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Research, Development, and Demonstration of Micro-CHP Systems for Residential Applications—Phase I:

Summary Version

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Phase I Final Report

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Disclaimer

Executive Summary

TIAX LLC, Kohler Company, GAMA, and the Propane Education & Research Council (the TIAX Team) conducted Phase I of a project, partially funded by the U.S. Department of Energy, Office of Electric Delivery and Energy Reliability (DOE/OE), and administrated through the National Energy Technology Laboratory (NETL), to develop a residential combined heat and power (Micro-CHP) system.

The key objectives of the Phase I effort were:

- *Market Research:* Conduct market research to help define the product specifications needed for the Micro-CHP system. These specifications include generation capacity, general packaging requirements (such as indoor vs. outdoor installation of the prime mover), and other product characteristics needed to meet U.S. market needs;
- *Technology Assessment:* Evaluate the energy-savings potential, prime-mover selection, load-management system, and other aspects of the Micro-CHP system design to further define the product specifications and to understand better its market potential;
- *Proof-of-Principle Design:* Develop initial conceptual drawings (including assemblies and key components), specifications for system components, and preliminary product cost estimates; and
- *Commercialization Strategy:* Develop a commercialization strategy for market entry.

This summary report excludes confidential information so that it can be disclosed to the public.

Key results from the Phase I effort are summarized below.

The key design characteristics for the conceptual design are:

- Prime mover/generator based on TIAX's free-piston Stirling engine (FPSE) power system, liquid cooled, with design modifications to extend life;
- 1.5 kW_e generation capacity;
- 15% (LHV) generation efficiency (minimum);
- Grid-supported grid-interface system;
- Electric energy storage using long-life, lead-acid batteries;
- Suitable for natural gas and propane fuels;
- Configured for households having forced-air heating systems (but design is adaptable to hydronic heating systems);
- Prime mover installed indoors (exhaust products vented), packaged with the power-conversion and energy-storage systems;
- Furnace/air-handling unit packaged separately, including the heat-recovery heat exchanger (also installed indoors);

- Heat-dump radiator (used only during power outages) installed outdoors using ethylene glycol coolant for freeze protection;
- Engine coolant loop also captures heat from the combustion exhaust;
- Provide space heating only (not domestic water heating); and
- Annual interval for routine maintenance.

Projected installed cost (including furnace package) for high production volumes is $7000.

The U.S. Micro-CHP market is best served by having a FPSE power system manufacturer supply the prime-mover/generator assembly to a Micro-CHP OEM. This allows the FPSE manufacturer to capture the market volume for all FPSE power system applications. The OEM should be a major HVAC or standby power system manufacturer having a well respected brand, and well established sales and service networks.

We recommend additional market research to identify target customers and optimal paths to market. Key considerations in designing the market research include the types of consumers who are likely to consider Micro-CHP and the marketing approach needed to address each customer group.

Project Summary

The objective of the Micro-CHP Phase I effort was to develop a conceptual design for a Micro-CHP system including:

- Defining market potential;
- Assessing proposed technology;
- Developing a proof-of-principle design; and
- Developing a commercialization strategy.

TIAX LLC assembled a team to develop a Micro-CHP system that will provide electricity and heating. TIAX, the contractor and major cost-share provider, provided proven expertise in project management, prime-mover design and development, appliance development and commercialization, analysis of residential energy loads, technology assessment, and market analysis. Kohler Company, the manufacturing partner, is a highly regarded manufacturer of standby power systems and other residential products. Kohler provides a compellingly strong brand, along with the capabilities in product development, design, manufacture, distribution, sales, support, service, and marketing that only a manufacturer of Kohler's status can provide. GAMA, an association of appliance and equipment manufacturers, provided a critical understanding of appliance commercialization issues, including regulatory requirements, large-scale market acceptance issues, and commercialization strategies. The Propane Education & Research Council, a cost-share partner, provided cost share and aided in ensuring the fuel flexibility of the conceptual design.

Micro-CHP systems being commercialized in Europe and Japan are generally designed to follow the household thermal load, and generate electricity opportunistically. In many cases, any excess electricity can be sold back to the grid (net metering). These products, however, are unlikely to meet the demands of the U.S. market. First, these products generally cannot provide emergency power when grid power is lost—*a critical feature to market success in the U.S.* Even those that can may have insufficient electric generation capacities to meet emergency needs for many U.S. homes. Second, the extent to which net metering will be available in the U.S. is unclear. Third, these products are typically not designed for use in households having forced hot-air heating, which is the dominant heating system in the U.S.

The U.S. market will also require a major manufacturer that has the reputation and brand recognition, low-cost manufacturing capability, distribution, sales, and service infrastructure, and marketing power to achieve significant market size with a previously unknown and unproven product. History has proven time and time again that small-to-medium-size manufacturers do not have the resources and capabilities to achieve significant markets with such products.

During the Phase I effort, the Team developed a conceptual design for a Micro-CHP system that addresses key DOE and U.S. market needs:

- Provides emergency power adequate for critical household loads, with none of the key drawbacks associated with typical, low-cost emergency generators, such as liquid fuel storage, inability to power "hard-wired" loads, need to run temporary extension cords for plug loads, manual set up required, susceptibility to overload, and risk of failure due to lack of maintenance and infrequent operation;
- Requires no special skills to install—plumbers, electricians and HVAC technicians will typically have all necessary skills;
- Can be used with the major residential fuels in the U.S., including natural gas and propane, and can be easily adapted to fuel oil as well as emerging fuels as they become available; and
- Significantly reduces household energy consumption and energy costs.

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1. Introduction

Outlined below are the background and objectives for Phase I of our Micro-CHP system research, development, and demonstration effort.

1.1 Background

TIAX LLC, Kohler Company, GAMA, and the Propane Education & Research Council (the TIAX Team) conducted a project, partially funded by the U.S. Department of Energy, Office of Electric Delivery and Energy Reliability (DOE/OE), and administrated through the National Energy Technology Laboratory (NETL), to develop a residential combined heat and power (Micro-CHP) system. Table 1-1 outlines the key roles for each TIAX Team member. Table 1-2 provides an overview of the three-phase development project. DOE/OE elected to divide Phase I into two parts—Phase IA and Phase IB—as outlined in Table 1-3 and Table 1-4, respectively. This report documents the work completed under Phase I. The DOE has elected not to fund further development under Phases II and III, so this report is the final deliverable under the contract.

Table 1-1: Key Roles of TIAX Team Members

Team Member	Key Role
TIAX LLC	- Contractor - Cost Share
Kohler Company	- Manufacturing Partner
GAMA	- Accelerate acceptance by regulators through codes and standards support
Propane Education & Research Council	- Input/review by the propane industry - Cost Share

Table 1-2: Overview of Micro-CHP Project

Phase	Scope	Timeline	Budget
I	Conceptual design and commercialization strategy	Original: 1 year (complete by Sept. 2005) Current: Extended to June 2006[a]	$545,918 (total) $340,755 (DOE) 38% cost share[b]
II	Proof-of-principle prototype and laboratory testing	Estimated 1 year	$1.5 million (total) $900K (DOE) 40% cost share
III	Pre-production prototype, demonstration, and field testing	Estimated 1.5 – 2 years	$3 million (total) $1.2 million (DOE) 60% cost share

a) DOE contract allowed 90 additional days to complete work
b) $50,000 from PERC and about $155,000 from TIAX

Table 1-3: Overview of Phase IA

Task 1: Market Research/ Development of Detailed Product Specifications	Task 2: Technology Assessment	Task 5A: Review meetings, Reporting, and Project Management
- Establish generation capacity requirements - Establish cost and performance targets - Determine acceptable physical size - Assess market opportunity and competitive products	- Evaluate prime-mover options - Perform preliminary sizing and costing exercises - Model energy and energy-cost savings - Evaluate initial load-management, controls, and heat-recovery approaches	- Technical and program review meetings - Progress reports - Comprehensive final report - Kick-off meeting - Assist DOE with a go/no-go decision for proceeding with Phase IB - Participate in DOE Peer Evaluation Meetings

Table 1-4: Overview of Phase IB

Task 3: Develop Proof-of-Principle Design	Task 4: Commercialization Strategy	Task 5B: Review Meetings, Reporting, and Project Management
- Develop initial conceptual drawings - Develop detailed specifications for system components - Update performance model results - Develop system design and preliminary cost estimates	- Use market analysis to develop understanding of business opportunity, including drivers and barriers - Evaluate manufacturing options - Identify and select prime-mover source - Identify long-term cost impacts on manufacturing facilities - Identify preferred distribution network, key strategic partners and early market-introduction strategies - Explore industry-wide heating-system manufacturing practices to facilitate Micro-CHP integration	- Technical and program review meetings - Progress reports - Comprehensive final report - Assist DOE with a go/no-go decision for proceeding with Phase II - Participate in DOE Peer Evaluation Meetings

Figure 1-1 illustrates a typical installation of the Micro-CHP system. Key features of the system include:

- Operates turn-key—no human intervention required;
- Powers critical household loads during power outages;
- Operates on either propane or natural gas;
- Designed for forced-air home heating systems—the dominant heating system in the U.S.;

- Uses a small-capacity generator (1.5 kW) to lower costs and increase efficiency relative to larger capacity systems. Efficiencies are improved because the smaller generator cycles less and operates at part load less compared to larger systems;
- Uses an advanced load-management system including electric energy storage to maximize energy savings and extend utility during power outages.

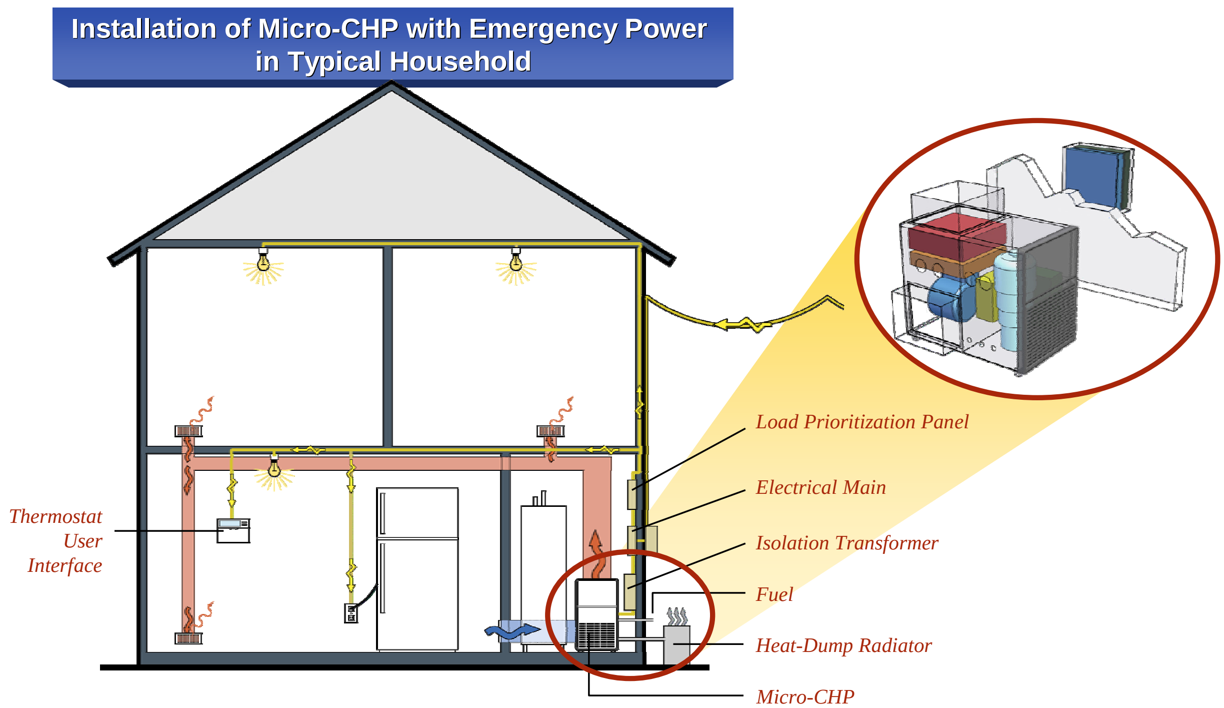


Figure 1-1: Installation of the Micro-CHP System in a Typical Household

To illustrate the capabilities of a small-capacity generator, Figure 1-2 shows the maximum fraction of household electric load that could be provided by the generator and the associated Capacity Factor[1]. The figure shows that a 1 kW generator could, in principle, supply close to 80 percent of the electricity used by a 3,000 sq. ft. home having gas appliances. In contrast, most standby residential generators (permanently mounted) currently sold in the U.S. exceed 5 kW in generation capacity—some are much larger than this.

[1] Capacity Factor is the ratio of the actual electric energy delivered by the generator over a year to the maximum possible electric energy delivered if the generator were operated continuously at full capacity.

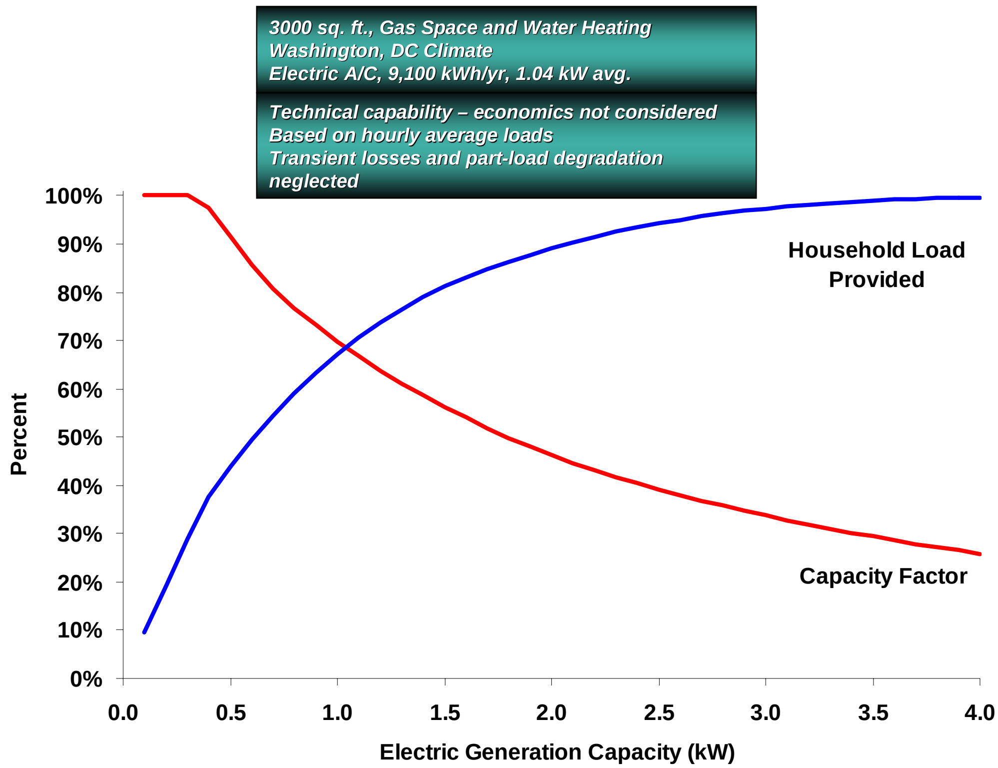


Figure 1-2: Load-Serving Capability of a Generator

1.2 Objectives

The key objectives of the Phase I effort were:

- *Market Research:* Conduct market research to help define the product specifications needed for the Micro-CHP system. These specifications include generation capacity, general packaging requirements (such as indoor vs. outdoor installation of the prime mover), and other product characteristics needed to meet U.S. market needs;
- *Technology Assessment:* Evaluate the energy-savings potential, prime-mover selection, load-management system, and other aspects of the Micro-CHP system design to further define the product specifications and to understand better its market potential;
- *Proof-of-Principle Design:* Develop initial conceptual drawings (including assemblies and key components), specifications for system components, and preliminary product cost estimates; and
- *Commercialization Strategy:* Develop a commercialization strategy for market entry.

