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GRID-CONNECTED FUEL CELL VEHICLES AS SUPPLEMENTAL POWER SOURCES

Timothy E. Lipman, PhD
Renewable and Appropriate Energy Laboratory
Energy and Resources Group
4152 Etcheverry Hall
University of California
Berkeley, CA 94720
Tel: 310/643-2243; Fax: 310/643-2243
E-mail: telipman@socrates.berkeley.edu

ABSTRACT

In addition to reducing criteria pollutant emissions, greenhouse gas emissions, and petroleum use from motor vehicles, fuel cell vehicles (FCVs) could also act as distributed electricity generating resources when parked at homes, offices, and shopping malls. FCVs could help to meet local power needs, reducing demand for grid power along with transmission and distribution losses, as well as supplying power to the grid during times of peak demand. Moreover, FCVs could potentially offer ancillary services such as emergency back-up power, spinning reserves, and power quality support. Use of FCVs in this way could both reduce the need to construct new stationary power plants to supply peak electricity demand loads, as well as help to pay down the costs of FCV ownership. Our analysis shows that the distributed electricity generating/support services that FCVs could provide could amount up to $1,700 per year for 14 hours of residential use per day with natural gas at $6/MMBTU, as much as $4,200 per year with inexpensive $4/MBTU natural gas, and up to $1,500 per year for 10 hours of office parking lot use per day, assuming $6/MBTU residential and $4/MBTU commercial natural gas prices that were observed a few years ago, before the recent price spikes. These benefits are highly sensitive to the assumed price of natural gas, and decline sharply as natural gas prices approach $10 per MBTU, but also do not include the potential value of grid ancillary services that the vehicles could provide. Furthermore, we find that FCVs used in this way could provide small greenhouse gas emission and significant air pollutant benefits in comparison with national average emissions from electricity generation today. However, since hydrogen for the FCVs would likely be produced locally, some shifting of air pollutant emissions from outside of urban areas to within urban areas is likely, even in the context of overall emission reductions.

INTRODUCTION

In addition to providing criteria pollutant, greenhouse gas, and energy use reductions relative to conventional vehicles, electric-drive vehicles (EVs) have also been proposed for use in providing a range of important services to utility electrical grids (Kempton and Letendre,1997). These vehicles could be used to meet the demands of connected local loads, could provide other important services to electricity grids, and/or could possibly even provide extra supply to help in meeting other nearby power needs. When not in use, battery EVs could be used for emergency backup power or to buffer the utility grid by charging off-peak, when electricity is plentiful, and supplying it back during times of peak demand and capacity constraint. Hybrid vehicles and fuel cell vehicles (FCVs) could act as generators, producing electricity from a liquid or gaseous fuel. All EV types could also potentially provide certain types of support services to utility grids, as well as helping to make intermittent renewable electricity generation more attractive by providing electricity when the capacity of these renewable sources is not fully available.

In fact, the potential for producing electrical power from vehicles is enormous; the generating capacity of an electrified U.S. motor vehicle fleet would be many times the entire capacity of all of the stationary power plants in the country. For example, in California, a fleet of 100,000 FCVs could produce about 2.9 GW of power for the grid, assuming 30 kW net fuel cell output power per vehicle and 95% vehicle availability. Even if the vehicles were only available as generating capacity 50% of the time, about 1.5 GW of generating capacity could be provided by each 100,000 vehicles.

The use of FCVs in this manner may be particularly attractive since many automobile companies are currently developing FCVs as replacements to conventional internal combustion engine vehicles. With their high operational efficiencies and clean and quiet operation, FCVs may become ubiquitous once they are introduced and have had time to work their way into the motor vehicle fleet. Unlike battery EVs, which simply store and release electricity, FCVs can convert chemical energy into electrical energy and can therefore act as distributed generation resources. And, unlike hybrid EVs, FCVs can generate electricity without combustion and with minimal noise and emissions.

