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Efficiency Analysis of Natural Gas Residential Micro-cogeneration Systems

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Many micro-combined heat and power (micro-CHP) technologies have emerged in the residential market in the recent years. However, the selection of a particular micro-CHP system for an application and investigating the trade-offs between micro-CHP and centralized power remain a problem. The present analysis compares three micro-CHP systems on the basis of energy, exergy, and marginal efficiencies. The systems feature different energy conversion technologies: Stirling engine (WhisperGen), spark-ignition internal combustion (IC) engine (FreeWatt), and polymer electrolyte fuel cell (PEFC) (EBARA Ballard). These systems are fueled by natural gas and produce power and heat for residential applications. The analysis suggests that the IC system provides the highest energy and exergy efficiencies at higher heat use (η_{energy} = 76.7%, η_{exergy} = 57.2%, and f = 0.71), while the PEFC operates at higher energy and exergy efficiencies at lower heat use ($\eta_{\text{energy}} > 29.0\%$, $\eta_{\text{exergy}} > 32.0\%$, and $f > 0.00$). The PEFC system exhibits the greatest marginal efficiency at any heat use ($\eta_{\text{marginal}} > 32.0\%$ and $f > 0.00$). Other important issues such as price, maintenance, noise, and emissions are discussed. The Stirling engine is the least expensive that requires the least maintenance. The fuel cell is the least noisy system with the least amount of emissions.

1. Introduction

Cogeneration is the simultaneous production of more than one useful form of energy (such as power and heat) from the same energy source.[1] This mode of operation often results in better use of the input energy source and offers many economic benefits. While most conventional micro-power devices reject excess heat, many new technologies have emerged that use the heat output even in small-scale residential applications. Current commercial units provide power in the 0.5−1.5 kW range and heat in the 5.0−10.0 kW range, depending upon the climate. The power is used directly or net-metered via the grid, and the heat is used for space or domestic water heating. Although micro-combined heat and power (micro-CHP) technology claims to be greener than centralized power, it is not very obvious how to select a particular micro-CHP system for an application, neither is it trivial what the trade-offs are comparing these systems to centralized power. This paper provides a tool for answering these important questions by performing energy, exergy, and marginal efficiency analyses to existing commercial micro-CHP systems.

WhisperGen, a New Zealand firm, manufactures micro-CHP units. It has developed two product lines of Stirling engines that use automotive-grade diesel fuel or natural gas, respectively. A pilot installation of the natural gas unit has been completed in 50 U.K. homes over the past 3 years, and more installations are scheduled.[2]

In 2007, American Honda Motor Co., Inc. and Climate Energy, LLC announced the official launch of FreeWatt, a new micro-CHP unit designed for residential applications. This system is fueled by natural gas and is comprised of an internal combustion (IC) engine developed by Honda and a furnace or boiler manufactured by Climate Energy. This system is being commercialized in the Northeastern U.S., where space heating is required because of the cold climate.[3]

Residential micro-CHP units based on fuel cell technology have been developed by EBARA-Ballard. The developed system uses polymer electrolyte fuel cell (PEFC) technology. EBARA-Ballard is the world's first commercial PEFC micro-CHP unit that has been developed for residential use. This unit operates on natural gas and is being considered by Tokyo Gas Co. Ltd. for large-scale implementation in Japan. In 2005, the first unit was installed at the prime minister's official residence.[4]

Many researchers have studied the cogeneration thermodynamics of large-scale power sources in terms of energy and exergy efficiencies. Kanoglu et al.[5] have suggested energy and exergy efficiency analyses for improved energy management in power plants. Rosen et al.[6,7] have developed approaches for thermodynamic assessment of integrated systems for cogeneration and district heating and cooling. Rosen[8] has established a method based on an energy and exergy analyses to compare cogeneration efficiencies for fuel cells, coal power plants, and nuclear power plants. Onovwiona et al.[9] have

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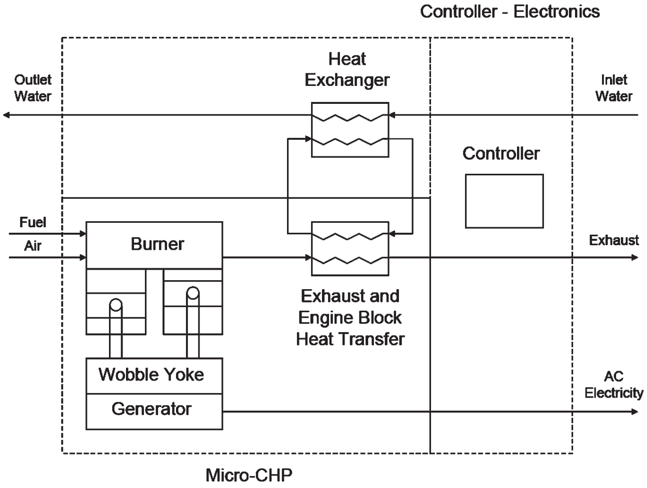

Figure 1. AC WhisperGen micro-CHP system.

