Argonne NATIONAL LABORATORY

ANL/ESD/08-4

Fuel Cycle Comparison of Distributed Power Generation Technologies

Energy Systems Division

About Argonne National Laboratory
Argonne is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC under contract DE-AC02-06CH11357. The Laboratory's main facility is outside Chicago, at 9700 South Cass Avenue, Argonne, Illinois 60439. For information about Argonne, see www.anl.gov.

Availability of This Report
This report is available, at no cost, at http://www.osti.gov/bridge. It is also available on paper to the U.S. Department of Energy and its contractors, for a processing fee, from:
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone (865) 576-8401
fax (865) 576-5728
reports@adonis.osti.gov

ANL/ESD/08-4

Fuel Cycle Comparison of Distributed Power Generation Technologies

by
A. Elgowainy and M.Q. Wang
Center for Transportation Research, Argonne National Laboratory

November 2008

CONTENTS

TABLES

FIGURES

FIGURES (CONT.)

ACKNOWLEDGMENTS

This study was supported by the U.S. Department of Energy, Assistant Secretary for Energy Efficiency and Renewable Energy, Fuel Cell and Hydrogen Infrastructure Program, under contract DE-AC02-06CH11357. We thank Fred Joseck and Pete Devlin of the Fuel Cell and Hydrogen Infrastructure program for their inputs to this study.

FUEL CYCLE COMPARISON OF DISTRIBUTED POWER GENERATION TECHNOLOGIES

Amgad Elgowainy and Michael Wang

ABSTRACT

The fuel-cycle energy use and greenhouse gas (GHG) emissions associated with the application of fuel cells to distributed power generation were evaluated and compared with the combustion technologies of microturbines and internal combustion engines, as well as the various technologies associated with grid-electricity generation in the United States and California. The results were primarily impacted by the net electrical efficiency of the power generation technologies and the type of employed fuels. The energy use and GHG emissions associated with the electric power generation represented the majority of the total energy use of the fuel cycle and emissions for all generation pathways. Fuel cell technologies exhibited lower GHG emissions than those associated with the U.S. grid electricity and other combustion technologies. The higher-efficiency fuel cells, such as the solid oxide fuel cell (SOFC) and molten carbonate fuel cell (MCFC), exhibited lower energy requirements than those for combustion generators. The dependence of all natural-gas-based technologies on petroleum oil was lower than that of internal combustion engines using petroleum fuels. Most fuel cell technologies approaching or exceeding the DOE target efficiency of 40% offered significant reduction in energy use and GHG emissions.

1 INTRODUCTION

Small power-generation units are typically located near the points of electric energy demand. A recent study for the U.S. Department of Energy (DOE) identified hydrogen fuel cells in the capacity range of 1–250 kW as a feasible technology for near-term application in the distributed electric power generation market (Mahadevan et al. 2007). One of the challenges to transform the market of fuel cells is the lack of information on life-cycle energy use and emissions performance. Many sectors of the U.S. economy are becoming increasingly aware of the need to reduce energy use and emissions of greenhouse gases. This document provides an analysis of the fuel-cycle energy use and greenhouse gas (GHG) emissions associated with the application of fuel cells to distributed power generation. In particular, the different fuel cell technologies — such as Proton Exchange Membrane (PEM), Phosphoric Acid Fuel Cell (PAFC), Molten Carbonate Fuel Cell (MCFC), and Solid Oxide Fuel Cell (SOFC) — are compared with combustion-based distributed generation technologies, such as microturbines and internal combustion engines (ICEs), as well as the various mixes of technologies associated with grid-electricity generation in different markets in the United States. Argonne National Laboratory's model for the assessment of Greenhouse Gases, Regulated Emissions, and Energy Use in

Transportation (GREET) has been modified and used as a tool to estimate the full fuel-cycle emissions and energy use for distributed generation technologies by tracking their occurrences from the primary energy source to the site of energy consumption for each technology (Wang 1999).

2 DISTRIBUTED POWER-GENERATION TECHNOLOGIES

Established technologies for the distributed power-generation market include ICEs and natural gas turbines. Emerging technologies — such as fuel cells — provide additional options for such a market. Internal combustion engines include spark-ignition engines powered by natural gas, liquefied petroleum gas (LPG), and gasoline, as well as compression-ignition engines powered by diesel. Combustion turbines can develop power over a wide range of capacity, ranging from several kilowatts to hundreds of megawatts. Microturbines are suited for the smaller-capacity applications (1–250 kW) targeted by this study. Fuel cell technologies are primarily powered by natural gas, which undergoes reformation to produce hydrogen gas for the fuel cell. This analysis also includes fuel cells powered by LPG and diesel. ICEs offer low first cost, easy start-up, proven reliability, good part-load characteristics, and heat recovery potential. The emissions of ICEs can be controlled by exhaust catalysts and through better control of the combustion processes. Internal combustion engines are suited for standby, peak demand, and combined heat and power (CHP) applications in the commercial and industrial markets of capacities less than 10 MW. Microturbines are small combustion turbines with outputs in the range of 30–200 kW. They are capable of producing power at efficiencies in the range of 25–30% by recuperating heat from the exhaust gas to the incoming air stream. Microturbines are appropriately sized for power-only or CHP applications. Microturbines have the advantages of no gearbox or lubricating oil requirements, and high engine speeds ranging from 80,000 to 100,000 rpm (Dunn 2000).

Fuel cells produce electric power through an electrochemical process in which hydrogen energy is converted to electricity. The hydrogen fuel can be produced from a variety of sources. The most economic source of hydrogen is steam reforming of natural gas. Several different liquid and solid media can be used to facilitate the fuel cell's electrochemical reactions. These media are phosphoric acid (PA), molten carbonate (MC), solid oxide (SO), and polymer electrolyte membrane (PEM). Each medium consists of a distinct fuel cell technology and unique performance characteristics. Although PEM fuel cells are suited for smaller capacities (2–200 kWe), PAFCs and MCFCs are suited for higher capacities (50 kWe–10 MWe) and (200 kWe–100 MWe), respectively. Solid oxide fuel cells cover a wide range of capacities, from 2 kWe to 100 MWe (Pehnt and Ramesohl 2003). Fuel cell overall efficiency can range from 23% to more than 60%, depending on the fuel cell technology, the power rating of the fuel cell, and system configuration (e.g., standalone, combined generation, or CHP). The electrical efficiencies of fuel cells, based on the primary fuel lower heating value (LHV), range from 23 to 40% for PEM fuel cells, 35 to 45% for PAFCs, 45 to 55% for MCFCs, and 30 to 55% for SOFCs (Pehnt and Ramesohl 2003; Cook 2007; DOE 2008). Combined fuel cell/gas turbine power generation is possible for high-temperature fuel cell technologies (such as SOFCs and MCFCs), resulting in higher efficiencies — potentially greater than 60%.

