanitation goods 2843 Surface active agents 2844 Toilet preparations 2851 Paints and allied products 2861 Gum and wood chemicals 2874 Phosphatic fertilizers 2875 Fertilizers, mixing only 2879 Agricultural chemicals, n.e.c. 2891 Adhesives and sealants 2892 Explosives 2893 Printing ink 2895 Carbon black 2899 Chemical preparations, n.e.c.	2812 Alkalies and chlorine 2819 Industrial inorganic chemicals, n.e.c. 2821 Plastic materials and resins 2865 Cyclic crudes and intermediates 2869 Industrial organic chemicals, n.e.c. 2873 Nitrogenous fertilizers

Figure 15: Sub-Industry Distinctions within the Chemicals Industry



Average load factor = 88%
Avg employees/facility = 122

Average load factor = 76%
Avg employees/facility = 56

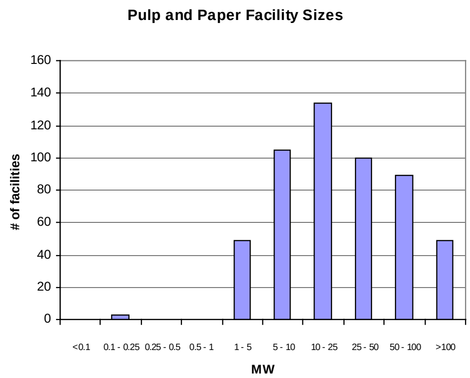
Forest Products

The forest products industry has been broken up into two distinct industries, pulp and paper and wood products (Table 13). This was done because pulp and paper mills tend to be much larger, and have much higher load factors than the remainder of the industry, as shown in Figure 16.

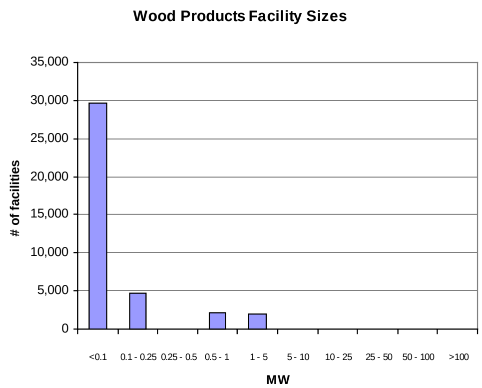
Table 13: Forest Products Industry Definition, by SIC Code

Pulp/Paper Mills	Wood products
2611 Pulp Mills 2621 Paper Mills 2631 Paperboard Mills	2411 Logging 2421 Sawmills & planing mills, general 2426 Hardwood dimension & flooring mills 2429 Special product sawmills, n.e.c. 2431 Millwork 2434 Wood kitchen cabinets 2435 Hardwood veneer and plywood 2436 Softwood veneer and plywood 2439 Structural wood members, n.e.c. 2441 Nailed wood boxes and shook 2448 Wood pallets and skids 2449 Wood containers, n.e.c. 2451 Mobile Homes 2452 Prefabricated Wood buildings 2491 Wood preserving 2493 Reconstituted wood products 2499 Wood products, n.e.c. 2652 Setup paperboard boxes 2653 Corrugated and solid fiber boxes 2655 Fiber cans, drums and similar products 2656 Sanitary food containers 2657 Folding paperboard boxes

Figure 16: Sub-Industry Distinctions within the Forest Products Industry



Average load factor = 98%



Average load factor = 83%

Glass

The glass industry includes all of SIC code 32 (Table 14).

Table 14: Glass Industry Definition, by SIC Code

Glass
3211 Flat glass 3221 Glass containers 3229 Pressed and blown glass, n.e.c. 3231 Products of purchased glass

Metal Casting

The metal casting industry includes all of SIC code 33 (Table 15).