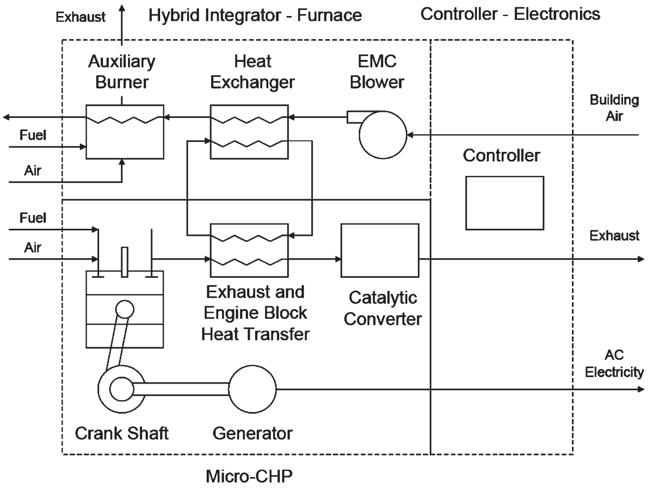

Figure 2. FreeWatt micro-CHP system.

conducted a review study of residential cogeneration systems that implement reciprocating internal combustion engines, microturbines, fuel cells, and Stirling engine technologies. Their thermodynamic assessment provides energy efficiencies for many commercial units. Harvey[10] has used the marginal efficiency approach, to be described later, in the assessment of residential cogeneration and district heating or cooling. While cogeneration in the megawatt power range has been well-studied, research has just emerged on performance assessment of residential micro-CHP units in the kilowatt range. Bonnet et al.[11] have suggested energy, exergy, and cost analyses for the potential of Ericsson engines in micro-CHP applications.

The current literature, however, lacks comparative studies for various types of power devices used for residential micro-CHP. The present study compares energy, exergy, and marginal efficiencies for three micro-CHP technologies based on natural gas. These technologies are external combustion (Stirling engine), IC engine, and PEFC. The study compares these systems and provides energy, exergy, and marginal efficiencies achieved by them. Furthermore, the systems are compared on the basis of price, maintenance requirements, noise, and emission levels.

2. Micro-CHP Systems Considered in the Analysis

2.1. Stirling Engine. The AC WhisperGen, shown in Figure 1, runs on natural gas. At rated performance, it provides 0.85 kW of electrical and 6.00 kW of thermal power. This system is comprised of a burner module, a Stirling engine module, a generator module, and a microprocessor controller. The burner features a continuous combustor with a single swirl nozzle that provides heat to the engine. The engine has a four-cylinder α-type double-acting arrangement that is hermetically sealed for prolonged periods of operation. Nitrogen is the working fluid inside the engine and is pressurized to 30 atm. For this engine, Clucas et al.[12] report a displacement of about 101 cm^3 (4 cm bore, 2 cm stroke) and a shaft speed of 1200−1500 rpm. The pistons are made of alloy steel and run in filled polytetrafluoroethylene (PTFE) lip seals backed with O rings. The internal heat exchangers (regenerators) of the engine are made out of copper. Carlgvist et al.[13] provide the operating characteristics of α-type double-acting Stirling engines. The AC WhisperGen provides 230 V and 50 Hz alternating current (AC) power. The overall system dimensions are 480 mm wide, 560 mm deep, and 840 mm high.