Fuel cell technologies have excellent part-load performance characteristics. However, the overall efficiency of fuel cells is impacted by the ratio of the parasitic power consumed by the auxiliary components relative to the stack power output. Like a battery, fuel cells produce direct current (DC) that must be run through an inverter to get alternating current (AC). Fuel cells are best suited for environmentally sensitive areas and customers who have concerns about power quality. Some fuel cell technologies are modular and capable of supplying power to small commercial and even residential markets; other technologies use high temperatures in systems that are suited for CHP and cogeneration applications. Fuel cells are inherently quiet and extremely clean running. The lack of moving parts minimizes maintenance needs (Dunn 2000). Tollstrup (2008) presented criteria pollutant emissions for distributed generation technologies (Figure 1). Figure 1 shows the low emissions associated with fuel cells in comparison with combustion generators. The horizontal lines in the figure indicate the 2007 distributed generation standards set by the California Air Resource Board (CARB).

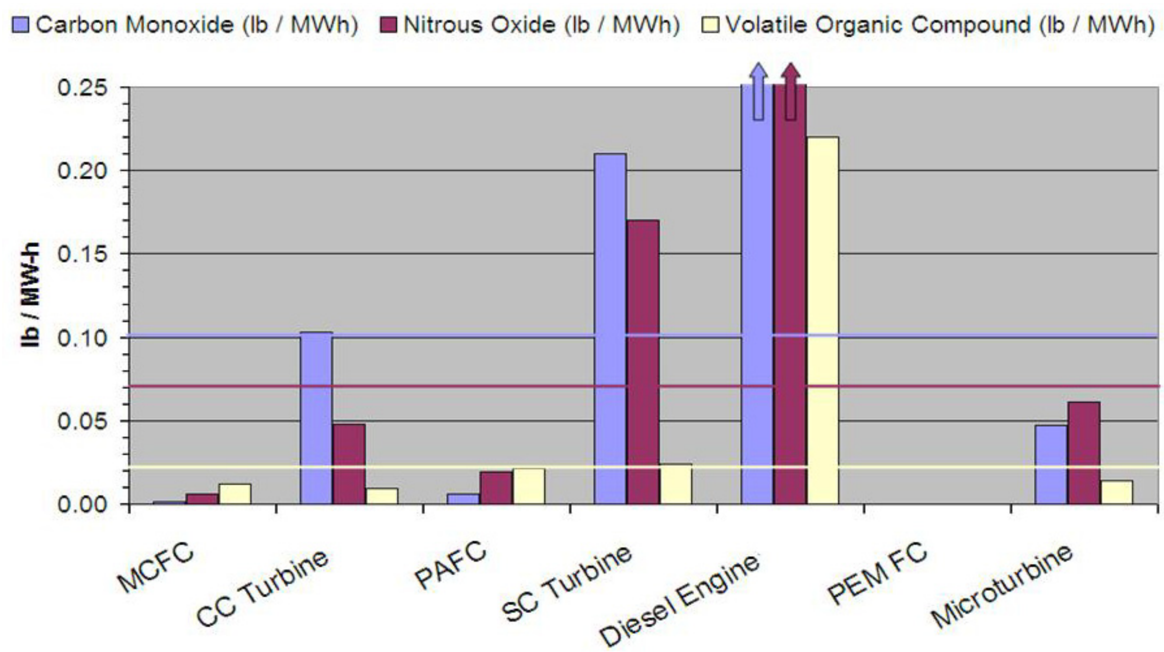

FIGURE 1. Criteria Pollutants Emissions for Distributed Generation Technologies (Source: Tollstrup 2008)

3 RESULTS OF FUEL CYCLE ENERGY USE AND GHG EMISSIONS

We examine the fuel cycle analysis of various power generation technologies by first identifying a unit of consumed electric energy, which is arbitrarily chosen to be 1 kWh or 3,412 Btu for this study, and then tracking the energy use and emission occurrences throughout the upstream processes, up to the primary source of energy for each technology. Each generation pathway includes the following three main stages:

1. The recovery, processing, and transportation of a primary fuel to the electric power generator;

2. The generation of electricity from the primary fuel (using a combustion technology or a reformer, plus a power generator); and

3. The on-site consumption of electricity.

The energy use and emission results are inherently dependent on the assumptions associated with each of the generation technologies. The key assumption for each technology is the generator's energy conversion efficiency, which is listed in Tables 1a and 1b for small power capacities (<10 kW) and large power capacities (>> 10 kW), respectively. The literature data indicate that the efficiency of fuel cell power generators varies with the generator's capacity, with higher efficiencies reported for the higher capacities. The primary difference between small- and large-capacity fuel cells is the ratio of the parasitic (balance of plant) power to the stack power output. Several studies reported details on the parasitic power requirements of the fuel cell (Pei et al. 2004; Buchi et al. 2005; Iiyama et al. 2008; Gemmen and Johnson 2006). The ratio of parasitic power to the fuel cell rated load is in the range of 10–20% for small fuel cells and less than 10% for large fuel cells, depending on the fuel cell technology and the type of auxiliary components employed for each fuel cell. Iiyama et al. (2008) provided detailed information on the shares of parasitic power consumption of individual auxiliary components for a 1-kW kerosene fuel cell system (Iiyama et al. 2008). An early development of that fuel cell system produced a net (LHV) electrical efficiency of 28% at rated load, while the corresponding efficiency of a more recent fuel cell development was 33%. The improvement in the overall system efficiency was a direct result of a 28% reduction in parasitic power consumption. The parasitic power consumption at rated load as a ratio of the input fuel energy was calculated at 18% and 13% for the original and improved fuel cell systems, respectively.