2. Market Research

We obtained market research data from several sources:

- A residential distributed energy market research study published by Primen [Primen 2004];
- A private market research study commissioned by Kohler for residential stationary standby generators; and
- Additional market research conducted by TIAX.

The results are summarized below. In this discussion, the term "standby generator" refers to permanently mounted generators that start up automatically to distinguish them from portable generators that require manual set up.

Table 2-1 summarizes the methodology for the Primen study. 1200 U.S. heads of households were surveyed online, plus an additional 101 from Ontario, Canada. This study provided valuable data on the market for stationary standby generators.

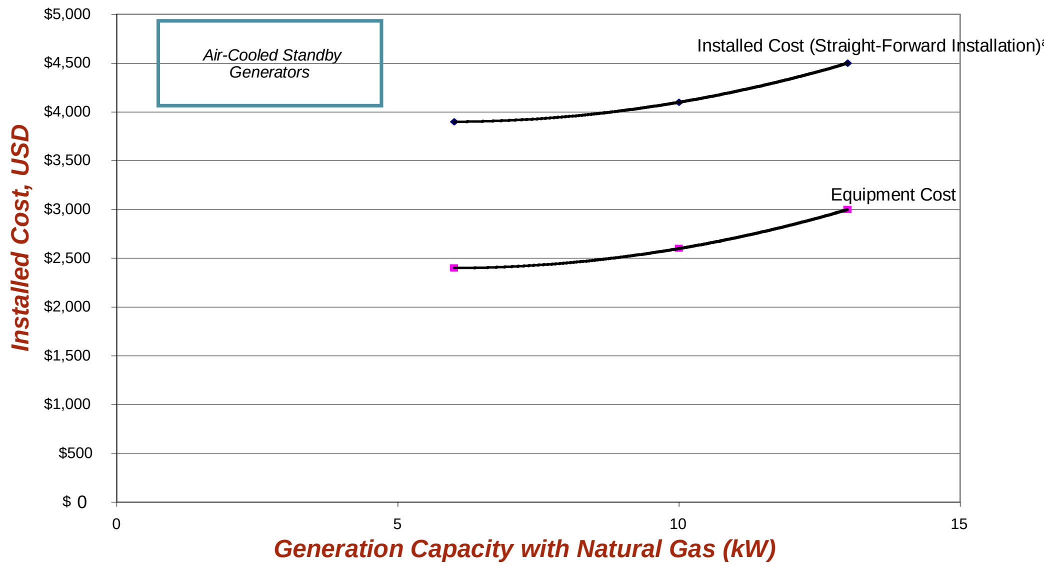
Table 2-1: Methodology for Primen Survey on Residential Emergency Generators

Characteristic	Description
Interview Type	Web-based
No. of Interviews	- 1200 U.S. - 101 Canada
Dates of Interviews	March 2004
Interviewee	Head of Household
Household Annual Income	Representative of U.S. population. Included oversample of households having incomes over $100,000

The Primen Study results also show that the most common loads served by residential generators are the refrigerator, some or all interior lighting, the furnace/heating system, and a pump (in descending order of frequency) [Primen 2004; Figure 6]. Study results further show that 17 percent of U.S. interviewees are interested in purchasing stationary standby generators within the next two years [Primen 2004; Figure 11].

Kohler commissioned a market research firm to conduct a survey of the stationary standby power market in the U.S. This study was completed prior to the start of the DOE Micro-CHP project. The results of this study have informed the work under Phase I.

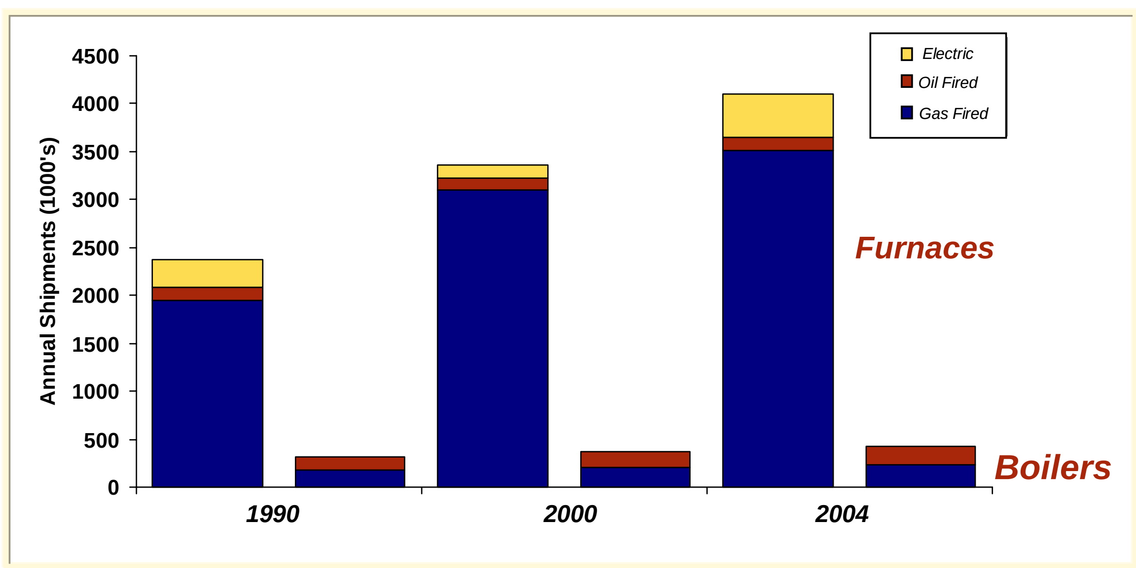
In late 2004, TIAX gathered equipment- and installed-cost estimates for stationary standby generators on the market at that time. Figure 2-1 provides a sample of those data from one manufacturer. Stationary standby generators can cost as little as $4000 installed for straight-forward installations.



[a] *More complex installations can increase installed costs by another $2000 or more.*

Figure 2-1: Sample Equipment and Installed Costs for Stationary Standby

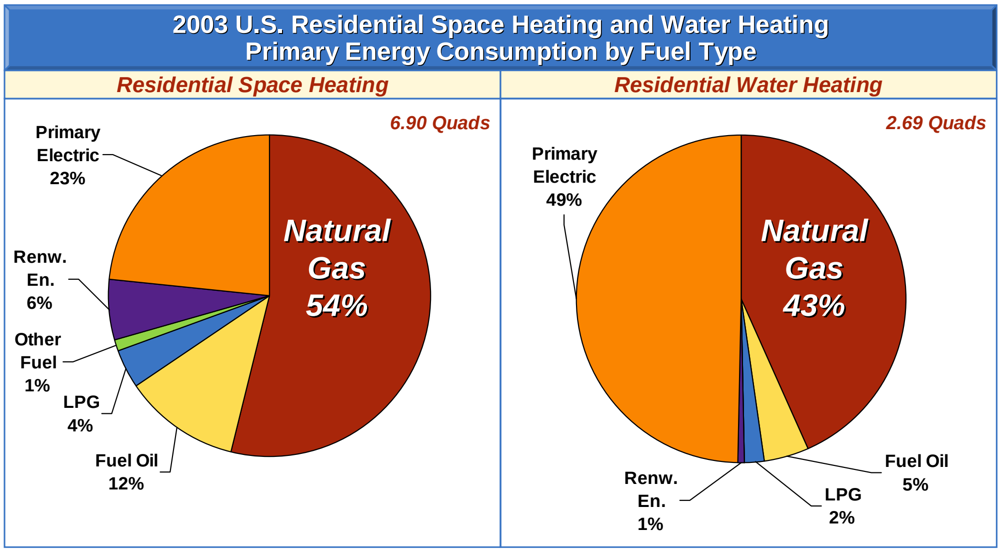
Figure 2-2 shows annual shipments for furnaces and boilers in the U.S. Furnaces outsell boilers ten to one in the U.S.



Source: [Data Book 2005; Table 5.6.1] 2004 electric furnace shipments assumed the same as 2000 shipments

Figure 2-2: Annual Shipments of U.S. Space-Heating Equipment (Residential and Light Commercial)

Figure 2-3 shows primary energy consumption[2] for U.S. residential space heating and water heating. Natural gas accounts for about 51 percent of the fuel consumed for residential space and water heating. Propane (LPG) accounts for less than four percent of residential space and water heating. Together, these fuels account for about 55 percent of residential space and water heating.



Source: [Data Book 2005; Table 1.2.3]

Figure 2-3: U.S. Residential Space-Heating and Water-Heating Primary Energy Consumption

[2] Primary energy consumption accounts for the losses during generation, transmission, and distribution of electricity. Losses during the transmission and distribution of other fuels are generally small.

3. Technology Assessment

We assessed various aspects of Micro-CHP performance and design as discussed below.

3.1 Performance Assessment

The objectives of our performance assessment were to project the energy and energy-cost savings associated with the 1RES Micro-CHP system, as these characteristics are the primary market differentiators between a Micro-CHP system and a stationary standby generator.

3.1.1 Simulation Model

We simulated operation of various Micro-CHP system designs using TIAX's CHP ToolSet™. CHP ToolSet performs an hourly analysis based on space-heating, water-heating, and electric load profiles for a representative household (see Figure 3-1). The user can input Micro-CHP system electric generation capacity, electric generation efficiency, temperature of heat recovery, fraction of thermal energy lost to ambient (i.e., the fraction that is not recoverable), operational strategy, and gas and electric utility rates. CHP ToolSet determines annual primary energy, energy-cost impacts, duty cycle, and capacity factor. We assumed that the Micro-CHP system can achieve the same overall efficiency as the heating system it displaces[3]. In reality, losses due to interconnecting piping and pumping parasitic loads could lower the efficiency of a Micro-CHP system.

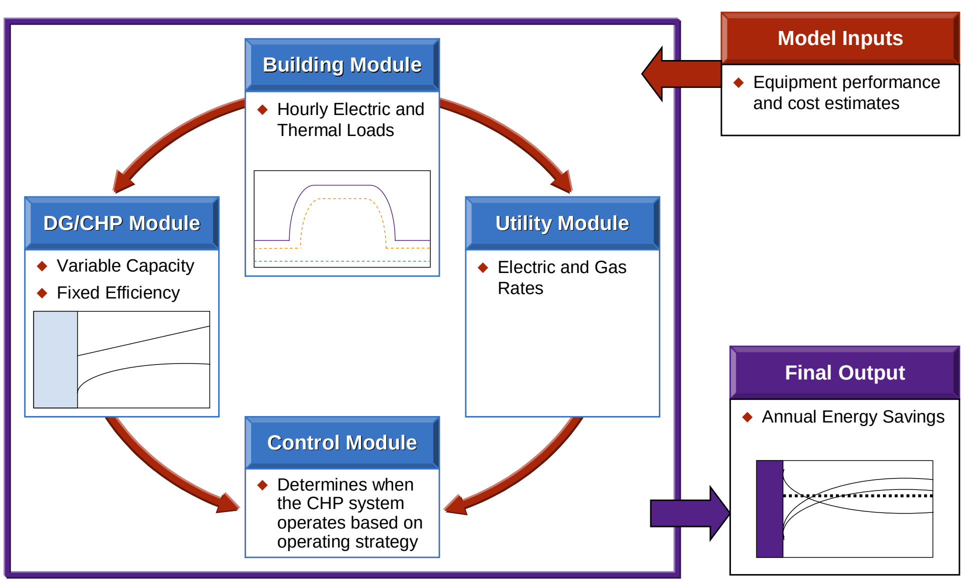


Figure 3-1: TIAX CHP Toolset™ Residential Performance Model

[3] For example, let's assume we are comparing an 82 percent (HHV) furnace to a Micro-CHP system having an electric generation efficiency of 15 percent (LHV), and that we are operating on natural gas. This generation efficiency converts to 13.6 percent (HHV). We then assume that the portion of fuel energy content available to deliver to thermal loads is 82 - 13.6 = 68.4 percent. Whether this energy is actually delivered to thermal loads depends on the operational strategy, and the relative electric and thermal loads at the specific time in question.

3.1.2 Household Load Profiles

We engaged Jackson Associates, Durham, NC to provide hourly electricity and natural-gas consumption profiles for households in five U.S. cities: Minneapolis; Chicago; Washington, DC; New York; and Sacramento[4]. We refer to these load profiles as MAISY® (Market Analysis and Information System) profiles. Each household is about 3,000 sq. ft. (+/- 10 percent) and uses natural gas for space heating and water heating. While 3,000 sq. ft. is significantly larger than average, it is representative of Kohler's target market. Tables 3-1 and 3-2 summarize other characteristics of the households. Table 3-3 lists the electricity and natural-gas consumption data provided in the MAISY profiles. Since CHP ToolSet requires thermal-load profiles, we converted the consumption data provided to thermal loads as shown in the table. Equipment efficiency assumptions used in the conversions do not necessarily match those used to evaluate the energy-cost savings of Micro-CHP (which are discussed in Section 3.1.3 below). Since the Micro-CHP system we are considering does not supply space cooling, we did not convert electricity consumption for space cooling to space-cooling thermal load.