The electricity produced by the engine can be used directly or net-metered via the grid. A coolant, circulating in the engine compartment and also in an exhaust heat exchanger, captures the thermal output. The engine is operated in heat mode, where it maintains a set coolant temperature to ensure that the heating demand is met.[14]

2.2. IC Engine. The FreeWatt IC engine is shown in Figure 2. At rated performance, it provides 1.20 kW of electrical and 3.26 kW of thermal power. This system is comprised of a furnace module with a high efficiency auxiliary burner, an EMC blower motor, a Honda micro-CHP module, a hybrid integration module, and a microprocessor controller. The Honda micro-CHP module is a single-cylinder, natural-gas-fueled, liquid-cooled, IC engine with a displacement of 163 cm^3. It includes an intake air silencer, oil and air filter, exhaust muffler, and a three-way catalytic converter. The combined efficiency (power and heat) of the engine is 85%. The engine is coupled to a 27 pole permanent magnet generator set. The Climate Energy system integrates a 95% efficient boiler or furnace to the Honda module.[3,9] The Honda micro-CHP module dimensions are 300 mm wide, 300 mm deep, and 500 mm high. The hybrid integration module dimensions are 630 mm wide, 730 mm deep, and 1120 mm high.

When the thermostat requires heat, the micro-CHP unit turns on and provides both heat and electricity. The heat from engine cooling and exhaust recovery is delivered to a heat exchanger in the hybrid integration module, where it is transferred to the return air stream from the building and then delivered to the building by the furnace blower. The system connects to the electricity grid using the on-board electronic inverter provided by the Honda micro-CHP module. Future FreeWatt models will allow for the integration of domestic hot water heaters.[3]

2.3. Fuel Cell. The EBARA-Ballard micro-CHP fuel cell, shown in Figure 3, offers both part- and full-load operation. At full load, it produces 1.00 kW of electrical and 1.52 kW of thermal power. This system is comprised of a fuel processor module, a PEFC module, an inverter module, and a hot water tank. The fuel processor is necessary because the PEFC requires hydrogen fuel. At startup, natural gas is used for warming the

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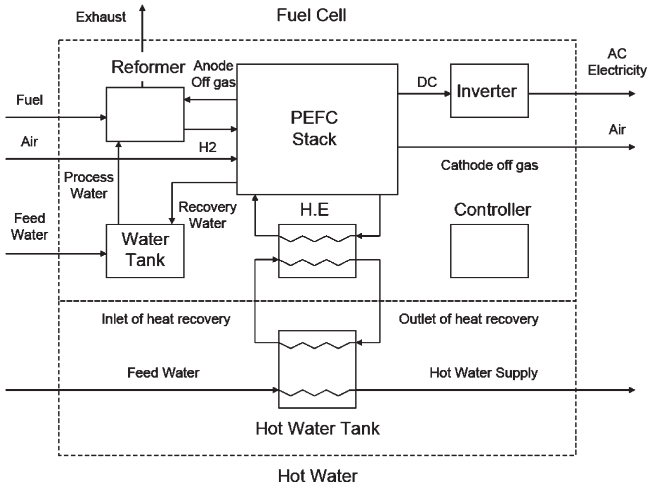

Figure 3. EBARA-Ballard micro-CHP system.[15]

reformer up to 1000 °C. When the temperature becomes stable, natural gas is reformed into hydrogen and carbon dioxide. The carbon dioxide is vented outside, and hydrogen is supplied to the cell stack, where it electrochemically reacts with oxygen and produces direct current (DC) power. The inverter transforms the DC power into AC power. Domestic water is heated by removing the heat from the stack, which is operating at 60 °C. Hot water is stored in a 200 L tank for later use. The heat from the reformer is not used.[9,15] The overall system dimensions are 800 mm wide, 350 mm deep, and 800 mm high.

These system capacities may appear too small for typical cold climate heating and power loads. It is, however, important to note that multiple installations and net metering are technically favorable because they provide better load following characteristics and avoid over sizing of the systems.

3. Theory

3.1. Model. A simple model has been developed for energy, exergy, and marginal efficiency analysis of the micro-CHP systems discussed in the previous section. This model is shown in Figure 4. The thermodynamic system under study is enclosed in a control volume. The major inputs and outputs are power, heat, fuel, air, and waste. In this model, the fuel and air enter and react in the chamber, where the energy of reaction is released and transformed into power by an engine-generator set or a fuel-cell stack. The reaction products leave the system after their remaining thermal energy is recovered. The heat recovery process involves the heat transfer from the products to water or air.