TABLE 1a. Energy Conversion Efficiency for Different Generation Technologies Typical for Capacities <10 kW, without CHP (based on LHV of the primary fuel)

Generation Technology	Energy Conversion Efficiency (from primary fuel to consumed electricity) (%)
Natural Gas ICE	23[a]
PEMFC	34[b]
PEMFC (DOE target)	40[c]
SOFC	40[d]
U.S. average mix (for baseline comparison)	38[e]
California (CA) mix (for baseline comparison)	45[e]

[a] SRI/USEPA 2005

[b] Kimura 2008

[c] DOE 2008

[d] Campbell et al. 2003

[e] GREET 1.8a, August 2007. These efficiencies are fossil energy conversion efficiencies

TABLE 1b. Energy Conversion Efficiency for Different Generation Technologies Typical for Capacities >10 kW, without CHP (based on LHV of the primary fuel)

Generation Technology	Energy Conversion Efficiency (from primary fuel to consumed electricity (%)
Microturbine	25[a]
Natural Gas ICE	35[a]
LPG ICE	35[b]
Gasoline ICE	35[b]
Diesel ICE	44[a]
NG PEMFC	36[a]
NG PEMFC (DOE target)	40[c]
NG SOFC	48[a]
LPG SOFC	47[b]
Diesel SOFC	46[b]
NG PAFC	40[d]
NG MCFC	49[e]
U.S. average mix (for baseline comparison)	38[f]
California (CA) mix (for baseline comparison)	45[f]

[a] Heath et al. 2005

[b] Assumption based on performance of similar technologies (data source not available).

[c] DOE 2008

[d] Binder 2006

[e] SRI/USEPA 2007

[f] GREET 1.8a, August 2007. These efficiencies are fossil energy conversion efficiencies.

The ratio of parasitic power to stack power varies with the variation in the fuel cell load profile. Part-load operation improves stack efficiency, but the parasitic power consumption adversely impacts the overall part-load performance. The overall system efficiency may increase or decrease over a wide range of operating load. Also, the DC-to-AC inversion efficiency varies with fuel cell operation load. Thus, a variable-load operation results in performance degradation because of the unsteady operation of the fuel cell. Consequently, steady-state testing of the fuel cell at peak performance or rated power generally predicts higher net electrical efficiency compared to the efficiency reported on the basis of actual field tests of performance. Performance obtained from field tests also incorporates the potential degradation in fuel cell performance over a longer period of operation. Gemmen et al. (2006) discussed in detail the evaluation of fuel cell system efficiency and degradation at development and commercialization stages. Although an ASME fuel cell test code exists for steady-state operation (ASME PTC-50), a more rigorous testing standard is needed for the seasonal rating of fuel cells on the basis of standard load profiles to determine the seasonal efficiency of fuel cells for different applications. Standards for seasonal ratings of fuel cells are particularly important for CHP applications (which are not considered in this study) to account for the recuperation of waste heat and its use in heating applications.

The net electrical efficiency values reported in the literature vary widely for a given fuel cell technology. Some of the observed variation is attributed to incomplete reporting of the basis of the reported efficiency (e.g., higher heating value [HHV] vs. lower heating value [LHV]) and whether or not the parasitic power consumption is included in the reported efficiency. Other factors affecting a particular fuel cell's net electrical efficiency include fuel utilization ratio, stack temperature, stack pressure drop, and power management control, in addition to ohmic resistance and polarization losses (Campbell et al. 2003; Hou et al 2007). Additionally, technological advances result in improved fuel cell performance over time. Thus, for a fuel cell technology, the efficiency value reported by an earlier study may be lower than that reported by a more recent study. For example, a U.S. Department of Defense (DoD) residential PEM demonstration project (2001–2004) reported an average PEMFC (LHV) electrical efficiency of 23.7% (White et al. 2005). However, a more recent analysis of residential fuel cell performance in Japan reported an average PEMFC (HHV) electrical efficiency of 28%, 30%, and 31% for installations made in 2005, 2006, and 2007, respectively, which reflects the rapid improvement in residential PEMFC efficiency (Kimura 2008). Our approach for this analysis is to first rely on the most recent net electrical efficiency reported from field-testing and then on data reported from experimentally controlled laboratory testing. Without efficiency data for a particular fuel/generation technology, we adopt the efficiency values reported for a similar generation technology.

The energy use and GHG emission results for the U.S. average and California mixes of electricity, as well as for coal and natural gas grid-generation technologies, are provided as baseline cases for comparison with those of different distributed-generation technologies. Tables 2 and 3 provide the mix of technologies in the U.S. and California markets and the energy conversion efficiency of each grid-generation technology in these markets, respectively. Note that a power loss of 8%, not included in Tables 2 and 3, is assumed for electricity transmission through the grid.

TABLE 2. Electricity Generation Mix and Generation Efficiencies in the United States (from GREET 1.8a)

Grid Generation Technology	Share (%)	Efficiency (%)
Residual Oil-Fired Power Plants	2.7	34.8
Natural Gas-Fired Boiler, Steam Cycle Power Plant	3.8	34.8
Natural Gas Turbine, Simple Cycle Power Plants	6.8	33.1
Natural Gas Turbine, Combined Cycle Power Plants	8.3	46.0
Coal-Fired Boiler, Steam Cycle Power Plant	50.7	34.1
Biomass-Fired Boiler, Steam Cycle Power Plant	1.3	32.1
Other Power Plants (renewable, e.g., hydropower plants)	7.7	Not Applicable
Nuclear Power Plant	18.7	Not Applicable

TABLE 3. Electricity Generation Mix and Generation Efficiencies in California (from GREET1.8a)

Grid Generation Technology	Share (%)	Efficiency (%)
Residual Oil-Fired Power Plants	0.7	34.8
Natural Gas- Fired Boiler, Steam Cycle Power Plant	8.3	34.8
Natural Gas Turbine, Simple Cycle Power Plants	14.9	33.1
Natural Gas Turbine, Combined Cycle Power Plants	18.3	46.0
Coal-Fired Boiler, Steam Cycle Power Plant	14.6	34.1
Biomass-Fired Boiler, Steam Cycle Power Plant	1.7	32.1
Other Power Plants (renewable, e.g., hydropower plants)	22.6	Not Applicable
Nuclear Power Plant	18.9	Not Applicable

The energy use and GHGs emissions results are provided in Figures 2–5 for technologies suited for power capacities smaller than 10 kW and in Figures 6–9 for technologies suited for power capacities greater than 10 kW. The energy use and GHGs emissions associated with each stage of the power generation pathway are stacked together to provide the total fuel cycle result for each generation technology. The energy use is provided in three forms that could be of interest to producers, consumers, and regulators: total energy, fossil energy, and petroleum energy. The total energy use is a prime indicator for the efficiency of the power-generation technology, while the fossil and petroleum energy uses provide indicators for the technology's potential of producing GHGs and for its reliance on foreign energy sources, respectively.