Table 3-1: MAISY Baseline Household Characteristics-Summary

Item	Description	Comments
Construction	• Suburban, single-family • 1-2 stories • Post-2000 construction • 2,800 to 3,320 sq. ft. conditioned space • Crawl space	• Floor space and stories vary by location
Available Fuel	Natural Gas	
Appliances/Heating and Cooling Equipment	• Conventional gas-fired furnace and water heater • Central A/C • Range: Gas in Minneapolis and Sacramento; Electric in remaining locations • Clothes Dryer: Electric in all locations • No hot tubs, heated pools, or water beds	• See Section 3.1.3 for further details
Occupancy	• 2-4 occupants	• Varies by location
Locations	• Minneapolis; Washington, DC; New York City; Sacramento; Chicago	

[4] In previous analyses reported under this project and in a conference paper published in 2005 [IATC 2005], we used household load profiles for Washington, DC that were adapted from load profiles developed by Lawrence Berkeley National Laboratory using DOE-2 simulations. The primary adaptation we made was extrapolating the LBNL profiles for a 2200 square foot home to a 3000 square foot home. We selected the MAISY profiles because they provided more climate regions and did not require extrapolation.

Table 3-2: MAISY Baseline Household Characteristics – Details

City	Minneapolis	DC	NYC	Sacramento	Chicago
Heated Sq Ft	3,070	3,000	3,320	2,800	3,020
Natural Gas Cooking	Yes	No	No	Yes	No
Home During Day	Yes	No	No	No	No
Washing Machine	Yes	Yes	Yes	Yes	Yes
Electric Dryer	Yes	Yes	Yes	Yes	Yes
Dishwasher	Yes	Yes	Yes	Yes	Yes
Freezer	Yes	No	No	No	No
Number Stories	1	2	2	2	2
Number of Adults	2	2	2	2	2
Number of Children	2	1	1	0	2
% of Single Family Dwelling Units 2,450-3,450 Sq Ft	25.9	19.6	26.3	14.3	23.0

Table 3-3: Summary of MAISY Consumption Data and Conversion to Load Data

Hourly Consumption Data Provided	Converted to Hourly Load Data	Assumptions for Conversions
Electricity for Lighting	Same	No conversion
Electricity for Space Cooling	Same	No conversion
Other Electricity	Same	No conversion
Natural Gas for Water Heating	Water-Heating Load	76% water-heating thermal efficiency and 0.76 kBtuh stand-by losses (typical values for 55% Energy Factor).
Natural Gas for Space Heating	Space-Heating Load	82% AFUE furnace, assuming constant efficiency
Other Natural Gas	Same	No conversion
Dry-Bulb Temperature	Same (not used in analysis)	No conversion
Wet-Bulb Temperature	Same (not used in analysis)	No conversion

Figure 3-2 compares the annual electric loads (consumptions) for the five cities. Here, the air-conditioning load shown is the electricity consumed for air conditioning (not the space-cooling load). Annual electric loads for the five cities vary from 9100 kWh in Washington, DC to 10,400 kWh in Sacramento.

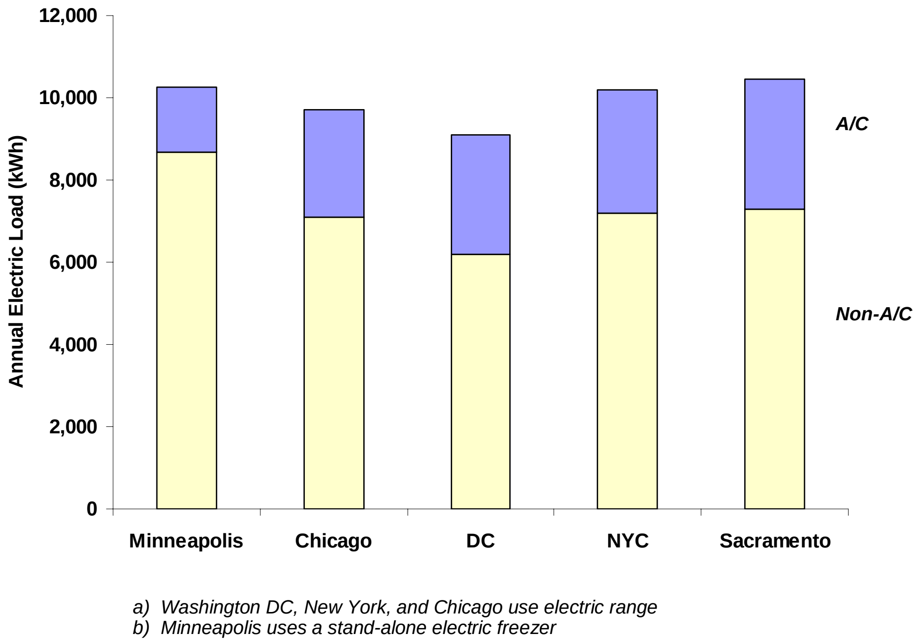


Figure 3-2: Annual Electric Loads for MAISY Load Profiles

Figure 3-3 compares thermal loads for the five cities. Annual water-heating loads vary from 12,000 kBtu in New York City to 16,500 kBtu in Minneapolis. Annual space-heating loads vary from 44,700 kBtu in Sacramento to 110,300 kBtu in Minneapolis. The fraction of the combined heating load associated with water heating varies from 13 percent in Minneapolis to 26 percent in Sacramento.

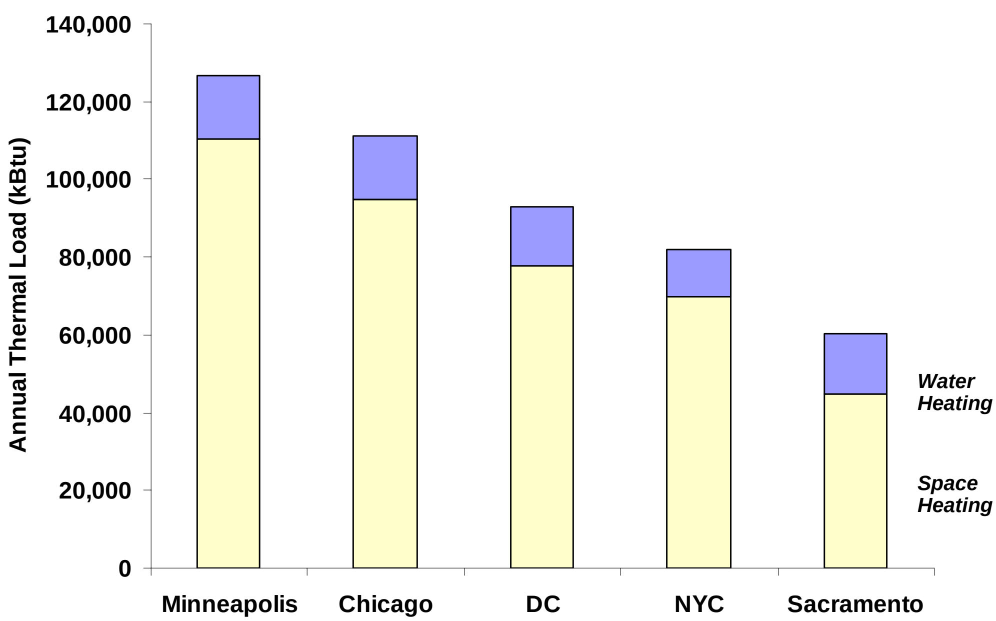


Figure 3-3: Annual Thermal Loads for MAISY Load Profiles

Figures 3-4 and 3-5 show load profiles for the year and for a sample day, respectively, for the Washington, DC household. The annual profiles are based on weekly averages and the daily profiles are based on hourly averages. The annual profiles clearly show the increased electric load during summer months (due to air conditioning) and the increased space-heating load in winter months. Water-heating load is fairly constant year round. The daily profiles clearly show the increased electric load during evening hours (when occupants are home and active) and the dual peak in water-heating load (one peak associated with morning showers and another peak in the evening).

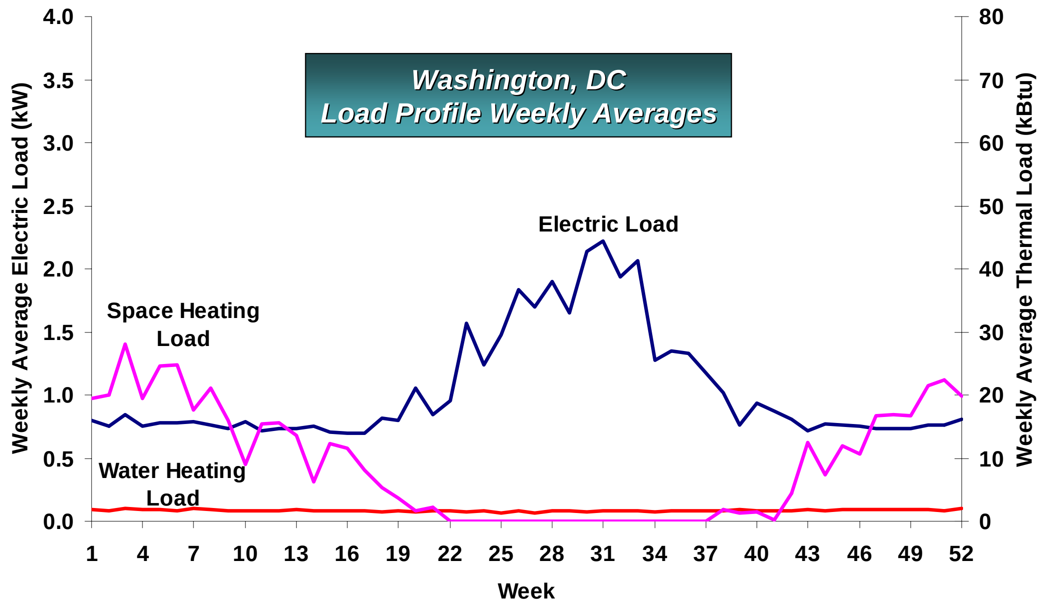


Figure 3-4: Annual Load Profiles for Washingtion, DC Household (weekly Averages)

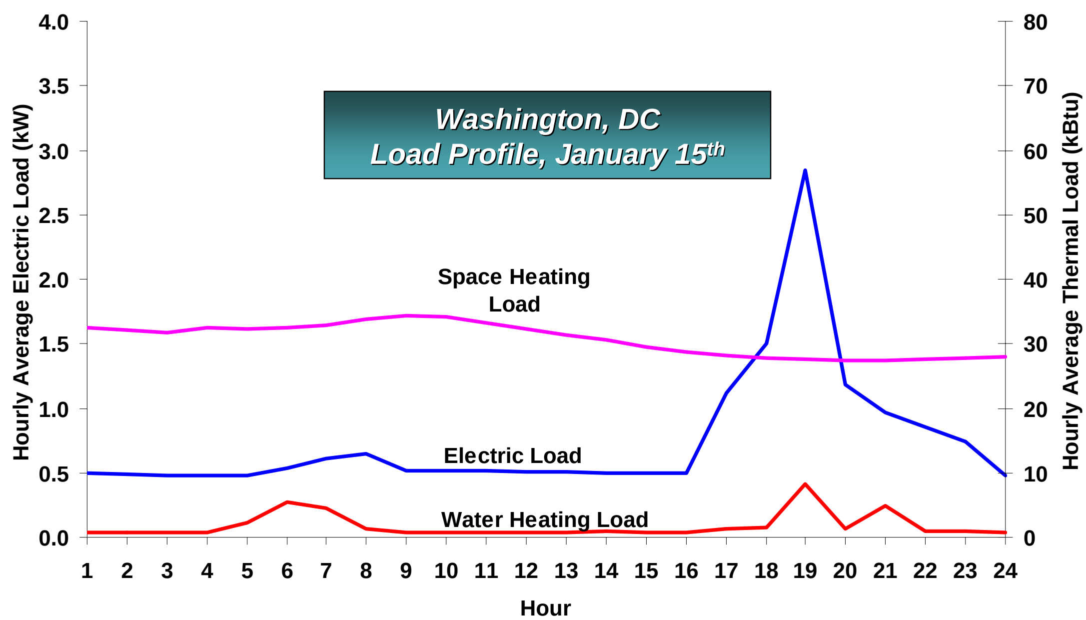


Figure 3-5: Sample Daily Load Profile for Washington, DC Household (Hourly Averages)

3.1.3 Equipment Performance Characteristics

Table 3-4 lists the household equipment performance characteristics that we assumed for each household to convert thermal loads back to fuel or electricity consumptions. As mentioned in Section 3.1.2 above, these are not necessarily the same characteristics assumed to convert the consumption profiles from MAISY to load profiles. Specifically, we selected the water-heater thermal efficiency (not including standby losses) to match the space-heating efficiency, which simplifies the performance model. This results in a water-heater efficiency that is slightly higher than current efficiency standards for residential gas water heaters. We assumed that the performance characteristics did not vary with load or ambient temperature.

Table 3-4: Household Equipment Performance Characteristics

Equipment	Capacity	Efficiency	Comments
Furnace	100,000 Btuh	82% AFUE	Gas-fired, non-condensing
Water Heater	40,000 Btuh	82% Thermal Efficiency and 0.76 Btuh Standby losses (typical for 59% EF)	Gas-fired, tank type
Air Conditioner	—	12 SEER	Central split system

3.1.4 Operational Strategies

Table 3-5 defines the four Micro-CHP operational strategies analyzed. While we included for comparison one scenario in which net metering[5] is allowed, net metering for non-renewable generation technologies is currently available to only about 14 percent of the U.S. population. The Energy Policy Act of 2005 requires public utility commissions to consider net metering, but it is not known whether this will result in increased availability of net metering for non-renewable generation technologies. Effectively, net metering provides the end user with a free, 100-percent-efficient, unlimited-capacity energy storage system (i.e., the electric grid).

Table 3-5: Operational Strategies

System Type	Net Metering Policy	Operational Strategy	Description
CHP	Full Retail Price[a]	Thermal Load Following	System operates to meet thermal load[b] and generates electricity opportunistically. Any excess electricity is sold to the utility at the full retail price
CHP	Not Available	Thermal and Electric Load Following	System operates to meet thermal load[b] or electric load, whichever is more limiting. Neither the thermal nor the electric load is exceeded.
CHP	Not Available	Electric Load Following	System operates to meet electric load, up to its maximum generation capacity. Excess thermal energy is dumped to the outdoor ambient
DG	Not Available	Electric Load Following	System operates to meet electric load, up to its maximum generation capacity. Thermal energy is not recovered

a) Limited availability in the U.S. for non-renewable technologies

b) If the household thermal load exceeds the thermal output of the generator, an auxiliary burner provides additional thermal energy.