3.2. Energy, Exergy, and Marginal Efficiencies. Energy efficiency is the most frequently used type of efficiency in thermodynamics. This type of efficiency gives the ratio of used energy in the form of heat and power to the input energy. An energy balance, applied to Figure 4, states that the energy input rate to a steady-state system must equal the energy output rate. Therefore, the energy balance can be written as eq 1

$$\dot{m}_F h_F + \dot{m}_A h_A = \dot{W} + \dot{Q}_R + \sum \dot{Q}_L + \sum \dot{m}_W h_W \qquad (1)$$

where h is the specific enthalpy and $\dot{m}$, $\dot{Q}$, and $\dot{W}$ denote mass flow, heat flow, and power, respectively. Subscripts F, A, R, L, and W denote fuel, air, heat recovery, loss, and waste, respectively. Note that, in eq 1, the total heat output of the system can be represented as the sum of the recovered heat and lost heat. This is shown in eq 2.

$$\dot{Q} = \dot{Q}_R + \sum \dot{Q}_L \qquad (2)$$

In most cogeneration systems, the amount of recovered heat that is used is not always the same and depends upon the instantaneous thermal load. Rosen[8] has used this fact and established a dimensionless parameter f that is defined as the fraction of the total heat that is used. Therefore, the heat use factor can be obtained from eq 3.

$$f \equiv \frac{\dot{Q}_R}{\dot{Q}} \qquad (3)$$

Considering eqs 1−3, one can obtain the energy efficiency using eq 4. Note that in this equation, the energy input is the total heating value of the fuel. Use of the heating value takes into account any irreversibilities that may exist in the heat release reaction process (for combustion systems) or in the electrochemical reaction process (for fuel cells), in addition to irreversibilities in the energy conversion processes.

$$\eta_{\text{energy}} = \frac{\dot{W} + \dot{Q}_R}{\dot{m}_F h_F} = \frac{\dot{W} + f\dot{Q}}{\dot{m}_F h_F} \qquad (4)$$

While energy efficiency provides useful understanding of the effectiveness of the input energy use, it does not provide information regarding how well the quality of the energy source is used. Heat and work are both forms of energy, but they do not have the same quality. Exergy analysis, on the other hand, accounts for this difference and evaluates a system for its *potential* to do work. Exergy efficiency is a measure of the performance of a system relative to the performance under reversible conditions for the same end states.[1] This type of analysis is very applicable to cogeneration systems, where both heat and power are produced. An exergy balance, applied to Figure 4, states that the exergy input rate to a steady-state system must equal the exergy output rate plus any exergy that is destroyed because of irreversibilities. Therefore, the exergy balance can be written as eq 5

$$\dot{m}_F \psi_F + \dot{m}_A \psi_A = \dot{W} + \dot{Q}_R (1 - T_0/T_R) + \sum \dot{Q}_L (1 - T_0/T_L) + \sum \dot{m}_W \psi_W + \dot{E}x_D \qquad (5)$$

where ψ is the specific exergy, $\dot{E}x_D$ is exergy destruction, and T_0, T_R, and T_L denote the ambient, heat recovery, and heat loss temperatures, respectively. It is important to note that the heat recovery and heat loss temperatures are not usually constant. In the context of cogeneration, as suggested by Kanoglu et al.,[5] the heat recovery temperature is an instantaneous source temperature from which the heat transfer occurs. Therefore, the exact exergy of a heat recovery process can be written as eq 6.

$$\dot{E}x_R = \int (1 - T_0/T_R) \delta \dot{Q}_R \qquad (6)$$

The calculation of exact $\dot{E}x_R$ for the heat recovery process, which includes device and product heat recovery, may require rigorous modeling, but it is possible to approximate this term by considering an effective heat recovery temperature, T_R, that is the average of the product temperature, T_P, and the waste temperature, T_W. Rosen[8] and Yuan[16] have

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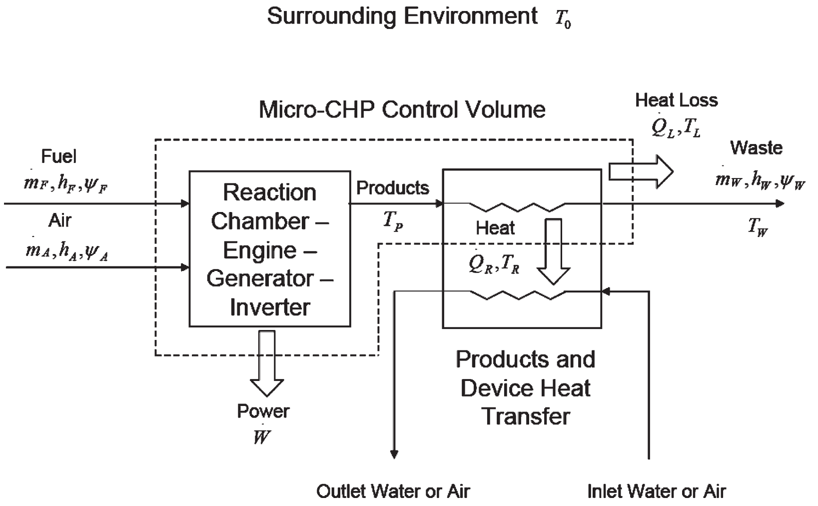