4 DISCUSSION OF RESULTS

Figure 2 shows the details of total energy use per kWh (3,412 Btu) of on-site electricity consumption for distributed generators with capacities less than 10 kW, as well as for grid-generation technologies and their mixes in the United States and California. The distributed generation technologies for this market (1–10 kWe) have low to moderate electrical efficiencies (23–40%). Total energy use by combustion generators is higher than those associated with all grid-generation technologies and their mixes in the United States and California. However, SOFC and PEMFC at 40% electrical efficiency offer total energy use comparable to the total energy use associated with the natural gas and coal grid-generation technologies, as well as the average generation mix in the United States.

Figure 2 shows that the energy use in the power-generation stage constitutes the majority of the total energy use of the fuel cycle because of the relatively low efficiency of that stage for all pathways.

As shown in Figure 3, fossil energy use follows a similar trend of the total energy use for all generation technologies. The energy use for the U.S. and CA mixes in Figure 3 does not include the renewable energy use in these mixes. As expected, all distributed generation technologies fueled by non-petroleum fuels exhibit very low dependence on petroleum energy, as shown in Figure 4.

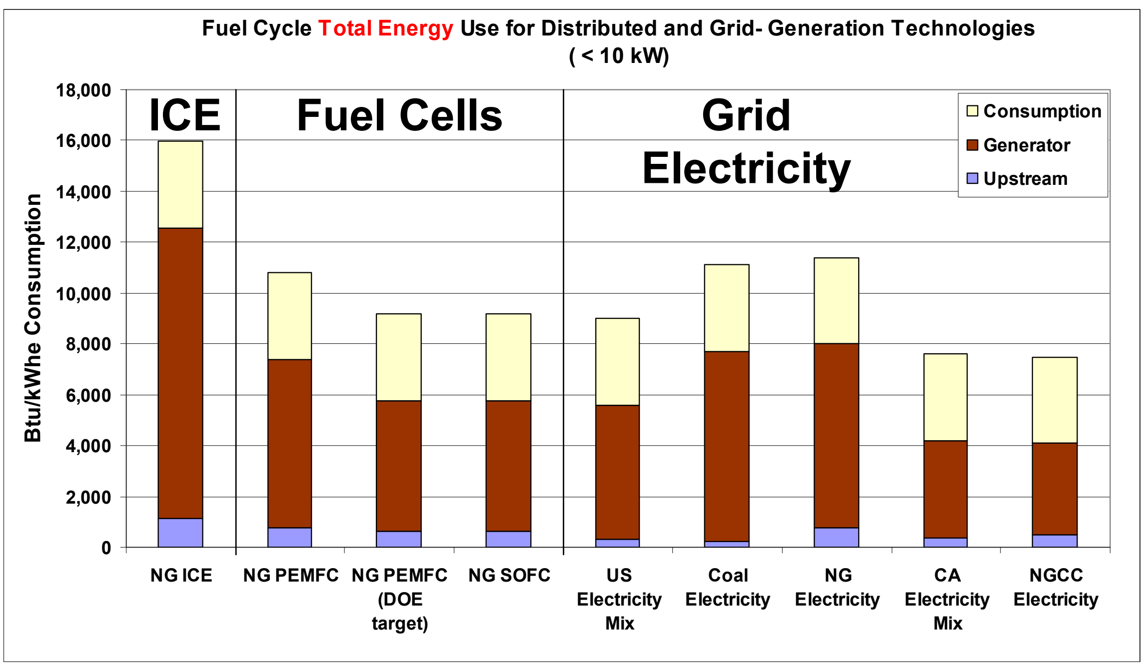

FIGURE 2. Total Energy Use by Electricity Generation Technologies for Capacities < 10 kW

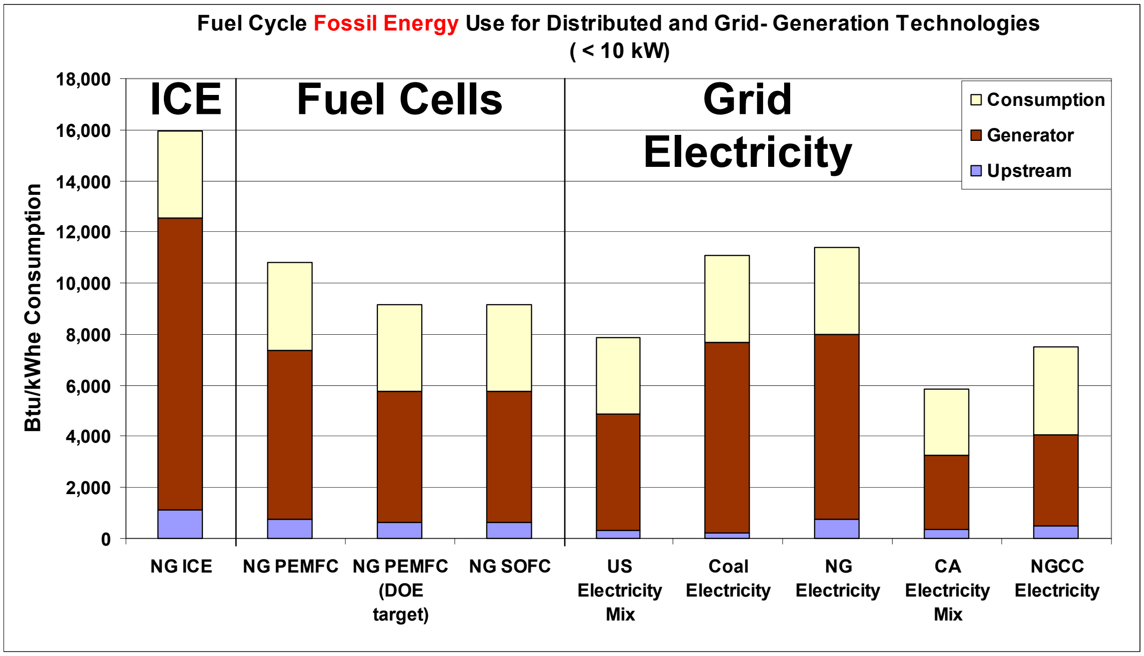

FIGURE 3. Fossil Energy Use by Electricity Generation Technologies for Capacities < 10 kW