There are two basic strategies for CHP system—thermal load following and electric load following. As the names imply, electric load following means the CHP system responds

[5] Net metering means that end users can sell unused electricity to the grid, usually at its full retail price. Net metering policies generally require that sales to the grid to not exceed purchases from the grid.

to the electric load, and generates thermal energy as a by product. Similarly, thermal load following means the CHP system responds to the thermal load, and generates electricity as a by product. A straight thermal-load-following strategy requires net metering (or a large energy storage device), since at times more electricity will be generated than can be used within the household. Therefore, we modified the thermal load following strategy when net metering is not available. We call the modified strategy the “thermal and electric load following” strategy. This strategy operates the CHP system only to the extent that both the electric and thermal output can be used within the household. At some times, electric loads will limit CHP system operation, while at other times thermal loads will limit operation.

Also included is a power-only (no heat recovery) scenario so that we can compare the benefits associated with distributed generation (DG) alone to those for CHP.

3.1.5 Energy Savings and Economics

We ran CHP ToolSet as described above to project the energy savings and economics (based on energy savings) of a Micro-CHP system. We used the MAISY household load profiles discussed above for Washington, DC and 2003 New York State average utility rates for most of our analyses[6]. New York State utility rates are higher than the national average ($0.1431/kWh and $11.44/MMBtu for NYS versus $0.0870/kWh and $9.62/MMBtu for the U.S.), and probably represent the most favorable third of utility rates across the country. The Washington, DC climate is representative of the average U.S. climate. At the end of this section, we include limited analyses of household loads for alternative utility rates.

Figure 3-6 shows the impacts of electric generation efficiency on annual energy-cost savings (as a percent of the $2800 annual household energy cost) for the four operational strategies, evaluated for a 1 kW generation capacity. Not surprisingly, the availability of net metering (at full retail value) enhances annual savings, but, as discussed above, net metering is not available to most U.S. households for non-renewable generation systems. For generation efficiencies above about 30 percent (LHV), the thermal-load-following and electric-load-following strategies provide similar savings. Electric power only (DG) systems don’t begin to save costs until generation efficiencies exceed about 30 percent (LHV). However, generation efficiencies above 30 percent (LHV) are unlikely to be available at the residential scale until advanced technologies such as solid-oxide fuel cells become available in Micro-CHP products. For current ranges of generation efficiencies typical of Stirling and IC engine generators (15 to 20 percent LHV), annual energy savings range from about $320 to $355 using the thermal-and-electric-load-following strategy and New York State utility rates.

Recovering heat for water heating adds cost and complexity to a Micro-CHP system, so its incremental energy savings should be considered in a design evaluation. Figure 3-7 shows the reduction in annual savings if only space heating is supplemented by recovered heat (i.e., water heating is provided solely by burning natural gas). For generation

[6] Obviously, using NYS utility rates and Washington, DC climate conditions will not represent any single, real Micro-CHP installation. However, this is a reasonable approximation of average U.S. climate conditions and utility rates in the most favorable third of the U.S.

efficiencies ranging from 15 to 20 percent (LHV), annual savings are reduced by about $60 to $80 when only space heating is supplemented.

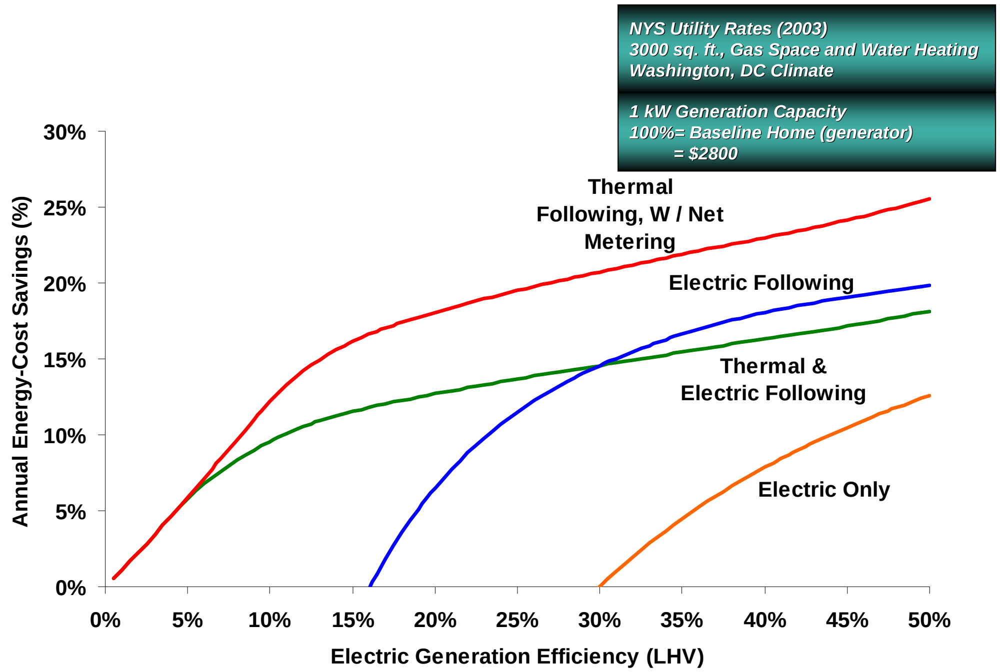
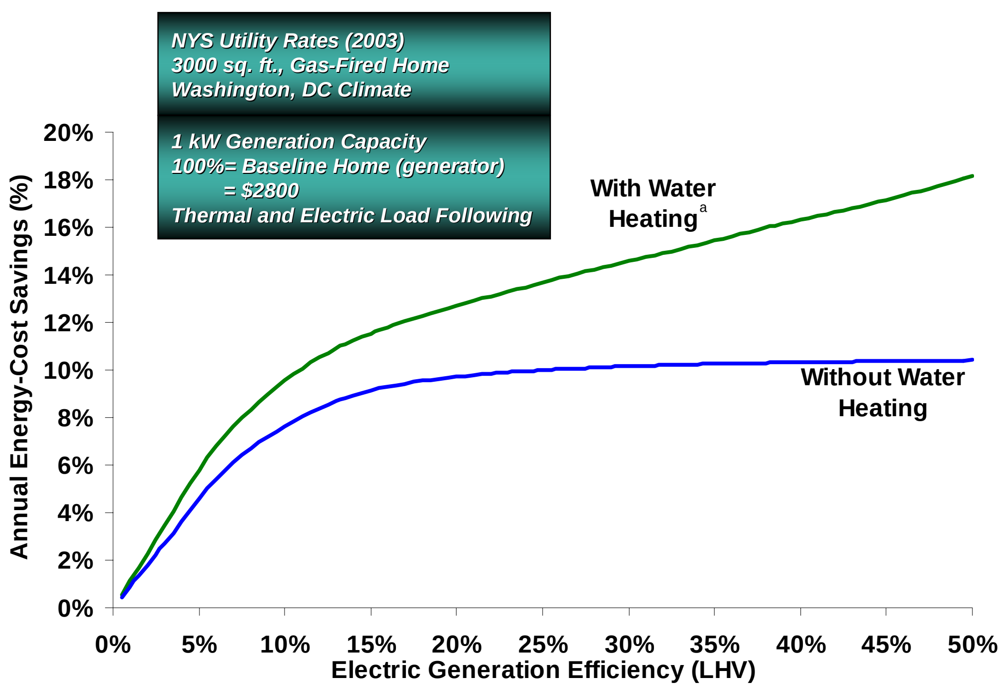


Figure 3-6: Annual Energy-Cost Savings



a) Optimistic estimate. Does not reflect efficiency impacts of increased part-load operation when water heating is provided.

Figure 3-7: Comparison of Annual Energy-Cost Savings with and Without Water Heating

Figure 3-8 shows the impacts of varying both generation capacity and efficiency on annual energy-cost savings. The figure clearly shows that, regardless of efficiency, energy-cost savings do not increase significantly for generation capacities over 1 kW for the household evaluated when net metering is not available. If net metering at full retail price is available, savings do not increase significantly for capacities over 1.5 kW.

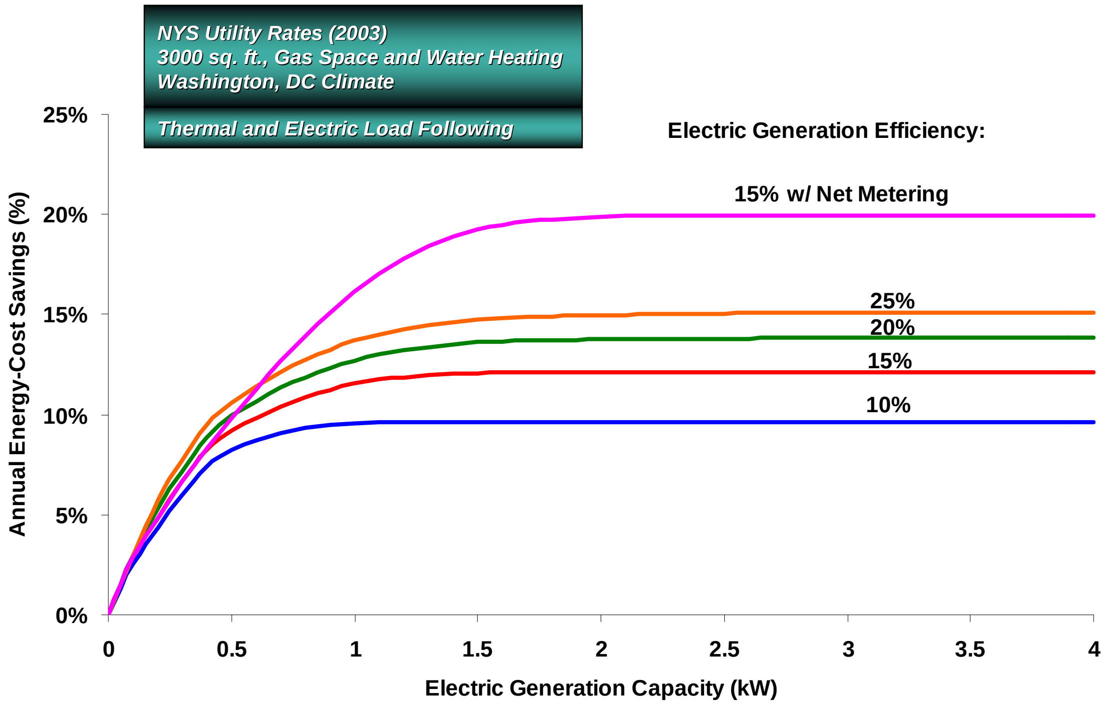


Figure 3-8: Impact of Generation Capacity and Efficiency on Energy-Cost Savings (MAISY, DC)

Figure 3-9 shows the fractions of household electric and thermal loads provided by a 1 kW Micro-CHP system as a function of generation efficiency for the thermal-and-electric-load-following operational strategy. As generation efficiency increases at a fixed generation capacity, less thermal energy is available to serve thermal loads. For example, a 1 kW, 15 percent efficient (LHV) Micro-CHP system provides about 37 percent of the household annual electric load and about 62 percent of the annual thermal loads. In comparison, a 1 kW, 20 percent efficient (LHV) Micro-CHP system provides about 41 percent of the annual electric load and about 48 percent of the annual thermal load.

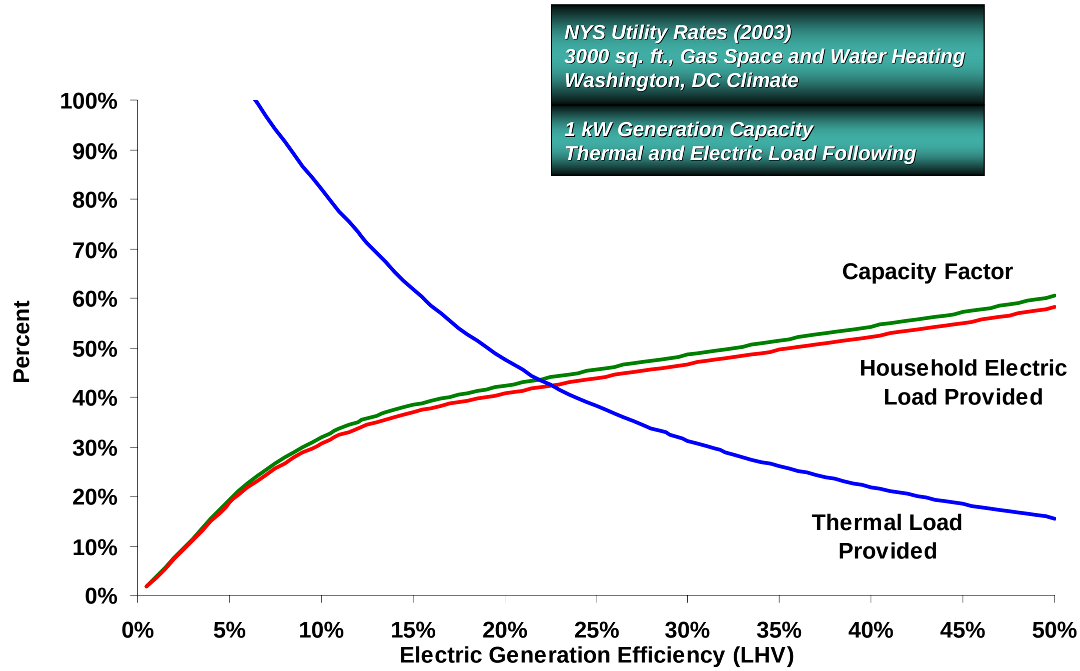


Figure 3-9: Impact of Generation Efficiency on Load Provided and Capacity Factor

Figure 3-10 shows simple payback periods (based on 2003 average New York State utility rates) for various installed-cost premiums as a function of electric generation efficiency. By installed-cost premium, we mean the installed cost of the Micro-CHP system, less the installed cost of the household's alternative investment (for example, the installed cost of a furnace and a standby generator). A furnace and standby generator cost at least $6000 installed (assuming straight forward installations). Simple payback periods are roughly 6 years for generation efficiencies of 15 to 20 percent (LHV) and installed-cost premiums of $2000. Payback drops to roughly 3 years if the installed-cost premium is $1000.

Figure 3-11 shows how annual energy-cost savings vary with utility rates. We analyzed three rate scenarios (2003 averages for New York State, California, and the nation) using electric and thermal loads for the Washington, DC area. As discussed above, annual savings using New York State rates vary from about $320 to $355 for generation efficiencies ranging from 15 to 20 percent (LHV). This drops to about $275 to $300 for California rates, and about $155 to $170 for average U.S. rates. Not surprisingly, the energy-cost savings are sensitive to utility rates.