Figure 4. General model for micro-CHP systems.

applied this approach and were able to calculate $\dot{E}x_{\mathrm{R}}$ for comparison purposes.

Considering eq 5 and an effective heat recovery temperature, T_{R}, one can obtain the exergy efficiency using eq 7. Note that in this equation, as well, the exergy input is the total exergy of the fuel. Again, this approach takes into account any irreversibilities that may exist in the heat release reaction process (for combustion systems) or in the electrochemical reaction process (for fuel cells).

$$\eta_{\mathrm{exergy}} = \frac{\dot{W} + \dot{Q}_{\mathrm{R}}(1 - T_0/T_{\mathrm{R}})}{\dot{m}_{\mathrm{F}}\psi_{\mathrm{F}}} = \frac{\dot{W} + fQ(1 - \dot{T}_0/T_{\mathrm{R}})}{\dot{m}_{\mathrm{F}}\psi_{\mathrm{F}}} \quad (7)$$

Marginal efficiency is a relatively new form of efficiency definition that was suggested by Harvey.[10] This type of efficiency is applicable to cogeneration systems especially from the point of view of reducing the use of primary energy. Marginal efficiency is defined as the power produced divided by the extra fuel energy used compared to the generation of heat alone. For a particular application, this type of efficiency analysis aids the decision makers to choose between a cogeneration system or separate power and heat producing systems. The marginal efficiency is given by eq 8

$$\eta_{\mathrm{marginal}} = \frac{\dot{W}}{\eta_{\mathrm{Boiler}}\,\dot{m}_{\mathrm{F}}h_{\mathrm{F}} - \dot{Q}_{\mathrm{R}}} = \frac{\dot{W}}{\eta_{\mathrm{Boiler}}\,\dot{m}_{\mathrm{F}}h_{\mathrm{F}} - f\dot{Q}} \quad (8)$$

where η_{boiler} is the boiler efficiency associated with the heat producing system alone. If the efficiency of the central power plant times the transmission efficiency is smaller than the marginal efficiency, then the use of cogeneration is justified from the perspective of saving primary energy.

4. Results and Discussion

4.1. Energy, Exergy, and Marginal Efficiency Analyses. To compare the energy, exergy, and marginal efficiencies for different micro-CHP technologies, it is best to evaluate their performance based on a common fuel. For this reason, all of the systems chosen for the analysis are fueled by natural gas.

Equation 4 is used to calculate the energy efficiencies. Natural-gas-specific enthalpy is approximated by that of methane because natural gas is comprised of more than 90.0% methane by volume.[17] Use of methane as a surrogate for natural gas is justified because natural gas composition varies from one jurisdiction to another. In addition, this assumption greatly simplifies the analysis, while it does not alter the general systems comparison results. Both the lower heating value (LHV) and higher heating value (HHV) of a fuel may be used for energy efficiency analysis. However, the LHV is more appropriate when the product water is in the vapor phase, and the HHV is more appropriate when the product water is in the liquid phase. The energy efficiency of these systems is calculated using both the LHV and HHV of methane. Bejan[18] tabulates the LHV and HHV of methane as 802.3 and 890.4 kJ/mol, respectively. The power and heat output of each system is obtained from Table 1.

Equation 7 is used to calculate the exergy efficiencies. Natural-gas-specific exergy is, again, approximated by that of methane. Bejan[18] tabulates the exergy of methane as 830.2 kJ/mol. For the AC WhisperGen and FreeWatt systems, the calculation of exact heat recovery temperature, T_{R}, can be very difficult; hence, T_{R} is approximated as the average of the product temperature, T_{P}, and the waste heat temperature, T_{W}. Table 1 provides these temperatures. For the EBARA-Ballard system, however, the heat recovery temperature, the stack temperature, is constant and known to be 60 °C.

