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### **Title**

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### **Authors**

Marnay, Chris  
Rubio, F. Javier  
Siddiqui, Afzal S.

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# Shape of the Microgrid

*Chris Marnay, F Javier Rubio, and Afzal S Siddiqui*  
Ernest Orlando Lawrence Berkeley National Laboratory  
C\_Marnay@lbl.gov \* tel: +1.510.486.7028

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Restrictions on expansion of traditional centralized generating and delivery systems may be becoming so tight in the industrialized countries that they cannot reasonably be expected meet future electricity demand growth at acceptable cost. Meanwhile, technological advances, notably improved power electronics that permit grid interconnection of asynchronous generation sources, is tilting the economics of power generation back towards smaller scales, thereby reversing a century long trend towards the central control paradigm. Special power quality requirements or opportunities for combined heat and power applications make on-site generation an even more attractive option for customers. The existence of a significant amount of electricity sources dispersed throughout the low voltage distribution system could create a power system quite different to the one we are familiar with and creating it offers significant research and engineering challenges. Moreover, the electrical and economic relationships between customers and the distribution utility and among customers may take forms quite distinct from those we know today. For example, rather than devices being individually interconnected in parallel with the grid, they may be grouped with loads in a semi-autonomous neighborhood that could be termed a microgrid.

A microgrid is a cluster of small (by the standards of current power systems, e.g. < 500 kW) sources, storage systems, and loads which presents itself to the grid as a legitimate single entity. The heart of the microgrid concept is the notion of a flexible, yet controllable electronic interface between the microgrid and the familiar wider power system, or macrogrid. This interface essentially isolates the two sides electrically; and yet connects them economically by allowing delivery and receipt of electrical energy and ancillary services (EE&AS) at the interface. From the customer side of the interface, the microgrid should appear as an autonomous power system meeting the power quality and reliability requirements of the customer. Such issues as local voltage, reliability, losses and quality of power should be those that support the customers' objectives. From the macrogrid side, however, the microgrid should appear as a legitimate entity akin to current interconnected generators or loads.

A key distinction between microgrids and our familiar arrangements is the expanded role of electricity endusers in determining the pattern of development of the overall power system, which must not only accommodate purchases and sales of EE&AS to and from established markets but also contractual agreements between microgrids. Fundamentally, the characteristics and capabilities of the microgrid will be determined by its internal requirements together with the technical, economic, and regulatory opportunities and constraints it faces, and not by established objectives for capacity expansion and reliability of the macrogrid. The goal of Consortium for Electric Reliability Technology Solutions (CERTS) work underway at the Berkeley Lab is to anticipate possible patterns of microgrid development that can help focus research efforts on the key technical problems that must be solved to enable microgrid deployment.

To this end, a customer adoption model for distributed energy resources (DER) is under development. Beginning from the perspective of a current individual customer, the model decides whether to adopt onsite generation. Done from a strictly economic point of view, this is a currently a comparatively simple problem, if equipment characteristics are known. Currently, manufacturer equipment price forecasts are accepted and no installation costs are considered. Given the cost of equipment, the cost of alternative delivered grid power, fuel (primarily natural gas) costs, the potential for revenues from the sale of energy into a power market, a small number of possible distributed generating technologies are evaluated. If any technologies are adopted, the model provides a simple operating schedule for them as well as profiles of purchase from and sale to the grid.

This model has been run for four prototypical southern California commercial customers, a grocery store, a restaurant, an office, and a mall. Figure I shows the capacities of distributed generation adopted in one example, the office, under various assumptions. Only 4 of the 30 available distributed generation options are picked in this example, solid oxide fuel cells of two different sizes, diesel generators, and microturbines.

The peak load of this particular customer is about 545 kW, so in most scenarios, it installs distributed generating capacity totaling around 50% of its peak. The third scenario from the left "Tariff" is a notable exception in which about 95% of peak capacity is installed. The three scenarios on the left represent three electricity purchase options, "PXRN" allows the customer to buy at 1999 California Power Exchange (PX) prices plus an adder of 6.39 ¢/kWh, which was calculated to make the customer revenue neutral relative to the applicable local Southern California Edison tariff. Under "Frate" the customer pays a fully hedged fixed electricity price, which is again revenue neutral, and is 9.70 ¢/kWh. Interestingly, the fixed rate option and the direct purchase at PX prices plus the adder gives remarkably similar results. This is in part due to the high size of the adder relative to the average price, 66%. Nonetheless, exposing this customer to PX price variability has surprisingly little effect on its technology choice or adoption level. Why then does the regulated tariff appear to have such a dramatic effect? The answer is that it contains a stiff monthly ratcheted demand charge of 10.20 \$/kW·month, if the peak monthly customer demand occurs in the on-peak hours of 12-18:00. The high contribution of this demand charge to the customer's overall bill results in its desperate efforts to install the lowest capital cost technologies "diesel" generators and "MT," or microturbines.