Despite this potentially attractive possibility, however, the use of FCVs as distributed generating resources faces technical, economic, and regulatory hurdles. These issues are discussed briefly below, followed by presentation of modeling analysis of the potential costs, benefits, and emissions implications of using FCVs as distributed generators in residential and commercial settings.

POTENTIAL APPLICATIONS AND KEY ISSUES

There are several potential possibilities for using FCVs as distributed generating resources. FCVs could be used to:

- produce power to meet the demands of local loads;
- provide additional power to the grid in a net-metered or electricity buy-back scenario, helping to meet demands in times of capacity constraint;
- provide emergency backup power to residences, offices, hospitals, and municipal facilities;
- provide "peak shaving" for commercial sites, reducing demand charges;
- provide ancillary services to the grid, such as spinning reserves, power quality support, VARs, and possibly other services; and/or
- provide buffering and additional power for grid-independent systems that rely on intermittent renewables.

However, despite these potential benefits, there are several key issues confronting the use of FCVs in this manner. Some of these issues, and some potential solutions, are as follows.

Fuel Cell Operation

Problems: Non-hybrid fuel cell systems with 75 to 100 kW peak power will likely be power limited to 30 or 40 kW for continuous operation while the vehicle is at a standstill due to thermal management issues. Fuel cell systems connected to loads in grid-independent operation may be subject to transient demands that would require a hydrogen fuel supply buffer and/or battery support system for adequate performance. Also, operating fuel cell systems in residential settings and meeting local loads only, which are often as low as 1 kW to 2 kW and rarely exceed 4 kW to 5 kW, will likely produce low fuel cell system operating efficiencies, particularly for stacks designed to operate at high pressure.

Solutions: Operate fuel cell systems at 4 kW to 30 kW and sell excess power to grid through net metering or other buyback scenario. Alternately, develop off-board auxiliary "blower" air supply systems for fuel cell stacks that allow low pressure, higher efficiency operation at low load levels (particularly important for stacks designed to operate at high pressure with a high compressor parasitic load).

Fuel Supply

Problems: Vehicles designed to operate on pure hydrogen may not be able to use reformate due to CO and sulfur catalyst poisoning issues. Vehicles will require some sort of hydrogen production support system based on steam methane reforming (SMR), electrolysis, partial oxidation reforming, auto thermal reforming, or other

Solutions: Use vehicle stacks with platinum-ruthenium catalysts that can operate on either neat hydrogen or reformate (e.g., Ballard Mark 900), or provide pure hydrogen production at commercial sites (and have no residential option for neat hydrogen vehicles other than emergency power using the fuel in the vehicle's tank). Focus R&D on developing low-cost hydrogen reformers, particularly continuing the development of multi-fuel reformers for vehicles that can run on natural gas as well as the vehicle's primary fuel.

Grid Interconnection

Problems: Reverse flow of electricity from EVs is currently not permitted under the National Electrical Code. Power flow into local distribution systems eventually will reach a limit due to difficulties in reverse flow into high-voltage transmission system. In the residential scenario, more than one household in 10 or 20 with grid-connected FCVs at 5-30 kW could be problematic, depending on distribution system topology and locations of other generators and loads. Utility on/off control of grid-connected EVs may be essential for lineworker safety, requiring a complex control system.

Solutions: Revise National Electrical Code to allow reverse-flow from vehicles, with appropriate safeguards. Analyze retrofitting substations to ensure that "tap changers" and line-drop compensators are compatible with reverse flow into high voltage transmissions systems, if this can be done with a reasonable level of efficiency loss. Investigate utility-to-vehicle wireless communication technology to provide emergency shut-down, real time load, and electricity price information for utility control centers and vehicle owners.

MODEL DESCRIPTION

Using a MATLAB/Simulink electricity load and generation model for analyzing the economics and environmental impact of grid-connected and grid-independent stationary and vehicle-based fuel cell systems, we have computed economic values and fuel upstream and local emissions from some scenarios of FCV use as distributed generators. These scenarios include provision of local demand plus sale of electricity to the grid from houses in the evening and nighttime hours (when it may only be highly valued by the grid in the early evening), and sale of electricity to the grid from offices during the day, when the electricity may be more highly valued. The Simulink model relates the dynamics of fuel cell systems, in terms of their efficiency as a function of power demand, with the load that they are supplying. This is one step beyond assuming a constant fuel cell system efficiency regardless of load, and reveals some important dynamics of fuel cell system operation when used in distributed generation mode.