Equation 8 is used to calculate the marginal efficiency. An arbitrary boiler efficiency is needed. A typical boiler efficiency is 85%; however, to produce conservative results, a boiler efficiency of 92% is considered.

Figures 5–7 show the energy, exergy, and marginal efficiencies, respectively, versus the heat use factor. These figures are based on the HHV calculation that provides the same baseline for comparison. The summary of the results is tabulated for rated performance in Table 2.

As Figure 5 shows, the energy efficiency of all systems starts at the power energy efficiency with no heat use ($f = 0$) and increases to the combined heat and power energy efficiency at rated performance. The curves would theoretically end at 100% energy efficiency if all of the heat is used ($f = 1$). The energy efficiencies of FreeWatt ($\eta_{\mathrm{energy}} = 76.7\%$ and $f = 0.71$) and EBARA-Ballard ($\eta_{\mathrm{energy}} = 74.9\%$ and

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(18) Bejan, A. *Advanced Engineering Thermodynamics*; John Wiley and Sons, Inc.: New York, 1988; pp 390–394.

Table 1. Rated Specification for the AC WhisperGen, FreeWatt, and EBARA-Ballard Systems[3,4,14] [a]

micro-CHP unit	fuel flow $\dot{V}$ (L/m)	power $\dot{W}$ (kW)	heat $\dot{Q}$ (kW)	product temperature T_P (°C)	waste temperature T_W (°C)
AC WhisperGen	18.30	0.85	6.00	500	110
FreeWatt	9.59	1.20	3.26	784[b]	100
				stack temperature T_R (°C)	
EBARA-Ballard	5.54	1.00	1.52	60	

[a] Temperature locations are shown in Figure 4. [b] To estimate the product temperature, a generic naturally aspirated gas engine with the same compression ratio is considered.

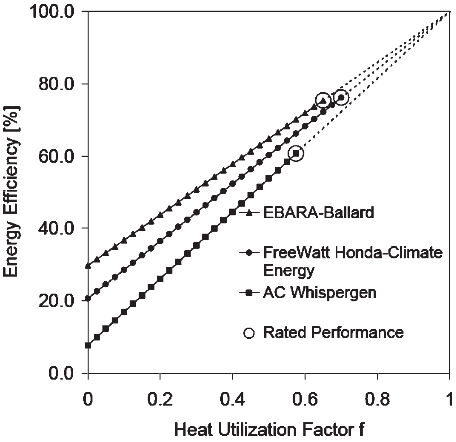

Figure 5. Energy efficiency for the natural gas micro-CHP systems (HHV).

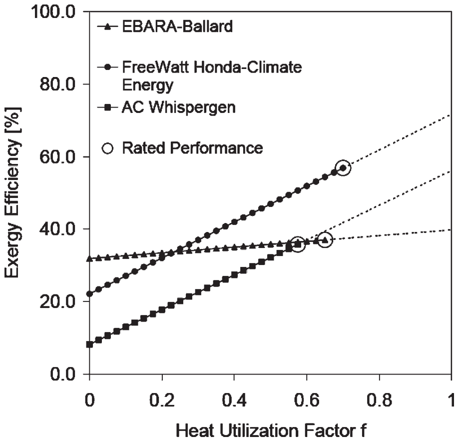

Figure 6. Exergy efficiency for the natural gas micro-CHP systems.

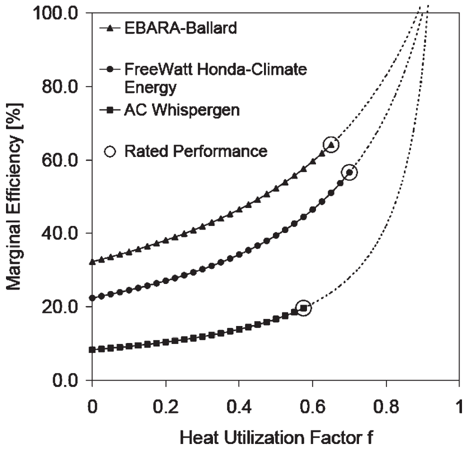

Figure 7. Marginal efficiency for the natural gas micro-CHP systems (HHV).

$f = 0.64$) systems are very competitive and higher than that of the AC WhisperGen ($\eta_{\text{energy}} = 61.6\%$ and $f = 0.58$).