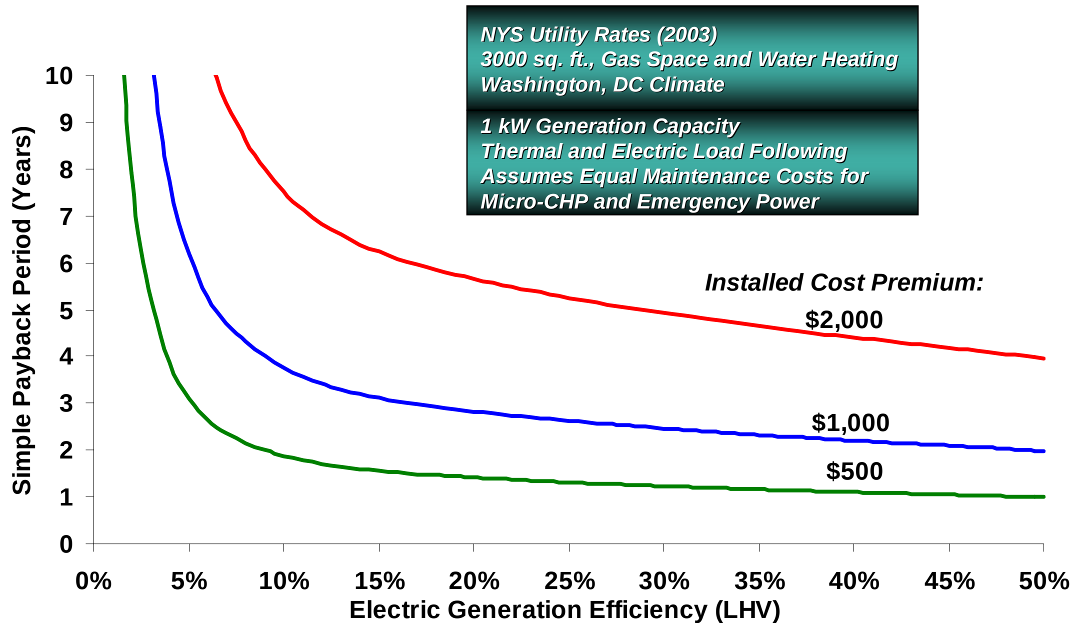


Figure 3-10: Simple Payback Period Based on Energy-Cost Savings

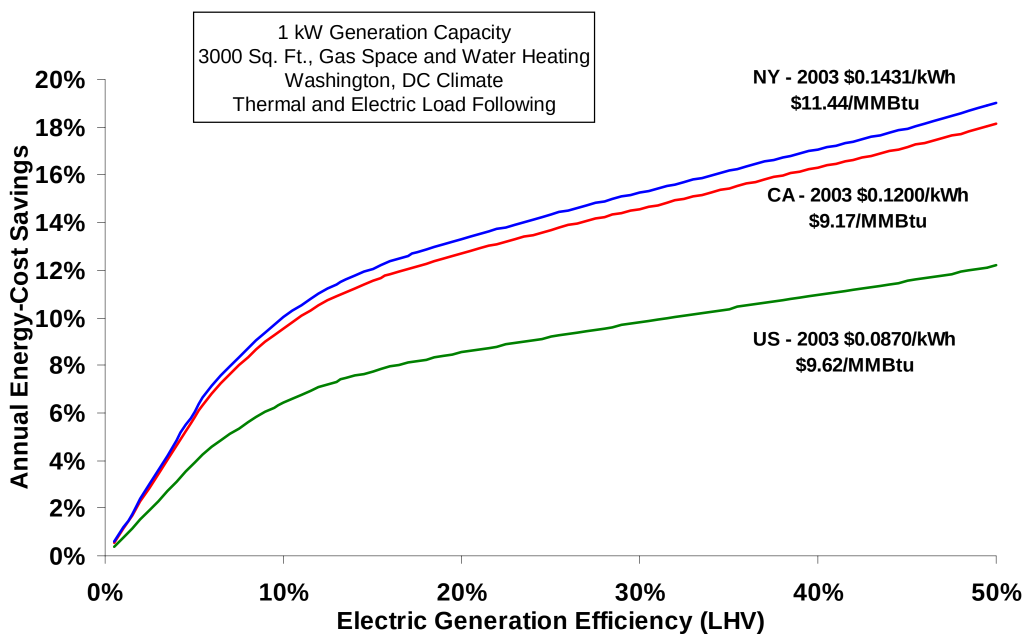


Figure 3-11: Annual Energy-Cost Savings for Various utility Rates (Washington, DC Loads)

3.2 Prime-Mover Assessment

One of the objectives of Phase IA was to select a prime mover[7] for the proof-of-principle design under Phase IB. In theory, there are a multitude of prime movers that could be used in Micro-CHP systems, including:

- Internal-Combustion Engines (ICE);
- Stirling engines (free piston and kinematic);
- Fuel cells (Proton-exchange membrane, solid oxide, and others);
- Rankine cycles (steam and organic);
- Thermophotovoltaic arrays;
- Thermoelectric devices; and
- Renewables (such as solar photovoltaic).

Long-life ICEs are currently the most common prime mover used in Micro-CHP systems, but Stirling engine Micro-CHP systems are being introduced in Europe. Our scope of work called for considering both the long-life ICE and the Stirling Engine. Table 3-6 compares the key characteristics of each prime mover for the Micro-CHP application. As suggested in the table, selection of prime mover requires consideration of other system characteristics. Prime-mover selection is discussed in Section 4.3 below, in consideration of other system characteristics.

Table 3-6: Summary of Prime-Mover Characteristics for Micro-CHP Applications

	IC Engine (Long Life)	Kinematic Stirling	Free-Piston Stirling
Representative Model	Honda GE 160V	Whisper Tech WhisperGen AC	TIAX MicroPower Prototype
Electric Generation Capacity (kW)	1	About 1	0.7
Electric Generation Efficiency at Full Load (LHV)	20%	11% for DC unit (AC unit may be lower[a])	16 to 22%
Specific Power (W/kg)[b]	N/A	About 9[c]	37 to 53
Emissions (ppm):			
NO_x	< 60	50 to 150	< 60
CO	N/A	100 to 400	< 100
Noise (dB(A) @ 1 m)	44[d]	63	< 55
Maintenance Interval (Hours)	6000	2000 to 3500	5000+
Commercial Availability	15,000 to 20,000 Honda 1 kW_e units installed in Japan. Few long-life ICEs available between 1 kW_e and 5 kW_e	WhisperGen is in low-volume sales	TIAX unit in prototype stage; SunPower (Microgen) close to commercial introduction in Europe

a) Results from Canadian test houses showed about 6 to 7 percent generation efficiency [CCHT 2003; Table 3].
b) For prime mover and power generation assembly. Does not include heat-recovery system.
c) Estimate based on specifications for marine DC unit.
d) With sound enclosure.

[7] The prime mover is the device that converts fuel to mechanical energy, or directly to electrical energy.

3.3 Load-Management Assessment

The performance assessment discussed in Section 3.1 above shows that almost all of the energy-cost savings associated with Micro-CHP can be achieved with a generation capacity as low as 1 kW. It is a premise of our design approach that a relatively small generator (1 – 2 kW) will be adequate for a significant portion of the U.S. market. However, we also view the provision of emergency power generation as a key design requirement. We assume that the target household is primarily concerned with powering only essential (or critical) electric loads during a power outage. Even with this limitation, some type of load management system, including electric energy storage, will be necessary. This is illustrated in Table 3-7, which compares critical loads for two scenarios—a suburban household and a rural household. Without load management, the suburban household would require a 3.1 kW generator and the rural household would require a 7.0 kW generator to power critical loads. With load management, the capacity requirement could be reduced to 0.8 kW for the suburban household and 1.0 kW for the rural household. Of course, the examples are not worst-case scenarios, even for households using gas-fired appliances. For example, some lighting, television, home computer, and/or home medical devices may be considered critical loads[8]. Also, as discussed below, electric energy storage and user-controlled load prioritization can eliminate the need for automatic load sequencing in most situations.

Table 3-7: Critical Electric Loads for Hypothetical Suburban and Rural Households

<table>
<tr><th colspan="3">Suburban Scenario</th><th colspan="3">Rural Scenario</th></tr>
<tr><th rowspan="2">Load</th><th colspan="2">Typical Power Draw, kW</th><th rowspan="2">Load</th><th colspan="2">Typical Power Draw, kW</th></tr>
<tr><th>Continuous</th><th>Start-Up</th><th>Continuous</th><th>Start-Up</th></tr>
<tr><td>Refrigerator</td><td>0.3</td><td>0.9</td><td>Refrigerator</td><td>0.3</td><td>0.9</td></tr>
<tr><td>Furnace</td><td>0.8</td><td>2.2</td><td>Furnace</td><td>0.8</td><td>2.2</td></tr>
<tr><td rowspan="3">Capacity Required, kW</td><td>No Soft Start</td><td>3.1</td><td>Freezer</td><td>0.3</td><td>0.9</td></tr>
<tr><td>With Soft Start[a]</td><td>1.1</td><td>Well Pump or Sump Pump</td><td>0.6 to 1.0</td><td>2.0 to 3.0</td></tr>
<tr><td>With Soft Start and Load Sequencing[b]</td><td>0.8</td><td rowspan="3">Capacity Required, kW</td><td>No Soft Start</td><td>7.0</td></tr>
<tr><td colspan="3" rowspan="2"></td><td>With Soft Start[a]</td><td>2.4</td></tr>
<tr><td>With Soft Start and Load Sequencing[b]</td><td>1.0</td></tr>
</table>

a) Assumes that the soft-start mechanism can completely eliminate in-rush current spike.
b) Assumes only one critical load operated at any given time. Automatic load sequencing is not our recommended approach to load management.

To gain further understanding of the functional requirements of a load-management system for Micro-CHP, we developed and tested a load-management algorithm, including a user interface. We then ran the test using TIAX's PlaceLab, a highly instrumented

[8] In warm, humid climates, air conditioning may be considered critical. However, as with homes having electric space- and water-heating systems, these homes are not part of the target market for this Micro-CHP system.

living space operated jointly by TIAX and the Massachusetts Institute of Technology (MIT). A participant lived in PlaceLab for eight days, during which we simulated a series of power outages and the responses of Micro-CHP systems having several different generation and electric-energy-storage capacities. We also provided a user interface that allowed the participant to continue using some non-critical loads, but prompted the participant to turn off non-critical loads if the simulated energy storage system fell below 50 percent state of charge. The results were useful in selecting the product specifications for the proof-of-principle design.

3.4 Packaging Concept Evaluation

We conducted a trade-off study comparing the key packaging options, including:

- Should the prime mover be located inside the home or outside?
- Should the prime mover be air cooled or water cooled?
- If the prime mover is located inside, how is heat rejected to the outside air when operating during a power outage and there is excess thermal energy?
- Should we provide water heating and space heating, or just space heating?
- If the prime mover is inside, should it be integrated with the air-handling unit, or kept separate?
- Should heat be recovered from the prime-mover exhaust using water or air?

We assumed that the system recovers combustion exhaust heat. Otherwise, we are unlikely to achieve thermal performance on par with a conventional furnace.

The results of our packaging trade-off study suggest that the favored packaging concept (see Figure 3-12) has the following characteristics:

- Prime mover installed inside, packaged separately from the air handling unit, and is water cooled;
- Water cooling loop for the engine is also used to capture heat from combustion exhaust;
- Domestic water heating is not provided; and
- Excess heat is rejected through an outdoor heat-dump radiator.

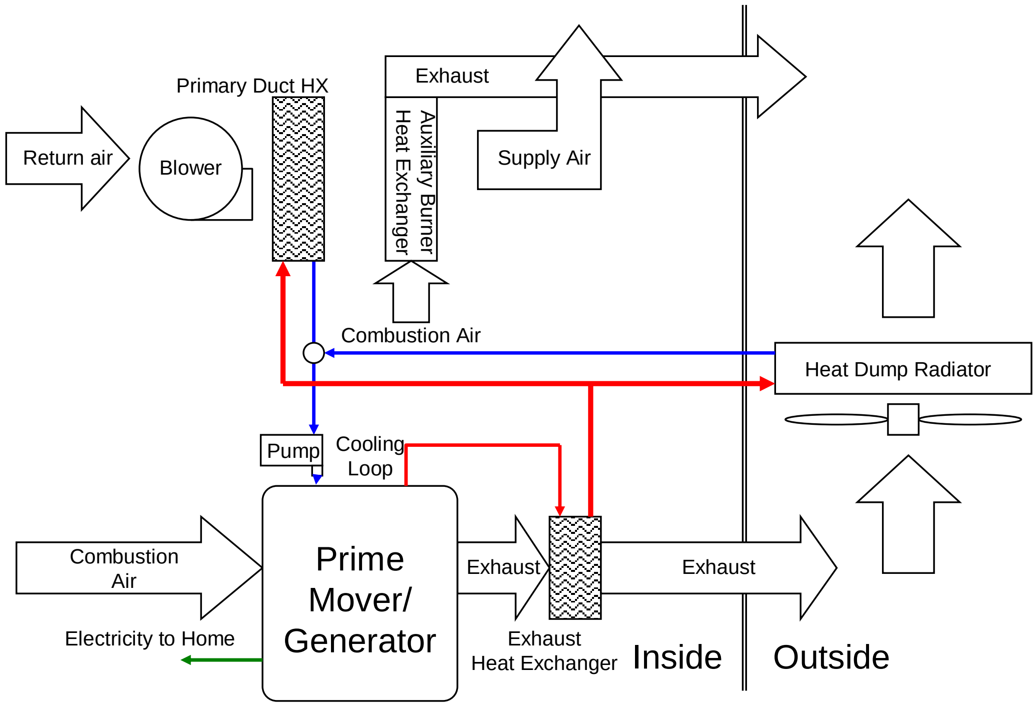


Figure 3-12: Preferred Micro-CHP Packaging Concept

The key factors influencing this selection were:

- Placing the prime mover indoors shortens piping runs (reducing thermal losses) and coolant pumping requirements (reducing parasitic electric loads);
- Packaging the prime mover separately from the air-handling unit provides greater installation flexibility (probably easier to place two items rather than one large item), and probably permits use of a standard air-handler design (only need to add a heat exchanger);
- Eliminating domestic water heating simplifies system design and installation, while reducing energy-cost savings by only about 20 percent; and
- Placing the heat-dump radiator outdoors reduces the size of the penetrations needed in the home envelope and lowers the fan power needed to reject heat (no pressure drop through ducting).