The simulations of fuel cell system operation are done hour-by-hour with respect to the load and electricity price and cost conditions a particular day, and also allowing for any combination of local load support plus supply to grid desired. For analysis of FCVs in commercial or industrial settings, up to 10 interconnected fuel cell systems can be modeled in meeting loads of up to 300 kW, with various options for optimizing the use of the systems. Finally, the Simulink model calculates the costs and emissions associated with producing hydrogen fuel through small-scale steam methane reforming (as either neat hydrogen or a less concentrated reformate stream) for use in the vehicles as they operate in residential (single vehicle reformer) and commercial (multiple vehicle reformer) settings. Emissions estimates include both fuel production upstream and reformer emissions, and the following species: oxides of nitrogen (NOx), reactive hydrocarbons (HCs), carbon monoxide (CO), sulfur dioxide (SOx), particulate matter (PM), and greenhouse gases (in CO_2 equivalent emissions considering other greenhouse gas (GHG) emissions in addition to CO_2).

INITIAL RESULTS

Tables 1 through 3 present analysis of operating FCVs as distributed generators at residential and commercial office sites. The residential scenarios analyzed include the possibility of:

- FCVs being used from 6 PM to 8 AM to meet local loads only;
- FCVs being used from 6 PM to 8 AM to meet local loads, plus supplying enough power back to the grid during the day to allow the same amount of excess power to be withdrawn from 8 AM to 6 PM (and therefore having a net-metered electricity bill of $0), and
- FCVs supplying a full 30 kW of electricity to the grid from 6 PM to 8 AM and obtaining a en electricity price for excess sales equal to $0.11 per kWh up to the even net-metered level and then $0.08 thereafter.

In addition to non-hybrid FCVs with 75 kW net power and 30 kW sustained discharge capability, also analyzed for residential settings are battery hybrid FCVs with 20 kW of net fuel cell power, of which 15 kW can be continuously withdrawn.

The analysis results show that the cost of generating electricity from FCVs based at residences varies dramatically from $0.05 per kWh to $0.40 per kWh, depending on the scenario and the price of natural gas. Non-hybrid FCVs meeting local residential loads only do not appear to be able to do so economically, but they can become so under net-metering or "sale-to-grid" scenarios, particularly with natural gas prices of $6 per million British thermal units (MBTU) or below and assuming that low-cost (and relatively low hydrogen purity) very small-scale steam reformers can be produced. Battery hybrid FCVs, with smaller fuel cell systems and better operating efficiencies at low load levels, can be somewhat more economically attractive in residential settings, with net savings to the vehicle owner of approximately $0.48 to $1.08 per day with natural gas at $6 per MBTU and $1.03 to $5.63 per day with natural gas at $4 per MBTU. Particularly attractive are scenarios in which the FCVs operate in net-metered or grid-sale settings, since the fuel cell systems are operating closer to peak efficiency levels. This suggests that vehicle owners can potentially achieve cost savings while at the same time contributing to expanded grid capacity (at least at natural gas prices typical of the past several years before the recent run-up in prices).

Additionally, a group of ten FCVs meeting a daily commercial electricity load profile of up to 290 kW has been analyzed, with one key finding being that for the load profile analyzed significantly greater cost savings could be achieved for the company if at least some of the vehicle use could be spread out for ten hours from 8 AM to 6 PM compared with eight hours from 9 AM to

5 PM. This is due to the additional demand charges saved by "shaving" more of the peak building load. Under the most optimistic conditions, whereby the ten vehicles can operate at 30 kW, can obtain natural gas at $4 per MBTU, have on-board, multi-fuel reformers that can operate on natural gas (making an expensive outboard reformer unnecessary), and can sell power in excess of demand to the grid at $0.08 per kWh, up to $60 could be generated each day. This equates to $1,500 per year for each vehicle owner (assuming operation 250 days per year).