Table 15: Metal Casting Industry Definition, by SIC Code

Metal Casting
3321 Gray and ductile iron foundries
3322 Malleable iron foundries
3324 Steel investment foundries
3325 Steel foundries, n.e.c.
3363 Aluminum die-castings
3364 Nonferrous die-castings, except aluminum
3365 Aluminum foundries
3366 Copper foundries
3369 Nonferrous foundries, n.e.c.

Mining

The mining industry includes all of SIC codes 10, 12 and 14 (Table 16).

Table 16: Mining Industry Definition, by SIC Code

Mining
1011 Iron ores
1021 Copper ores
1031 Lead and zinc ores
1041 Gold ores
1044 Silver ores
1061 Ferroalloy ores except vanadium
1081 Metal mining services
1094 Uranium-Radium-Vanadium ores
1099 Miscellaneous metal ores, n.e.c.
1221 Bituminous coal and lignite surface mining
1222 Bituminous coal underground mining
1231 Anthracite mining
1241 Coal mining services
1411 Dimension stone
1422 Crushed and broken limestone
1423 Crushed and broken granite
1429 Crushed and broken stone, n.e.c.
1442 Construction sand and gravel
1446 Industrial sand
1455 Kaolin and ball clay
1459 Clay, ceramic and refractory minerals, n.e.c.
1474 Potash, soda and borate minerals
1475 Phosphate rock
1479 Chemical and fertilizer mineral mining
1481 Nonmetallic minerals services, except fuels
1499 Miscellaneous nonmetallic minerals, except fuels

Oil and Gas Exploration and Production

The oil and gas exploration and production (oil and gas E&P) industry is comprised of all of SIC code 13 (Table 17).

Table 17: Oil and Gas E&P Industry Definition, by SIC Code

Oil and Gas E/P
1311 Crude Petroleum and Natural Gas 1321 Natural Gas Liquids 1381 Drilling Oil and Gas Wells 1382 Oil and Gas Field Exploration Services 1389 Oil and Gas Field Services, n.e.c.

Petroleum

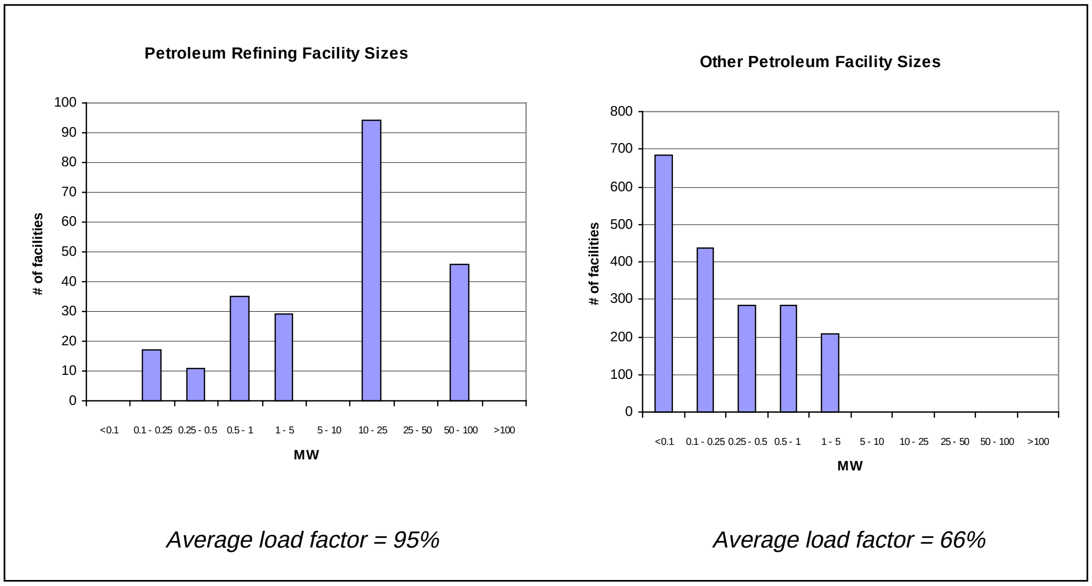
The petroleum industry has been divided into two distinct industries, petroleum refining and other petroleum (Table 18).