4. Product Specification for Phase IB

Based on a combination of the market research results and the technology assessment documented above, we established the product specifications for the proof-of-principle design to be completed under Phase IB. The product specification is summarized in Table 4-1, and the rationale for each specification is discussed below.

Table 4-1: Summary of Detailed Product Specification for Phase IB

Characteristic	Specification
Electric Generation Capacity	1 to 2 kW (specified under Phase IB)
Electric Generation Efficiency	15% (LHV) minimum
Electric Energy Storage Capacity	As required
Prime-Mover Type	Free-Piston Stirling Engine
Packaging	Prime Mover (PM) located indoors PM packaged separately from air handler PM water cooled Engine coolant also recovers heat from combustion exhaust Excess heat rejected through outdoor heat-dump radiator Space-heating only (no domestic water heating)
Fuel Type(s)	Natural gas and propane
Installed-Cost Target (High-Volume Production)	$6000 (revised under Phase IB)
Interval for Routine Maintenance	Annual

4.1 Generation Capacity, Generation Efficiency, and Energy Storage Capacity

As shown in Section 3.1 above, a 1 kW generation capacity will achieve most of the energy-cost savings potential for households having gas-fired appliances. The results of our testing (Section 3.3 above) suggest that a 1 kW generator with electric energy storage should be adequate to power most households (assuming gas-fired appliances) during a power outage. However, acknowledging that some households will have unique critical loads, and that the power requirements of common critical loads vary, we specify the generation capacity as 1 to 2 kW to allow some contingency.

While the analyses conducted in Section 3.1 above are based on a 1 kW generation capacity, Figure 3-8 clearly shows that energy-cost savings do not increase significantly for generation capacities over 1 kW. Therefore, a 2 kW generation capacity will not significantly improve energy-cost savings in most households. The final selection of generation capacity under Phase IB will consider the incremental cost of increasing generation capacity as well as the performance characteristics of the electric energy storage system selected.

Figure 3-7 above shows that electric generation efficiencies over 15 percent (LHV) provide diminishing energy-savings benefits, especially if domestic water heating is not provided. Therefore, we set the minimum generation efficiency at 15 percent (LHV).

4.2 Packaging

As outlined in Section 3.4 above, our starting point for packaging is:

- Prime mover installed inside, packaged separately from the air handling unit, and is water cooled;
- Water cooling loop for the engine is also used to capture heat from combustion exhaust;
- Domestic water heating is not provided; and
- Excess heat is rejected through an outdoor heat-dump radiator.

4.3 Prime-Mover Type

The prime-mover assessment in Section 3.2 above compares the various prime-mover options: long-life ICE, kinematic Stirling, and free-piston Stirling. The only commercially available, long-life ICE under 5 kW_e that we uncovered is the 1 kW_e Honda engine developed for Micro-CHP. Likewise, kinematic and free-piston Stirling engines under 5 kW_e are generally about 1 kW_e or less. Regardless of the prime-mover type selected, additional prime-mover development will likely be needed. Therefore, commercial availability was not a key differentiator.

We selected Stirling over ICE because:

- Stirling engines, having much lower carbon monoxide emissions, are much safer for indoor installations. Even with proper venting, exhaust leaks to the indoors can occur;
- Stirling engines are inherently quieter, requiring less sound attenuation, again facilitating indoor installation;
- Stirling engines have greater fuel flexibility due to external combustion; and
- With fewer moving parts, external combustion, and no oil sump, Stirling engines should ultimately require less maintenance and be more reliable.

We further selected the free-piston Stirling engine (FPSE) over the kinematic Stirling engine (KSE) because FPSE:

- Is much smaller and lighter;
- Is inherently more reliable because the working fluid is hermetically sealed; and
- Is quieter.

4.4 Cost Targets

Our preliminary installed cost projection, based on achieving high production volumes, was $6000. We later revised the cost projections based on the proof-of-principle design (see Section 6.4).

4.5 Maintenance Interval

Households generally expect that major appliances (furnaces and air conditioners) to require annual routine maintenance. Households are unlikely to accept maintenance intervals that are shorter than what they are already accustomed to for other major appliances. Therefore, we set the interval for routine maintenance at one year.

5. Market Potential

Competing products and market potential are discussed below.

5.1 Competing Products

The dominant micro-CHP manufacturers currently are:

- SenerTec Dachs, Germany (part of the Baxi Group): 5.5 kW_e, using long-life ICE; and
- Honda, Japan: 1.0 kW_e, using long-life ICE.

Several other manufacturers are ramping up production capability for the European market, including products with free-piston and kinematic Stirling engines. Honda and Climate Energy announced their partnership in April 2005 to offer a Micro-CHP system for the U.S. market.

5.2 U.S. Market Potential

With a 15 percent (LHV) generation efficiency, providing space heating only, and using New York State utility rates, the annual energy-cost savings associated with the Micro-CHP system is about $255 (see Figure 3-7 above). Even with relatively favorable utility rates, the energy-cost savings alone are unlikely to justify the installed-cost premium compared to the purchase of a conventional furnace. To achieve market success, the perceived value of back-up power and the environmental benefits will also need to influence the purchase decision.

6. Proof-of-Principle Design

The proof-of-principle design task incorporated three main subtasks:

- Prime-mover evaluation (receiving most of the effort);
- Electrical design; and
- Mechanical design.

Each of these subtasks is discussed below.

6.1 Prime-Mover Evaluation

The key activities under this subtask were:

- Select free-piston Stirling engine (FPSE) technology;
- Finalize generation capacity; and
- Evaluate FPSE design for the Micro-CHP application.

Each of these activities is discussed below.

6.1.1 Technology Selection

As summarized in Section 4 above, we selected free-piston Stirling engine (FPSE) technology for the prime mover under Phase IA. Under Phase IB, we selected the specific FPSE technology to use. We considered FPSE technologies available from three major developers in the capacity range of interest (1 to 2 kW):

- Infinia Corporation (formerly Stirling Technology Corporation);
- Sunpower, Inc. (technology licensed to Microgen Energy LTD); and
- TIAX LLC.

Table 6-1 compares the key differentiating characteristics of the three FPSE technologies. Compared to the other two, the TIAX design is simpler and inherently lower cost, but this design was developed for portable power applications and requires some design modifications to achieve the life required for Micro-CHP applications. Perhaps the key advantage of the TIAX design, which weighed heavily in our decision, is having direct access to the technology developers and the confidential details of the design. Based on the above, we selected the TIAX FPSE design, and included an activity to evaluate the design for longer-life applications (see Section 6.1.3 below). Figure 6-1 illustrates the key characteristics of the TIAX FPSE design.

Table 6-1: FPSE Technology Comparison

Design Characteristic	Infinia	Sunpower	TIAX
Bearings and Piston Seal	Flexure bearings and clearance seal	Quasi-aerostatic gas bearings and planar springs	Coated piston and clearance seal
Configuration	Gamma[a]	Beta[b]	Gamma[a]
Comments	• Costly and difficult to align during assembly • Requires larger diameter piston due to limited stroke	• Costly • Multiple springs required • Requires larger diameter piston due to limited stroke • Shaft connecting the displacer piston to the spring goes through the power piston	• Currently designed for 5000 hour life. Requires design modifications to achieve Micro-CHP life requirements

a) Displacer and power pistons are in separate cylinders.
b) Displacer and power pistons are in the same cylinder.

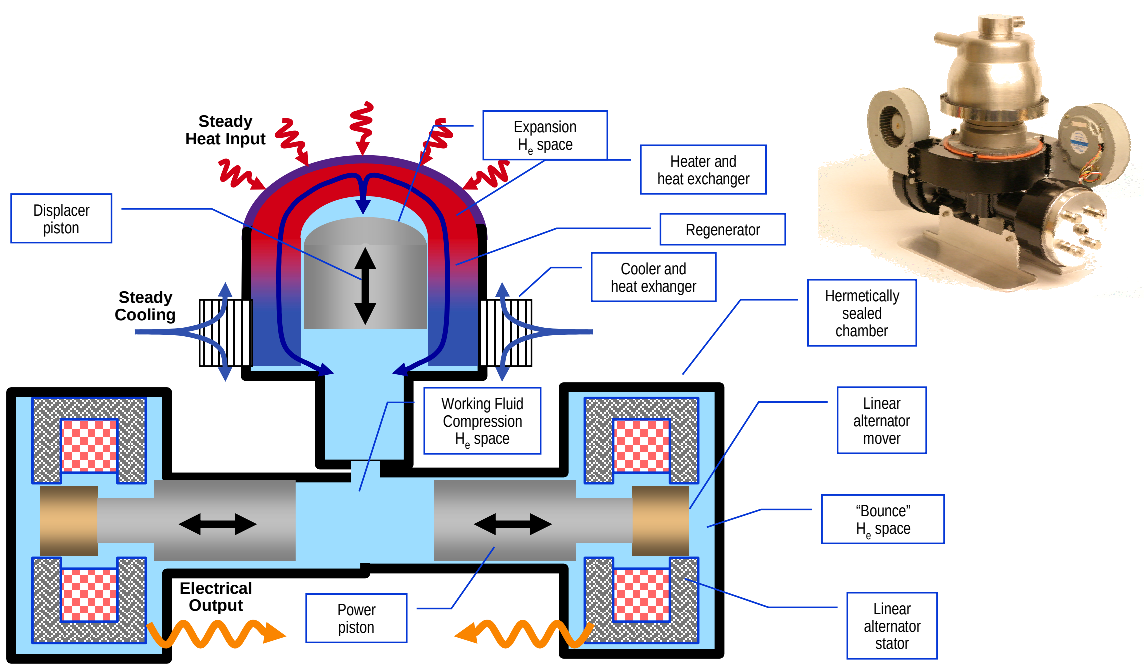


Figure 6-1: Key Characteristics of the TIAX FPSE Design

6.1.2 Generation Capacity

The Phase IA analysis (see Section 4 above) narrowed the desired generation capacity range to between 1 and 2 kW. Under Phase IB, we selected the specific generation capacity for use in the Micro-CHP system.

Three system characteristics must be considered simultaneously—generation capacity, short-term energy storage and long-term energy storage. A capacitor will provide short-term power for motor start and other instantaneous current demands. A battery energy storage system will provide long-term energy storage to accommodate loads when demand temporarily exceeds generator capacity. The generator and battery should be sized to avoid battery charge falling below 50 percent for 95 percent of the time in an average gas-heated home.

Two components contribute to the overall Micro-CHP system capacity:

- Usable generator capacity: The maximum amount of electric power the CHP system can generate continuously. The expected range for rated capacity is between 1 and 2 kW. The rated capacity should, at a minimum, be greater than the power requirements for generator parasitics and a standard sump pump; and
- Usable storage capacity: The CHP system will have battery storage to help meet peak power demands and to supplement capacity during grid outages. We estimate the necessary usable storage capacity is between 1 and 4 kWh (based on the assessment discussed in Section 3.3 above), with a power rating between 3 and 10 kW. With a 1 to 2 kW generator, the Micro-CHP system could provide 4 to 12 kW for limited periods.

To provide further insight into battery and generator sizing, we conducted an analysis using a representative load profile for a 3000 sq.ft., Washington, DC home. The results (not included herein) provide the unique set of battery and generator capacity combinations that will meet 100 percent of this home's electric power needs, excluding air-conditioning loads. The results can be used to complete the system based on a size input from other analysis or to select a well balanced system for emergency operation. Based on these results, we chose a generation capacity of 1.5 kW and the appropriate storage capacity. The generator and energy storage system together provide leeway for short-term spikes resulting from simultaneous use of high-power loads such as a sump pump, microwave, toaster, hair dryer, etc.

6.1.3 Life Extension

To date, TIAX's FPSE design efforts have focused on portable power applications having life requirements of no more than about 5000 hours. However, the Micro-CHP application requires a 20,000 to 40,000 hour life expectancy. We, therefore, evaluated design modifications that will extend the life of the TIAX FPSE design (which are not reported in this summary version) with promising results.

6.2 Electrical Design

Key activities under this subtask were:

- Specify grid interface;
- Select energy storage technology; and
- Select and size power-conversion components.

Each of these activities is discussed below.

6.2.1 Grid Interface

We evaluated two systems for grid interface—a grid-parallel system and a grid-supported system. The characteristics of each are listed in Table 6-2. We assumed that net metering (selling electricity back to the utility, usually at full retail price) will not be available for most fossil-fuel-fired Micro-CHP installations. Figure 6-2 illustrates the grid-parallel system. The grid-supported system is proprietary, and is not detailed herein. Table 6-3 outlines the relative merits of each system. We selected the grid-supported system because we believe that simplifying the grid interface is critical to simplifying the utility approval process, which has historically been a significant barrier for residential distributed generation and CHP systems. Further, the energy-cost penalty for the grid supported system is modest.

Table 6-2: Characteristics of Grid-Interface Systems Evaluated

Grid-Parallel System (Baseline)	Grid-Supported System
• Conventional renewable DG interface (but without net metering) • Grid and Micro-CHP work in parallel to supply household loads • Requires protection against back feeding the grid if generation exceeds household loads • Requires transfer switch to disconnect the house from the grid during a power outage	• Isolates Micro-CHP generator from the grid • Micro-CHP generator powers only selected household loads • Provides uninterrupted power when grid power fails

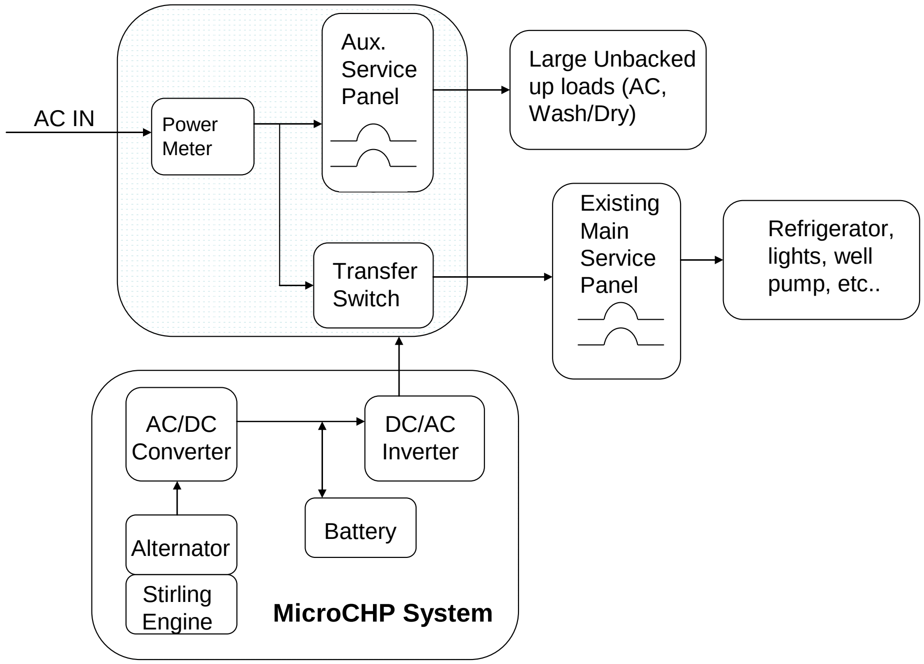


Figure 6-2: Grid-Parallel Grid-Interface System

Table 6-3: Relative Merits of Each Grid-Interface System

Advantages of Grid-Supported System	Disadvantages of Grid-Supported System
• Inherently grid isolated: – No automatic transfer switch and associated hardware to disconnect from the grid – Simpler and faster utility approval process – Fewer issues with non-standardized utility interconnection requirements	• Requires some additional components • \$20 to \$50 per year reduction in energy-cost savings (from about \$250 to about \$200 – \$230) associated with power-conversion losses alone[a] • May lower battery life—more battery charge/discharge cycles

a) For 3000 sq.ft. home in Washington, DC. Some losses may provide useful space heating.