EMISSIONS

The Simulink model allows analysis of emissions from hydrogen production from natural gas including upstream natural gas production and distribution “fuel cycle” emissions, as well as emissions from the natural gas reforming process. These emissions are divided into their “urban” and “non-urban” components, and rely on three different natural gas production upstream analyses (Wang 1996; Acurex 1996; Delucchi 1997). This emissions analysis shows, using the GREET (Wang) model emissions estimates for example, that use of FCVs to produce electricity in conjunction with small-scale SMR hydrogen production (with about 35% overall efficiency, LHV basis) would reduce GHG emissions (in CO_2-equivalents that include other GHGs as well as CO_2) by about 25 g/kWh, or about 4%, compared with a national average mix of current electricity generation. Overall emissions of NOx, PM, and SOx would be sharply reduced (by 78% to 98%), emissions of HCs would be reduced by about 25%, and emissions of CO would be increased by about 30%. However, since we have assumed that hydrogen production for these scenarios would be near the point of use, a higher percentage of emissions would be located within urban areas than is the case with conventional electricity production (with large generators that are mainly located outside of cities), and some increase in urban emissions is implied even in the context of overall net emission reductions. However, we note that these urban emissions increases would be lower than those from the use of diesel generators or microturbines, which also are being considered for use as distributed generators.

FUTURE WORK AND CONCLUSIONS

In addition to exploring alternative methods of hydrogen production and vehicle fueling, further analysis will focus on analyzing a representative set of annual building load profiles, including potential daily and seasonal variations, in order to more accurately assess the potential costs and benefits of these vehicle-to-grid connection schemes over a typical year. Additional research will address the potential value of grid ancillary services that could be provided by FCVs, the potential effects of various policy and incentive measures, possibilities for using fuel cell system waste heat to boost overall system efficiencies, and the net impacts of using FCVs in place of conventional vehicles when their use for transportation is combined with their use as distributed generating assets.

This analysis shows that grid-connected FCVs in residential and commercial settings can potentially supply electricity at competitive rates, in some cases producing significant annual benefits to vehicle owners while at the same time producing additional capacity to utility grids. However, for electricity produced from FCVs to be attractive in competition with all electricity generation, including large base-load powerplants, natural gas prices must return to lower levels, on the order of $6 per MBTU, or alternate methods of fueling the vehicles with economical sources of hydrogen must be explored. It is vitally important that vehicles be able to produce electricity at high overall system efficiencies, on the order of 35% (LHV), and this suggests that powering residential loads from the vehicles, without allowing for higher power operation and net-metered or grid sale of electricity, is unlikely to be attractive except perhaps in the case of provision of emergency backup power. Even if they have difficulty competing with base-load powerplants, however, FCVs and other EVs are likely to still find interesting niches providing electricity at times when it is highly valued, such as with time-of-use metering or through the ability to bid on the spot market where rates rise with peak load, and through grid ancillary service support. Given this potential, efforts should focus on removing regulatory impediments to reverse power flow from vehicles, pushing the development of small, low-cost fuel reformers for FCVs, and continuing to assess the costs and benefits of various market niches for vehicle-to-grid interaction.