Table 18: Petroleum Industry Definition, by SIC Code

Petroleum Refining	Other Petroleum
2911 Petroleum Refining	2951 Asphalt paving mixtures and blocks 2952 Asphalt felts and coatings 2992 Lubricating oils and greases 2999 Petroleum and coal products, n.e.c.

As in the wood products industry, the distinction between these two sub-industries is primarily one of facility size and load factor (Figure 17).

Figure 17: **Sub-Industry Distinctions within the Petroleum Industry**



Steel

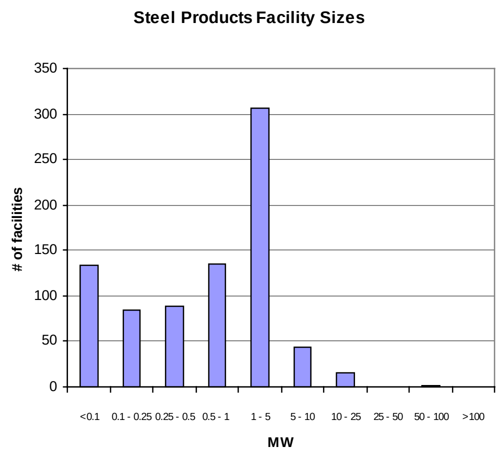
The steel industry has been divided into two distinct sub-industries, steel mills and steel products (Table 19).

Table 19: Steel Industry Definition, by SIC Code

Steel Mills	Steel Products
3312 Blast Furnaces and Steel Mills	3313 Electrometallurgical Products 3315 Steel wire and related products 3316 Cold finishing of steel shapes 3317 Steel pipe and tubes

Those facilities included in steel products tend to be slightly smaller, both in terms of their power demand and average number of employees, and have slightly lower load factors (Figure 18). Also, note that the steel mills sub-industry includes large integrated steel mills and smaller "mini-mills".

Figure 18: Sub-Industry Distinctions within the Steel Industry



Average load factor = 93%
Avg employees/facility = 786

Average load factor = 86%
Avg employees/facility = 85

Textiles

The textile industry includes all of SIC code 22 (Table 20).

Table 20: Textile Industry Definition, by SIC Code

Textiles
2211 Broadwoven fabric mills, cotton
2221 Broadwoven fabric mills, manmade fiber and silk
2231 Broadwoven fabric mills, wool
2241 Narrow fabric mills
2251 Womens hosiery, except socks
2252 Hosiery, n.e.c.
2253 Knit outerwear mills
2254 Knit underwear mills
2257 Wet knit fabrics
2258 Lace and warp knit fabrics mills
2259 Knitting mills, n.e.c.
2261 Finishing plants, cotton
2262 Finishing plants, manmade
2269 Finishing plants, n.e.c.
2273 Carpets and Rugs
2281 Yarn spinning mills
2282 Throwing and winding mills
2284 Thread mills
2295 Coated fabrics, not rubberized
2296 Tire cord and fabrics
2297 Nonwoven fabrics
2298 Cordage and twine
2299 Textile goods, n.e.c.

Appendix F: Calculation of Economic Benefits

With the potential market penetration of each technology/industry/application combination calculated, the economic benefits were calculated on a ¢/kWh basis for each technology and application. To calculate this value, a baseline technology was defined for each application. It is assumed that if micropower technologies achieve the potential markets identified in this analysis, they will displace this baseline technology. As such, all savings associated with this change in technologies can be directly described as the economic benefit associated with micropower technologies.

It should be noted that there are a several additional economic benefits that have not been characterized in this study. Among these are those benefits associated with the manufacture of micropower machinery (job creation and GDP growth) and the tangential growth in industries related to a transition in industrial power production (consulting, engineering and energy services).

The baseline technologies for each application are identified in Table 21.