6.2.2 Energy Storage

The energy storage system performs several important functions, including:

- During emergency operation, provides supplemental generation capacity to meet peak loads and allow more loads to operation simultaneously;
- During emergency operation, provides a source for additional power during sudden increases in load (while generator ramps up to meet the load); and
- During either emergency or normal operation, provides a sink for excess power generated during sudden drops in load (while generator ramps down).

The purpose of this activity was to select the energy storage technology. We considered two battery chemistries for energy storage—lead acid and lithium ion. We selected lead acid because:

- The weight and size reduction associated with lithium ion is not a big advantage for stationary applications;
- The greater cycle life associated with lithium ion does not reduce battery size requirements because:
  - Emergency power requirements drive the battery capacity requirements; and
  - Depth of discharge is allowed to exceed normal limits during emergencies; and
- Projected costs for a lithium-ion battery system are significantly higher, compared to those for a high-end lead-acid battery system.

Clearly, cost considerations were the primary factor in our selection.

We verified that high-end lead-acid batteries (such as Genesis Pure lead-acid batteries—see Figure 6-3) can meet the three major life requirements for a ten-year replacement cycle, as summarized in Table 6-4.

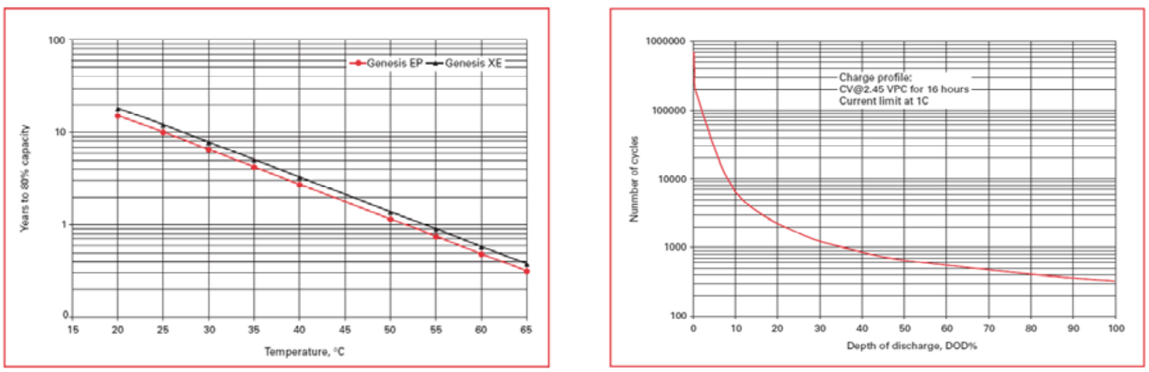


Figure 6-3: Life Characteristics of Genesis Pure Lead-Acid Batteries

Table 6-4: Life Characteristics of Genesis Pure Lead-Acid Batteries Compared to Application Requirements

Characteristic	Life Expectation for Genesis Pure Batteries	Life Requirement for Micro-CHP
Float Life (Life at Full Charge)	12 years at normal basement temperatures (20°C)	10 years
Deep Charge/Discharge Cycle Life (to 50% of Full Charge)	600 cycles	Less than 100[a]
Normal Charge/Discharge Cycle Life (0.1% of Nominal Capacity)	200,000 or greater	Roughly 100,000

a) Estimated. Deep charge/discharge cycles occur only during emergency operation.

6.2.3 Power Conversion

The power-conversion system converts and inverts both generated power and grid power for selected loads and provides energy storage. We developed a conceptual design for the power-conversion system that is consistent with the grid-supported grid interface system (discussed in Section 6.2.1 above). Key components of the power-conversion system are:

- DC link;
- Power-factor-corrected rectifier (PFC) to convert grid power to DC power while providing constant load to the grid connection;
- Synchronous power converter (SPC) to convert the 80 Hz (nominal) AC output from the FPSE linear alternators to DC power;
- DC/DC buck boost converter to step up the voltage from the batteries to the DC bus; and
- Inverter to invert power from the DC bus to 60 Hz, pure-sine-wave, AC power.

6.3 Mechanical Design

Key activities under this subtask were:

- Select and size balance-of-plant components (heat-recovery coil, heat-dump radiator, pump, fan, blower, piping, etc.);
- Develop packaging concept; and
- Develop conceptual drawings.

Each of these activities is discussed below.

Based on the 1.5 kW generation capacity selected (see Section 6.1.2 above), we developed the conceptual design for the FPSE prime mover. We maintained the T-shape design configuration of the current TIAX prototype (two, horizontally opposed, power pistons and a vertically oriented displacer). Figure 6-4 illustrates the 1.5 kW design.

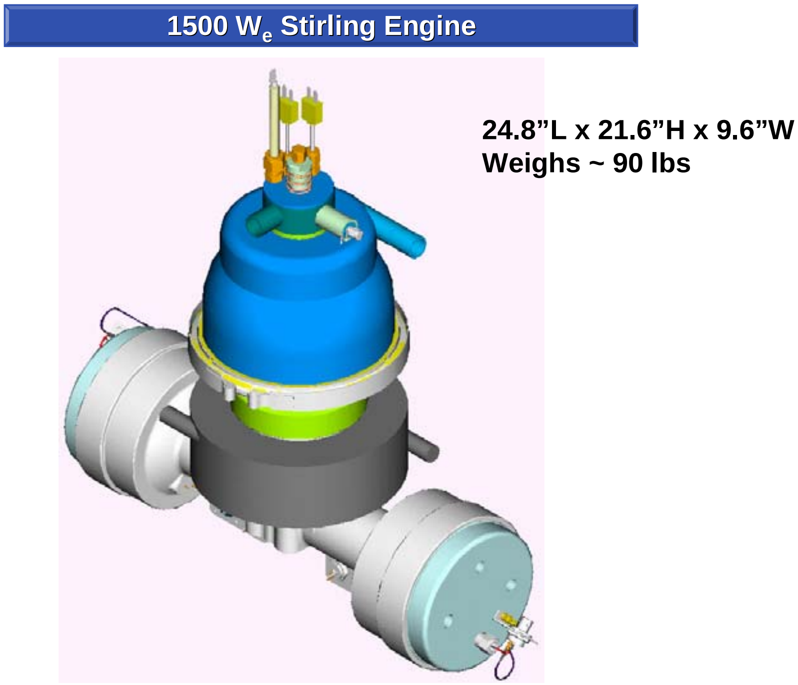


Figure 6-4: 1.5 kW FPSE Generator

Based on the estimated dimensions of the 1.5 kW FPSE and other major components, we conceptually designed the packaging for the Micro-CHP system. For flexibility and ease of installation (including lifting and fitting the system through standard door openings), we elected to package the furnace and heat-recovery coil separately from the generator and power-conversion system. Figures 6-5 and 6-6 show the resulting generator and furnace/heat-recovery coil packages, respectively. Figure 6-5 shows two concepts for packaging of the generator and power-conversion system—one having the heat-dump radiator inside the package and cooling air ducted from outdoors, and the other having the heat-dump radiator located outdoors. Under Phase IA, we determined that the heat-dump radiator should be located outdoors, however, we verified that decision under Phase IB. Table 6-5 compares the two packaging concepts. The results suggest that placing the heat-dump radiator outdoors is preferable, largely because it minimizes parasitic power consumption, which impacts available generation capacity during emergency operation.

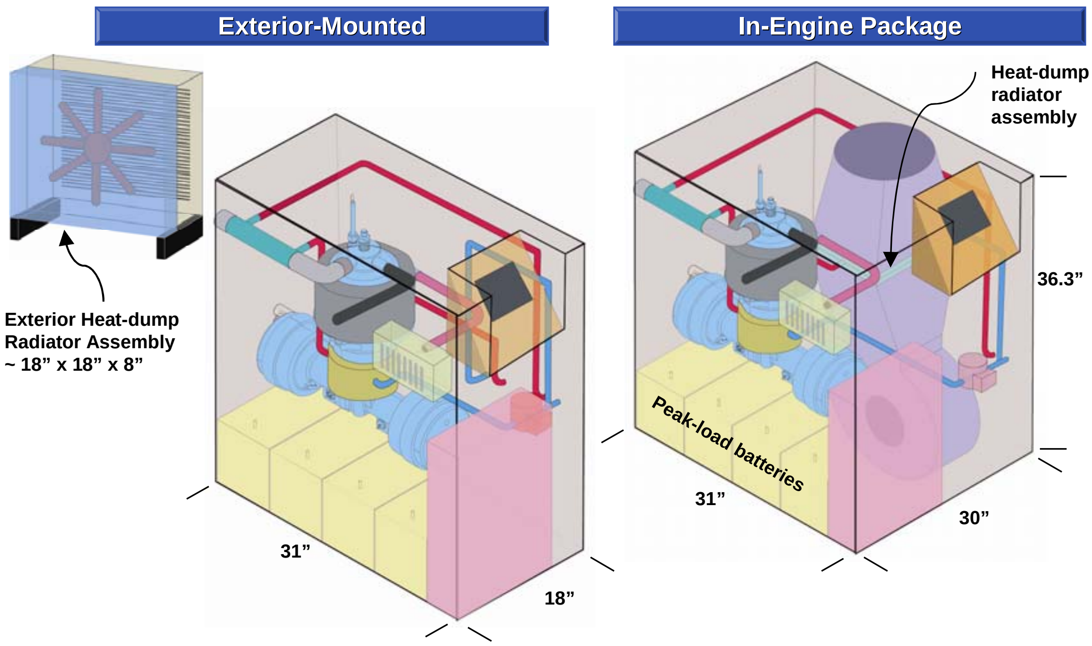


Figure 6-5: Conceptual Packaging of the Generator and Power-Conversion System (Two Options)

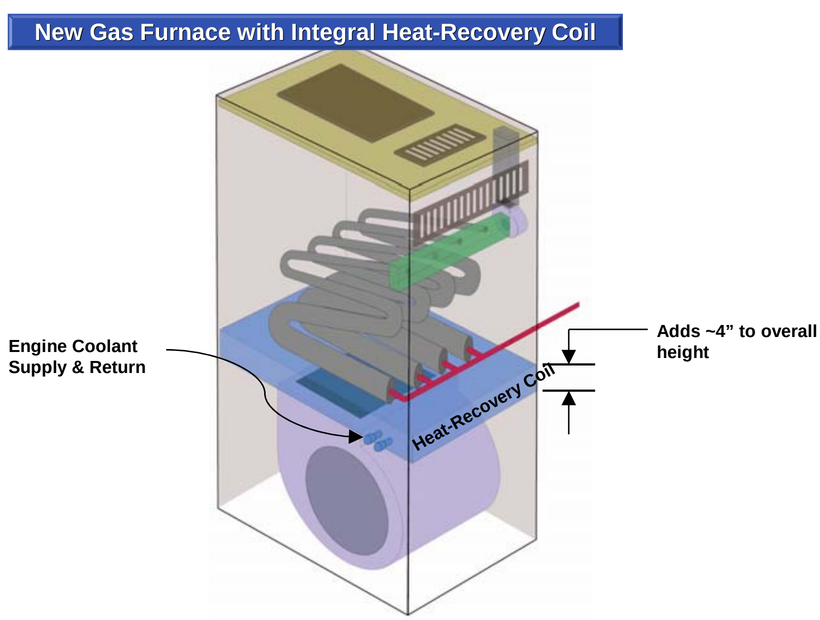


Figure 6-6: Conceptual Packaging of the Furnace and Heat-Recovery Coil

Table 6-5: Comparison of Indoor and Outdoor Installation of the Heat-Dump Radiator

	Radiator Installed Outdoors	Radiator Installed Indoors
Installation Challenges	Radiator mounted separately, outdoors	Two, 10-inch diameter air ducts to outdoors. Must avoid excessive pressure drop in ducting.
Coolant Freeze Protection	Coolant loop must use ethylene glycol or heat tracing	Freeze protection not required
Maintenance	Annual coil inspection, with cleaning if needed	Annual inspection of duct openings, filter, with cleaning if needed
Parasitic Power Consumption during Emergency Operation	**~ 0.12 kW (fan & circulator)**	**~ 0.41 kW (blower & circulator)**

Figure 6-7 illustrates a typical basement installation of the Micro-CHP system, including the three major packages—the engine package, furnace with integral heat-recovery coil, and the heat-dump radiator.

- **Engine Package** – contains Stirling engine, control and power electronics, batteries, and coolant circulator / 3-way valve.
- **Heat-Dump Radiator -** used only during non-heating season when emergency back-up is needed.
- **Gas Furnace with Integral Heat-Recovery Coil** – standard gas furnace modified to include a hydronic coil between the blower and the gas burners, adding about 4” to the overall height.