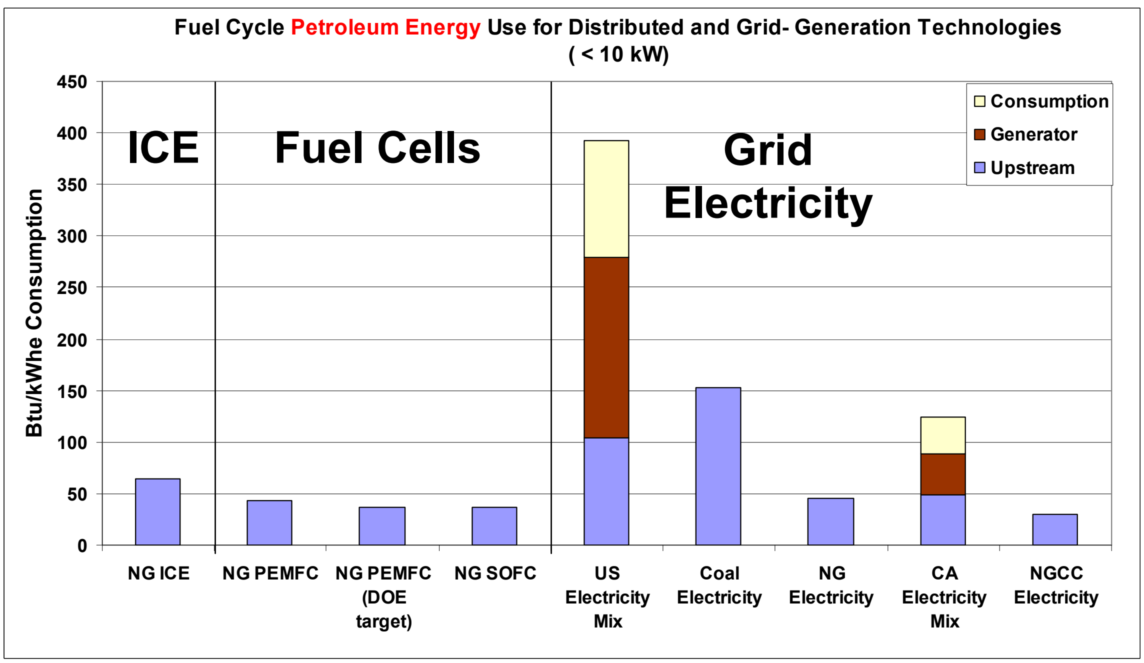

FIGURE 4. Petroleum Energy Use by Electricity Generation Technologies for Capacities < 10 kW

Figure 5 shows the fuel-cycle GHG emissions for different distributed power generators with capacities smaller than 10 kW and different grid-generation technologies and mixes. While the natural gas ICE exhibits higher GHG emissions than most grid-generation technologies (mainly because of their lower power generation efficiency), fuel cells generate lower GHG emissions compared to the U.S. generation mix. Figure 5 suggests that small, high-efficiency fuel cells provide benefits in terms of energy use and GHG emissions compared to grid-generation technologies. Recent advances in low-capacity fuel cell technologies demonstrated efficiencies that approached or met the DOE target efficiency of 40%. Thus, small fuel-cell power generators may penetrate light commercial and residential markets based on energy and emissions benefits, in addition to the other advantages, such as the quiet operation, the reliability of power generation, or the potential use of waste heat for on-site heating applications. However, the high initial cost of fuel-cell-generation technologies renders them more suitable for applications with greater power demand, which is the subject of the following discussion.

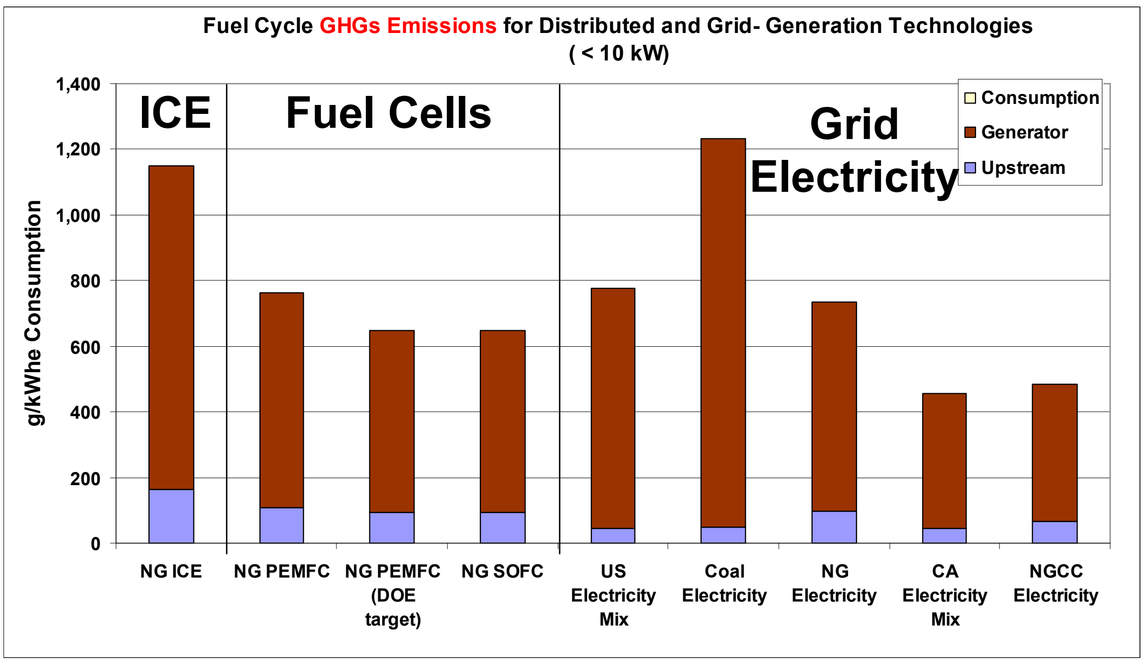

FIGURE 5. GHGs Emissions by Electricity Generation Technologies for Capacities < 10 kW

Among the distributed generation technologies with capacities much greater than 10 kW (suited for the commercial/industrial markets), microturbines exhibit a higher use of energy, as shown in Figure 6, mainly because of their relatively lower energy-conversion efficiency. The NG-driven SOFC, at 48% electrical efficiency, exhibits energy use similar to that of the California grid mix, but lower than that of the U.S. grid mix and all other distributed generation technologies. Generation technologies with same electrical efficiency but using different fuels exhibit different fuel-cycle energy use, mainly because of the different energy use in the upstream processes associated with producing and transporting each fuel to the power generator. For example, the fuel-cycle energy use of the gasoline ICE is greater than that of the natural gas

ICE, as shown in Figure 6, because the recovery of conventional and synthetic crude and the subsequent refining and transportation processes to produce gasoline require more energy than the corresponding processes associated with the recovery, processing, and transportation of natural gas. A similar observation can be made in Figure 6 for the upstream energy consumption of diesel and natural gas SOFCs. Figure 6 also indicates a much lower upstream energy use for a diesel ICE in comparison with a gasoline ICE, which might appear counterintuitive because the feedstock and upstream processes are similar for both fuels. However, the lower upstream energy use for a diesel ICE is attributed to the higher efficiency of the diesel engine compared to that of the gasoline engine, which results in a relatively lower diesel consumption per unit of generated electricity.