Table 21: Baseline Technologies Displaced by Micropower of Fuel Cell Hybrid Technology

Industrial Power Application	Baseline Technology Displaced (unit measured)
Simple Generation	Local grid electricity (¢/kWh)
Traditional Cogeneration	Local grid electricity (¢/kWh)
Tightly-Coupled Cogeneration	Local grid electricity (¢/kWh)
Backup Power	1998 vintage state-of-the-art 1 MW reciprocating engine ($/kW)
Remote Power	1998 vintage state-of-the-art 1 MW reciprocating engine ¢/kWh)
Premium Power	Not quantified due to small market and complexity of estimating savings
Generation Using Wastes & Biofuels	Not quantified complexity of estimating savings

As many of the savings are calculated on a local basis (due to variation in local state electricity rates), but the economic benefits are calculated for each technology, independent of industry or location, a weighted average calculation for each technology has been performed. This has been done by:

1. Calculating the price of produced electricity in all states where a technology is economically attractive (which by definition is less than the local grid-electricity price).
2. Calculating the average savings for each industry over all states in which a given technology is economically attractive, weighted by the fraction of facilities located in each of the economically-attractive states (on an application-specific basis).

3. Calculating the average savings for each technology over all industries, weighted by the total power demanded in each industry.

The end result of this series of calculations is a value in ¢/kWh representing the average savings associated with each unit of power produced by a given technology.

Rationales for the each of the baseline technologies are given below.

Simple Generation

At the sub-MW scale that micropower technologies will be produced at, there are almost no existing technologies that can produce electricity at a lower cost than that provided by the grid. Indeed, this explains the ubiquitous nature of the grid, since throughout much of the 20th century, the lowest cost power generation system was a large (>100 MW) plant that provided electricity to a broad mix of customers.

As a result, the vast majority of the industrial facilities that currently produce on-site power are large; too large, in fact for the micropower technologies considered in this analysis. If micropower technologies are to be sold in any significant volume, they must therefore be able to produce power at a lower cost than the local grid. The economic benefit to the industries that elect to use such power can then be directly calculated as:

(the local cost of grid power) – (the cost of on-site micropower, given local gas prices)

Traditional Cogeneration

As with simple generation, the vast majority of equipment installed for cogeneration in the United States have been at scales well in excess of those considered in this study, with the exception of fuel cell hybrids. The technology that will likely be displaced is therefore not a cogeneration system, but two independent systems, consisting of a connection to the local grid (for electricity) and a boiler (for the production of steam and/or hot water).

In cogeneration applications, the cost of electricity produced from micropower technologies, as defined in this study has included a credit for the fuel that is *not* burned in a boiler[19] to raise steam or hot water. This credit has the result of lowering the cost of produced electricity in all locations, which in turn has the effect of increasing the number of states in which it is economically attractive to maintain on-site power generation equipment.

---

[19] With an assumed efficiency of 80% (useful thermal energy out/fuel energy in)

It is important to recognize that there are two distinct effects here. The first of these (reducing the cost of produced electricity) has the effect of increasing the ¢/kWh savings over the local grid. The second of these (increasing the number of states with attractive energy rates) will tend to increase the potential market for a given technology, but may serve to *reduce* the ¢/kWh electric savings, since the competing price in these states will by definition be lower. However, so long as an industry has thermal needs which may be met by micropower technologies operating in a cogeneration capacity, the net effect will be an increase in the total dollar savings.

Tightly-Coupled Cogeneration

Again, with the exception of fuel cell hybrids, the small size of the facilities considered in this study suggests that they are less likely to use on-site power generation equipment. These facilities therefore, typically use grid power. Where needs for direct heat or hot gases are needed, they are met through simple burners and furnaces.

As with traditional cogeneration, the fuel savings associated with tightly-coupled cogeneration is incorporated into the effective price of produced electricity. As a result, to the extent that tightly-coupled cogeneration can make simple generation more economically attractive, the ¢/kWh savings will therefore be the difference between the grid price and the price of produced electricity.