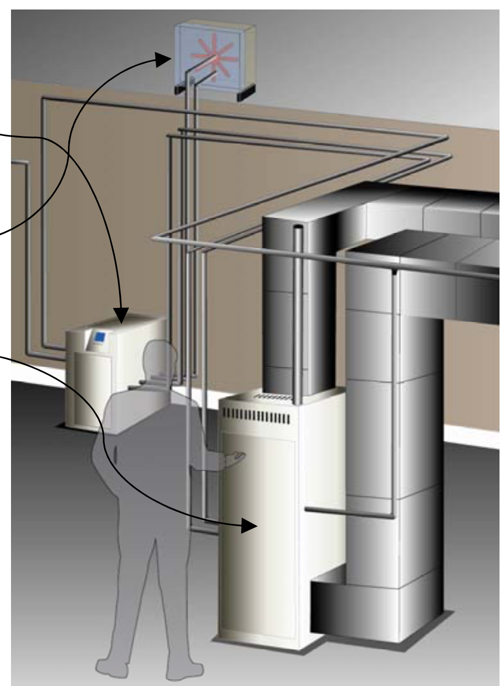


Figure 6-7: Typical Basement Installation of the Micro-CHP System

We also developed a conceptual design for the user interface (see Figure 6-8). The user interface is modeled after an electronic thermostat (which is now commonly used in US homes). An LCD display and LED status lights informs the user when grid power has failed, indicates the charge status of the energy storage system, and allows users to select priority loads during a grid outage.

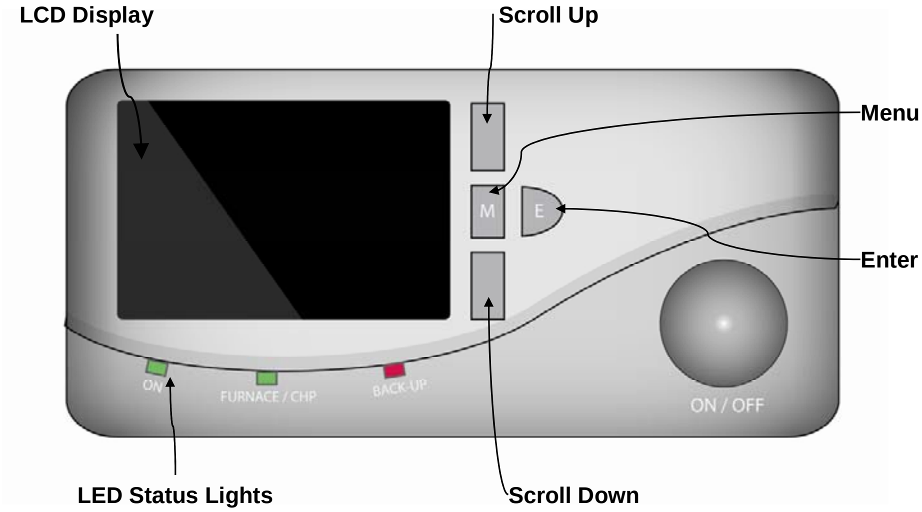


Figure 6-8: Conceptual Design of the Micro-CHP System User Interface

6.4 Refined Cost Estimate

In Phase IA, we developed a preliminary cost projection for the Micro-CHP system (see Section 4.4). After completing the conceptual design under Phase IB, we updated the cost projection. Key revisions are in the cost of the power-conversion system and the energy storage system. The revised projection indicates that the installed cost of the Micro-CHP system will be about $7000 (about $1000 higher compared to our Phase IA target) in high-volume production. Depending on the cost of a conventional furnace and standby generator, the Micro-CHP system will have an incremental cost of between $0 and $2000. With annual energy-cost savings on the order of $200, payback periods will likely be between 0 and 10 years.

7. Commercialization Strategy

We kept the commercialization strategy general so that it will be applicable to a variety of potential manufacturing partners. Key activities were to:

- Define the geographic focus for the U.S.;
- Outline a manufacturing strategy and an approach to secure manufacturers; and
- Outline additional market research needs.

While the market for Micro-CHP systems is global, there are important differences between the U.S. market the other major markets (primarily Europe and Japan). Table 7-1 lists the key differences between the U.S. market and those of Europe and Japan.

Table 7-1: Comparison of U.S. Micro-CHP Market to the European and Japanese Market

U.S. Market	Europe/Japan Markets
Energy costs are relatively low, so energy savings potential is lower	Energy costs are relatively high, so energy savings potential is higher
Net metering policies are generally limited to renewables	Net metering for CHP is more common, and growing
Greater extremes in weather and an aging grid infrastructure make emergency power capability more important	Emergency power is less valuable due to the relatively milder climates and higher grid reliability
80% of residential fossil-fuel heating systems are warm-air furnaces[a]	80% (or more) of residential fossil-fuel heating systems are hydronic

a) Estimate based on [Data Book 2005; Tables 5.6.1 and 5.6.9].

We also explored the likely geographic distribution of the U.S. Micro-CHP market. We estimated annual energy-cost savings by state, using state-average utility rates and by dividing states into three climate regions (to account for differences in thermal loads). The results are shown in Figure 7-1. The northeast presents the best market opportunity for Micro-CHP because of its concentrated population and high energy-cost savings potential (resulting from the combination of high utility rates and a long heating season).

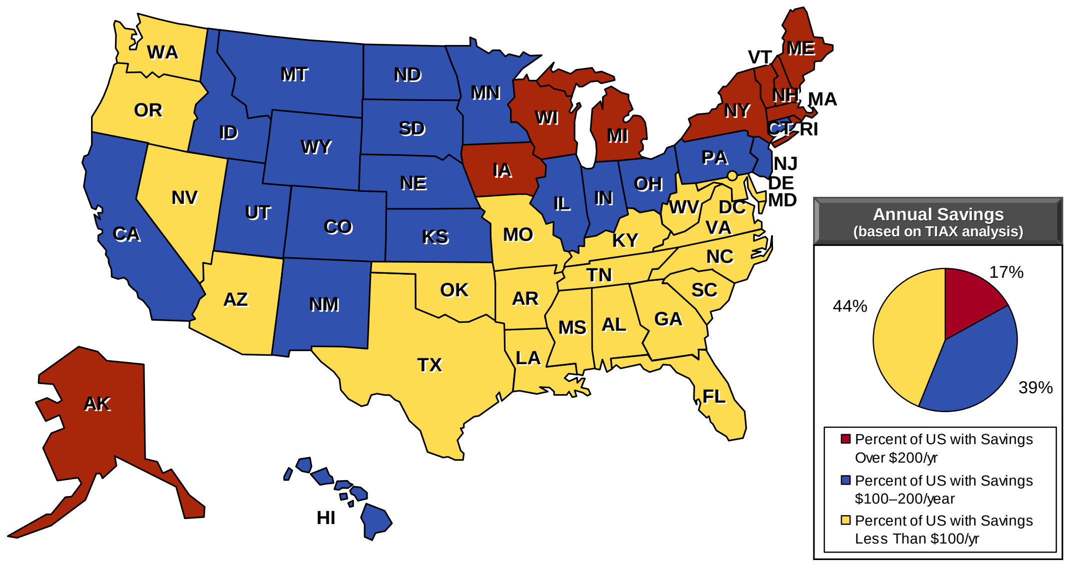


Figure 7-1: Regional Variation in Projected Energy-Cost Savings

Strong drivers of market demand have yet to develop in the U.S.; therefore, the market opportunity can only be estimated within broad ranges. Because the U.S. market will begin small, the Micro-CHP original equipment manufacturer (OEM) will likely purchase the FPSE prime mover from a supplier that is also developing FPSE for other applications. The FPSE supplier will likely need the combined potential of a range of FPSE market opportunities to justify the capital investment for a FPSE manufacturing capability. Example FPSE market opportunities are illustrated in Figure 7-2. TIAX is in active discussions with a number of major manufacturers who have interest in a broad range of applications for FPSE power systems.

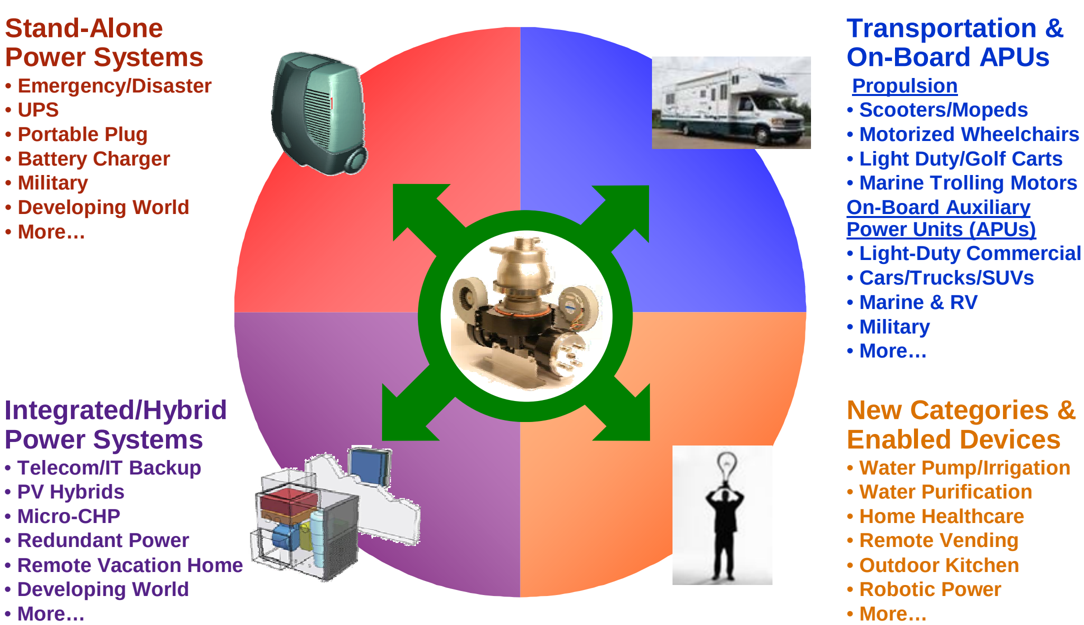


Figure 7-2: Potential Applications for FPSE Power Systems

Figure 7-3 illustrates the likely roles of the two manufacturers—the Micro-CHP OEM and the FPSE supplier. The OEM should be a major manufacturer having existing market channels and a strong brand in the HVAC and/or stand-by power markets. The key benefits of such an OEM are:

- Customers value brand name to reduce risk;
- Brand names establish quality;
- Well established service networks reduce cost, and are perceived as reputable and permanent; and
- Consumers must be able to trust manufacturers when buying long-life products (10 to 20 years).

In addition, manufacturers that emphasize premium features (such as Carrier, York, and Lennox) are better candidates for Micro-CHP compared to those that emphasize low cost (such as Goodman).

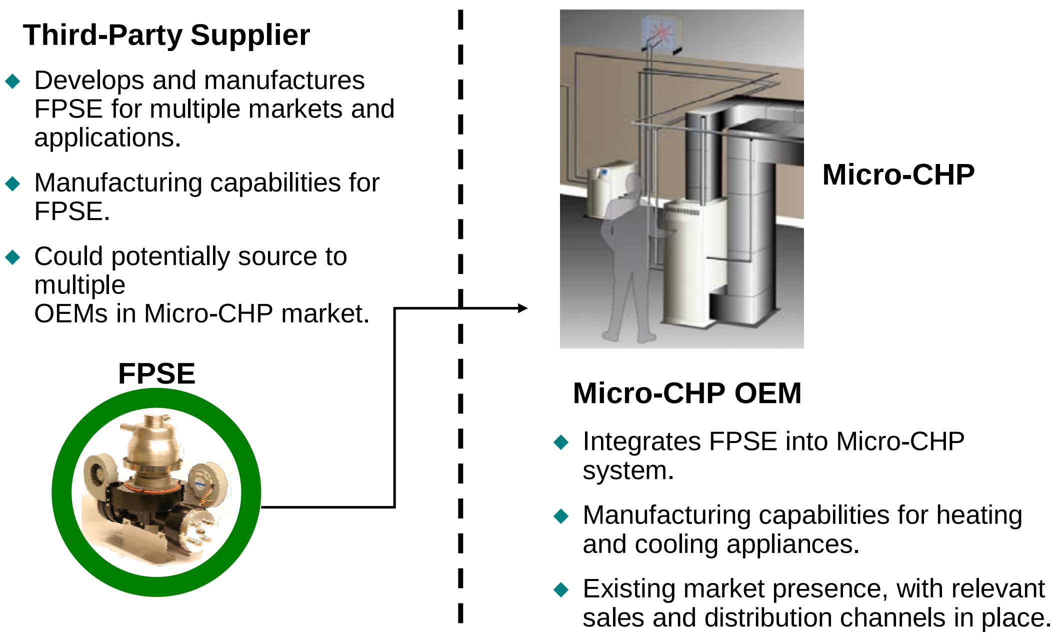


Figure 7-3: Roles of the Micro-CHP OEM and the FPSE Supplier

Because Micro-CHP is a new product that combines multiple features, we believe that further research is needed to identify target customers and optimal paths to market. Some factors to consider in designing the market research include:

- Micro-CHP can appeal to multiple customer groups:
  - Environmentally conscious consumers—saving energy is valued above and beyond only its economic value;
  - Safety/security-minded consumers—emergency power is of significant value;
  - Technology adopters—buying the latest technology is important; and
  - Utility companies—value of energy savings, peak-load shaving, and emergency back-up accrues to utilities; and

- The marketing approach to each customer group will differ:
  - Trade-offs in design and feature sets are different;
  - Communication channels to reach and educate customers are different;
  - Emphasis of specific features and benefits is different; and
  - Market and retail outlets to supply these customers are different.

8. Conclusions and Recommendations

Key conclusions from the Phase I effort are:

- The key design characteristics for the conceptual design are:
  - Prime mover/generator based on TIAX's free-piston Stirling engine (FPSE) power system, with design modifications to extend life, using liquid cooling;
  - 1.5 kW_e generation capacity;
  - 15% (LHV) generation efficiency (minimum);
  - Grid-supported grid-interface system (as defined in Section 6.2.1 above);
  - Electric energy storage using long-life, lead-acid batteries;
  - Suitable for natural gas and propane fuels;
  - Configured for households having forced-air heating systems;
  - Prime mover installed indoors, packaged with the power-conversion and energy-storage systems;
  - Furnace/air-handling unit packaged separately, including the heat-recovery heat exchanger (also installed indoors);
  - Heat-dump radiator installed outdoors using ethylene glycol coolant for freeze protection;
  - Engine coolant loop also captures heat from the combustion exhaust;
  - Provide space heating only (not domestic water heating);
  - Annual interval for routine maintenance;

- Projected installed cost for high production volumes is $7000; and

- The U.S. Micro-CHP market is best served by having a FPSE power system manufacturer supply the prime-mover/generator assembly to a Micro-CHP OEM. This allows the FPSE manufacturer to capture the market volume for all FPSE power system applications. The OEM should be a major HVAC or standby power system manufacturer having a well respected brand, and well established sales and service networks.

We recommend additional market research to identify target customers and optimal paths to market. Key considerations in designing the market research include the types of consumers who are likely to consider Micro-CHP and the marketing approach needed to address each customer group.

9. References

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