A MICRO-GRID WITH PV, FUEL CELLS, AND ENERGY EFFICIENCY

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ABSTRACT

A micro-gird is an electrically isolated set of power generators that supplies all of the demand of a group of customers. This work evaluates the potential of a micro-grid composed of photovoltaics (PV), fuel cells, and energy efficiency investments and a set of residential customers. It concludes that: (1) PV, fuels cells (operated in a cogeneration mode), and energy efficiency may all be an economically attractive part of a micro-grid; (2) there is a fairly good match between supply and demand on an annual, monthly, and hourly basis; (3) fuel cells (operated in a cogeneration mode) and PV complement each other in terms of electricity supply because fuel cell electricity production peaks in the winter while PV electricity production peaks in the summer; (4) a relatively small number of customers (less than 50) can result in a reliable micro-grid; (5) customer loads that are more certain result in a smaller micro-grid; and (6) micro-grids may represent a new market for PV, fuel cells, and energy efficiency.

1 INTRODUCTION

Distributed generation technology development has been largely driven by two forces. Utilities have pushed development as a potential new and effective way to solve transmission and distribution system capacity constraints and to improve electric grid operation (1), (2), and (3). Customers have also pushed distributed generation development by demanding lower cost and more reliable sources of electricity. Distributed generation manufacturers have responded to and pursued these market forces with partial success. The newly emerging regulatory environment will create new opportunities that will spur development and lower the threshold to distributed generation penetration. One opportunity that has been identified is referred to as micro-grids (4).

A micro-gird is an electrically isolated set of power generators that supplies all of the demand of a group of customers. A potential advantage of a micro-grid is that it may have a lower cost than the existing utility service. This is because the micro-grid is not burdened with the cost of the transmission and distribution system as well as other existing stranded investments. A potential disadvantage of a micro-grid is that it has to reliably supply all of the demand without the benefits of a diverse load profile (since there are fewer customers) and a diverse generation profile (since there are fewer generators).

A previous work began the development of a methodology to assess the economic feasibility of micro-grids (4). Results indicated that, in the right situations, micro-grids may be an economic alternative to either the existing utility service or distributed generation backed up by the utility grid.

2 OBJECTIVE

The objective of this work is to evaluate the potential of a micro-grid given a specific set of technologies and measured hourly electric load profiles. The technologies are photovoltaics (PV), fuel cells, and energy efficiency investments. The data are for a representative set of residential customers from Pacific Gas and Electric Company's (PG&E's) system. The paper: (1) describes how these three technologies compare to the existing utility system; (2) evaluates the economics of the system; (3) assesses the match between supply and demand on an annual basis; and (4) examines micro-grid reliability.

3 RESULTS

3.1 System Description

This work assumes that the micro-grid is composed of PV, fuel cells, and energy efficiency investments. To give a broad perspective of how this system differs from the existing utility service, consider the following comparison of the existing utility system to the proposed system.

The average U. S. residential customer purchased 10,500 kWh of electricity and 600 therms of natural gas in 1995 (5). As shown in the top part of Fig. 1, there is substantial waste in the current method of providing customers with this energy, both in the generation and transmission of the electricity as well as the efficiency of the end-use devices that use the energy. The figure shows that two-thirds of the primary fuel consumed is lost in waste heat and only one-third is used to provide power, light, and usable heat (6).

Now, consider the distributed system shown in the bottom part of Fig. 1. The system is composed of energy efficiency investments, a 2-kW fuel cell, and a 1.3-kW photovoltaics system (PV). The fuel cell is only operated in a cogeneration mode (i.e., it is only operated when the consumer has both electrical and heating requirements), and it has a 25 percent electrical efficiency and a 70 percent thermal efficiency. As shown in the bottom of the figure, this system supplies all of the consumer's annual electricity needs so that no electricity comes from the central utility.