Backup Power

At present, the vast majority of the backup power capacity in this country is met with reciprocating engines. The ability of these devices to start quickly and follow transient loads, their low cost, and their availability in small sizes (relative to other power technologies) has given them a distinct advantage in this application. If other technologies are to find markets for backup power, they will do so only if they offer an economic benefit over these existing devices. Since the load factors of these devices are extraordinarily low (typically <10%), their economic value can be very nearly approximately by their capital cost. New technologies will take their place only if they have a lower installed $/kW, provided they meet the technical requirements. The economic benefits of these technologies can therefore be assumed to be this first cost differential.

Note that since all the replaced technologies will likely be considerably older than the new technologies, we have assumed that by 2010, the backup power technologies likely to be replaced will be 1998-vintage reciprocating engines. As a result, the economic benefit is also calculated if the 1998-vintage engine is replaced by an advanced, lower cost 2010-vintage engine.

Remote Power

As with backup power, the vast majority of remote power in this country is met with reciprocating engines.[20] However, the cost and performance of these engines will show some variation with fuels, as those operating on diesel fuel (the fuel of choice for many remote applications) display lower capital costs, higher O&M costs and higher efficiencies than those running on natural gas. Also as with backup power, the displaced technology in 2010 is assumed to be a 1998-vintage engine.

Assuming that diesel fuel costs $5/MMBtu[21], the cost of electricity produced from a 1998 diesel reciprocating engine has been calculated by assuming that the engine has a 5-year economic life with no terminal value and by applying a 15% pretax discount rate to all cash flows. This calculated cost of electricity was used as the baseline for all remote power generation in the Mining, Wood Products and Pulp and Paper industries.

In the Oil and Gas E&P industry, natural gas is commonly available at zero or no cost. As such, the baseline technology for remote power generation was assumed to be a 1998-vintage natural gas reciprocating engine with $0.50/MMBtu fuel. As with the other industries, the engine was assumed to have a 5 year economic life, and all cash flow calculations used a 15% pretax discount rate.

Premium Power

The economic savings associated with the onsite provision of premium power were not calculated in this analysis. Where needs exist, they are currently met with a variety of technologies, including batteries, power electronics and inverters, all of which may or may not be coupled to traditional power generation equipment.

These technologies have vastly different costs, reflecting the fact that the decision to seek out premium power is ultimately based not upon the value of the electricity, so much as it is based on the cost of not having high-quality electricity. As an example, consider the electronics industry, where well-defined wave forms are absolutely critical to the synthesis of semi-conductor wafers in which lines of silicon must be laid down to increasingly tighter tolerances. Without premium power, this type of facility literally could not be in business, and will therefore be willing to pay substantial premiums to secure this power. At the other extreme, some paper mills use DC-drive motors to roll paper as it dries. The changing elasticity of the drying paper requires tight control of these motors, and some facilities have found that the cheapest way to deliver this control is with a DC system. However, this is certainly not the only solution, and the pulp and

---

[20] One significant exception is in the Oil and Gas E&P industry, where much of the remote power on off-shore platforms may be produced from small (<10 MW) gas turbines. For simplicity, this analysis has compared only to reciprocating engines.

[21] The U.S. average price in 1998.

paper industry would therefore be expected to pay a markedly lower premium for such power.

Given these complexities, and given the relatively small size of the total market relative to other applications, the economic benefits of power production from micropower machinery have not been estimated.

Wastes & Biofuels

Wastes and biofuels have been broken into two distinct classes – solid fuels, which will require gasification before they can be converted into electric power, and liquid and gaseous fuels, all of which have been assumed to be directly convertible into electricity for all micropower technologies by 2010. Examples of the former include wood wastes and paper sludge produced in the forest products industries, while examples of the latter include hydrogen offgases from chlor-alkali plants, mixed offgases from separations processes in the chemical and petroleum industries and blast furnace gases produced in the steel industry.

