Feasibility Study of Fuel Cell Residential Energy Stations

by

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Bachelor of Science in Computer Science, University of Southern California, 1990

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Abstract

Electricity provisioning has historically satisfied demand by centralized generation and pervasive distribution through an extensive transmission and distribution network. Once demand increases beyond a fixed threshold, however, the capacity of the generation, transmission and distribution can become crippled and the mal-effects of periodic brownouts and skyrocketing prices may ripple through the nationwide grid system. The traditional response to this constraint is to build new facilities. However, an alternative approach getting increased attention is to satisfy local demands by incrementally investing in distributed generation. Distributed generation facilities can be strategically sited to deliver combined heat and power (CHP) near the source of consumption at unprecedented efficiencies. Presently the distributed generation market remains largely focused on industrial and commercial peak-shaving and emergency back-up applications. The residential market is a frontier yet to be tackled. Residential electricity tariffs, in contrast, are the highest among all sectors and household users are responsible for a large proportion of the peak demand and usage growth. For residential self-generation needs, fuel cell technology is foreseen to be an ideal solution stemming from its low noise, negligible pollution and high efficiency operation. This thesis will assess the market viability of fuel cell technologies for residential distributed generation application. More specifically, the study will consider single household (5 kW) proton exchange membrane fuel cells versus hybrid solid oxide fuel cell with integrated gas turbine (10 kW) technologies for the household end-use and determine the competitiveness and sustainability of each choice.

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Background

Electricity constitutes a critical input in sustaining the Nation's economic growth and development and the well-being of its inhabitants. However, the by-products of electricity production also pose serious threats to its beneficiaries as well as the environment. Most of these culprits stem from the emissions introduced by the combustion of fossil fuels, which accounts for nearly 70 percent of the total electricity generated in the United States.[1] Often cited emission concerns include CO_2 that causes global warming, SO_2 and NOx that trigger acid rain, and volatile organic and particulate matters that induce respiratory illnesses. In the prevailing rate-setting approach for power projects, however, only costs associated with electricity provision are taken into account with the exclusion of costs related to environmental side effects. To the extent that these impacts remain largely unaccounted for, except for basic emission mitigation overheads stipulated by law, the price of power generation is, in fact, artificially deflated from the real cost.

The electricity industry is in the midst of profound and comprehensive change, including a return to the local and neighborhood scale in which the industry's early history is rooted. In the beginning, power stations were established locally in the neighborhood it served. As demand increased, the high capital costs and low reliability of power stations dictated a migration toward a grid based regional transmission infrastructure. The grid melded the diverse loads of many customers, shared the costly generating capacity, and made it possible to obligate urban consumers to subsidize services to the minority rural users. By the start of the twenty-first century, however, electricity service has become pervasive and the logic of clustering demand is losing its validity. To a certain extent, power plants have matured to cost less than the proportion of the grid they occupy and are more reliable than the established transmission infrastructure. Therefore, the grid has become a liability rather than an asset in the evolving energy landscape. At the same time, central thermal power plants have stopped gaining efficiency and economics through scale and have mostly fallen out of favor since the 80's. In their place, megawatt size plants have continued to improve (versus their gigawatt predecessors) and the decentralization movement toward point-of-use kilowatt size systems has picked up momentum.[2]

Distributed power generation is expected to gain momentum in supplanting large centralized power stations due to a variety of factors, e.g. increased power demand, the need for high quality or reliability power, deregulation of the power industry, less susceptibility to terrorist attacks and growing environmental concerns. The fuel cell technology is envisioned to be the ultimate distributed generation choice of the future. Unlike the combustion schemes, fuel cells

[1] S. Kanhouwa et al., 1995, "Electricity Generation and Environmental Externalities: Case Studies", Energy Information Administration , US DOE report DOE/EIA-0598
[2] A. Lovins et al., 2002, "Small is Profitable", Snowmass, CO: Rocky Mountain Institute

extract the energy from fuel feedstock through a solid state electrochemical process which is highly efficient and environmentally benign. Although fuel cells are not yet widely commercially viable, there appear to be no insurmountable technical obstacles that will prevent fuel cells from enjoying commercial success. The main challenge right now is undoubtedly the prevailing high cost of this technology.[3]

There are six different types of fuel cells that have received varying degrees of development attention. Presently, the 80°C proton exchange membrane fuel cell (PEMFC) and the 700-1000°C solid oxide fuel cell (SOFC) have been identified as the forerunner fuel cell technologies that will capture a significant market share. As these two fuel cell types are targeted for early commercialization in the residential (1-10 kW) and commercial (25-250 kW) end-use markets, system studies in these areas are of particular interest. The basic components of a fuel cell power plant consist of a fuel processor, fuel cell power module, power conditioning equipment for dc-to-ac inversion, and process gas heat exchangers. Depending on the operating temperature, fuel cells produce varying grades of waste heat that can be recovered for process heating, gas compression requirements, or exported for cogeneration (or trigeneration) purposes. The applicability of this waste heat can significantly impact system efficiency, economics, and environmental emissions.

The proton exchange membrane fuel cell (PEMFC) generally operates at about 80-85°C. The operating temperature is set by both the thermal stability and the ionic conductivity characteristics of the polymeric core materials. To get sufficient ionic conductivity, the proton-conducting polymer electrolyte requires liquid water. Thus, temperatures are generally limited to less than 100°C and above 0°C. The low-operating temperature allows the PEMFC to be brought up to steady-state operation rapidly. This characteristic, coupled with its lightweight, high power density features, makes PEMFC attractive for smaller scale transportation and stationary applications. However, the low temperature operation also results in low-grade waste heat that is not suitable for most cogeneration applications except water heating and makes thermal integration with high temperature fuel processing equipment difficult. The system efficiency of a stationary PEM power plant is expected to approach 40% (LHV). As with other low temperature fuel cells, the PEMFC requires pure hydrogen source for operation. Since hydrogen is not readily available, it is typically obtained by reforming a hydrocarbon fuel, such as methanol or natural gas, or through electrolyzing water. Typically, hydrocarbon reforming approaches are preferred due to their higher efficiencies and minimal electrical consumption. However, the reformed fuel will need to undergo extensive filtration to eliminate undesirable gas species such as CO and H_2S, which are detrimental to PEMFC

[3] M.L. Perry and T.F. Fuller, 2002, "A Historical Perspective of Fuel Cell Technology in the 20th Century", Journal of The Electrochemical Society 149 (7) S59-S67

electrodes/catalysts. CO ppm levels of 10 or greater can poison the platinum catalyst in PEMFC, causing severe degradation in cell performance.[4]

Solid oxide fuel cell (SOFC) generally uses an Yttria-stabilized Zirconia ceramic material as the electrolyte (ionic conductor) layer and operates at the highest temperature (1000°C/1800°F) of all fuel cell types. As oppose to PEMFC, SOFC does not require pure hydrogen but merely hydrogen-rich fuel source (reformate) and can be very tolerant to fuel impurities. Typically, the hydrogen fuel is internally reformed (using its own heat and both internal and external water sources) from natural gas via a steam reforming procedure. Carbon monoxide presence in the fuel stream is not a problem for SOFC and, in actuality, can be used as supplemental fuel (instead of oxidizing H_2 to produce free electrons and H_2O it can oxidize CO to produce current and CO_2). Because of the high operating temperatures of the SOFC, they are attractive for co-generation and tri-generation purposes. Even without cogeneration benefits, SOFCs can theoretically achieve higher operating efficiency than PEMFC at about 50%. When integrated with a gas turbine (SOFC-GTs), SOFCs are expected to realize 70-85% (LHV) system efficiencies which represent a significant leap over all energy conversion technologies. In the next ten years, SOFC prices are projected to decline to $800-1,000 per kW range. In the interim, material costs and durability remain the biggest challenges for SOFC. These problems, ironically, are caused by the same attribute that give SOFC its operating advantages, namely its high operating temperature. As a result, there remain some challenging thermal (e.g. coefficient of thermal expansion matching), mechanical (e.g. stack integrity), and chemical (e.g. oxidation and corrosion of metal parts) engineering feats that require sound resolutions before SOFC can be commercialized.

The provision of both electricity and heat (cogeneration) for building applications is a significant development objective for fuel cells. The ability of each fuel cell type to meet the highly variable building energy requirements will depend on both its electrical and thermal performance characteristics and their coincidence to the usage demands. One measure of a thermal-electric system's ability to provide both heat and electricity to the site is its thermal-to-electric ratio. It has often been postulated that the characteristically high thermal-to-electric ratio of SOFCs will make them attractive in meeting the thermal loads of various combined heat and power (CHP) applications. The high-grade waste heat produced in a SOFC can be utilized to drive a gas turbine while the bottoming cycle can include an absorption chiller and/or boiler for space heating and cooling, process steam, and/or hot water making functions. The type of heat recovery used is dependent on the application requirements and the resulting cogenerative efficiency will depend on the design.

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[4] R. J. Braun et al., 2000, "Review of State-of-the-art Fuel Cell Technologies for Distributed Generation", Madison, WI: Energy Center of Wisconsin Report 193-2

It is argued in the book "Energy Aftermath" that the new paradigm in the structure of energy systems over the next few decades rests upon integrated energy solutions.[5] The key, as the author predicts, is to achieve synergy through horizontal rather vertical integrations. One example cited is the combination of coal gasifier, gas turbine and steam turbine. Ideally, the modules for the system can be interjected independently, e.g. gas turbine follows by steam turbine then gasifier, and each stage adds value to the whole. In this case, combined cycle turbines achieve better efficiency and gasifier permits fuel diversity. The resulting arrangement will be rated on the qualities of cleanliness, reliability, safety, economics, and robustness.

Such merits have been illustrated by the prototyping of a novel hybrid system based on two forefront technologies, personal turbine (PT) and SOFC. Researchers at the University of Genoa in Italy have validated a 17.3 kW PT integrated with a 31 kW SOFC to achieve partial- and full-load cogeneration efficiency of 55%. The efficiency is largely limited by the equipment size and high ancillary losses, e.g. less effective heat exchanger due to length and higher relative consumption of electricity by on-board devices. When the exhaust heat (~15 kW worth) of this hybrid system is utilized for low-grade steam, hot-water supply, chiller, hot-air supply for drying, and/or desalination purposes, the overall fuel utilization efficiency of the hybrid plant can be bolstered to >63%.[6] Although the combined output of this SOFC-PT prototype still exceeds 36 kW (where 12.3 kW are consumed by internal mechanisms such as compressors and electronics), there exist opportunities to miniaturize this hybrid concept to 10 kW size appropriate for household applications. One of the approach to achieve such goal is to incorporate a 5 kWnet PT and a 5 kW SOFC module to form a 10 kW system while preserving their independent operability. When performing in hybrid mode, the system will be capable of achieving the specified electrical output. However, in a partial failure mode, the PT or SOFC, whichever has not mal-functioned, can continue to operate until the system undergoes controlled shutdown for repair. In this fashion, high system efficiency can be accomplished during normal operation and reliability can be assured through the redundant layout.

The remainder of this paper will investigate the economic, technical and structural intricacies of the residential energy market. After that, a fundamental techno-economic analysis of SOFC-PT and PEMFC will be conducted to assess their mass-market appeals. Subsequent to the these analyses, the paper will highlight some important policy and regulatory trends that may influence fuel cell commercialization including environmental factors as the driving force for this emerging technology. Finally, the work will conclude with strategic

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[5] T. Lee et al., 1990, " Energy Aftermath", Boston, MA: Harvard Business School Press

[6] L. Magistri et al., 2002, "A Hybrid System Based on a Personal Turbine (5 kW) and a Solid Oxide Fuel Cell Stack: A Flexible and High Efficiency Energy Concept for the Distributed Power Market", Transactions of the ASME Vol. 124-850

recommendations aiming to create practicable diffusion models for fuel cells to succeed in specific residential market segments.

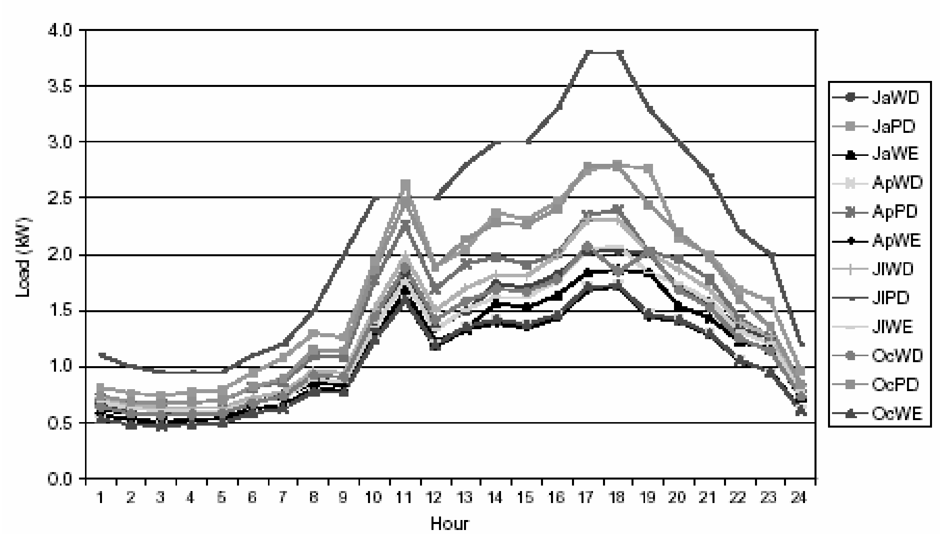
Residential market

The Electric Power Research Institute has identified four plausible long-term markets and types of energy solutions that fuel cell power systems may be viable contenders. They include (1) providing lowest cost energy (electric and thermal) to end-users; (2) providing solutions for combined heat and power (CHP); (3) providing high power quality or back-up premium power; and (4) providing peak-shaving solutions.[7] The residential market for fuel cells constitutes an environment where all of these types of solutions may be readily applicable. Based on the high residential rates in some regions, particularly Northeast, fuel cell co-generation systems may be competitive even in the $2000 to $3000 per kW spectrum. The low noise and emission characteristics of these electrochemical devices will make them ideal for home installations. In terms of CHP co-generation, even the lowest temperature PEMFC will be able to provide heat exportation for hot water making. When fuel cell generators are installed in grid parallel fashion or integrated with battery banks, the service level and reliability will be nearly perfect. Since the average retail rates are already much higher than base-load tariffs, it may be presumed that peak-shaving application of fuel cell distributed generators may be even more promising in the residential sector. Despite all of these fundamental strengths, there will remain technical and structural challenges for residential size fuel cells. These issues including violent load variability, utility imposed stand-by charges, incomplete regulations and standards related to fuel cell devices and complications related to interconnection, distribution and service channels, and others. The subsequent sections will examine these topics and some proposed solutions.

Residential load curve

The typical household electrical requirements tend to exhibit large spikes in the morning and evening time bands and dips in the daytime and midnight time slots. For a relatively large single family dwelling, the peak demand will rarely exceed 4 kW while the baseline load may be as low as 0.5 kW (see Figure 1) according to a recent compilation of residential load profiles for the California region. According to the data, during July peak days (which is representative of typical summer consumption), the peak electrical demand generally occurs in the afternoon hours and may range from 1.5–3.8 kW. In contrast, the October weekend days may only require peak power of less than 1.7 kW even at the extremity.

[7] Dan Rastler, 1999, "Challenges for fuel cells as stationary power resource in the evolving energy enterprise", Journal of Power Sources 86 (2000) 34-39



Ja denotes "January", Ap denotes "April", Jl denotes "July", Oc denotes "October"
WD denotes "week day", PD denotes "peak day", WE denotes "weekend day"
Peak day = average of 3 peak days of the month
Week day = 22 weeks days - 3 peak days
Weekend day = 8 weekend days in a 30 day month

Figure 1-Electrical load profile of large residential site in California.

A similar study in Japan also demonstrated large variability in time of day and seasonality consumption patterns (see Figure 2). The results showed baseline demand of around 1 kW and peak demand of around 13 kW may be possible from a single household. This study differs somewhat with the California study as it included heating demands as a function of the electrical consumptions. Due to the relatively generous heating requirements and fluctuating load factors that are deduced from the experiment, the researchers in Japan have recommended using batteries as load buffers and all-electric heating appliances.[8] However, utilizing batteries for load balancing or peak shaving may present some complications due to the added cost, complexity, heftiness, loss efficiency and limited longevity of these devices. It certainly appears to be simpler and perhaps less capital-intensive to supplement distributed generation (DG) capacity with grid power. There are instances, however, where grid connection may not be accessible or peak electricity rate may be exceedingly high. In these cases, the integration of battery banks may pose economic sense.