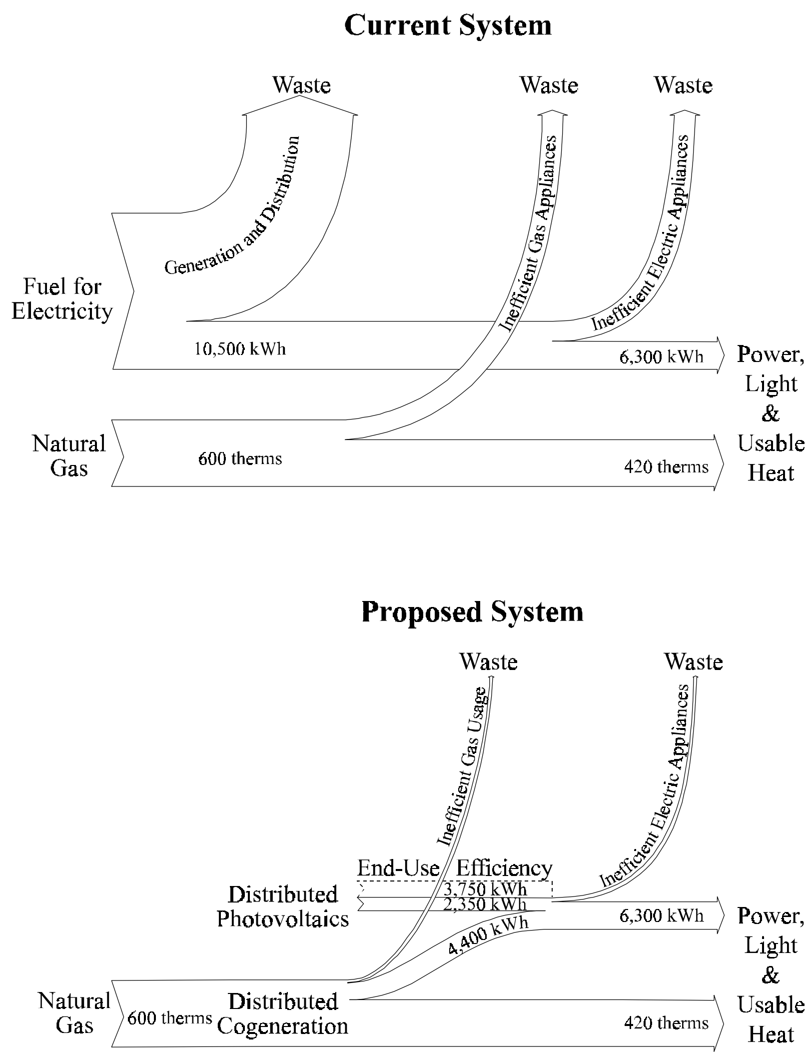

Fig. 1. The system.

TABLE 1. ECONOMIC DATA AND ELECTRICITY COSTS

	Lights	AC Tune-Up	Fuel Cell (cogen)	Refrig.	Gas Dryer	PV	Fuel Cell (non-cogen mode)
Capital Cost ($)	$200	$250	$2,000	$750	$500	$2,000	-
O&M Cost (¢/kWh)			1.0				1.0
Grid Cost (¢/kWh)			1.5			1.5	1.5
Fuel Cost (¢/kWh) (Gas cost is $0.70/therm)			-		3.0	-	9.6
Size (kW)			2.0			1.3	-
Life (years)	7	10	11	10	10	15	7
Elec. Prod./Savings (kWh/yr)	750	600	4,400	1,200	1,200	2,350	2350
Electricity Cost ($/kWh)	$0.050	$0.057	$0.081	$0.085	$0.087	$0.103	$0.163

3.2 System Economics

TABLE 1 presents the cost and performance assumptions for each of the investments. The investments are listed in order of cost with the least cost investment in the first column. Fig. 2 and the last row in the table present the cost of electricity based on these assumptions and a 6 percent after tax discount rate (a rate that a residential customer could obtain through a 9 percent home equity loan and 35 percent tax bracket). The figure includes PG&E's current residential rates for comparison (7).

There are several observations to make in the figure and the table. First, the cost of electricity for the generation investments includes a charge of 1.5 ¢/kWh (or about $100 per year) to pay for operating the micro-grid.

Second, all of the investments except the fuel cell operated in a non-cogeneration mode[1] have a lower cost of electricity than PG&E's existing rates. This result is sensitive to the fact that the assumed PV capital cost is lower than one would pay in the market today without any subsidies and that 2-kW residential cogeneration fuel cells are available in the market.

Third, the cost of electricity for the fuel cell operated in a non-cogeneration mode (the left column in TABLE 1) is $0.163/kWh while the cost of electricity in a cogeneration mode is $0.081/kWh; that is, the non-cogeneration mode costs twice as much as the cogeneration mode. This is primarily due to the fact that additional natural gas is consumed but the waste heat is not used in a non-cogeneration mode and secondarily because the fuel cell life is shortened by increasing its annual operating hours. Thus, even though the customer owns the fuel cell, it should only be run in a cogeneration mode. This suggests that it makes economic sense for a customer to purchase both a fuel cell and a PV system and then to only operate the fuel cell in a cogeneration mode.