As with premium power, the decision to convert *solid* wastes and biofuels into power is based on a complex series of economic choices. Most notably, these include avoided tipping fees and environmental regulations. Tax credits such as those that were recently rescinded in California may also play a significant role. A crude estimate of the significance of these factors is observed in the Department of Energy's report on direct-fired biomass,[22] which describes current, commercially available technology that is 23% efficient, has O&M costs of 1 ¢/kWh and costs $2,000/kW. At a 15-year life and a pre-tax discount rate of 15%, this equates to a delivered electricity cost of almost 5 ¢/kWh. Clearly, for industry to use such machinery, there must be benefits above and beyond the low-cost provision of electricity. While these costs will be lower for liquid or gaseous fuels, there may still be substantial exhaust clean-up costs associated with the incineration of non-traditional fuels.

For liquid and gaseous wastes, there are multiple power generation technologies that are already commercially available, depending upon the type and purity of the wastes produced. For particularly dirty wastes (tars, mixed gases, etc.), boilers, steam turbines and reciprocating engines may be used, while cleaner wastes may be used in gas turbines as well. However, none of the micropower technologies are likely to be employed by facilities with power demands of less than 10 MW. In these locations today, it is most likely that where wastes exist, they are simply combusted and converted into heat, which may (but not always) be used to meet industrial process heat needs.

---

[22] *Renewable Energy Technology Characterizations*, December 1997 (U.S. DOE).

To the extent that micropower and fuel cell hybrid technologies reach costs low enough to convert these wastes into electric power at or below the local electricity price, they can provide opportunities for facilities to reduce the amount of power they purchase. On a ¢/kWh basis, the economic benefit of these technologies can therefore be assumed to be the difference between the cost produced and purchased power. This difference has been calculated in the same manner as described for simple generation, with the assumption that the fuel has zero cost.

References

DeLuchi, M.A. *Emissions of Greenhouse Gases from the Use of Transportation Fuels and Electricity*. Center for Transportation Research, Argonne National Laboratory. U.S. Department of Energy, November 1993.

Energy Information Administration, U.S. Department of Energy. *Form EIA-826, "Monthly Electric Utility Sales and Revenue Report with State Distributions"*. Washington DC. Taken from EIA website on 12/98; as of this date, the 1998 prices were based upon estimates of full-year sales.

Energy Information Administration, U.S. Department of Energy. *Manufacturing Consumption of Energy 1994*. Washington DC. Issued December 1997.

Energy Information Administration, U.S. Department of Energy. *Natural Gas Monthly*. Washington DC. July 1998.

Energy Information Administration, U.S. Department of Energy. *Petroleum Marketing Monthly*. Washington DC. November 1998.

Gilshannon, S.T. and D.R. Brown. *Review of Methods for Forecasting the Market Penetration of new Technologies*. U.S. Department of Energy, December, 1996.

Renewable Energy Technology Characterizations (EPRI Topical Report No. TR-109496). Prepared by the Electric Power Research Institute and the U.S. DOE Office of Utility Technologies, December 1997.

SERI Report TR-790. Prepared by the Institute for Energy Analysis. 1974.

U.S. Department of Commerce, Bureau of the Census. *1992 Census of Manufactures*. Washington DC. Issued September 1996.

U.S. Department of Commerce, Bureau of the Census. *1992 Census of Mineral Industries*. Washington DC. Issued September 1996.

U.S. Department of Commerce, Bureau of the Census. *1996 Annual Survey of Manufactures*. Washington DC. Issued February 1998.

U.S. Department of Commerce, Bureau of the Census. *Survey of Plant Capacity: 1994*. Washington DC. Issued September 1996.

Appendix G: Sample Questionnaire

Attached is the questionnaire used for microturbines. The other questionnaires were very similar, incorporating some specific modifications as dictated by the technology in question.