The other cases are sensitivities to the PXRN case. The assumed natural gas price in PXRN is the mean of prevailing residential rates and city gate prices. "HighNatG" actually imposes residential prices, and "LowNatG" allows the customer to use natural gas priced at the city gate price. Not surprisingly, the LowNatG rate results in more MT capacity. The "IntRate" option raises the interest rate by 2 percentage points, which also favors the low capital cost technologies. "10Turnkey" and "50Turnkey" raise the first cost of fuel cells to 10% and 50%, respectively, above the otherwise accepted manufacturer forecasts. In the 50% case, fuel cells are eliminated entirely. "Standby C." imposes a stand by charge of 6.40 \$/kW·month, and "Free Sales" allows net metering for the customer. The results of this example illuminate several points. First, under the optimistic cost assumptions, the overall cost savings of this customer compared to the tariffed bill are about 20-25% in all scenarios. Second, single customer technology adoption is not unlike traditional utility system adoption, resulting in a mix of base and peak load technologies. A key difference, however, is that the customer always has the option of buying from the grid. Third, only in one case, and this is the most

extreme of any studied to date, does the customer come close installing enough capacity to disconnect entirely from the grid. Fourth, the price of purchase alternatives can dramatically affect decisions. The structure of the prevailing tariff in the "Tariff" scenario drives an outcome quite distinct from the other cases. Also, in this case, the office self provides about 60% of its electricity demand, whereas in all other scenarios it self provides about 90%. Therefore, in the tariffed example, the office installs much more capacity yet generates much less power less efficiently. Fifth, overall, these customers did not sell significant amounts of electricity into the grid because PX prices rarely exceeded marginal cost, and rarely exceed the retail price. In other words, the key customer benefit from self provision derives from avoiding the transmission and distribution and retailing cost of power, i.e. the non-commodity costs. Finally, although the cost assumptions used in this example are simplistic, results do show the potential competitiveness of self generated electricity with purchases. Note that although many costs are ignored, notably installation costs, on the other hand, many other potential advantages of distributed generation, notably combined heat and power application, are, likewise overlooked. Also, PX prices have been much higher in the summer of 2000 than in the 1999 data used in this example.

Finally, Figure 2. shows an example operating schedule emerging from the customer adoption model. This schedule is established for a microturbine at the grocery store on the peak day of each month. As is clear, the model assigns this resource to a familiar load following role.

The emergence of new small scale generation and power electronics technologies coupled with the increasing difficulty of the traditional centralized power system to expand is tending to economically favor on-site self provision of electricity. These small sources may ultimately be clustered with loads in microgrids that are designed, built, and operated to meet the reliability and power quality requirements of the microgrid and not the macrogrid. Nonetheless, the microgrid will likely remain interconnected and will be an economic actor in EE&AS markets. This configuration will require significant technical innovation but can yield significant economic and environmental benefits. An understanding of likely patterns of distributed generation adoption could direct research and development towards the engineering problems that must be solved before microgrid deployment can advance. As a first step in this process, a simple customer adoption model has been developed and applied to four typical commercial customers, assumed to be in southern California. The results of this effort suggest that distributed generation could be attractive in all cases, that a combination of technologies may be adopted by the customers, and that customers will likely partially self provide and partially buy from the grid, and only occasionally sell.