As Figure 6 shows, the exergy efficiency of all systems starts at the power exergy efficiency with no heat use ($f = 0$) and increases to the combined heat and power exergy efficiency at rated performance. The exergy efficiency of FreeWatt ($\eta_{\text{exergy}} = 57.2\%$ and $f = 0.71$) is the highest because the heat transfer occurs at the highest temperature for this system ($T_R = 442$ °C). Exergy efficiency of EBARA-Ballard ($\eta_{\text{exergy}} = 37.0\%$ and $f = 0.64$) is lower than that of FreeWatt because the heat recovery temperature for this system is much lower ($T_R = 60$ °C) and there is no significant rise in the exergy efficiency by heat use. The exergy efficiency of the AC WhisperGen ($\eta_{\text{exergy}} = 36.2\%$ and $f = 0.58$) is the lowest because, although the heat recovery temperature for this system is high ($T_R = 305$ °C), the power exergy efficiency of this system is very low initially. The power and heat exergy efficiencies in Table 2 best show the dependence of exergy efficiency on the heat recovery temperature.

As Figure 7 shows, the marginal efficiency of all systems starts at the power marginal efficiency with no heat use ($f = 0$) and increases to the combined heat and power marginal efficiency at rated performance. As the curves show, marginal efficiency is more sensitive to higher heat use factors. The marginal efficiencies of FreeWatt ($\eta_{\text{marginal}} = 57.4\%$ and $f = 0.71$) and EBARA-Ballard ($\eta_{\text{marginal}} = 63.5\%$ and $f = 0.64$) systems are very competitive and higher than that of the AC WhisperGen ($\eta_{\text{marginal}} = 20.1\%$ and $f = 0.58$).

Fossil-fuel power-plant energy efficiencies vary substantially according to technology and the scale of power generation. Microturbines exhibit the lowest power efficiency (23−26%). The highest power energy efficiency belongs to large combined-cycle cogeneration (47−55%).[10] A study by Papazoglou[19] shows that actual transmission efficiencies can reach 91% for a 100% power factor. Hence, the combined plant and transmission power energy efficiency can be estimated to range from 20.9−23.7% to 42.8−50.0%. Therefore, the marginal efficiencies for the FreeWatt and EBARA-Ballard systems suggest that they are better choices than grid electricity from the viewpoint of saving primary energy. This is true because the power-plant energy efficiency times the transmission energy efficiency is lower than the marginal efficiencies calculated for the two micro-CHP systems.

4.2. Other Considerations. While energy, exergy, and marginal efficiency analyses provide important information regarding the performance of the above micro-CHP systems from the viewpoint of thermodynamics, it is important to consider other issues such as price, maintenance, noise, and emissions as well.

Many developers or end users consider the cost of a technology as the primary factor for decision making. The AC WhisperGen is currently being sold for £3000 (U.S. $6170) in the U.K. residential market, but the price is

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(19) Papazoglou, T. M. *Electr. Power Energy Syst.* **1990**, *12*, 69–70.

Table 2. Energy, Exergy, and Marginal Efficiencies for Rated Performance of Micro-CHP Systems Based on the LHV and HHV

micro-CHP unit		f	power energy η_{energy} (%)	heat energy η_{energy} (%)	energy η_{energy} (%)	power exergy η_{energy} (%)	heat exergy η_{energy} (%)	exergy η_{energy} (%)	marginal η_{marginal} (%)
AC WhisperGen	LHV	0.65	8.5	59.9	68.4	8.2	28.0	36.2	26.4
	HHV	0.58	7.6	54.0	61.6	8.2	28.0	36.2	20.1
FreeWatt	LHV	0.81	22.9	62.1	85.0	22.1	35.1	57.2	76.6
	HHV	0.71	20.6	56.1	76.7	22.1	35.0	57.2	57.4
EBARA-Ballard	LHV	0.75	33.0	50.0	83.0	31.9	5.1	37	78.6
	HHV	0.64	29.7	45.2	74.9	31.9	5.1	37	63.5

expected to fall with higher rates of production. The FreeWatt system has been listed for U.S. $13 500 for residents of Massachusetts. Because FreeWatt has only been recently commercialized, it is likely that the price will drop with more sales in the years to come. No reliable cost estimation for the EBARA-Ballard system is available to the authors, but it is expected to cost more. Although the initial installation cost of micro-CHP systems may seem higher than conventional technologies, over the long run, they provide economic benefit for added income from producing electricity. For each installation, a breakeven point can be estimated using the capital investment amount, service cost, inflation rate, price of electricity and natural gas, and possible rebates for sustainable energy. These parameters vary from one jurisdiction to another as well as time. Therefore, the estimation of the breakeven point is outside the scope of this paper.