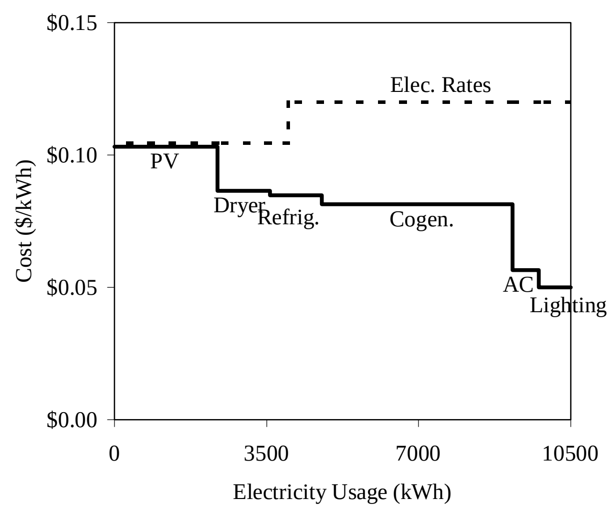

Fig. 2. Cost of electricity costs and PG&E rates.

[1] The cost of electricity in the non-cogeneration mode equals the annual cost of operating the unit in both cogen and non-cogen modes ($740) minus the annual cost of operating the unit in the cogen mode ($357) divided by the number of kWhs that the non-cogen mode produces (2,350 kWh) or $0.163/kWh.

3.3 Annual, Monthly, and Hourly Match Between Supply and Demand

The previous subsection evaluated the economics of a system with energy efficiency, a fuel cell operated in a cogeneration mode, and a PV system. This section addresses the technical issue of how well supply matches demand on an annual (Fig. 3), monthly (Fig. 4), and hourly basis (Fig. 5). The solid lines in each figure represent electricity supply and the dashed lines represent electricity demand.

Fig. 3 presents the annual match between supply and demand. It shows that this system supplies all of the consumer's annual electricity needs: the energy efficiency investments reduce electricity consumption by 36 percent, the fuel cell operated in a cogeneration mode provides 42 percent of the electricity consumption, and the PV system provides 22 percent of the electricity consumption.

Fig. 4 presents the match on a monthly basis. The energy produced by the fuel cell is based on natural gas consumption patterns of PG&E's customers (9) and a 25 percent electric conversion efficiency; these consumption patterns are similar to national averages (5). The energy produced by the PV system is based on the output of PV systems that are part of SMUD's PV Pioneers Program (3).

Fig. 4 shows that there is a fairly good match between supply and demand on a monthly basis. It also shows that PV systems and cogeneration fuel cells complement each other: the cogeneration fuel cell has high production during the winter when space and water heating needs are greatest (but the amount of available sunshine is at a minimum) and the PV system has high production during the summer when there is a lot of sun (but there are no space heating needs).

Fig. 5 presents the hourly match between supply and demand. The figure is based on average daily electric consumption by month for PG&E's residential customers (8). The x-axis for each graph is from midnight to midnight and the y-axis is from 0 to 2.5 kW. Notice that, while supply is not perfectly matched to demand on an hourly basis, the match is pretty good.

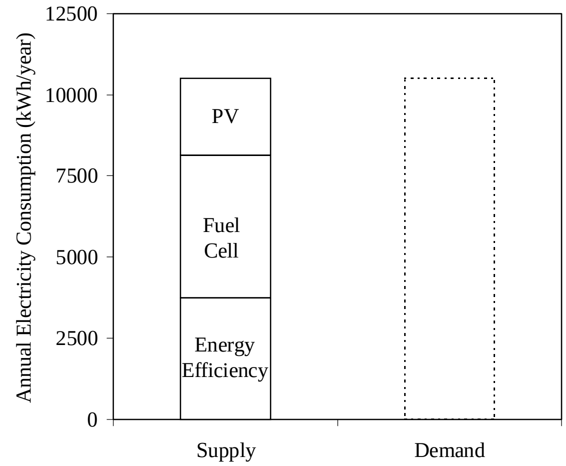

Fig. 3. Annual match between supply and demand.