[8] Kimihiko Sugiura, et al., 2002, "Feasibility study of co-generation system with direct internal reforming-molten carbonate fuel cell (DIR-MCFC) for residential use", Journal of Power Sources 106 (2002) 51-59

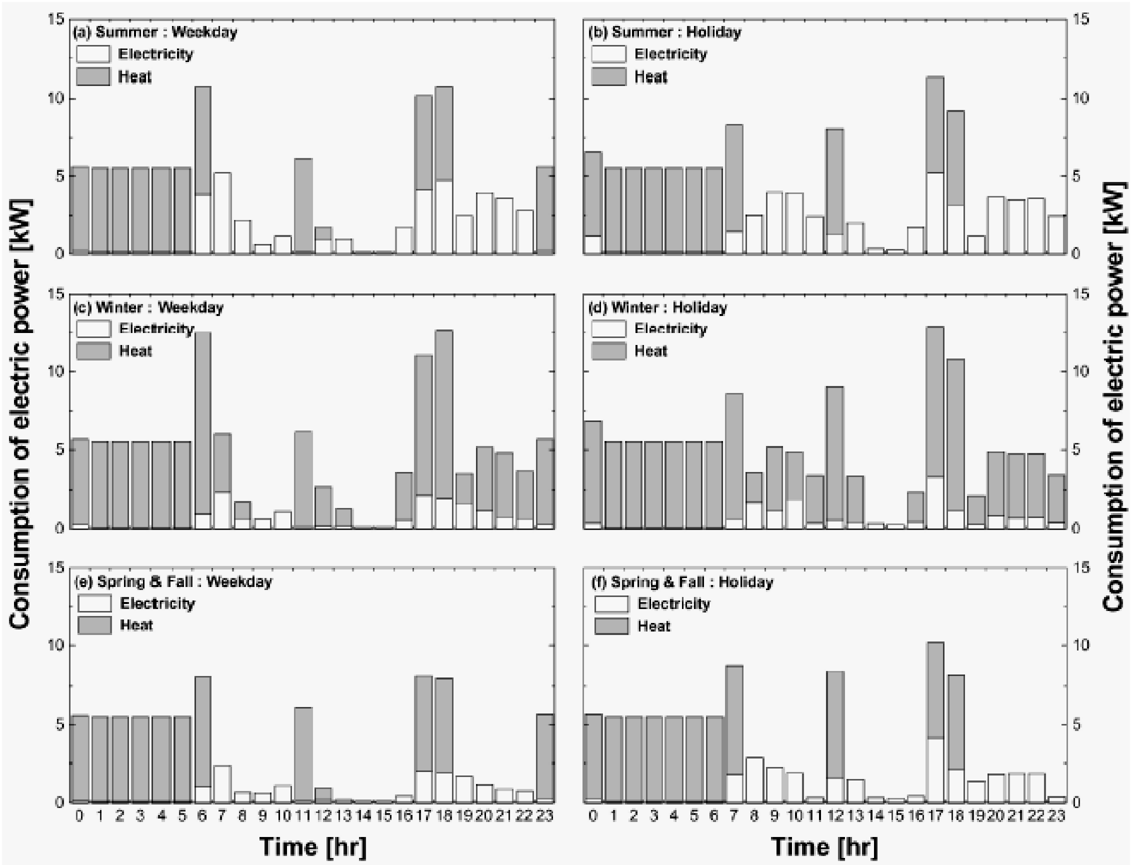


Figure 2-Electric consumption profile of an Osaka model house.

Figure 3 below corresponds to a residential load data compilation by University of Wisconsin - Madison incorporating residential electric and thermal consumption findings generated by their peers. The derived plots are in reference to an average Wisconsin home and the state's corresponding annual weather pattern. The conclusions reached about residential energy demands for the simulated home are (1) On a relative basis, large and rapid electrical energy load changes are typical for single family residential dwellings. Hourly average electric loads are near 1 kWe. The attempt to follow electrical load changes requires millisecond response times; (2) Large and rapid changes in domestic hot water usage (relative to electricity usage) are common. The magnitude of these demand peaks could be reduced with thermal storage, but nevertheless the annual hourly time-averaged hot water thermal-to-electric ratio (TER) is near 1.0; (3) Space heating loads in winter can reach large TER values (>25), especially in the early morning hours, and relatively constant TER demands (~5) until the late evening; and (4) To meet household thermal and electrical energy demands without batteries or grid connection it will require a fuel cell system capable of fast electrical response with flexible TER output capability.[9]

[9] Robert J. Braun, 2002, "Optimal Design and Operation of Solid Oxide Fuel Cell Systems for Small-scale Stationary Applications", University of Wisconsin-Madison, Madison, WI

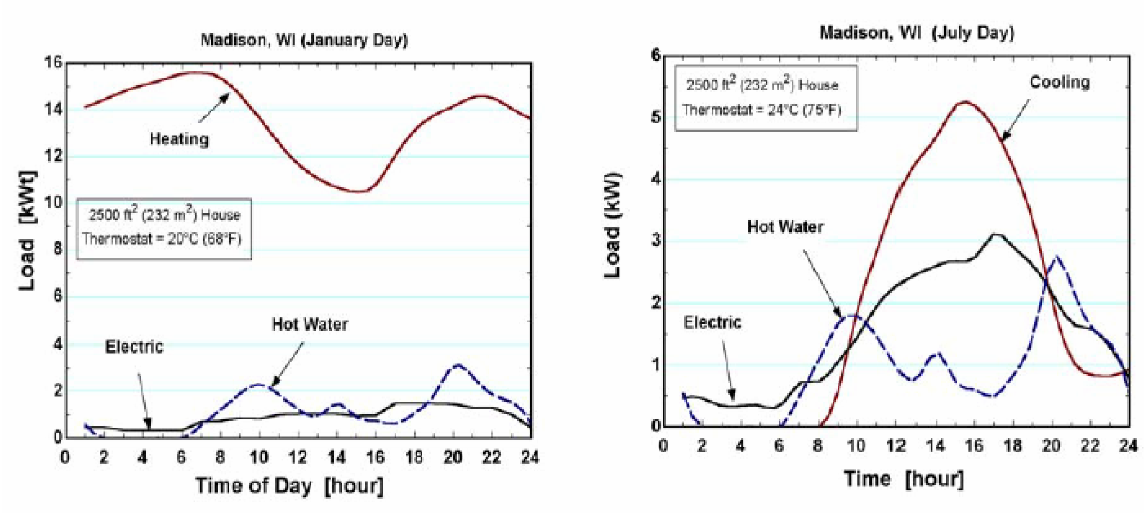


Figure 3-Residential load profile in an average 2500^2 feet Madison, WI home

In addition to demand variability, the topic of load management in residential usage is very active due to the sector's proportionally large peak demand burden. It is estimated that residential customer comprise of 41% of peak load. If this peak burden can be eliminated, it is further postulated that 20% of the nation's generation, transmission and distribution capacities can be divested. [10] In practice, utilities in California and Arizona have attempted to curb peak load problems with PV DG investments to alleviate summer congestions. Other states and municipalities are testing time-of-use concepts to trim peak usage. In essence, the value of peak shaving will be inherently higher than the electricity rates themselves. The aggregate value will include the base-load cost, the price of standby infrastructure, the marginal cost of outages and swaps, and efficiency losses due to extra layers of mechanisms instituted to deal with the transient loads. As these costs climbs, the usages of DG solutions for peak load buffering will become even more sensible.

Batteries for load buffering

Most of the batteries used in current distributed home power systems, e.g. PV, were actually designed for use in deep-cycle electric vehicle or recreational vehicle applications where the recharge can be carefully controlled and complete for every cycle. Insufficient battery recharge and poor charge control results in long periods of low state-of-charge which can be detrimental to some batteries depending on design. Lead-acid batteries are mostly used in integrated power systems. Improved valve regulated lead-acid (VRLA) batteries are now emerging in utility applications. Advanced batteries (such as lithium ion and zinc/bromine) are being developed and are at different levels of size and

[10] Lew W. Pratch, 2003, "Zero Energy Buildings", US Department of Energy, Presented at 2003 RESNET Conferance

readiness for utility operation. Batteries are complex devices whose performance is a function of many variables, including rate and depth of charge and discharge, temperature, and previous operating history. Extremely high discharges (thousands of amperes) and rapid switching between open circuit, charge or discharge are possible from modern battery systems. When the batteries are replaced, essentially all battery materials (e.g., lead, acid, plastic casing) are captured and recycled. A peak shaving application for a home power system may require the battery to boost the output of the generator to meet peak loads for 1-2 hours a day. The charging profile for the battery, which is pivotal in determining battery life, is controlled by the power conditioning system (PCS). Continually undercharging a flooded lead-acid battery will cause it to sulfate, thereby greatly reducing battery life. Overcharging a VRLA battery at moderately high rates and above will cause it to dry out, thereby also shortening its life. Thus, the design and operation of the PCS is a major determinant of the system life cycle costs. Battery energy storage systems operate at an AC-to-AC efficiency of about 75%, and, therefore, consume some energy. The cost of an energy storage system is affected primarily by four drivers: (a) the initial cost of the storage subsystem, (b) the cost of the power converter, (c) the cost of the balance of system, and (d) the cost of integration components. Regarding the cost of these subsystems, a 30 kWh battery unit will cost approximately $1050 with a lifespan of about 3 years. The remaining electrical components such as PCS, inverter and max power tracker may already be synergistic with the fuel cell electrical subsystems and should add marginally to the total cost.

Net metering

There are approximately 40 state net metering programs currently in place around the United States. These programs allow excess local electricity generation to be supplied to the regional utility grid for a credit that can then be used later to supply demands that are not met by the local source. In some cases, excess generation must be “taken back” from the grid on a monthly basis and in other cases any excess can be carried over from month to month with the final net billing accounted on an annual basis. Of the state net metering programs, some states such as California only allow PV and wind systems to be net metered while others may include all renewable systems. In a few states, natural gas powered fuel cells, microturbines and other non-renewable systems can also be net metered. Potentially, the abilities to integrate local generators to the grid and implement net metering may be the most effective mean of load buffering and cost reduction for DG resources.

There are two basic ways in which commercial fuel cell systems can be net metered. First, they can achieve this in a manner analogous to current net metering programs whereby overall billing would be assessed on a monthly or annual basis. One argument against including fuel cell systems in these traditional net metering programs is that while PV and wind systems tend to have peak availability in the daytime and afternoon periods, coincident with the grid demand peak, to the extent that fuel cell systems are sized to meet most or all of the peak building electrical loads, much of the excess fuel cell power may be available only off-peak. For this reason, the more acceptable method may be to accept fuel cell production credits for net metering only during times of peak-demand. This selective credit scheme, however, will likely diminish the overall cost effectiveness of fuel cell DG solutions.

A second type of net metering is "short term" net metering where the fuel cell system is again connected in parallel to the grid but, in this case, simply relies on grid power to take up the transient load. The power used from the grid could be purchases or "repaid" by operating the fuel cell system at excess power and supplying net power to the grid over a short period of time until the "borrowed" power had been replaced. The potential advantage to this approach is that the installed fuel cell system does not need to completely meet the demand but can simply provide a baseline supply, e.g. 1 to 2 kW, therefore it can eliminate adding load buffering systems such as battery or hydrogen storage and operate at optimal efficiency. Although this type of "short term" net metering is potentially promising, it is also more challenging from a utility billing and administration perspective and thus will not likely to emerge as mainstream practices in the near timeframe.

It is worth pointing out that one potential barrier for net metering may arise from the limitations of existing distribution infrastructure to accept power inflows. At this time, reverse flow of electricity from distributed generators into the local grid and eventually the high-voltage transmission system is governed by equipment design and safety restrictions. For bidirectional flows to emerge as standard practice, it may be necessary to retrofit substations to ensure that "tap changers" and line-drop compensators are compatible with reverse flow operation. Additionally, the interconnecting scheme will need to address communication and control mechanisms for transmitting emergency shut-down commands and real-time load and pricing data to the local generators. [11]

Residential cooling and heating requirements

Based on 2002 data presented by DOE EERE (see Figure 4), the average household consumption of energy for space heating, space cooling and water heating amounted to about 58% of the overall residential demand. These three usage categories also account for the bulk of peak power share in general. In addressing peak shaving and energy efficiency applications, it is therefore intuitive to incorporate DG system designs that can support these energy-intensive and highly variable functions. Although there are several heating and cooling options for home use, there are fewer choices that can take advantage of fuel cell's waste heat. In a University of Wisconsin study, it is suggested that the

[11] Timothy E. Lipman, et al., 2002, "Fuel Cell System Economics: Comparing the Costs of Generating Power with Stationary and Motor Vehicle PEM Fuel Cell Systems", Energy Policy S0301-4215(02)00286-0

space heating thermal requirement of a typical household can often be ten times greater than the electrical load. It can thus be seen that the use of residential fuel cell power systems to serve space-heating loads is difficult to achieve through thermal energy alone and will likely require supplemental electric heating facilities. One potential approach to mitigate this lofty thermal and electrical discrepancy may be to design the DG system to maximize thermal energy output first and secondarily consider for electrical efficiency. In contrast, the domestic hot water demand illustrates a better match between the magnitudes of thermal energy available from the fuel cells and the thermal energy required. In any respect, the ensuing sections will describe some of the thermally activated cooling and heating technologies available for fuel cell CHP consideration.

End Use	Quad	%
Space Heating	6.6	33%
Space Cooling	2.0	10%
Water Heating	3.0	15%
Lighting	1.2	6%
Refrigeration	1.7	9%
Wet Clean	0.9	5%
Cooking	0.9	5%
Electronics	1.0	5%
Computers	0.1	1%
Other	0.7	3%
Total	**19.9**	**100%**

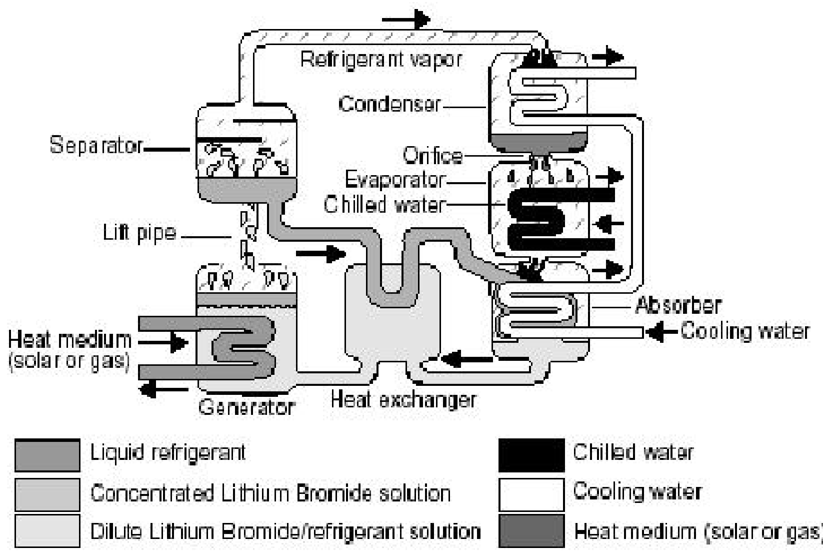
Figure 4-Residential energy profile (data year 2002)

In most CHP applications, the exhaust gas from the electric generation equipment is ducted to a heat exchanger to recover the thermal energy in the gas. Generally, these heat exchangers are air-to-water heat exchangers, where the exhaust gas flows over some form of tube and fin heat exchange surface and the heat from the exhaust gas is transferred to make hot water or steam. The hot water or steam is then used to provide hot water or steam heating and/or to operate thermally activated equipment, such as an absorption chiller for cooling and heating or a desiccant dehumidifier for dehumidification. In some applications air-to-air heat exchangers can be used. In other instances, if the emissions from the generation equipment are low enough, such as the case with fuel cell systems, the hot exhaust gases can be mixed with make-up air and vented directly into the heating system for building heating. In the majority of installations, a flapper damper or "diverter" is employed to vary flow across the heat transfer surfaces of the heat exchanger to maintain a specific design temperature of the hot water or steam generation rate.