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TABLES

Table 1: Non-Hybrid Fuel Cell Vehicle Operating in Residential Setting

	Local Load Only	Local Load Plus Supply to Grid (net metering)	Local Load Plus Supply to Grid (no limit)
Number of Vehicles	One	One	One
Connection Time of Day and Days per Year	6 PM until 8 AM 300 days/yr	6 PM until 8 AM 300 days/yr	6 PM until 8 AM 300 days/yr
Peak / Avg. Electrical Load (24 hours)[a]	3.8 kW / 2.2 kW	3.8 kW / 2.2 kW	3.8 kW / 2.2 kW
Peak / Max. / Avg. FC System Power[b]	75 kW / 30 kW / 1.82 kW	75 kW / 30 kW / 3.7 kW	75 kW / 30 kW / 30 kW
Fuel Supply	NG Reformate	NG Reformate	NG Reformate
Reformer Efficiency	70% SMR	70% SMR	70% SMR
Reformer Capital Cost and Capital Recovery Factor[c] (5% rate, 15 year life)	$2,000 0.13	$2,000 0.13	$2,000 0.13
Approximate O&M (FC system + reformer)	$0.01/kWh	$0.01/kWh	$0.01/kWh
FC System Degradation[d]	$0.00188/kWh	$0.00188/kWh	$0.00188/kWh
Total Energy Produced	25.5 kWh	52.5 kWh	420.0 kWh
Average Total Efficiency for FC and Reformer (LHV)	8.9%	17.0%	35.6%
COE ($/kWh) (NG @ $4/MBTU)	$0.17/kWh	$0.10/kWh	$0.05/kWh
COE ($/kWh) (NG @ $6/MBTU)	$0.24/kWh	$0.15/kWh	$0.07/kWh
COE ($/kWh) (NG@ $10/MBTU)	$0.40/kWh	$0.23/kWh	$0.11/kWh
Net (Cost)/Benefit per Day[e] (NG @ $4/MBTU)	($1.45)	$0.27	$13.74
Net (Cost)/Benefit per Day[e] (NG @ $6/MBTU)	($3.41)	($1.83)	$5.69
Net (Cost)/Benefit per Day[e] (NG@ $10/MBTU)	($7.33)	($6.04)	($10.42)

Notes: COE = cost of electricity; FC = fuel cell; LHV = lower heating value basis; MBTU = million British thermal units; NG = natural gas; O&M = operation and maintenance.

[a] Variable load profile for summer day in Southwest U.S.

[b] Assumes that 75 kW fuel cell system can be operated at 30 kW continuously without overheating.

[c] Effective reformer cost could be 0$ if multi-fuel reformer is integrated into vehicle.

[d] Assumes that stack would last 40,000 hours with low power operation and that high volume production fuel cell system cost is $75/kW ($5,625 for 75 kW system).

[e] Assumes that retail price of electricity is $0.11 per kWh and that excess power can be sold at $0.08 per kWh once total daily (net metered) needs are met.

Table 2: Battery Hybrid Fuel Cell Vehicle Operating in Residential Setting

	Local Load Only	Local Load Plus Supply to Grid (net metering)	Local Load Plus Supply to Grid (no limit)
Number of Vehicles	One	One	One
Connection Time of Day and Days per Year	6 PM until 8 AM 300 days/yr	6 PM until 8 AM 300 days/yr	6 PM until 8 AM 300 days/yr
Peak / Avg. Electrical Load (24 hours)[a]	3.8 kW / 2.2 kW	3.8 kW / 2.2 kW	3.8 kW / 2.2 kW
Peak / Max. / Avg. FC System Power[b]	20 kW / 15 kW / 1.82 kW	20 kW / 15 kW / 3.7 kW	20 kW / 15 kW / 15 kW
Fuel Supply	NG Reformate	NG Reformate	NG Reformate
Reformer Efficiency	70% SMR	70% SMR	70% SMR
Reformer Capital Cost and Capital Recovery Factor[c] (5% rate, 15 year life)	$2,000 0.13	$2,000 0.13	$2,000 0.13
Approximate O&M (FC system + reformer)	$0.01/kWh	$0.01/kWh	$0.01/kWh
FC System Degradation[d]	$0.00188/kWh	$0.00188/kWh	$0.00188/kWh
Total Energy Produced	25.5 kWh	52.5 kWh	210.0 kWh
Average Total Efficiency for FC and Reformer (LHV)	26.9%	36.0%	31.3%
COE ($/kWh) (NG @ $4/MBTU)	$0.07/kWh	$0.06/kWh	$0.06/kWh
COE ($/kWh) (NG @ $6/MBTU)	$0.09/kWh	$0.08/kWh	$0.08/kWh
COE ($/kWh) (NG@ $10/MBTU)	$0.14/kWh	$0.12/kWh	$0.12/kWh
Net (Cost)/Benefit per Day[e] (NG @ $4/MBTU)	$1.12	$2.46	$5.63
Net (Cost)/Benefit per Day[e] (NG @ $6/MBTU)	$0.48	$1.47	$1.08
Net (Cost)/Benefit per Day[e] (NG@ $10/MBTU)	($0.82)	($0.53)	($8.09)

Notes: COE = cost of electricity; FC = fuel cell; LHV = lower heating value basis; MBTU = million British thermal units; NG = natural gas; O&M = operation and maintenance.