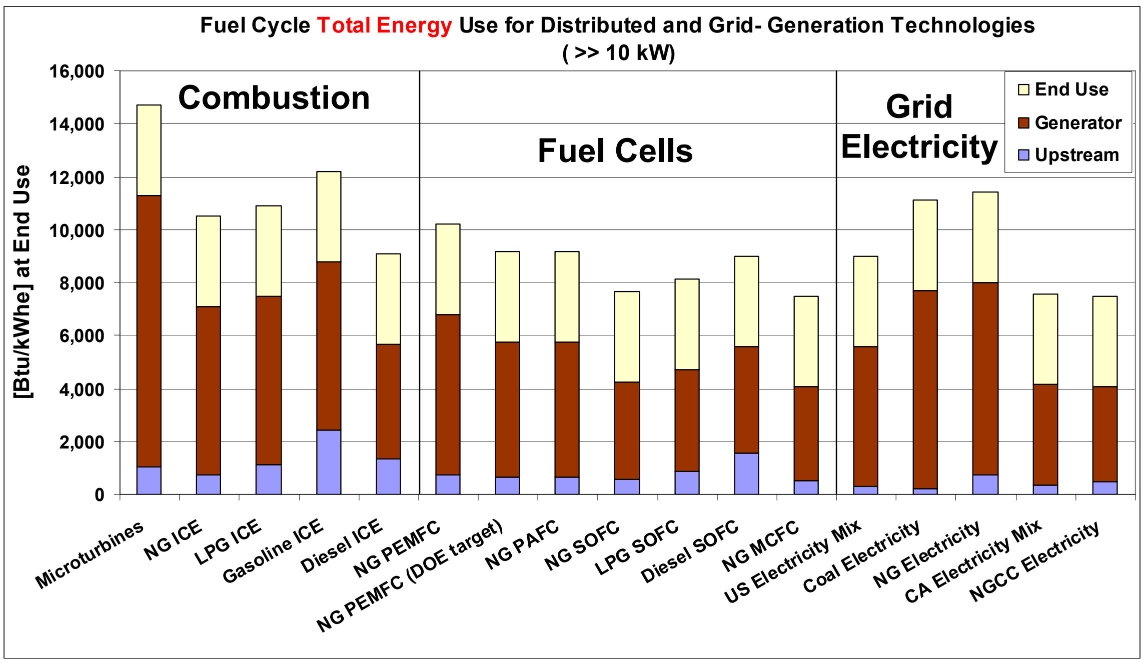

FIGURE 6. Total Energy Use by Electricity-Generation Technologies for Capacities >> 10 kW

Figure 7 shows a trend of the fuel-cycle fossil energy use similar to that in Figure 6, except for the relatively low fossil fuel consumption in the U.S. and CA grid mixes, which generate 28% and 43% of their electricity from non-fossil sources, respectively. The petroleum energy use is low for all generation pathways, as shown in Figure 8, except for the ICE and SOFC technologies powered by gasoline, diesel, or LPG since 100% of the gasoline and diesel fuels and 40% of the LPG fuel are produced from petroleum sources. The U.S. and California grid-generation mixes involve a small percentage of electricity generation from the petroleum-based residual oil, thus resulting in a small consumption of petroleum energy. Natural-gas-based generation technologies involve an insignificant use of petroleum fuels, the use of which mainly occurs in the recovery and processing of the natural gas.

Figure 9 shows the fuel-cycle GHG emissions associated with different distributed- and grid-generation technologies. Fuel cells produce lower GHGs emissions than those produced by combustion technologies. Figure 9 also shows that high-efficiency fuel cells, such as SOFC, produce GHG emissions comparable to those produced by the California generation mix, which generates 43% of its electricity from non-fossil renewable and nuclear sources. The combustion technologies of microturbines and ICEs produce GHG emissions comparable to - or slightly higher than - those produced by the U.S. generation mix. Although diesel engines are more efficient than natural gas ICEs, the higher carbon content of diesel per unit energy results in GHG emissions comparable to those produced by the NG ICE. The above fuel cycle results suggest that fuel cells with higher capacities (>>10 kW) may penetrate the commercial/industrial power markets as a result of their high energy efficiency and reduced GHG emissions compared to alternative combustion technologies.

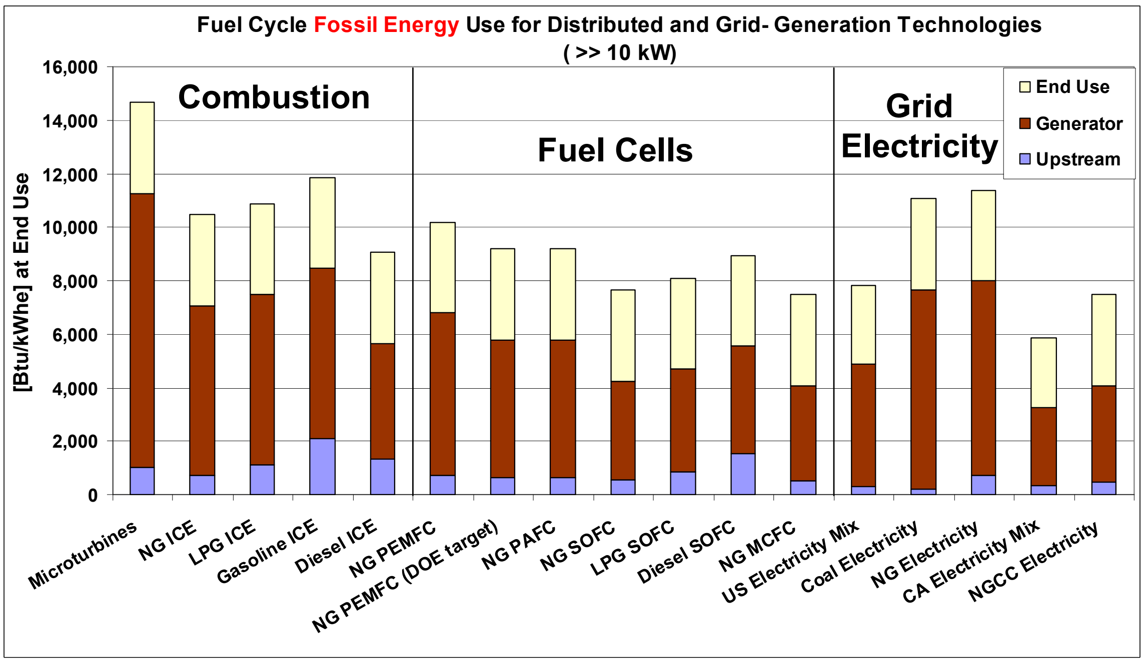

FIGURE 7. Fossil Energy Use by Electricity-Generation Technologies for Capacities >> 10 kW