One method to provide space heating is through the deployment of a radiant heating system or, more specifically, hydronic radiant heating. Hydronic heating systems use tubing embedded in the floor or ceiling to carry heated fluids to the room. Most hydronic heating systems use water that is treated to improve its resistance to freezing or corrosion of ferrous system components. Hydronic radiant heating systems are closed loop and nearly maintenance free. Advanced systems may include valves or injection loops to precisely control temperatures in each zone. Hot water from a boiler or hot water heater is the medium for heat transfer in a hydronic system. Installation and materials costs have made aluminum finned copper tubing the most effective style. Although radiant heating may provide better comfort factor versus forced air which de-humidifies the air and tends to be noisy and breezy, the technology continues to be more expensive to purchase and install. A household hydronic heating system can be stapled to the underside of the sub-floor, embedded in a concrete slab, or strung between the ceiling joists to radiate down from the ceiling when floor installation is prohibitive. When embedded in a concrete slab, response time is slow and gradual, so the water must circulate constantly and the thermostat set at the desired temperature and left alone. When fuel cell heat is employed for hot water generation, it might be cost advantageous add a hydronic radiant heating system to increase the cogeneration benefits.

Absorption chillers are cooling machines that use heat as the primary source of energy for driving an absorption refrigeration cycle. These chillers require very little electric power (0.02 kW/ton) compared to electric chillers that need 0.47 to 0.88 kW/ton, depending upon the type of electric chiller. Absorption chillers have fewer and smaller moving parts and are thus, quieter during operation than electric chillers. These chillers are also environmentally friendly in that they use water as a naturally benign refrigerant. Commercially available absorption chillers can utilize one of the four sources of heat: (1) Steam; (2) Hot water; (3) Exhaust gases; and (4) Direct combustion. All absorption chillers, except those that use direct combustion, are excellent candidates for providing cooling of the load in a CHP system for a building. Modern absorption chillers can also work as boilers for providing heating during winter and feature new electronic controls that provide quick start-up, automatic purge and greater turndown capability than many electric chillers. Maintenance contracts and extended warranties are also available on absorption chillers at costs similar to those for electric chillers.

Two types of absorption chillers are commercially available, namely single-effect and multiple-effect versions. Compared to single-effect chillers, multiple-effect absorption chillers cost more to own (higher capital cost) but are more energy efficient and thus less expensive to operate (lower energy cost). The overall economic attractiveness of each chiller depends on many factors, including the cost of capital and cost of energy. In comparing absorption chillers with electric chillers, the basic cooling cycle is the same. Both systems use a low-temperature liquid refrigerant that absorbs heat from the water to be cooled and converts to a vapor phase (in the evaporator section). The refrigerant vapors are then compressed to a higher pressure (by a compressor or a generator), converted back into a liquid by rejecting heat to the external surroundings (in the condenser section), and then expanded to a low- pressure mixture of liquid and vapor (in the expander section) that goes back to the evaporator section and the cycle is repeated. The basic difference between the electric chillers and absorption chillers is that an electric chiller uses an electric motor for operating a compressor used for raising the pressure of refrigerant vapors and an absorption chiller uses heat for compressing refrigerant vapors to a high-pressure. The rejected heat from the power-generation equipment (e.g. microturbines and fuel cells) may be used with an absorption chiller to provide the cooling in a CHP system.



Source: Energy Efficiency and Renewable Energy Network (EREN), U.S. DOE. (http://www.eren.doe.gov/femp/prodtech/parafta_appc.pdf)

Figure 5-Absorption chiller operating principal

Current absorption chillers ranging from 3 to 1500 refrigeration tons (RT) are available commercially (see Table 1). A typical home may employ 3 RT of absorption chiller for space cooling purpose.

Supplier	Capacity Range, RT
Broad USA	100 - 2,600
Carrier Corporation	100 - 1,700
Dunham-Bush, Inc.	100 - 1,400
McQuay International	100 - 1,500
Robur Corporation	3 - 25

The Trane Company	100 - 1,600
Thermax USA	10 - 1,400
Yazaki Energy Systems	10 - 100
York International	120 - 1,500

Table 1-Absorption chiller commercial vendors

Retail electricity rates

The average national retail electricity rate has remained relatively stable over the past ten years, hovering between 8.04 to 8.43 ¢/kWh. The highest regional rates are experienced by populations in the New England and Middle Atlantic where average price of 11.74 ¢/kWh has prevailed based on 2002 annual data from the Energy Information Administration (EIA). Within these regions, New York State has the highest average rate of 14.1 ¢/kWh. Nationwide, the state of Hawaii takes the lead with 16.4 ¢/kWh. In contrast, Washington state residences only have to pay 5.2 ¢/kWh on average. As a result of the disparate cost structure, the high rate states are often the most vocal advocates for distributed generation and energy efficiency projects.

Period	Residential	Commercial	Industrial	Other	All Sectors
1991	8.04	7.53	4.83	6.51	6.75
1992	8.21	7.66	4.83	6.74	6.82
1993	8.32	7.74	4.85	6.88	6.93
1994	8.38	7.73	4.77	6.84	6.91
1995	8.40	7.69	4.66	6.88	6.89
1996	8.36	7.64	4.60	6.91	6.86
1997	8.43	7.59	4.53	6.91	6.85
1998	8.26	7.41	4.48	6.63	6.74
1999	8.16	7.26	4.43	6.35	6.66
2000	8.22	7.22	4.46	6.38	6.68
Sources: Energy Information Administration					

Table 2-Electric utility average revenue per kWh by sector in (cents) (Source: EIA)

With the push for deregulation, wholesale electricity prices have become more volatile. This volatility, as illustrated by the power crisis in California, has been attributed, in large part, to the outdated single per-kWh tariff scheme rather than a more appropriate time-of-use schedule. This is an important issue that has so far not been addressed in the restructuring process. Arguably, prices can only be driven to such high levels because demand does not moderate when prices rise; i.e., demand is inelastic. In the restructured U.S. electricity markets, this inelasticity is extreme because so few consumers pay real-time prices. Until metering capacity, tariff structures, and contracts are in place to allow a significant number of customers to reduce power use when prices rise, extreme price spikes are likely to continue. In principle, one way to improve reliability in restructured markets would be through the widespread exposure of retail customers to time-of-use or real-time prices. Most consumers today pay rates that do not vary with time or load. Real-time pricing would help customers determine how much electricity to consume and when. If customers are exposed to high price spikes in times of peak demand, many will likely reduce demand or adjust the timing of their consumption (load shifting) to reduce the magnitude of these price spikes or consider self-generation, thus reducing demand on the system when it is most taxed.

If real-time pricing is to be a widespread option, substantial advances will be necessary in communication and metering technology and infrastructure. For example, widespread installation of affordably priced real-time or time-of-use meters will be necessary for participating customers. Automated data acquisition devices will be necessary to track individual load profiles. System controls that can monitor numerous local control hubs will be necessary as real-time pricing dramatically increases the information management burden for the system operator. Policy mechanisms that encourage price responsiveness would enable at least some customers to benefit from real-time pricing. Granting customer access to more time-sensitive energy price information is fundamental. Distinguishing prices on a coarse level, such as on- and off-peak, is a way to initiate a transition to more a refined system real-time pricing. Such a distinction could encourage load shifting during peak times and be more cost effective given the currently available metering technology and infrastructure. The updated metering technology will also benefit DG industries by enabling effective peak-shaving and load balancing operation. Additionally, the time-of-use pricing will create new classes of customers who may be constrained to higher tariffs due to their predominately peak usage pattern. These customers may be prime lead-users of fuel cell DG technologies even at premium cost.

Natural gas price

More than 60% of U.S. households currently have natural gas service to their homes, although these natural gas consumers are concentrated in the West, Midwest, and Gulf Coast regions. The Northeast, with more than 40% of homes using oil for heat, is an example of a region where potential use of natural gas is largely untapped in the residential market. The nationwide percentage of new home hook-ups captured by natural gas is estimated to have risen to 64% in 1998, reflecting a continued preference of natural gas for residential space heating.[12] While its share of total residential primary energy consumption remains about the same over time, natural gas use in the residential sector is projected to grow by 1.1 percent per year through 2025. Natural gas is an abundant resource in the U.S. At year-end 1999, U.S. recoverable natural gas resources were 1,279 TCF of dry gas, including the U.S. Department of Energy's estimate of 167 TCF of proved reserves (Proved reserves are the volume of

[12] AA/CERA: Natural Gas Trends, 2000

natural gas known to exist and estimated to be recoverable with the application of current technology at existing prices).[13] This translates into a sixty-six year supply at current production levels. Some natural gas analysts believe that the U.S. has several hundred years of natural gas supplies.[14] Mexico and Canada also have large resource bases of natural gas.

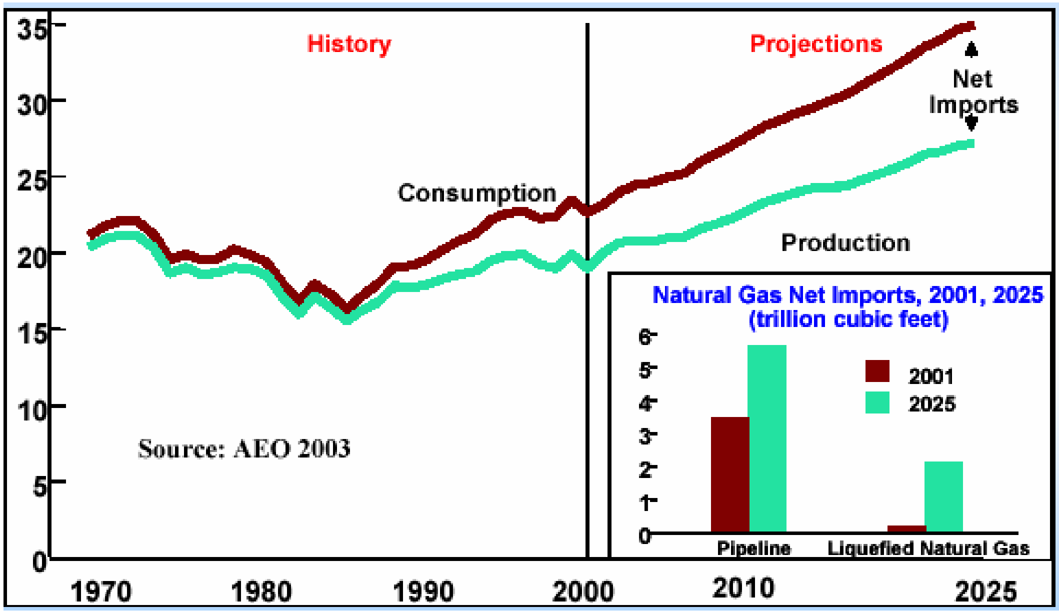


Figure 6-Natural gas supply, consumption and import projections (Source: EIA)

Based on recent EIA projections, the consumption and production rates of natural gas will diverge further in the medium term. However, this widening deficit will likely not cause much price fluctuations due to the abundance of import opportunities including shipments of liquefied natural gas (LNG) into the four available ports in the U.S. In fact, as a result of the unusual price hikes in 2001, the projected residential NG price going forward 25 years is calculated to decrease by 0.70% annually on average. If inflations are taken into consideration, natural gas price in the future will likely be even more affordable than the current environment. Even if fuel cells and other natural gas DG devices end up compounding the demand in any meaningful fashion, the fact that most of these solutions will incorporate cogeneration or trigeneration capabilities can effectively offset much of the additional usage.

[13] EIA: U.S. Crude Oil, Natural Gas, and Natural Gas Liquids Reserves 1999 Annual Report
[14] American Gas Association: Natural Gas Supply Outlook, December 29, 1998

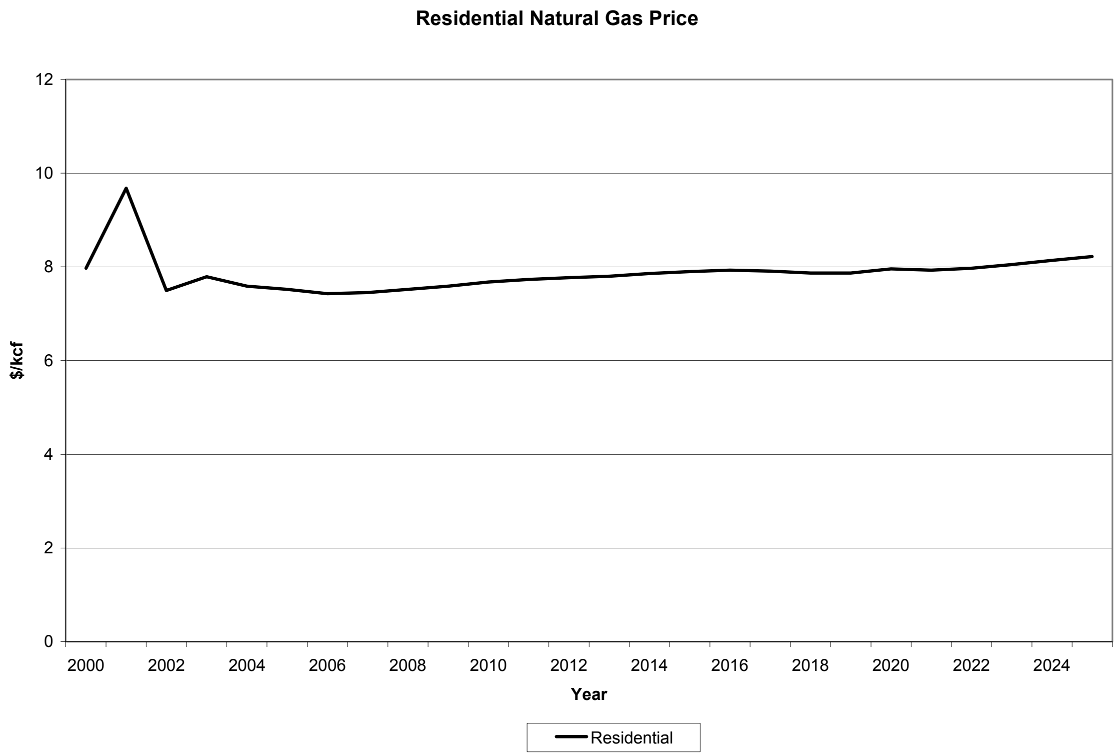


Figure 7-Residential natural gas price projection in 2001 dollars (1 mcf = 1.07 Gj = 1.01 MMbtu) (Source: EIA)

Energy use and housing unit projections

Residential energy consumption is projected to increase by 27 percent between 2001 and 2025. Most (75 percent) of the growth in total energy use is related to increased use of electricity. Sustained growth in housing in the South, where almost all new homes use central air conditioning, is an important component of the national trend, along with the penetration of consumer electronics, such as home office equipment and security systems. Newly built homes today are, on average, 18 percent larger than the existing housing stock, with correspondingly greater needs for heating, cooling, and lighting. Under current building codes and appliance standards, however, energy use per square foot is typically lower for new construction than for the existing stock. Further reductions in residential energy use per square foot could result from additional gains in equipment efficiency and more stringent building codes, requiring more insulation, better windows, and more efficient building designs.

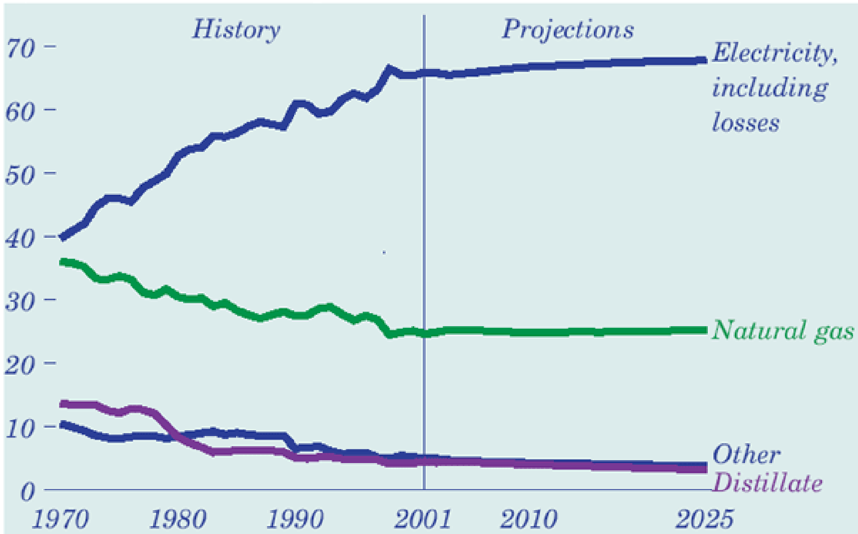


Figure 8-Energy consumption projections (Source: EIA)

Residential housing units are forecasted to increase by 1.05% per year through 2025. On the average, there will be 810, 290 and 80 thousand new single-family, multi-family and mobile homes constructed each year from 2005-2025, respectively. The average square feet of the residential dwelling will be around 1758 square feet per unit by 2025. Although there are no specific data for the size differentials, it is intuitive to assume that average single-family house will be larger than typical multi-family and mobile homes.