The FreeWatt system requires an oil change, including filter, and spark plug change every 6000 h. At 12 000 h interval there is a need to replace a crank breather filter. Also at longer intervals (6 to 8 years) the oxygen sensor and the engine coolant may be required to change. The system is advertised to run up to about 40 000 h (10 years) before any major service may be required. In comparison to FreeWatt, WhisperGen requires less maintenance. Stirling engines have a sealed operating chamber and low-wear mechanisms. With small capacities, the service intervals are 5000−8000 h. The nitrogen working fluid, however, needs to be refilled every 1000 h.[14] Although fuel cell systems do not have as many moving parts as the heat engines, they require frequent maintenance and some component replacement that could be costly. EBARA-Ballard requires minor maintenance together with pumps and fans replacement. A major overhaul requires catalyzer, reformer, and stack replacement. Stack replacement is expected every 4−8 years. Periodic filter replacement is carried out every 2000−4000 h.[9]

The name *WhisperGen* was chosen because the engine produces very little noise, the same noise level as a refrigerator (63 dB).[14] FreeWatt operates at a noise level of 47 dB.[3] Both systems are packaged with an enclosure to achieve this low noise level. Fuel cells are inherently quiet; therefore, the only noise associated with the EBARA-Ballard system is from fans and compressors. No published noise level data are available at this time.

Exhaust emissions is the other important issue. There are currently no reliable data available to report the emission levels for pollutants produced by the WhisperGen and FreeWatt systems. Similar Stirling engines run fuel lean, and the internal exhaust gas from the recirculation system preheats air and fuel gas to limit the maximum temperature and, hence, control NO_x formation. Typical natural gas Stirling engines produce 65−100 ppm NO_x, 35−55 ppm CO,[9] and less than 10 ppm unburned hydrocarbons. Advanced NO_x, CO, and unburned hydrocarbons control in IC engines is achieved by use of catalytic converters. Typical cogeneration natural gas IC engines equipped with catalytic converters produce less than 35 ppm NO_x (NO equivalent), less than 35 ppm CO, and less than 65 ppm unburned hydrocarbons (methane equivalent).[9] EBARA-Ballard outperforms the other two systems with 4.8 ppm NO_x and negligible CO and unburned hydrocarbon emissions.[15]

5. Conclusions

In the present analysis, three distinct micro-CHP technologies have been compared: a Stirling engine, an IC engine, and a PEFC. Energy, exergy, and marginal efficiency analyses provide a useful tool in the thermodynamic assessment of these systems.

The energy, exergy, and marginal efficiencies of a system are strong functions of the system power cycle, system size, and the fuel used. Consideration of the above residential micro-CHP systems of small capacity that are all run using the same fuel provides a comparison criteria for such systems in general. This is true because such small devices are technologically simple and the type of fuel used imposes well-defined thermodynamic limits on the efficiencies calculated.

The analysis suggests that the IC engine system provides the highest energy and exergy efficiencies at higher heat use, while the PEFC system operates at higher energy and exergy efficiencies at lower heat use. The fuel cell system exhibits the greatest marginal efficiency at any heat use. Among the three systems, the Stirling engine system is offered at the lowest price and requires the least maintenance, while the fuel cell system is the most expensive and requires frequent maintenance. The PEFC system generates the least amount of noise and produces the lowest level of emissions. Because of the rising prices of primary energy in the form of fossil fuels and also the rising environmental concerns and regulations, it is expected that the residential micro-CHP market will grow substantially in the years to come.

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Nomenclature

CHP = combined heat and power
HHV = higher heating value
IC = internal combustion
LHV = lower heating value
PEFC = polymer electrolyte fuel cell
$\dot{E}x$ = exergy flow
$\dot{Q}$ = heat flow
T = temperature

$\dot{W}$ = power
f = heat use factor
h = specific enthalpy
$\dot{m}$ = mass flow rate

Greek Symbols

α = α-type Stirling engine
η = efficiency
ψ = specific exergy

Subscripts

A = air
D = destruction
F = fuel
L = loss
P = product
R = heat recovery
W = waste
0 = surrounding environment