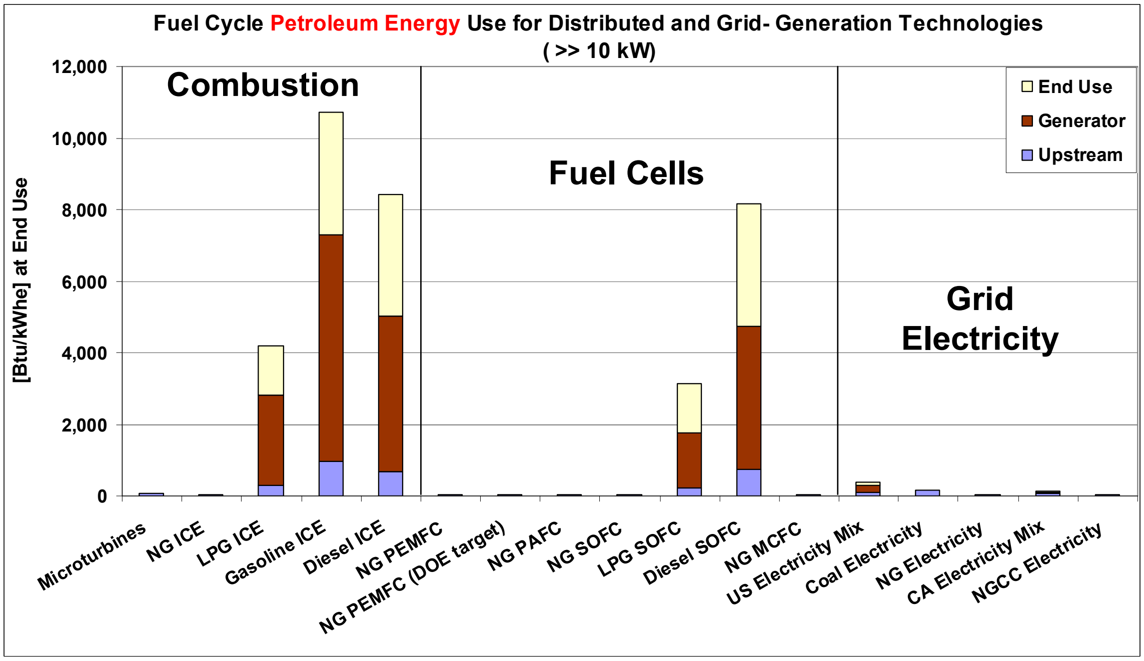

FIGURE 8. Petroleum Energy Use by Electricity-Generation Technologies for Capacities >> 10 kW

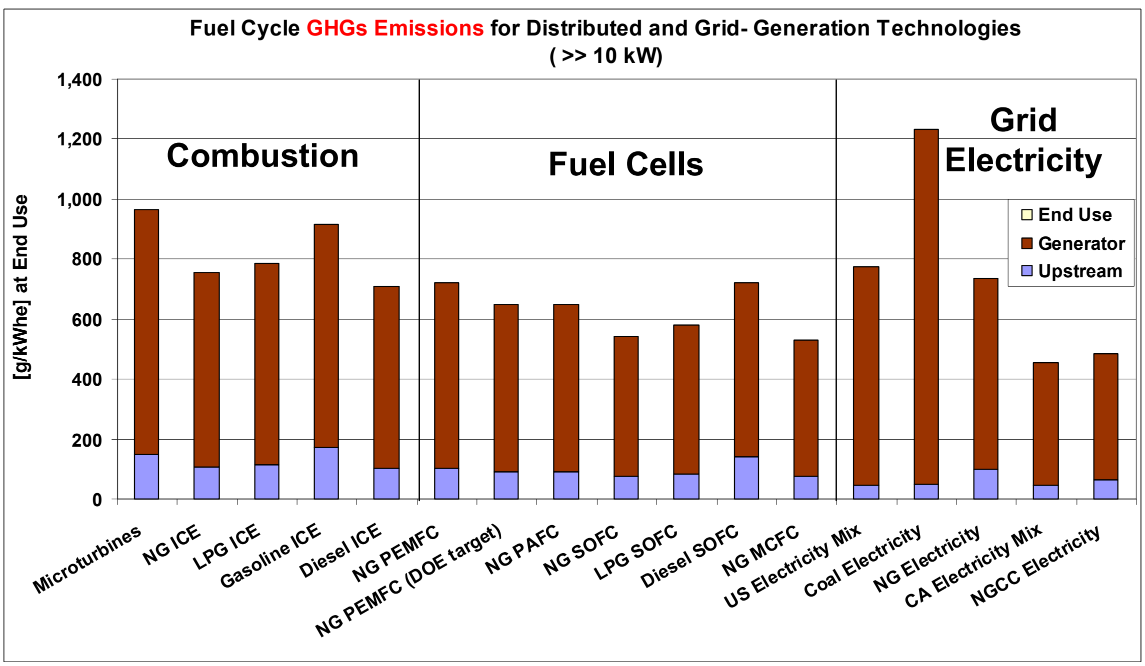

FIGURE 9. GHGs Emissions by Electricity-Generation Technologies for Capacities >> 10 kW

5 CONCLUSIONS

The fuel-cycle energy use and GHG emissions associated with the stationary application of fuel cells for distributed power generation were compared with the combustion technologies of microturbines and ICEs, as well as with various grid-generation technologies and mixes in the United States and California. The fuel cycle for each generation technology included the three stages of fuel production, electricity generation, and electricity consumption at end use. The electricity generation energy use represented the majority of the total fuel-cycle energy use for all generation pathways. Fuel cell technologies exhibited lower GHG emissions than those produced by the U.S. grid mix of technologies and all other distributed generation technologies. Higher-efficiency fuel cells, such as SOFC and MCFC, exhibited energy consumption comparable to that of the California grid mix, but lower consumption than all combustion technologies. Natural gas fuel-cell technologies offered lower dependence on petroleum oil when compared with the alternative diesel and LPG generation technologies. Fuel cell technologies offer such advantages as reliability and the potential use of waste heat for on-site heating applications. They can readily penetrate the distributed electricity markets on the basis of energy efficiencies and/or GHG emissions advantages.