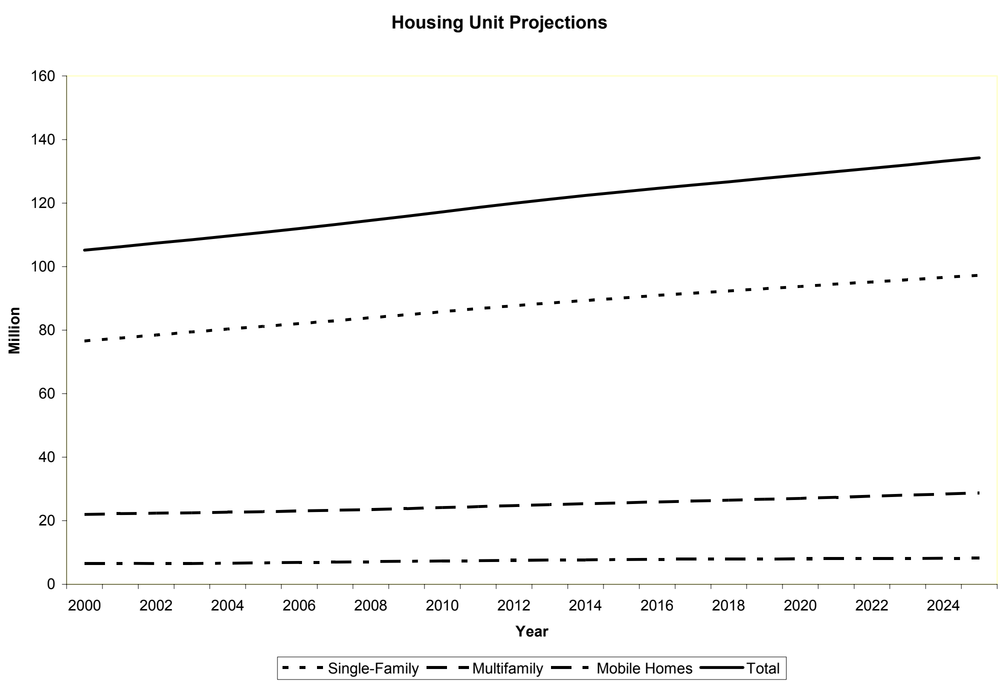


Figure 9-Aggregate housing unit projection (Source: EIA)

Distribution and service options

Retail energy service providers (RESP) are considered most receptive to the adoption of fuel cells in the near term. These independent energy providers will most likely be involved in offering residential as well as commercial and industrial customers with bundled energy services including CHP, uninterruptible or premium power, and energy bill and risk management through onsite power systems. RESPs will be focused on meeting specific customer needs with tailored solutions without concerns for stranded assets or rate-making restrictions as opposed to utility distribution companies. Some of those needs in residential application, such as combining low noise, low emission, CHP and on-demand operation, can be best met by fuel cells. However, the RESPs will also be more risk aversive than, for instance, utility distribution companies in terms of reliability of the deployment options. Therefore, fuel cell technology must be well-proven or a reliability assurance scheme such as µGrid (explained in later section) can be easily accommodated before they become mainstream offerings. Due to the novelty and complex nature of fuel cell systems, RESPs will most likely not own and operate these devices but rather enter into contractual agreements with manufacturers. Thus, a firm set of market and contractual risk management mechanisms between fuel cell vendors, owner/operators and RESPs will need to be developed to facilitate this distribution channel.

Certain end-users such as residential customers may also be early adopters for fuel cell power systems but, in the long term, it will be RESPs that eventually thrust fuel cells into the early majority market. To prevail in the mass market, fuel cell systems will have to approxinate appliance-like feature. Even if this trait can be attained, end-users will still prefer service solutions rather than to buy and operate hardware. To win over direct end-user demand, fuel cell power systems must provide specific and compelling reasons and tangible values. Some of these reasons may include low cost energy; CHP needs; reliability concerns; grid independent desires; service level improvements; and environmental consciousness. There will remain key challenges in the direct sales model even if demand ratchets up. Foremost, the manufacturers will need to establish nationwide if not worldwide marketing, sales, distribution, installation, service and education/training channels. Additionally, fuel cell vendors will have to contend with building designers that possess limited knowledge of fuel cell systems and their integration process, purchasers that may wish to have various financing options and utility distribution companies that are likely to impose interconnection charges to recuperate stranded line costs.

Master planned communities

Master Planned Communities are large new home communities that typically feature community entries, parks, recreational areas, schools and shopping centers. Within a planned community there are smaller subdivisions offering a variety of home styles and price levels to choose from. These new communities may present good opportunities for DG integrations on a scale that can meaningfully decrease the system, installation and maintenance costs. The ideas of integrating DG and energy efficiency technologies are gaining traction in various new residential developments. For instance, Shea Homes is building 306 homes in San Diego that are equipped with solar water heaters and about 100 will incorporate 1.2 kW or 2.4 kW PV supplemental generators. These new concept homes are attracting a lot of buyer interest and have nearly sold out as soon as they are released. Another example is Centex Zero Energy Building (ZEB) Homes. These houses are built with 3.6 kW PV system and advanced insulation materials to achieve near zero grid reliance. Given the high cost of PV technologies today, at least $2000 per kW, homeowners still seem to be willing to pay a premium for clean, self-generation features. For the fuel cell entry market, new track or community scale home sites appear to be impressive ingress points. Since these track developments tend to incorporate limited number of designs and be build in clusters and at volume, the forefront work and costs of designing fuel cell cogeneration units into the home mechanical and electrical system and allocating or training installers for the integration efforts will be much more cost-effective than dealing with custom or retrofitting housing projects.

Building codes and regulations

Siting issues are more pronounced if the DG system creates noise, emissions, or has a negative visual impact. Photovoltaic systems can usually avoid siting problems, particularly if they are integrated into the roof of a building, but they may face resistance in some communities with strict rules on building appearance, or in areas designated as historic. Small wind turbines are generally not recommended for urban locations due to visual and potential noise impacts, but are usually easy to site in rural locations. Fuel cell systems are generally easy to site because of their low emissions, silent operation and non-intrusive appearance. If fuel cells are to be installed indoors then applicable building codes and permits will also apply. Although local inspectors are often not required to follow the National Electrical Code (NEC), many do refer to Article 690 of the NEC for guidance on equipment and wiring safety for small renewable energy system installations. Article 690 of the NEC specifically discusses photovoltaic systems, but much of the information is pertinent to small wind and other DG systems as well.

Fuel cells generally produce direct current and require an inverter and other power conditioning equipment to connect to the grid. Power conditioning equipment may also include charge controllers if a storage device is used, and generally includes surge protection, grounding, and instrumentation and meters. UL1741 sets the standards for power conditioning equipment. Additionally, state and local building enforcers and affiliated utility may also require manual disconnects, special meters, isolation transformers, redundant breakers, and other devices for grid interconnection.[15] In order to safely circulate electricity to the house and transmit to the grid, there are other balance-of-system considerations. These may include power conditioning equipment that has been discussed and additional safety equipment and/or meters. Safety features protect grid-connected and stand-alone small renewable energy systems from being damaged or harming people. The essential safety apparatus include the following:

Safety disconnects: Automatic and manual safety disconnects protect the wiring and components of the DG system from power surges and other equipment malfunctions. They also ensure that the system can be shut down safely for maintenance and repair. In the case of grid-connected systems, safety disconnects ensure that the generating equipment is isolated from the grid, which is important for the safety of people working on the grid transmission and distribution systems.

Grounding equipment: This equipment provides a well-defined, low-resistance path from the DG system to the ground to protect it against current surges from lightening strikes or equipment malfunctions. Ideally, both the DG system and balance-of-system equipment should all be grounded including any metal enclosures.

Surge protection: These devices also help protect DG system in the event that nearby power lines (in the case of grid-connected systems) are struck by lightening or unusual surges occur.

If the DG system is connected to the electricity grid, it is necessary to provide meters to keep track of the electricity exported and drawn from the grid. Some power providers will allow the use a single meter to record the excess electricity the DG system feeds back into the grid (the meter spins forward when electricity is used and backward when electricity is fed). Power providers that don't allow such a net metering arrangement will require the installation of a second meter to measure the electricity that is fed into the grid.

[15] http://www.eere.energy.gov/der/buy_install_system.html

SOFC and PEMFC

Current fuel cells slated for residential applications are mainly targeted at single household capacities. As such, fuel cells for this market have mostly been designed to generate between 1 kW to 10 kW of electricity outputs. Generally, residential fuel cell units are the combination of three major components - fuel process/reformer, fuel cell stack and inverter. The reformer takes a hydrogen rich fuel and strips off the hydrogen. Most often, the source of hydrogen is a hydrocarbon fuel, such as natural gas, propane, or methanol. Due to the high operating temperature of SOFCs and its robust impurity tolerance, the hydrocarbon fuel can usually be reformed internally through a simplified fuel processor and the reformate gas, which usually contains some amounts of CO and CO_2, can be consumed directly without additional purification process. A typical steam methane reforming process is depicted in the diagram below.

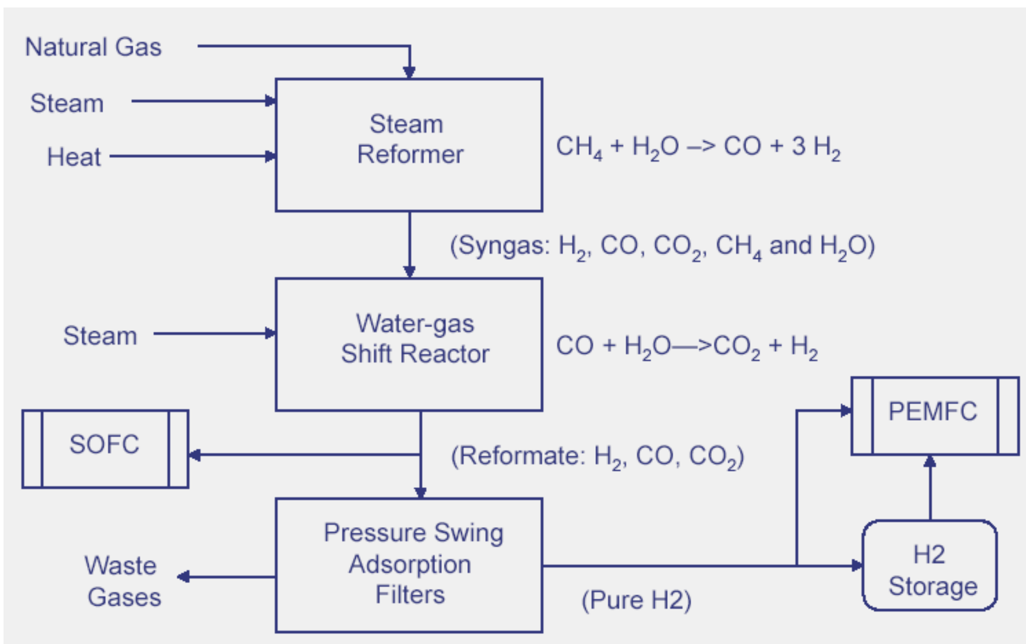


Figure 10-Typical steam methane reforming for fuel cell integration

As opposed to SOFC which can consume CO as fuel, PEMFC is highly sensitive to this impurity and others due the use of platinum catalysts. As a result, the reformer for PEMFC will require fine filtration components to reduce the contaminants, such as CO, down to less than 10 ppm levels. Once the hydrogen or reformate gas is generated or supplied, the fuel cell stacks can take the fuel and combine it with oxygen to creates electricity through an electrochemical process. The electricity generated by the stack will be in the form of direct current and the quantity and size of the stacks will determine the amperage and the stack interconnection method will dictate the voltage. Finally, the inverter takes the direct current electricity from the fuel cell stack and transforms it into alternating current, compatible with the electricity grid. To increase the efficiency of the system, the heat produced by the unit can be used for space or water heating, although heating water will be the most likely application for PEMFC due to the low grade heat it rejects.

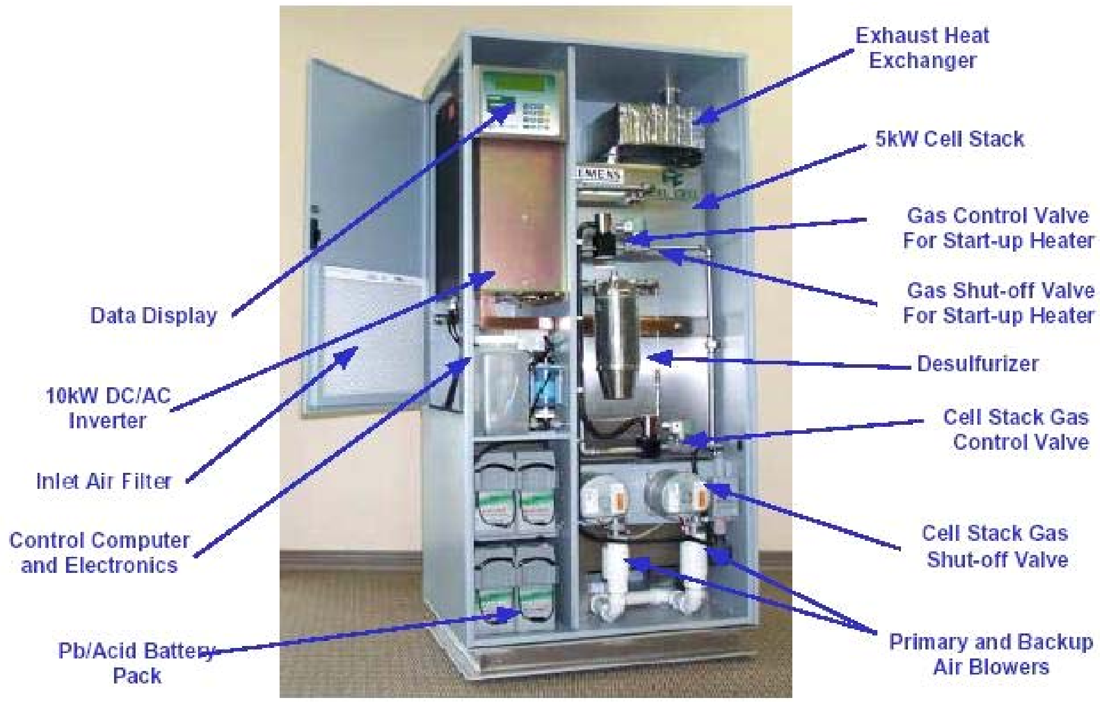


Figure 11-Siemens 5 kW SOFC system

Fuel cells have many modes of operation. Ideally, the fuel cell will provide all of the power needs to the home, which is termed independent operation. The fuel cell can also work with the existing power grid to supply power. Often this operating mode is coined grid parallel. This grid-connected operation can be done several ways. For example, the fuel cell could be sized to provide a baseline level of electricity with the grid supplying the extra power needed to support the electrical load. This mode, which is usually called baseline operation, would allow the unit to run at its maximum efficiency at all times. Alternatively, the fuel cell unit could be used in a peak-shaving mode. The majority of power would be supplied from the grid, but any power required greater than a pre-set limit would be supplied by the fuel cell. Peak-shaving is generally used in commercial or industrial settings to reduce demand charges during peak electricity usage times but can be equally applicable for residential customers billed on time-of-use tariff scheme. However, if the fuel cell unit is not running constantly and cools down while not in use, the start-up time can be significant, which severely impacts the efficiency. As discussed earlier, fuel cell can also combine the functions of independent operation and peak-shaving (or load leveling) by incorporating electrical storage devices such as batteries or ultracapacitors. In this fashion, the fuel cell will operate in baseline mode all the time and excess electricity will be used to charge the storage devices and, during times of excess demand, the stored electricity can be retrieved.