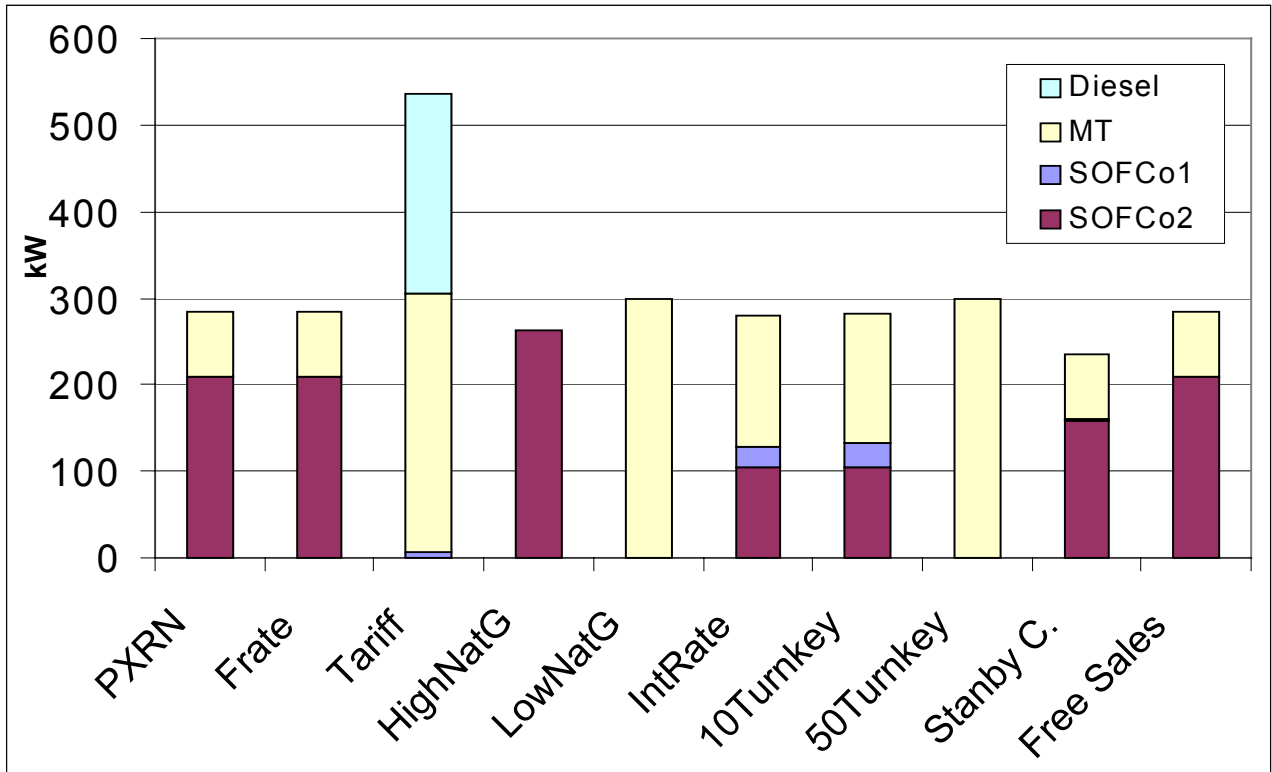


Figure 1: Customer Adoption Model Capacity Results for an Office

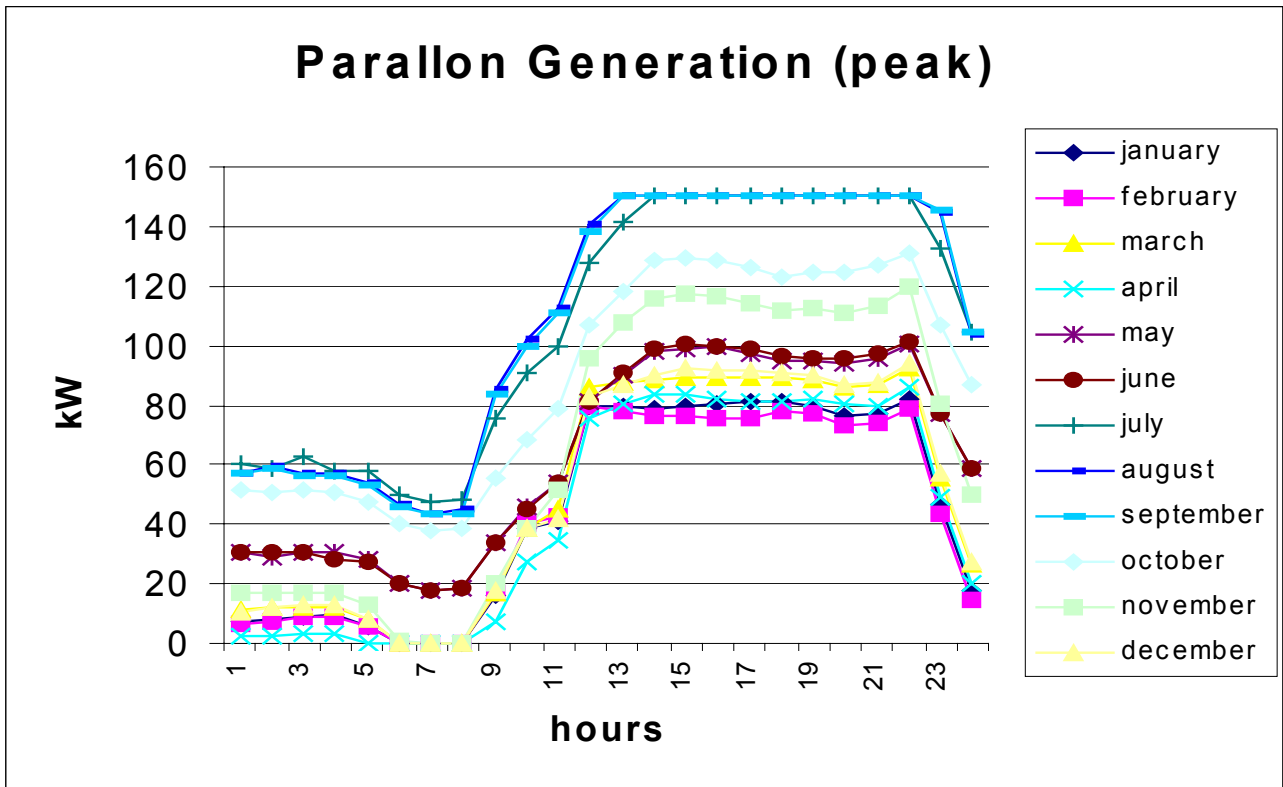


Figure 2: Monthly Peak Day Operational Results for the Office Microturbine