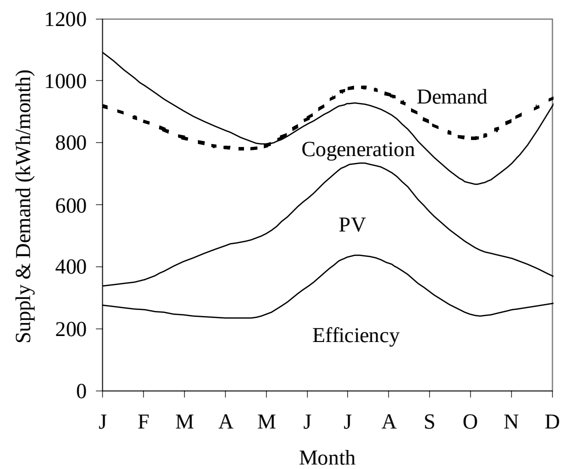

Fig. 4. Monthly match between supply and demand.

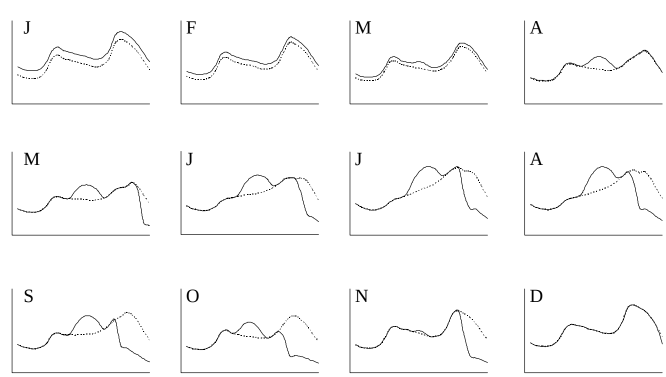

Fig. 5. Hourly match between supply and demand for representative days.

3.4 System Reliability

The match between supply and demand taken to its limit (i.e., the instantaneous match between supply and demand) is the issue of system reliability. One way to provide system reliability is to pay the existing utility to manage the system imbalances (as shown in TABLE 1, about $100 per year is allocated for system operation). Another approach is to use this money to fund the operation of a micro-grid.

A previous work, which focussed on the generation aspect of reliability, showed that a micro-grid can provide system reliability (4). The micro-grid provides reliability by reducing the chance that all of the generation units on the grid will fail simultaneously or that all consumers on the grid will experience a peak demand at the same time. When everything else is held constant, the greater the number of customers on the grid, the more reliable the system.

The factors that determine the required size of the micro-grid are: the desired level of reliability; the size, number, and outage rates of generating units; and the loads and degree of uncertainty associated with the loads. We will make the following assumptions: (1) the micro-grid must have an outage probability of less than 1 day in 10 years during the peak load; (2) each customer has a 2-kW fuel cell that has a 1 percent outage rate (this translates to an outage of about 8 hours per month); (3) the peak occurs at 7:00 p.m. in the winter so there is no sunlight available and no generating capacity from the PV; and (4) the average customer demand at the time of the peak, net of the savings from the energy efficiency investments, is 1.4 kW.

In order to illustrate how load uncertainty affects the size of the micro-grid, assume that each customer has a base load of 0.5 kW and three uncertain loads so that their expected demand is 1.4 kW. For example, customers could have three loads that are 0.6 kW each and that occur with a 50 percent chance each (so that the peak load is 0.5 kW + 3*0.6 kW = 2.3 kW and occurs with a chance of $0.50^3 = 0.125$ while the average load is still 0.5 kW + 3*0.6 kW*0.5 = 1.4 kW); another combination would be three loads that are 1.2 kW each that occur with a 25 percent chance each.

As in the previous work, a binomial probability distribution analysis is used to evaluate system reliability. In this case, however, the analysis is applied to both generation and loads (so that it is a two-dimensional analysis). Fig. 6 presents the peak load per customer (which, given the way it is modeled, is an indication of the level of load uncertainty) versus the required number of customers. For example, a micro-grid with 7 customers that each have a constant 1.4 kW demand has the same level of reliability as a micro-grid with 58 customers that each have a 6 kW peak demand.[2]

The basic message of the figure is that there is a tradeoff between managing the individual customer's loads and the required number of customers in the micro-grid: the less customer load uncertainty, the fewer the number of customers that are needed to provide adequate reliability.