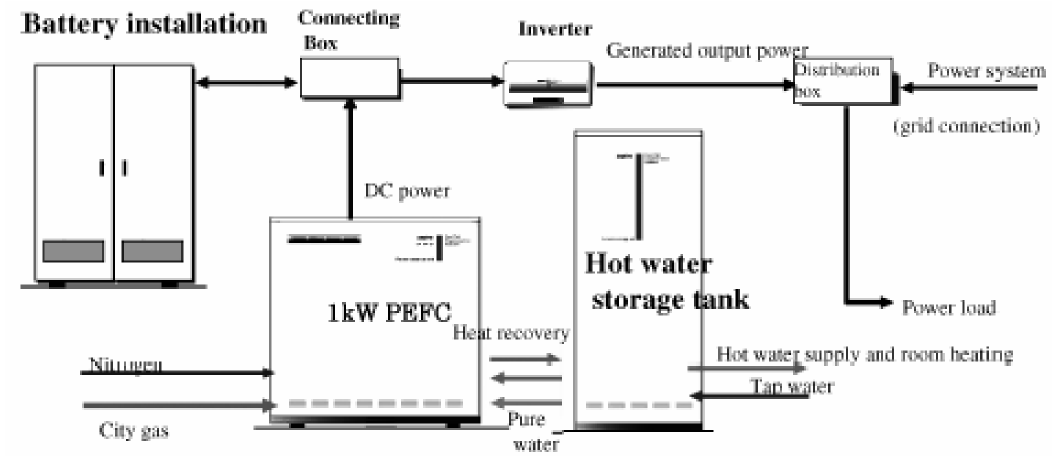


Figure 12-Example of PEMFC home system setup

PEMFC fuel processor overhead

From the viewpoint of a small power generator, the PEMFC has recently been highlighted as an attractive dual use candidate for both transportation and home co-generation applications. PEMFC is singled out for automobile use as a result of its low temperature, light weight and quick startup capabilities. This synergy between transportation and stationary uses may enable PEMFC to reach scale production quickly and thus benefiting it from an accelerated experience curve and economy of volume. Though the PEMFC is suitable as the power supply for vehicles that consume hydrogen or methanol as fuel, a home co-generation system will have to adapt to pipeline natural gas as feedstock to be viable. Therefore, all natural gas PEMFC systems will require fuel processor to first convert city gas to hydrogen. The most efficient fuel converters to date are various reforming (autothermal, partial oxidation, or steam) devices. However, all of these reformers will require high temperature (>700º C) to function and the low quality heat expelled by the PEMFC (<100º C) will likely not be sufficient to support the reformer requirements. As a result, the reformer module will usually have to be equipped with natural gas/hydrogen burners or electric heaters to generate additional thermal energy. This added fuel or electric consumption will diminish the overall efficiency of the PEMFC system and the high temperature nature of the reformer will cancel out the low temperature, quick start benefits of PEMFC when operated on hydrocarbon fuel.

With the current PEMFC technology, a quick response to the changes in electrical load is difficult to achieve. This is mainly attributable to the slow response of the gas-reforming unit and not a problem caused by the fuel cell plant. Improving the sluggish response of reformers will be the key to alleviate the predicament. Companies such as Ballard of Canada have been very successful at improving the response of the methanol reforming process by employing a heat-exchanger type reformer. Similar successes for natural gas reforming have been reported by other parties. Typically, improved response can also be created by using a hydrogen buffer or storage in the system. For instance, 1 kW of electricity for 5 minutes at 40% fuel cell efficiency requires some 70 liters of hydrogen. This requirement can be supplied by compressed hydrogen tanks no larger than the size of an expansion tank in water heating systems.[16] Additional problem associated with PEMFC is the stringent hydrogen purity requirements. Most times, when reformer is deployed, the gas cleanup is achieved by forcing the syngas from the reformer through microporous metallic or ceramic adsorbate or membranes to trap impurities. The utilization of these purification devices will dictate pressurized environment, around 10 to 20 atm, thus adding costs, on top of the purification processor itself, to the housing and piping components.

Reformers for 1 to 5 kW fuel cells are difficult to construct efficiently and cost effectively in general regardless of fuel cell types. However, the requirement of an extensive gas post-processor in a natural gas fed PEMFC will exacerbate the problem. Due to thermal dynamics, for instance, it is difficult to design heat exchanges that are below a certain threshold length and thermal controllers and burners that can perform precisely in very confined spaces against small thermal masses. For a small reformer, the entire device make-up is the same as an industrial version except everything will need to be miniaturized. Intuitively, a miniature device, e.g. 50 standard cubic fee per hour (scfh) suitable for a 1 kW PEMFC, will cost more per unit of output than conventional units in the order of >5000 scfh. As an example, a pressure swing adsorption unit (gas purifier using ceramic or mineral adsorbate) of 50 scfh may cost negligibly less than a 500 scfh unit and occupy only marginally less volumetric space. Even if a 50 scfh size reformer can be built economically and compactly, the efficiency of such a miniscule unit will suffer as a result of negative economy of scale.

SOFC transient limitations

Due to their high temperature nature, solid oxide fuel cell systems often have difficulties in following the dynamic electrical load due to both the response time of fuel delivery system (seconds) and cell-stack thermal response (minutes). Even in hot standby mode, the thermal lag of the cell-stack has been estimated to range from 120 – 1200 seconds. It is conceivable that the SOFC will eventually modulate up or down in power output in a relatively slowly changing manner, while the instantaneous power demand is served by the electric grid (or battery banks in stand-alone systems). However, there are additional considerations to operate a SOFC in load-following fashion. In traditional power generation systems, a load step of 20-25% of the generator rating is considered large, causing significant transients stress. Distributed power systems, such as in residential applications, will require load steps of 50-60% of system rating without causing safety or stability problems for both the fuel cell system

[16] N.M. Sammes, et al., 2000, “Small-scale fuel cells for residential applications“, Journal of Power Sources 86 (2000) 98-110

components and the load. Load step changes of this magnitude may take several minutes or longer for fuel cell systems due to the thermal lag of the fuel cell and fuel processing hardware as mentioned. Additionally, proper steam-to-carbon ratios in the fuel reformer feedstock must be maintained during these operation changes in order to ensure no harmful carbon deposition occurs in either reformer or fuel cell stack components. Issues of safe operation and control also exist when stepping down in load. During this process, excessive unreacted fuel will exit the fuel cell stack for a short period of time and enter the combustor. Depending on how the fuel cell stack is thermally integrated with the afterburner, the excessive fuel oxidation and heat release may generate large temperature gradients in the fuel cell components and downstream heat exchangers, causing excessive thermal stresses or exceeding the temperature limits of the hardware. Reading from these constraints, it appears the most effective mode to operate a SOFC is perhaps to run it in a baseline manner and utilize the grid power to moderate excess supply and demands (net metering).

Micro- and personal turbines

Microturbines generally refer to a new class of combustion turbines producing between 25 to 50 kW of electrical power. For residential applications, this capacity range is deemed too large except for some multi-family housing applications. Nonetheless, as turbine size decreases, its efficiency also degrades due to significantly lower aerodynamic efficiencies of the smaller blade dimensions. On the other hand, small turbines offer the advantage of faster transient operation. There are few commercial examples of small turbines. A very small turbo generator that was introduced for commercial use was the Nissan micro gas turbine rated at 2.6 kW. While never produced in large quantities, it nevertheless demonstrates the capabilities of the industry. For gas turbines in the power range of 5 to 25 kW, the term “personal turbine” has been used in several publications. Personal turbines (PT) can operate silently and vibration free in constant or variable speed modes, making them suitable for residential applications. When integrated with a SOFC, the exhaust gas stream of the fuel cell at about 900º C can be directly ported to the inlets of personal turbines to power the device. With the SOFC as the energy source, the burner section of the turbine can be eliminated or retained but only acting as a complementary afterburner. Even in variable speed mode, the SOFC-PT combination is estimated to achieve 55% efficiency.[17]

After heat recuperation and expansion, the exhaust temperature from the personal turbine is expected to remain at 250º C. With a heat exchanger module in place, approximately 15 kW of thermal energy can be recovered from the exhaust heat of a 10 kW SOFC-PT cogeneration unit, thus boosting the overall fuel utilization efficiency of the hybrid plant to about >63%. Since the natural gas

[17] C. McDonald, et al., 2002, “The Ubiquitous Personal Turbine - A Power Vision for the 21st Century”, Journal of Engineering for Gas Turbines and Power, ASME, October 2002, Vol. 124, pg. 835-844

has been desulfurized in the reformer module (collected in a absorbent bed and typically sent back to manufacturer for recycling), there is no concern about sulfuric acid formation and corrosion (resulting from temperature below sulfuric acid dew point) in the exhaust system when discharge temperature is reduced further by the heat exchanger (as oppose to combustion turbine). Downstream of the heat recovery module a flue gas condenser can be added to facilitate water reclamation. In some applications, this recovered water may have economic value, particularly in arid regions such as the Middle East. Although the personal turbine is deemed highly mass producible, the cost of these machines can only be envisioned to reach $1000 /kW in the near term and $200 to $500 in the medium term due to inclusion of high temperature and wear-resistant materials.

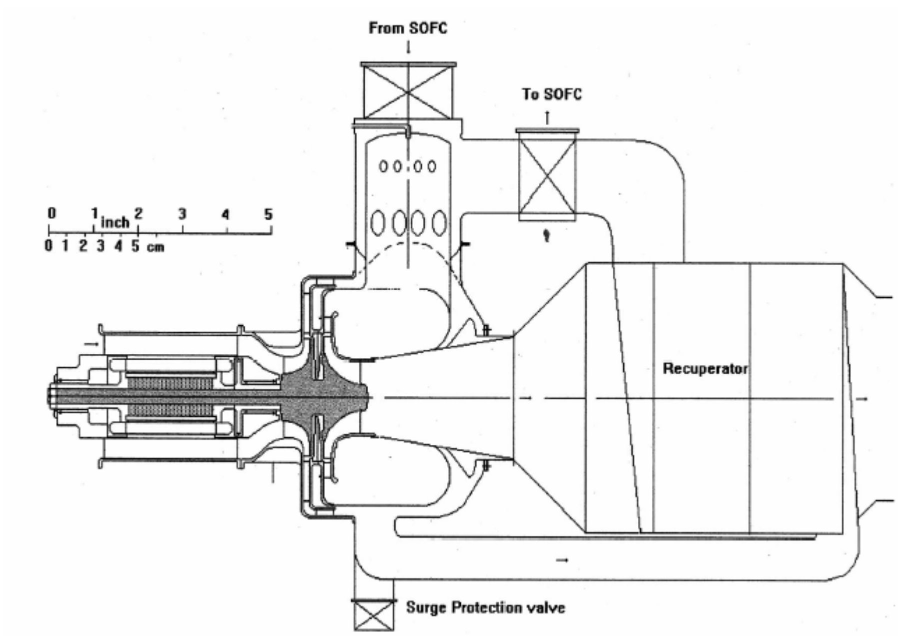


Figure 13-Design of SOFC mountable Personal Turbine

Balance of system (CHP)

Making use of the one-half to two-thirds of energy lost as waste heat in most electrical generation is the easiest and best way to increase the overall efficiency of the nation's thermal and electric generation infrastructure. Because DG occurs near the user, it provides far more opportunities to use this waste heat in CHP (combined heating & power or cooling, heating & power) applications than do large central generation plants. The value of thermal energy is estimated to range from 2.0 to 3.0 ¢/kWh. The average efficiency of producing separate heat and power, which is around 45 percent, can be increased to more than 80 percent if the waste heat produced from electricity generation is utilized. CHP systems have the potential to use heat output from power generation for meeting cooling needs as well as heating requirements. For instance, a compressor-driven cooling system running on electricity could be replaced by an absorption chiller that provides cooling by using rejected heat from power generation. This CHP system reduces peak load demand by shifting what is typically a large peak-coincident electrical load from air conditioning to a thermal load. From the perspective of the utility, this strategy reduces peak system load at times of greatest demand where the marginal cost of power is the highest. In most parts of the U.S., building cooling is required in addition to building heating. Meeting this peaky, weather-sensitive load will alleviate much of the stranded costs on the centralized power system. For example, in California air conditioning is estimated to be responsible for about 29 percent of peak electricity demand, yet this end-use consumes only about 7 percent of the state's electrical energy.[18] For home heating purpose, most hot water and space heating systems are fairly simple, so there are few technical barriers to fuel cell integration.

A recent simulation carried out by University of Wisconsin-Madison has demonstrated significant reduction of utility expenses from a 2 kW 800ºC SOFC-water heater CHP system for a typical home of 2500 square feet (see Figure 14). The 2-kW rated SOFC system was conceptualized to be equipped with two-tank hot water heaters. The unit system capital cost for this design was estimated to be $1,925/kW. The total system capital cost, including the second hot water tank for waste heat recovery, was estimated to be $4100. Based on the assumptions of grid electricity price of 7 ¢/kWh and natural gas price of $4 /MMBtu, the employment of the SOFC CHP resulted in electric utility savings of $563, a 90% reduction. However, in the case where no heat was recuperated, the gas utility requirement increased 169% from $123 to $331 due to SOFC fuel consumption (see Table 3) and even in the case of the CHP model the gas bill will jump by 115%. Overall, the SOFC CHP system was calculated to provide a simple payback of about 10 years. Annual simulation of the fuel cell system without any maintenance shut down shows the annual fuel cell system cogeneration efficiency (LHV basis) to be 84.3%. Over the course of the year, the SOFC met 91% of the total house electric energy requirement. On the thermal side, the fuel cell system was able to provide 54% of the total annual domestic hot water energy requirements.

The University of Wisconsin study further determined that the electric capacity factor (defined as the kWh supplied by the fuel cell divided by the maximum kWh it could have supplied) of the 2 kW SOFC may be too large for single-household use, as only 46% of its annual electrical energy production capacity was utilized. Employing a smaller fuel cell system of 1 kW could conceivably double the electric capacity factor to 92%. The thermal capacity factor of the fuel cell, defined as the kWh recovered from the exhaust gas divided by the kWh that could have been supplied had the exhaust gases been reduced to the water main temperature, was also used to evaluate performance. An 81% thermal

[18] Owen Bailey, et al., 2002, "An Engineering-Economic Analysis of Combined Heat and Power Technologies in a μGrid Application", Ernest Orlando Lawrence Berkeley National laboratory, Report: LBNL-50023

capacity factor was achieved in cogeneration mode, displacing 4,800 kWh of thermal energy that otherwise would have been provided by the hot water heater. This high degree of waste heat recovery was possible due to the use of a 2-tank thermal storage configuration. From the thermal capacity standpoint, the 2 kW SOFC system was about the correct size.[19]

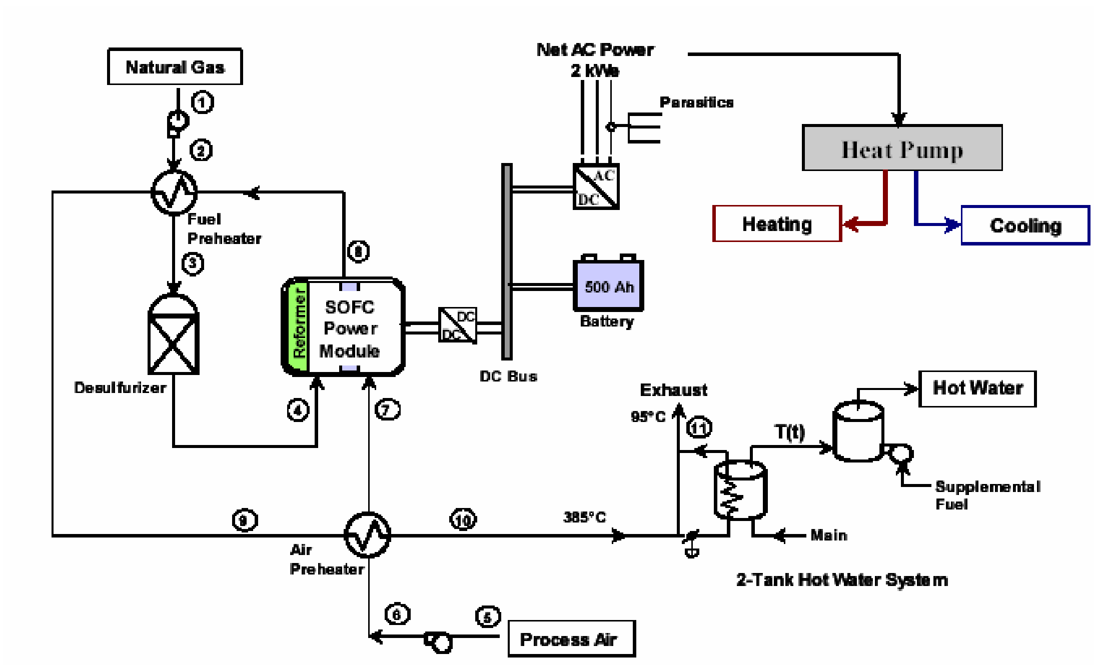


Figure 14-A conceptual SOFC with thermal storage CHP system

System	Electric ($)	Gas ($)	Total Cost ($)	Payback (yrs)
Grid electricity; gas-fired water heater	622	123	745	(base case)
SOFC + grid backup; gas-fired water heater	59	331	390	10.9
SOFC + grid backup; cogeneration with gas-assist	59	265	324	9.8

Table 3-Economic summary of 2-kw SOFC-water heater cogen system

It is worthwhile to point out that if a typical 1000ºC SOFC was utilized for the UoW experiment the amount of thermal energy available will be higher. As well, the use of a larger SOFC system will invariably increase the thermal outputs. One alternative method to take advantage of the residual thermal capacity from a larger SOFC cogeneration unit is to extend the water heating functions to space heating. This can easily be achieved by adding a hydronic radiant heating

[19] Robert J. Braun, et al., 2001, "Assessment of Solid Oxide Fuel Cells in Building Applications", Madison, WI: Energy Center of Wisconsin Report 207-R

system. During Summer time, the excess thermal energy can be directed to an adsorption chiller for cooling effects. To enable the entire scheme to achieve economic parity or viability, a “net metering” or energy storage system (e.g. electrolysis for making hydrogen which will be discussed subsequently) will likely be a necessity.