Opportunities for Micropower and Fuel Cell/Gas Turbine Hybrid Systems in Industrial Applications

Manufacturer Questionnaire - Microturbines

Instructions

This questionnaire has three parts; (i) contact information, (ii) product attributes tables and (iii) general questions. Please complete all three. *Please mark with an "*" any data you would like to have kept confidential.*

Feel free to provide additional data and comments you think are important and make extra copies of the product attributes tables if you need to. ***When describing where the technology could be in the future, do not be constrained by current product limitations. Think of what is possible and realistic given appropriate R&D, including that which could benefit from OIT support over the long term.***

After you have completed the questionnaire, please fax it back to the attention of Mr. Hiu Au at (617) 498-7007. Also, if you could mail to Mr. Au your latest brochures and product literature, that would be very much appreciated. Our mailing address is:

20 Acorn Park
Cambridge, MA
02140-2390

Please complete and return the questionnaire by Month Date. Your prompt attention to this request is greatly appreciated.

Definitions

Products currently available – currently available or on the market by the year 2000

Products under development – will be available in the next 3-5 years

Products circa 2010 – will be available in the 2005-2010 timeframe

Products circa 2020 - will be available in the 2010-2020 timeframe

Contact Information

Name	
Title	
Organization	
Phone	
Fax	
E-mail	
Mailing Address	

Product Attributes – Currently Available and Under Development

	Products Currently Available			Products Under Development		
Product Name						
Date of Commercial Availability						
Product Dimensions (feet)						
Product weight (lbs)						
Electrical Output (kW)						
Fuel Capability (list fuel types)						
Estimated Selling Price ($/kW)						
Estimated Total Installed Cost ($/kW)						
Electrical Efficiency (% LHV)						
no recuperator						
with recuperator						
Waste Heat Recovery (Btu/hr-kW)						
no recuperator						
with recuperator						
Maximum Waste Heat Temperature (C)						
no recuperator						
With recuperator						
Estimated O&M Costs (¢/kWh)						
Emissions (g/kWh)						
NOx						
CO						
Methane						
Non-methane hydrocarbons						

Note: Items in bold are considered priority items.

Product Attributes – Future Products

	Products Circa 2010			Products Circa 2020		
Product Name						
Date of Commercial Availability						
Electrical Output (kW)						
Fuel Capability (list fuel types)						
Estimated Total Installed Cost ($/kW)						
Electrical Efficiency (% LHV)						
no recuperator						
With recuperator						
Waste Heat Recovery (MMBtu/hr-kW)						
no recuperator						
With recuperator						
Maximum Waste Heat Temperature (C)						
no recuperator						
With recuperator						
Emissions (g/kWh)						
NOx						
CO						
Methane						
Non-methane hydrocarbons						

Note: Items in bold are considered priority items.

1. *Please describe the basic maintenance requirements/goals of your technology (e.g., routine maintenance, time between major overhauls, major component replacement)?*

Current (within next 5 years)	***Future (5+ years from now)***

2. *What do you see as the main barriers/hurdles that need to be overcome to successfully commercialize your products (**please list products along with hurdles**)?*

(*i*) ***technical*** *(e.g., performance, materials, components, subsystems, manufacturing, fuel capability, cycle configurations, controls)*

Current (within next 5 years)	***Future (5+ years from now)***

(ii) ***regulatory*** *(e.g., siting, permitting)*

Current (within next 5 years)	***Future (5+ years from now)***

*(iii) **market** (e.g., cost, ownership, channels to market, need for demonstrations in particular applications, impact of electric industry restructuring)*

Current (within next 5 years)	***Future (5+ years from now)***

*3. Describe your technology development objectives (**please list products along with objectives**).*

Current (within next 5 years)	***Future (5+ years from now)***

4. What do you see as the most attractive applications for your technology (overall)?

Current (within next 5 years)	***Future (5+ years from now)***

6. Are you aware of any technology development needs that need to be addressed to improve the attractiveness and viability of industrial applications?

Current (within next 5 years)	***Future (5+ years from now)***

*7. Please list any additional product attributes that you think will make your technology successful (e.g., new cycle configurations, packaging options). Please indicate whether these are **existing**, **planned** or **desired** attributes, and please also list the relevant products.*

Current (within next 5 years)	***Future (5+ years from now)***

8. Please provide any additional comments or data that you feel are important.