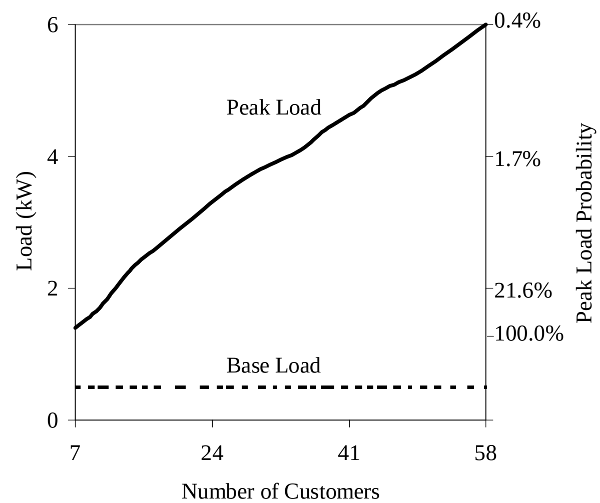

Fig. 6. Peak load vs number of customers in micro-grid.

4 CONCLUSIONS AND FUTURE WORK

Several conclusions can be drawn from this work: (1) PV, fuels cells (operated in a cogeneration mode), and energy efficiency may all be an economically attractive part of a micro-grid; (2) there is a fairly good match between supply and demand on an annual, monthly, and hourly basis; (3) fuel cells (operated in a cogeneration mode) and PV complement each other in terms of electricity supply because fuel cell electricity production peaks in the winter while PV electricity production peaks in the summer; (4) a relatively small number of customers (less than 50) can result in a reliable micro-grid; (5) customer loads that are more certain result in a smaller micro-grid; and (6) micro-grids may represent a new market for PV, fuel cells, and energy efficiency.

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[2] It is important to note that this result is specific to the assumptions presented in the text.

There are a number of barriers to actually building a micro-grid: (1) the capital cost of PV is a factor of 3 or 4 too high without any subsidies; (2) there do not appear to be any 2-kW residential cogeneration products available in the market; (3) a micro-grid in which each customer is both a product producer and a product consumer is a radical departure from the existing utility and may require a different market structure; and (4) while there is a fairly good match between supply and demand, a technical solution (such as the use of storage or load control) is needed for the times when the two are not perfectly matched.

In terms of future work: (1) more needs to be known about the imbalance between supply and demand on a fine time scale; (2) there needs to be a better characterization of load uncertainty; this will give an indication of the potential value of load control; (3) consideration should be given to segmenting customer loads and then providing varying levels of reliability in order to reduce the required number of customers in the micro-grid; (4) the flexibility value of the micro-grid should be quantified; (5) the analysis needs to be repeated for a specific set of customers using measured electricity and natural gas consumption data; and (6) a demonstration micro-grid needs to be built.

5 REFERENCES

(1) Shugar, D. S., "Photovoltaics in the Utility Distribution System: The Evaluation of System and Distributed Benefits," *Proceedings of the 21st IEEE PV Specialists Conference*, Kissimmee, Florida, May 1990

(2) Wenger, H. J. and T. E Hoff, *The Value of Photovoltaics in the Distribution System: The Kerman Grid-Support Project, Final Report*, Pacific Gas and Electric Company and the U.S. Department of Energy, San Ramon, CA. May 1995

(3) Wenger, H. J., T. E. Hoff, J. Pepper, *Photovoltaic Economics and Markets: The Sacramento Municipal Utility District as a Case Study*, Sacramento Municipal Utility District, California Energy Commission, and North Carolina Solar Center, September 1996, http://www.energy.ca.gov/development/solar/index.html

(4) Hoff, T. E., H. J. Wenger, C. Herig, and R. W. Shaw, Jr., "Distributed Generation and Micro-Grids," Conference Proceedings of the 18th Annual North American Conference of the USAEE, September 1997, http://www.PacificEnergy.com

(5) Annual Energy Outlook 1997, Energy Information Administration, Report DOE/EIA-0383(97), December 1996

(6) Hoff, T. E., H. J. Wenger, J. P. Weyant, and C. Herig, "Reduce, Reuse, and Renew: One Possible Approach to Global Climate Change," working paper, 1998, http://www.PacificEnergy.com

(7) Pacific Gas and Electric Company's Schedule E-1, 1998, http://www.pge.com/customer_services /business/tariffs/

(8) California Public Utilities Office of Ratepayer Advocates, Load Data, http://162.15.5.2:80/wk-group/dai/dai1/

(9) Personal Communication with Andrea Gough at the California Energy Commission, January 1998