Hydrogen as energy carrier/storage

Hydrogen is an abundant and clean energy carrier; however, it must be harnessed by first applying energy. One simple method of making hydrogen is through an electrolyzer. The electrolysis process can be described as the reverse operation of a fuel cell where electricity is spent to decouple water molecules. Although electrolysis machines have been around commercially for decades, the industry has not grown beyond mainly niche markets. Two problems associated with electrolysis are its low efficiency, around 40% versus steam reforming of >80%, and sole reliance on electricity. With the advent of hydrogen-based fuel cell automobiles, however, the electrolysis industry is vying for a piece of this potentially vast and untapped market for on-site hydrogen generation. Some proponents of electrolysis are pushing for renewable energy integration to offset its electricity intensive pitfalls. Others have proposed to take advantage of off-peak electricity to reduce production cost. Although there remain many questions about electrolyzer’s role in a hydrogen transportation economy, the fact that it can benefit from cheap electricity is hard to debate.

Electricity, however, is not cheap, and neither is the infrastructure required to electrolyze, compress, and store large amounts of hydrogen. With electricity at 5 ¢/kWh, the cost of hydrogen would be about $10 per thousand standard cubic feet, or about $5 per gasoline gallon equivalent (GGE). Although this price might be acceptable in the near term, the medium-term targets of the Department of Energy are about $1.50 to $2.50 /GGE. The ways to achieve the price objectives through electrolysis pathway are limited to improve the efficiency of the technology, decrease the cost of electricity and/or reduce the capital cost. Lowering the cost of electricity is imperative since this “feedstock” is about five times more expensive than fossil fuel (e.g. natural gas used for reforming) and constitutes about 80% of the resulting hydrogen selling price assuming electricity price of 5 ¢/kWh. Recent progresses in proton exchange membrane (PEM) electrolyzer systems have demonstrated the ability to improve cost much quicker than conventional alkaline electrolyzers. This will make electrolyzers more competitive in the near future. On the other hand, efficiency gains for electrolysis systems are not likely to materialize at least in the visible horizon.[20]

As net metering might be unavailable or uneconomical in some instances, one way to store excess electricity produced from the fuel cell DG devices is to convert it into hydrogen. Since the marginal cost of production for these DG

[20] C.E. Gregoire Padro, et al., 1999, “Survery of the Economics of Hydrogen Technologies”, National Renewable Energy Laboratory, Report: NREL/TP-570-27079

resources are quite low, approximately equaling to the cost of feedstock, the utilization of the excess capacity for hydrogen generation should be quite attractive. Once the hydrogen is produced and stored, it can then subsequently be used for automobile fueling, resold to distributors or supplied to neighborhood fuel cells. Since larger electrolyzers are more cost effective, one optimal approach is to hook-up a sufficient scale electrolyzer to the µgrid (discussed in the subsequent section) for each neighborhood or community. In this fashion, the amount of excess electricity for hydrogen production will be more stable and ample. Certainly, if the electricity resell price is sufficiently high (e.g. peak rate), the DG or µgrid owners may elect to redirect the excess power to the central grid and idle the electrolysis equipment. In any regard, the prime benefits of this scheme is that all of the fuel cell systems within the µgrid can operate in baseline mode and disregard the pains of load-matching and buffering.

Micro-grid concept

A microgrid (µgrid) is a semi-autonomous grouping of loads and generation under some form of coordinated control, active or passive. It is connected to the power grid, as we currently know it, by some form of interface that allows the µgrid to appear to the wider grid as a legitimate entity under grid rules, e.g., as a generator. The expectation is that improved small-scale generating technology, limits on the continued expansion of the current power system, the potential for application of combined heat and power (CHP) technologies, and improved customer control over service quality and reliability will together make generation of electricity close to end uses competitive with central station generation. A typical µgrid may be a cluster of generators producing loads capable of operating in a coordinated fashion autonomously or semi-autonomously from the wider power grid. The cluster would most likely exist on a small dense group of contiguous geographic sites, but could be more dispersed and transfer electrical energy through a distribution network and/or heat energy through other media. The generators and loads within the cluster are placed and coordinated to minimize the cost of serving electricity and heat demand, given prevailing market conditions, while operating safely and maintaining power balance and quality.

The heart of the µgrid concept is the notion of a controllable interface between the µgrid and the wider power system. This interface can separate the two sides electrically, but connects them economically. On the inside, the conditions and quality of service are determined by the µgrid, while flows across the dividing line are motivated by the prevailing valuation of energy and other services on either side of the interface at any instant. From the customer side of the interface, the µgrid should appear as an autonomous power system functioning optimally to meet the requirements of the customer. Operating schedules and reliability performance should be those that support the customers' objectives. From the wider power system side, however, the µgrid should appear as a good citizen of the grid, whether it be a net source, sink, or both at various times. In its simplest form, the interface could be a simple barrier that allows the µgrid to island itself and resynchronize as desired. While operating in island mode, the µgrid need serve only its own requirements, although the control capability to facilitate this may be complex. While operating in normal connected mode, the µgrid must be accommodating to the central grid requirements.[21]

The recent trend in diminishing transmission expansions (see Figure 15) will lead to more grid constraints and increased congestion. Traditionally, transmission upgrade decisions were dominated by local need, and pricing for wholesale transmission services was a secondary concern. In an increasingly deregulated market, third-party uses of the transmission system will come to predominate. In competitive markets, the transmitting utility is required to provide wholesale transmission services based on rates, charges, terms, and conditions that permit the recovery of all costs incurred in connection with transmission and necessary associated services. These include any benefits to the transmission system of providing the transmission service and the costs of any expansion of transmission facilities. Due to the large capital requirement, long pay-back period and escalating competition, the justifications for transmission projects are increasingly difficult to prevail. Many utilities, therefore, have been driven to investigate distributed generation resources as a way to defer transmission and distribution investments. This emerging business environment will create new opportunities that spur development and lower the cost threshold of emerging technologies. Nonetheless, the service level and reliability of any new technologies will need to be on par with grid power experiences. One such opportunity that may be able to satisfy all stakeholders is the µgrid of distributed generators.

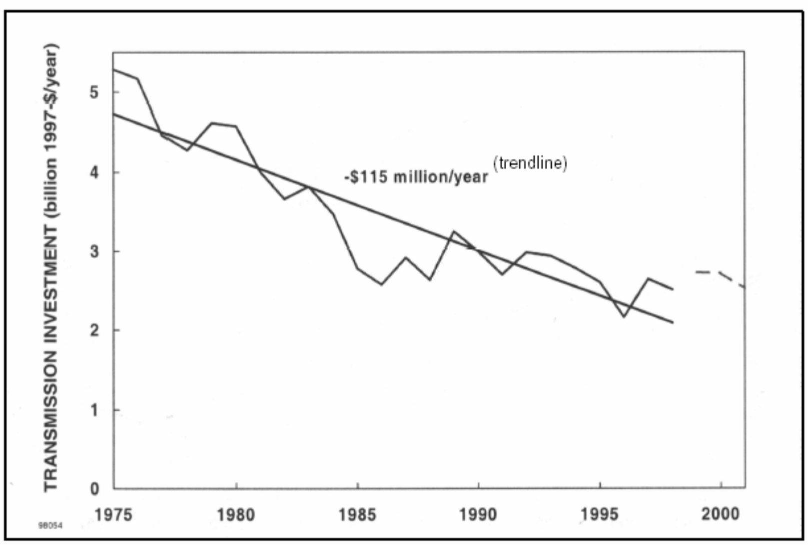


Figure 15-Annual transmission investments by investor-owned utilities (1975-1998)

[21] F. Javier Rubio, et al., 2001, "CERTS Customer Adoption Model", Lawrence Berkeley National Laboratory, Berkeley CA, Report: LBNL-47772

Based on existing literature which focused on the reliability aspect of distributed generation, it has been projected that µgrid can provide additional system stability. The reliability of the µgrid has been deduced to be a function of the size, number and outage rates of the generation units in conjunction with the demands and uncertainty associated with the loads. For instance, assuming that each customer has a base load of 0.5 kW and three uncertain loads, 50% probability of 0.6 kW each, so that their peak demand is 0.5 kW + 3*0.6 kW = 2.3 kW, and expected demand is 0.5 kW + 3*0.6 kW*0.5 = 1.4 kW, the peak load occurrences will be 0.5^3 = 0.125 or 12.5% chance at any given time for a given customer.[22] However, as the equation fails to disseminate, if the individual loads or house-to-house demands are highly correlated, the opportunity for load leveling will disappear quickly. Irregardless, when a µgrid of high number of DG units are assembled, e.g. >50, the ability of the µgrid to load balance will become increasingly acceptable. Additionally, the single point connection to the central grid will simplify and economize the interconnection efforts while the abundant standby power will help improve reliability to µgrid users, albeit at some cost (projected to be around 1.5¢ per kWh of standby premium).

Residential fuel cell costs

Several analyses have been conducted on the potential for small stationary PEM fuel cells to produce power for homes. These include studies by Arthur D Little, Princeton University, and Directed Technologies Inc., among others. These studies have generally concluded that PEM fuel cells systems for single family residences will only become attractive when system capital costs fall to relatively low levels, well below $1000/kW. However, these studies have found that when larger systems are examined, e.g. for multi-family housing installations, the systems can be cost-effective at somewhat higher capital cost levels. Furthermore, due to economy of scale, the larger fuel cell systems are expected to cost less in terms of $/kW than systems slated for smaller end-users. These two factors taken together suggest that the multi-family market segments are likely to be more attractive for early fuel cell entry.

A common formula used for calculation cost of electricity provided by DG and has been adopted by DOE utilizes the variables of system turnkey cost (CC in $/kW), capital cost recovery factor (CRF), average system efficiency (η for 0-1.0), fuel cost (FC in $/GJ), hours of operation per year (H) and operation and maintenance costs (O&M in $/kW-year). The equation will compile the cost of electricity in terms of $/MWh and can be multiplied by 1/1000 to derive $/kWh costs. The formula is as follows:

[22] Christy Herig, et al., 2001, "A Micro-grid with PV, Fuel Cells and Energy Efficiency", National Renewable Energy laboratory, Golden CO

$$COE = \frac{CRF * CC}{H} + \frac{3.412 * FC}{\eta} + \frac{O \& M}{H}$$

Applying the above equation to 3 scenarios of interest, the net cost or savings on electricity per year are appraised:

Assumptions\Scenario	**SOFC-PT**	**SOFC**	**PEM**
Natural gas cost (FC)	\$10/GJ[f]	\$10/GJ	\$10/GJ
DG system cost	\$3000/kW	\$2500/kW	\$2500/kW
System size	10 kW	5 kW	5 kW
Installation cost	\$250/kW	\$300/kW	\$300/kW
Heating & cooling integration[a]	\$300/kW	\$300/kW	\$100/kW
Turnkey cost (CC)	\$3550/kW	\$3100/kW	\$2900/kW
O&M cost[b] (O&M)	\$200/kW-yr	\$250/kW-yr	\$250/kW-yr
Capital recovery factor (15 year life, 8% interest rate) (CRF)	0.12	0.12	0.12
Days of operation / year	360	360	360
Hours of operation / year (H)	8640	8640	8640
System efficiency (η)	63%[c]	48%[d]	33%[e]
Cost of electricity (COE)	5.4¢/kWh	7.1¢/kWh	10.3¢/kWh
National retail rate average	8.2¢/kWh	8.2¢/kWh	8.2¢/kWh
Net Saving (loss) before interconnection charges	2.8¢/kWh	1.1¢/kWh	(2.1)¢/kWh

Note: (a) integration into water heater and absorption chiller systems.
(b) include stack replacement cost of \$100/kW-yr.
(c) assuming 55% co-production efficiency and adding 8% for heating and cooling cogen benefits.
(d) assuming 40% production efficiency and adding 8% for heating and cooling cogen benefits.
(e) assuming 30% production efficiency and adding 3% for heating cogen benefits.
(f) 1 GJ = 0.948 MMBTU

Sensitivity Analysis	**SOFC-PT**	**SOFC**	**PEM**
Natural gas cost (FC)	\$8/GJ	\$8/GJ	\$8/GJ
COE	4.3¢/kWh	5.7¢/kWh	8.3¢/kWh
Natural gas cost (FC)	\$15/GJ	\$15/GJ	\$15/GJ
COE	8.1¢/kWh	10.7¢/kWh	15.5¢/kWh
System efficiency (η)	70%	50%	40%
COE	4.9¢/kWh	6.8¢/kWh	8.5¢/kWh
System efficiency (η)	50%	35%	28%
COE	6.8¢/kWh	9.8¢/kWh	12.2¢/kWh

Table 4-Rough calculation of fuel cell cost of electricity

Although the tabulated cost of electricity appears to be competitive in today's market environment, there are some pitfalls to consider in the assumptions. For one, the model assumes full capacity operation, 360 days a year with no degradation of efficiency. This is a very optimistic view in spite of the realistic operating potentials. Given the way the formula is constructed, any declines in the hours of operation will cause the COE to edge up. On the other hand, the fuel cost and system cost parameters are chosen to be moderately conservative as to offset other opportune considerations. By far, the formula is high sensitive to system efficiency and fuel cost inputs. These two factors will predict most of the production price and should be evaluated carefully.

Environmental benefits

Contrary to popular beliefs, fuel cells are not entirely pollution free. Due to the feedstock conversion necessity (from CH_4 to H_2), the inconsumable carbon in the natural gas or methane will be oxidized and released into the atmosphere in the form of CO_2 gas. Although lower than gas fired plants, the amount of carbon dioxide exhausted from fuel cells will still be considerable. Due to this awareness, there have been increasing efforts devoted to carbon sequestration research; however, none has surfaced thus far to be broadly viable. At this time, the only zero carbon DG plant is perhaps the combination of renewable energy with electrolysis to support the feedstock requirements of fuel cells or other hydrogen powered generators. In any respect, when fuel cell CHP is compared to standalone gas turbine generators, the amount of CO_2 reduction is estimated to be in the order of 0.37 kg/kWh or about 62% less (see Figure 16).