6 RECOMMENDATIONS FOR FUTURE ANALYSIS

On the basis of the analyses discussed in this report, we recommend the following research:

- Investigate combined fuel cell/gas turbine or CHP potential for high-temperature fuel cells,
- Determine the potential of biogas/landfill gas-powered fuel cells,
- Evaluate the effectiveness of H_2 from renewable sources (long-term central production),
- Characterize criteria pollutants emissions characterization, and
- Conduct potential market size and economic analysis by market size and location.

7 REFERENCES

Binder, M., 2006, "Phosphoric Acid Fuel Cells," California Energy Commission Fuel Cell Workshop, Sacramento, CA (May 31) [URL: http://www.energy.ca.gov/pier/conferences+seminars/2006-05-31_fuel_cell_workshop/presentations/2006-05-31_BINDER.PDF] (accessed November 6, 2008).

Büchi, F., M. Reum, S. Freunberger, and A. Delfino, 2005, "On the Efficiency of Automotive H_2/O_2 PE Fuel Cell Systems," Proceedings of the 3rd European PEFC Forum, Session B09, Thursday, 7 July, File No. B091.

Campbell, A., J. Ferral, and N. Minh, 2003, "Solid Oxide Fuel Cell Power System," IEEE 0-7803-7906-3.

Cook, B., 2007, "Fuel Cell Industry: Longer-Term Potential, But High Relative Costs Limit Near-Term Opportunity," North America Equity Research, J.P. Morgan Securities Inc., November 30, 2007 [URL http://www.jpmorgan.com/cm/Satellite?blobcol=urldata&blobheader=application%2Fpdf&blobkey=id&blobtable=MungoBlobs&blobwhere=1158468317365&ssbinary=true&blobheadername1=Content-disposition&blobheadervalue1=attachment;filename=Fuel_Cell_Industry:_Longer-Term_Potential,_But_High_Relative_Costs_Limit_Near-Term_Opportunity.pdf] (accessed November 6, 2008).

DOE: U.S. Department of Energy

DOE, Energy Efficiency and Renewable Energy Office, Hydrogen, Fuel Cells and Infrastructure Technologies Program web page [URL: http://www1.eere.energy.gov/hydrogenandfuelcells/fuelcells/pdfs/fc_comparison_chart.pdf (accessed November 6, 2008).

Dunn, S., 2000, Micropower: The Next Electrical Era, Worldwatch Institute, Paper 151.

Gemmen, R.S., and C. D. Johnson, 2006, "Evaluation of Fuel Cell System Efficiency and Degradation at Development and Commercialization," *Journal of Power Sources* 159(1):646–655.

Heath, G., P. Granvold, A. Hoats, and W. Nazaroff, 2005, "Quantifying the Air Pollution Exposure Consequences of Distributed Electricity Generation," University of California Energy Institute (UCEI).

Hou, Y., M. Zhuang, and G. Wan, 2007, "The Analysis for the Efficiency Properties of the Fuel Cell Engine," *Renewable Energy,* 32(7):1175–1186.

Iiyama, S., H. Katayama, Y. Tokita, K. Higashino, and, K. Sato, 2008, "Development of 1-kW Class Kerosene-Reformed Fuel Cell System," Fuel Cell Seminar 2008, DEM25B-5, Phoenix, AZ, October 27–30, 2008.

Kimura, T., 2008, "Result of the Residential Fuel Cell Extensive Demonstration Project in Japan," Fuel Cell Seminar 2008, DEM23-1, Phoenix, AZ, October 27–30.

Mahadevan, K., K. Judd, H. Stone, J. Zewatsky, A. Thomas, H. Mahy, and D. Paul, 2007, "Identification and Characterization of Near-Term Hydrogen Proton Exchange Membrane Fuel Cell Markets," Battelle for U.S. Department of Energy (April) [URL http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/pemfc_econ_2006_report_final_0407.pdf] (accessed September 17, 2008).

Pehnt, M., and S. Ramesohl, 2003, "Fuel Cells for Distributed Power: Benefits, Barriers and Perspectives," Fuel Cells for Distributed Power (June) [URL http://www.panda.org/about_wwf/where_we_work/europe/what_we_do/wwf_europe_environment/initiatives/climate/publications/index.cfm?uNewsID=7364 (accessed November 6, 2008).

Pei, P., M. Ouyang, Q. Lu, H. Huang, and X. Li, 2004, "Testing of an Automotive Fuel Cell System," *International Journal of Hydrogen Energy,* 29:1001–1007.

SRI/USEPA: SRI International/U.S. Environmental Protection Agency

SRI/USEPA 2007, "DFC 300A Molten Carbonate Fuel Cell Combined Heat and Power System," Environmental Technology Verification Report for FuelCell Energy, Inc., 2007, SRI/USEPA-GHG-VR-41, September.

SRI/USEPA 2005, "Gas-Fired Internal Combustion Engine Combined With Heat Recovery System," Environmental Technology Verification Report for Aisin Seiki Co., LTD, 2005, SRI/USEPA-GHG-VR-37, September.

Tollstrup, M., 2008, "Transportation and Stationary Power Integration Workshop: A California Perspective," Fuel Cell Seminar 2008, Phoenix, AZ, October 27, 2008.

Wang, M., 1999, "GREET 1.5 – Transportation Fuel-Cycle Model," ANL/ESD-39, Center for Transportation Research, Argonne National Laboratory, Argonne, IL.

White, M., Lux, S., Knight, J., Binder, M., Holcomb, F., and Josefik, N., 2005, "DOD Residential Proton Exchange Membrane (PEM) Fuel Cell Demonstration Program," Volume 2 – Summary of Fiscal Years 2001–2003 Projects [URL: http://dodfuelcell.cecer.army.mil/library_items/FINAL_PEM_Report_Vol_II.pdf] (accessed November 6, 2008).

Argonne
NATIONAL LABORATORY

Energy Systems Division
Argonne National Laboratory
9700 South Cass Avenue, Bldg. 362
Argonne, IL 60439-4815

www.anl.gov

UChicago Argonne LLC

A U.S. Department of Energy laboratory
managed by UChicago Argonne, LLC