[a] Variable load profile for summer day in Southwest U.S.

[b] Assumes that 20 kW fuel cell system can be operated at 15 kW continuously without overheating.

[c] Effective reformer cost could be 0$ if multi-fuel reformer is integrated into vehicle.

[d] Assumes that stack would last 40,000 hours with low power operation and that high volume production fuel cell system cost is $75/kW ($1,500 for 20 kW system).

[e] Assumes that retail price of electricity is $0.11 per kWh and that excess power can be sold at $0.08 per kWh once total daily (net metered) needs are met.

Table 3: Non-Hybrid Fuel Cell Vehicles Operating in Commercial Setting

	Local Load Only 8 Hours per Day	Local Load Only 10 Hours per Day	Local Load Only 10 Hours per Day Reformer Integrated
Number of Vehicles	Ten	Ten	Ten
Connection Time of Day and Days per Year	9 AM to 5 PM 250 days/yr	8 AM to 6 PM 250 days/yr	8 AM to 6 PM 250 days/yr
Peak / Avg. Electrical Load (24 hours)[a]	290 kW / 162 kW	290 kW / 162 kW	290 kW / 162 kW
Peak Usage Saved and Value of Savings[b]	20 kW $6/day	110 kW $33/day	110 kW $33/day
Peak / Max. / Avg. FC System Power[c]	75 kW / 30 kW / 28.25 kW	75 kW / 30 kW / 27.80 kW	75 kW / 30 kW / 27.80 kW
Fuel Supply	NG Reformate	NG Reformate	NG Reformate
Reformer Efficiency	70% SMR	70% SMR	70% SMR
Reformer Capital Cost and Capital Recovery Factor[d] (5% rate, 15 year life)	$100,000 0.13	$100,000 0.13	$5,000 (for NG hookups only) 0.13
Approximate O&M (FC system + reformer)	$0.01/kWh	$0.01/kWh	$0.01/kWh
FC System Degradation[e]	$0.00188/kWh	$0.00188/kWh	$0.00188/kWh
Total Energy Produced	2,260 kWh	2,780 kWh	2,780 kWh
Average Total Efficiency for FC and Reformer (LHV)	35.7%	35.7%	35.7%
COE ($/kWh) (NG @ $4/MBTU)	$0.06/kWh	$0.06/kWh	$0.05/kWh
COE ($/kWh) (NG @ $6/MBTU)	$0.08/kWh	$0.08/kWh	$0.07/kWh
Net (Cost)/Benefit per Day[f] (NG @ $4/MBTU)	$7.86	$39.18	$57.98
Net (Cost)/Benefit per Day[f] (NG @ $6/MBTU)	($35.41)	($14.04)	$4.77

Notes: COE = cost of electricity; FC = fuel cell; LHV = lower heating value basis; MBTU = million British thermal units; NG = natural gas; O&M = operation and maintenance.

[a] Variable load profile for summer day in Southwest U.S.

[b] Value of savings based on $9 per kW monthly demand charge.

[c] Assumes that 75 kW fuel cell system can be operated at 30 kW continuously without overheating.

[d] Effective reformer cost could be 0$ if multi-fuel reformer is integrated into vehicle. The reformer costs shown are based on estimates in Ogden et al. (1996).

[e] Assumes that stack would last 40,000 hours with low power operation and that high volume production fuel cell system cost is $75/kW ($5,625 for 75 kW system).

[f] Assumes that retail price of electricity for commercial customers is $0.06 per kWh.