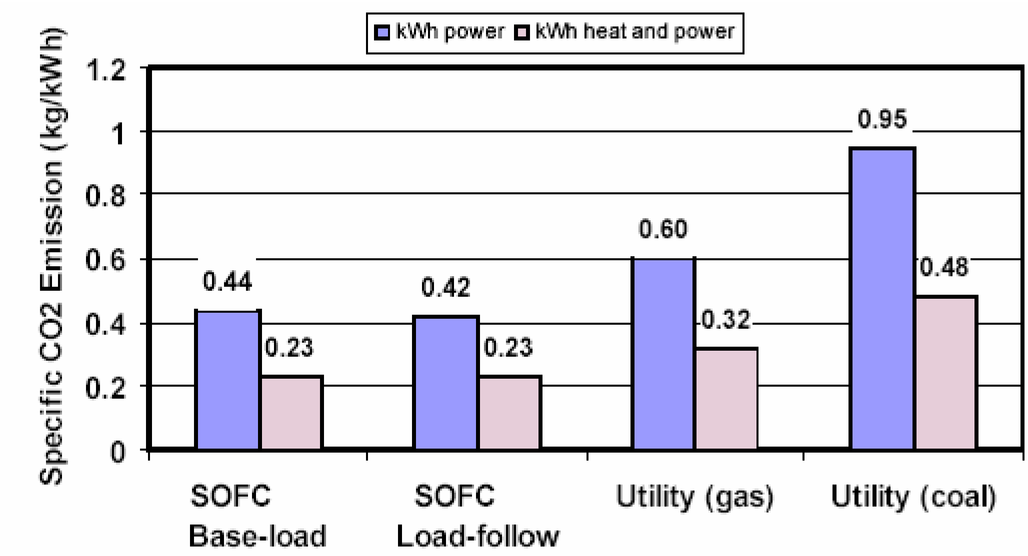


Figure 16-CO_2 Emission Comparisons

It is likely that a carbon emissions market will emerge in the next few years, starting in industrialized countries that have shown active interest in fulfilling the Kyoto climate change protocol. The market mechanisms will ensure that the most cost-effective options are selected to mitigate carbon emissions. Although there is still considerable uncertainty in the magnitude of carbon costs, recent studies in the USA and in the European Union indicate a large savings potential, both in the supply- and demand-side, with a tax of less than USD$100 per metric ton (t) of carbon. In the European Climate Change Program, it was shown that the European Union could reduce its carbon emissions in 2010 by 8%, using technology options under a tax of USD$70 /t. Intuitively, the effect of a carbon tax would be to stimulate the adoption of "greener" generation technologies since they emit less carbon per kWh of electricity produced.[23] Based on these predictions, a SOFC CHP plant of 10 kW in size operating at maximum capacity year round may be able to receive up to *$3241 (3.7 ¢/kWh)* in carbon tax credits if used to replace traditional gas-fired plants and *$6307 (7.2 ¢/kWh)* in lieu of dirtier coal-fired plants based on the $100 /t figure.

In terms of environmental friendliness, fuel cell's real strength arises from its non-combustion operating principle. Consequently, fuel cell emission streams usually contain only trace amounts of CO, NO_x, SO_x, unconsumed hydrocarbon and particulate matter. From human health standpoint, these compounds are more harmful than CO_2 and can be more directly linked to acid rains and brown clouds where as CO_2 as the major cause of global warming is still undergoing deliberation. The cost of abatement for these pollutants may be best derived from the added equipment or process overheads to comply with regulatory guidelines. The least expensive mechanisms for reducing NOx emissions are based on lowering the combustion temperature to lower thermal NOx. This can be accomplished by injecting water or steam with the combustion air or by specialized designs of the combustion chambers. Exhaust gas treatment can be performed with non-selective or selective catalytic reduction (NSCR or SCR). In the both NSCR and SCR, an ammonia or urea solution is sprayed into the exhaust gases from the power generator where NH_3 reacts with NOx to form Nitrogen and water vapor. The difference is that NSCR employs lower temperature injections but additional catalyst to achieve the effect. NSCR is commonly used in conjunction with rich-burn IC-engines while SCR is applied more often to gas turbines. Efficient operation of SCR requires careful control of the ammonia spray and the exhaust gas temperature. SCR can add *$500 to $900 per kW* to the cost of small gas turbines (<5 MW) and on the order of *$250 per kW or less* to larger turbines. Low NOx burners cost about the same as water or steam injection. Scrubbers can be used to reduce SOx emissions. This is accomplished by injecting calcium carbonate in the form of a lime or limestone solution with SO_2 in the exhaust gases to produce CaSO3 and CO_2. Carbon monoxide can be forced to react with oxygen in the exhaust using a catalyst to form CO_2. Wet and dry equipment are available to reduce particulates in the exhaust.[24] In aggregate, these cost burdens may represent a good portion of the installed cost and should be incorporated into the DG economic model.

[23] Afzal S. Siddiqui, et al., 2001, "The Implications of Carbon Taxation on Microgrid Adoption of Small-Scale On-Site Power Generation Using a Multi-Criteria Approach", Lawrence Berkeley National Laboratory, Report: LBNL-49309
[24] http://www.bchp.org/prof-emission.html

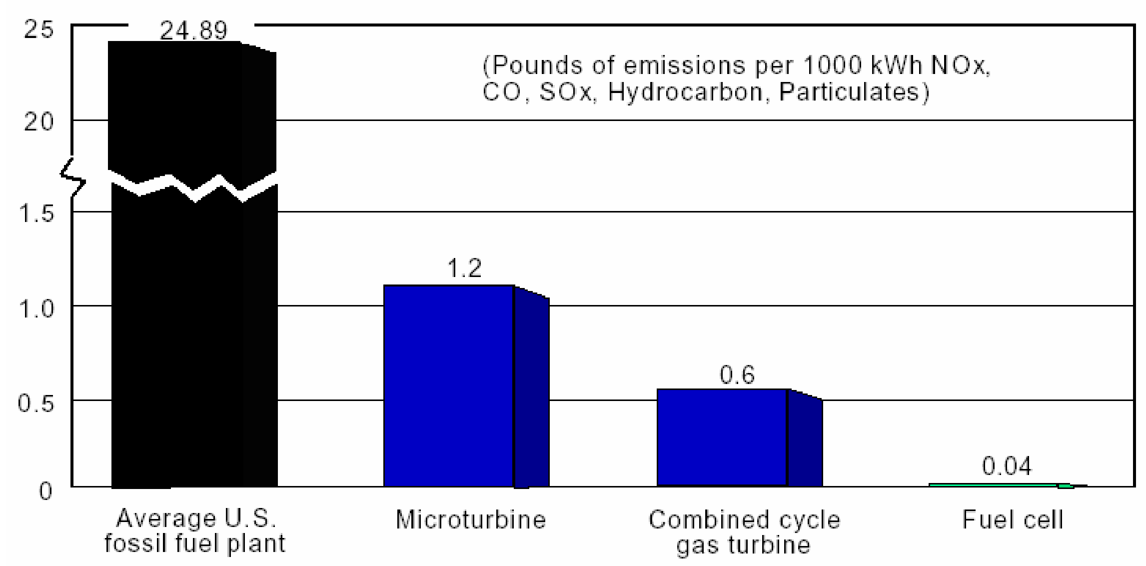


Figure 17-Air pollutions from power generation

System standards

Currently, the broad range of distributed generation equipment must either comply with regulations designed for large, central power stations or comply with regulations originally written specifically for renewable power plants or cogeneration systems. This, together with the considerable variation in regulations from state to state and utility to utility, has led to an increasing number of regulatory and policy initiatives addressing distributed generation, particularly in deregulated states. At this time, ASME, ANSI, NFPA, NEC, UL and other organizations are developing standards for fuel cells. The ANSI, NFPA and NEC standards address the safe operation, construction, installation, and acceptable performance of all fuel cell units. Specifically, some applicable standards include ANSI Z21.83 - 1998, Stationary Fuel Cell Power Plants; NFPA 50A - the Standard for Gaseous Hydrogen Systems at Consumer Sites; NFPA 54 - the Fuel Gas Code; the National Electrical Code Article 692; and various product specific UL Standards. The ASME standard seeks to rate the performance of a wide range of fuel cell types and sizes. The standard created by ASME calls for testing at a single, steady-state point of operation. NIST, on the other hand, is pursuing a method of test and accompanying rating methodology to test the transient operation of fuel cell systems.

Interconnection standards

Grid interconnection has been identified by industry groups as the most significant barrier to the installation of distributed generation technologies. Electric utilities are understandably quite sensitive to the issues of independent generators' usage of the grid and their effects on coordinated safety and liability control. This has led some utilities to place overly conservative restrictions on interconnected systems, causing added costs that may make a DG installation economically unfeasible. These issues can be compounded if the electric utility also perceives distributed generation as a competitor. Typical requirements by the utilities or distribution entities include DG equipment that prevents power from being fed to the grid when the grid is de-energized (for example, for power line maintenance), manual disconnects that are easily accessible to utility personnel, and power quality requirements such as limits on the interconnected system's effects on "flicker" and other types of distortion. Systems may also be required to automatically shut down in the event of electrical failures — to accomplish this, protective schemes at the grid interface may include a synchronizing relay, protection against under- and over-voltage, protection against under- and over-frequency, phase and ground over-current relays, ground over-voltage relays, and more. Even more restrictive (and expensive) requirements can include an isolation transformer for the system and liability insurance against worst-case scenarios of damage to utility equipment and harm to utility personnel.[25]

Currently, no nationally recognized standards for interconnection exist. Many of the processes that are employed today were developed for large qualifying facilities rather than DG resources. Another problem is the difficulty in standardizing protective equipment that is needed to ensure safe interconnection. Utilities have developed individual technical interconnection requirements to maintain their grid performance and minimize negative operational impacts of DG. However, as small generators proliferate, such individualized attention will not be practical. Thus, standards are needed for a cost-effective interconnection solution that does not jeopardize the safety and reliability of the electric power system. Currently, the IEEE is working on such standards under the umbrella of the IEEE standard for Interconnecting Distributed Resources with Electric Power System (IEEE Standard P1547), but they will take some time to apply. IEEE has already approved Standard 929-2000 for connecting photovoltaic systems under 10 kilowatts to the electric grid. Additionally, UL Standard 1741 Titled Inverters, Converters, and Controllers for Use in Independent Power Systems aims to create DG equipment standards to minimize the risk of fire or of electric shock or injury to persons from electrical components. Similarly, National Electric Code, NFPA70, provides some guidelines on installation of electrical equipment to reduce human and property hazards. Connection rules are not the only issue. The emerging needs of DG for dispatch, metering, communication, and control standards must also be addressed. One key is to develop a national process that is transparent and efficient and does not burden distributed generators or distribution companies.

Many states are also working on their own interconnecting standards. For the most part, the interconnecting rules for small renewable generators are much more established than the broader distributed generation category. As of the latest count (6/6/2001), there are only five states that have completed their DG interconnection rules. These include California, Delaware, New York, Ohio and

[25] http://www.eere.energy.gov/der/grid_interconnection.html

Texas. Of the states that have initiated work in this area, Arizona, Illinois, Michigan, Pennsylvania, and Wisconsin are near the final stages of drafting their standards. The pack that are in the beginning stages of standard setting include Florida, Massachusetts, Nevada, New Hampshire, Utah, Virginia and West Virginia.[26]

Market and players

Table 6 contains the list of known commercial enterprises engaged in residential fuel cell development. For the most part, the developers are concentrated in U.S., Canada and Japan with more focused on PEMFC technologies. Certainly, the residential market is receiving much attention resulting from the diversity of its end-users and preferential price barriers. Since the customer base are more diverse and needs are equally scattered, there are more chances to acquire early adopter who may pay a premium for some user-specific reasons, e.g. “green” advocates, techies, remote users, utility skeptics, independence minded, etc. If even only 10% of the residential customers switch to fuel cell power, this minority stake will represent almost $10 billion per year in utility revenue. If the market scope is expanded to the global arena, there will be more opportunities stemming from power hungry developing nations and environmentally sensitive developed countries. Observing from an estimate by United Nations (see Figure 18), the worldwide residential DG market will reach about 8 GW of installed base by 2020. This is a tremendous growth from the starting point of less than 1 GW in 2005.

Company Name	Product	Remarks
Acumentrics Corporation	Tubular SOFC	Permits fast startup
Avista Labs	PEMFC	Subsidiary of Avista Corp.
Ballard Power Systems	PEMFC	Transportation & Stationary
Ceramatec, Inc.	Planar SOFC	Partner with McDermott Technology
Dais-Analytic Corp.	PEMFC	Acquired by ChevronTexaco
Fuel Cell Technologies Ltd	Tubular SOFC	Licensed from Siemens-Westinghouse
Fuji Electric Co Ltd	PEMFC	
General Motors	PEMFC	Transportation & Stationary
Global Thermoelectric	Planar SOFC	Merging with Quantum Fuel Systems
Hydrogenics Corporation	PEMFC	
Idatech LLC	PEMFC	Subsidiary of Idacorp
Matsushita Electric Work	PEMFC	

[26] Interstate Renewable Energy Council.

Mitsubishi Electric Corp.	PEMFC	
Nuvera Fuel Cells	PEMFC	Merged from Epyx Corp & De Nora Fuel Cells
Plug Power Inc	PEMFC	Joint venture between DTE Energy & Mechanical Technology Inc.
Proton Energy Systems	PEMFC	Reversible fuel cell systems
Sanyo Electric Co.	PEMFC	
Sulzer Hexis	Planar SOFC	Subsidiary of Sulzer Group
Toshiba International Fuel Cell Corp.	PEMFC	Joint venture with UTC Fuel Cells
Toyota	PEMFC	Transportation & Stationary
UTC Fuel Cells	PEMFC	Transportation & Stationary

Table 5-Residential fuel cell developers

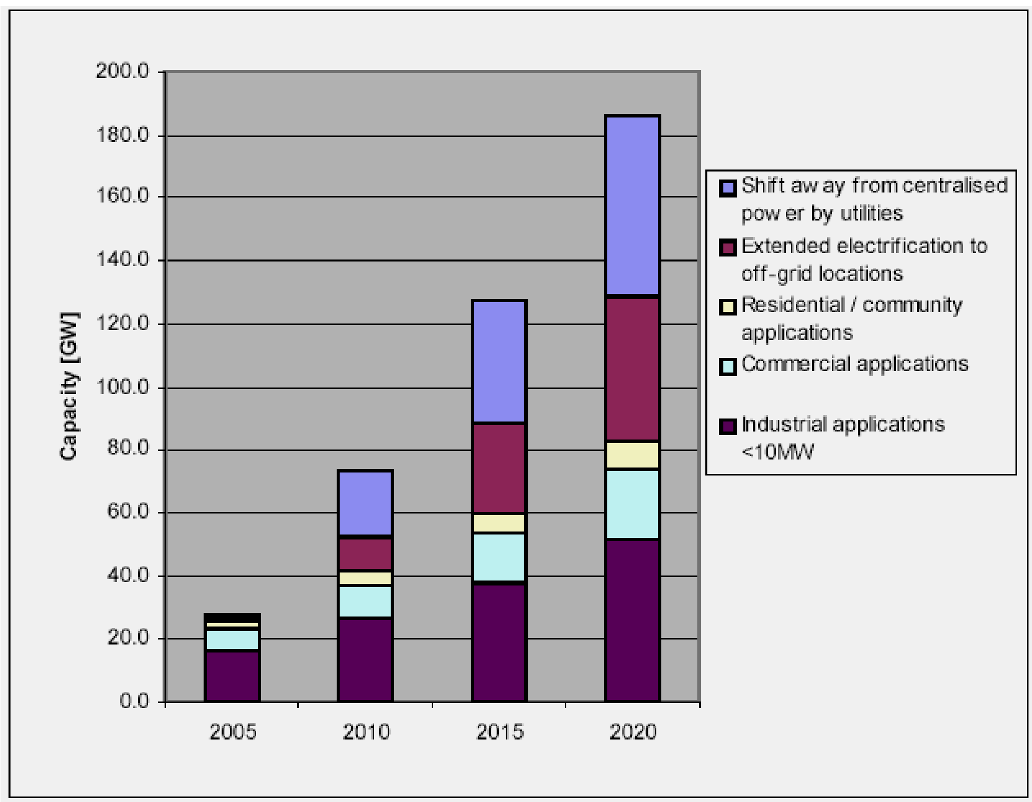


Figure 18-Global DG growth by market (Source: UN)

Policy & Incentives

One important exogenous factor that will influence fuel cell developments is undoubtedly the effects of government policy. First, it is useful to distinguish between demand-side policy and supply-side policy for inducing innovations and commercial demand. Supply-side policy is a "push" strategy which is accomplished mostly by funding R&D and demonstrations. The demand-side policy, on the other hand, seeks to "pull" innovation by creating or expanding the market for certain technology. Government procurement guidelines and tax incentives can be used to achieve some demand stimulating effect. Alternatively, laws can be written to require implementations of certain technology either directly or indirectly. For instance, the state of California recently has passed a new clean air act that requires automakers to sell zero emission vehicles starting from 2005. Both the supply and demand side policies help stimulate innovations and market entry. The differences are investments will either be made by the public (supply-side) or the private (demand-side) sector.[27] In terms of demand-side policy successes, one can look no further than the wind turbine technology. Massive incentives that mandated high electricity tariffs for renewable sources in California induced quick market development, in which Danish technology—already backed for years in Denmark—assumed a leading edge. Costs declined, and cheaper, more reliable technologies, developed on the back of the Californian incentives, led to rapid growth, particularly in Europe and India. During the 1990s, installed capacity grew at about 25% per year and costs continued to decline.

Deregulation

Deregulation is designed to separate power production from distribution with the promise of lowering electricity prices through competition. The breakup of the current power utility monopolies into separate, unregulated business segments is a necessary step towards that end. In a deregulated environment, the organizational structure will likely be comprised of power producers, billing and metering companies, and power marketers who act as middlemen between producers and consumers (the transmission and distribution system will remain a regulated entity). Increased grid-electricity prices will accelerate the introduction of fuel cell technology. On the other hand, lower electricity prices could slow the penetration of new generation technologies into the market. Accomplishing the goal of lowering electricity prices for businesses and consumers is uncertain and complicated by the available installed capacity (and power demand), grid conditions (from moment to moment), real-time pricing, and demand side management practices. All of these factors can substantially affect electricity price volatility and the real cost of supplying power and thereby, cloud the future success of fuel cells.

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[27] J. Loiter, 1997, "Technological Change and Public Policy: A Case Study of the Wind Energy Industry", Cambridge, MA: MIT Thesis

Independent of deregulation, several driving forces are creating interest in a paradigm shift from centralized to decentralized power generation. The demand for high power quality to operate increasingly sophisticated end-use equipment is one such driver. The monetary importance of power quality was quantified by one study that estimated power fluctuations cause annual losses of $12 to $26 billion nationwide. For a precision machining plant, it has been estimated that voltage sag with 0.1 second duration can cause losses of $250,000 in lost product and labor costs to reconfigure the facility. Another driver promoting the use of distributed generation resources is avoided costs associated with upgrading transmission and distribution (T&D) systems to meet growing capacity requirements. This effect will intensify as the expanding energy market continues to outdistance the addition of new generation facilities. On average, the U.S. demand for power increases at a rate of about 2% annually and the present world energy demand exceeds the planned addition of 1200 GW of electricity by 2005. A final motivating force is the technology advancements in distributed power generation which have made high efficiency, low cost devices that can be sited close to the demand thereby improving power quality and avoiding the cost of expanding T&D infrastructure possible.

Incentive Programs

At the moment, financial incentives available for purchase and/or operation of fuel cell are still limited. However, there are several pending senate and house bills, if approved, that will expand financial supports to residential fuel cell deployments. At the state level, California appears to be most progressive. Its Self-Generation Incentive Program, administered by PG&E, SCE, SoCal Gas, and San Diego Regional Energy Office (for customers in SDG&E's service territory), is funded at $125 million per year, through 2004 and provides $2.50 /watt incentive up to 40% of project cost for non-renewable fuel cells that integrates CHP functions. In 1995, Congress appropriated funds for the Office of the Deputy Under Secretary of Defense, Environmental Security (ODUSD-ES) to establish a competitive, cost-shared, near-term Climate Change Fuel Cell Program (H.R. 103-747). Currently, the program provides up to $1,000 per kilowatt of power plant capacity not to exceed the limit of one-third of the total program cost (capital and installed costs, pre-commercial operation). The program thus far has funded mainly DoD and commercial installations but is available to fuel cell projects from 3 kW and up. Project funding from 1995 through 2002 have varied from $2 to $8.4 M annually since its inception.

Related to congressional bills still in deliberation, the Energy Tax Incentive Act of 2003 would provide a 30 percent credit for the purchase of qualified stationary or portable fuel cell power plants. The credit for any fuel cell may not exceed $1,000 for each kilowatt of capacity. The credit would be nonrefundable and would be allowed against the regular and alternative minimum tax. The depreciable basis of the property would be reduced by the amount of the credit.

A qualified fuel cell power plant must provide electricity-only generation efficiency of greater than 30 percent and generate at least 1 kilowatt of electricity. The qualified fuel cell power plant must be installed on or in connection with a dwelling unit located in the United States and used by the taxpayer as a principal residence. Expenditures for labor costs allocable to onsite preparation, assembly, or original installation of property are also eligible for the credit. Special proration rules would apply in the case of jointly owned property, condominiums, and tenant-stockholders in cooperative housing corporations. When approved, the credit would apply to purchases after December 31, 2002 and before January 1, 2008. The Hydrogen Fuel Cell Act of 2003 pushed by Senator Joe Lieberman includes tax credit provisions for residential fuel cell installations equating to 30 percent of the expenditure with a limit of $1000 per kW of cost. This bill also encompasses hydrogen refueling infrastructure tax credits for any retail hydrogen refueling property up to $30,000, and, for residential hydrogen refueling property not to exceed $1,500 per site. The infrastructure clauses are similar to the Hydrogen Transportation Wins Over Growing Reliance on Oil (H2GROW) Act proposed by House Policy Chairman Christopher Cox and Senator Ron Wyden. The H2GROW will provide for several hydrogen fuel related sales and income tax credits. One part of the proposal calls for fuel retail sales credit of 50 cents for each gasoline gallon equivalent of hydrogen sold at retail by the taxpayer used to propel a fuel cell motor vehicle. Additionally the gross income derived from the sale will be exempted from regular or alternative minimum tax. Another minor feature is the provision of tax credit equaling to 50 percent of the amount paid or incurred by the taxpayer for the installation of qualified residential hydrogen fuel cell vehicle refueling property. The credit allowed under the infrastructure clause will not exceed $1,000 for residential self-use installations.

Outside of financial incentives, there are numerous pollution abatement bills that may serve to improve the market appeals of fuel cell technologies. The Climate Stewardship Act of 2003 intends to create tradable allowances of greenhouse gas (GHG) emissions. The Clean Power Act of 2003 aims to slash nitrogen oxide and sulfur dioxide emissions by 75 percent, mercury output by 90 percent, and carbon dioxide emissions by roughly 25 percent through the use of a cap and trade system. The Clean Smokestacks Act and Clean Power Plant and Modernization of 2001 also incorporated restrictions similar to the Clean Power Act. These emission control bills will indirectly boost the value of clean DG technologies.

Conclusion

There is growing momentum in favor of distributed versus centralized generation as a result of deregulated and competitive business environment and increasing pressure from clean air mandates. Fuel cells for local and self generation deliver unique set of benefits that may soon make them attractive in certain niche applications. Relative to wind and solar energy, fuel cell can be more compact and better provide for on-demand power. Compared to diesel engine or gas turbine, a fuel cell will result in lower noise and air pollutions and achieve better efficiency. When arranged in CHP setting, fuel cell can provide most of the household energy requirements with great degree of independence. For the residential market, fuel cell technology may be most viable due to the high electric tariff and diverse user prospects in this sector. There are, however, several technical and economic barriers prohibiting broad-base diffusion in the immediate timeframe. These road blocks can be boiled down to cost, reliability and channel issues. Based on the research and analysis conducted in this paper, the following problems and solutions are evident:

Problem: Grossly variable load patterns in single household environment.
Solution: Utilize µgrid and central grid to load balance demand.

Problem: Deficient load-following / transient capabilities of fuel cell.
Solution: Operate fuel cell in baseline mode and use net metering to hedge capacity.

Problem: High cost of fuel cell system.
Solution: Target high rate and CHP users such as those located in the Northeast or Hawaii; improve efficiency through co-production and CHP; lobby for emission and CHP tax credits: and push for purchase tax and buy-down incentives.

Problem: Net metering may not be available for off-peak output.
Solution: Use the excess capacity to power µgrid or electrolyzer.

Problem: Electric utilities are reluctant customers.
Solution: Sale through retail energy service providers, natural gas companies , balance of system vendors (absorption chiller, radiant heater, HVAC, etc), or directly to end-users.

Problem: Retrofitting costs may be uneconomical.
Solution: Target master planned communities or new multi-family housing.

Problem: Incomplete and overlapping codes and standards.
Solution: Collaborate with NIST, ASME, UL, IEEE, NEC and NFPA to establish uniform codes and standards.

Based on this investigation, it is further deduced that PEMFC might be best suited as a 1 to 2 kW load-following CHP (only water heating) plant equipped with bottled hydrogen to facilitate fast transient performance. Conversely, SOFC might be more optimal as a 10 kW co-generation CHP (both space and water heating) system operating in baseline mode and coupled with net metering connection. The configuration options of the SOFC co-generation system are illustrated in Figure 18 below. Both PEMFC and SOFC, however, may benefit from a µgrid environment where the possible deployment scheme is devised in Figure 19. If the suggested community based setup can be cost-effectively implemented, it is perceived that both PEMFC and SOFC can co-exist and prosper in the retail DG market within reasonable time horizon.

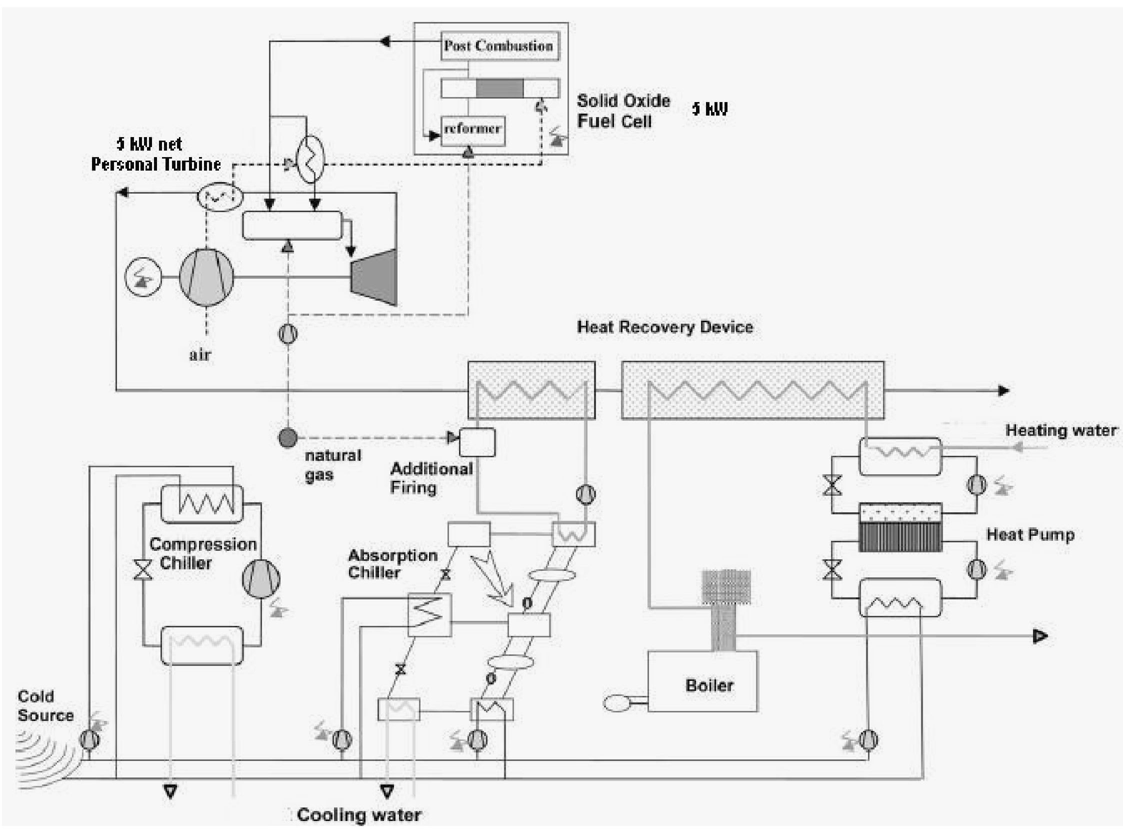

Figure 19-Prospective SOFC CHP solution for residential application

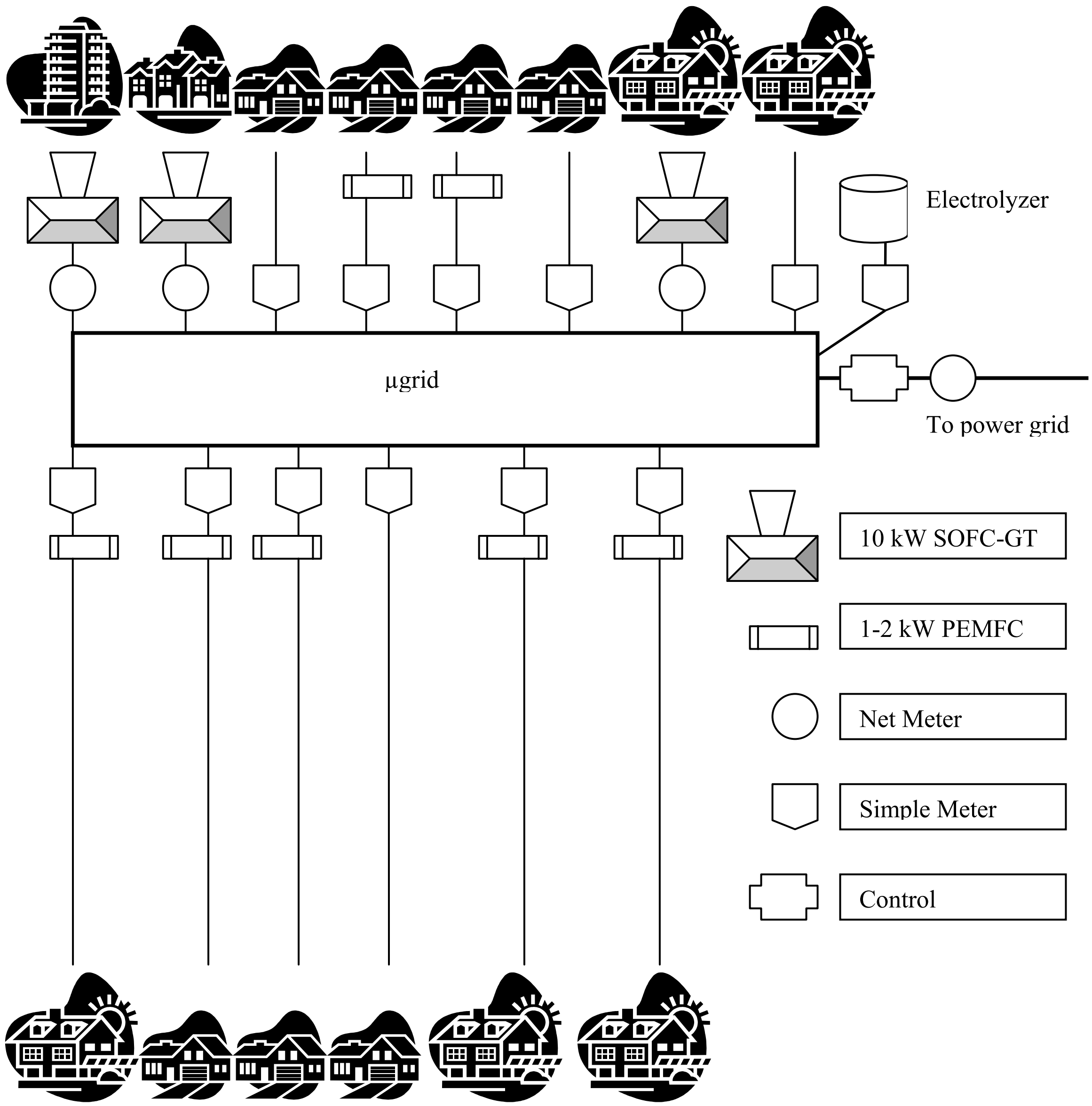

Figure 20-Illustration of fuel cell DG and micro-grid setup