Performance Assessment of Cogeneration Systems in California

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Abstract

Over the past several years, customer-sited cogeneration systems have been viewed as one way to mitigate electrical supply shortages. On the utility side, achieving this goal requires that cogeneration systems operate at a relatively high capacity factor, especially during peak periods. On the customer side, the cogeneration system must be capable of reducing operating costs. Our firm has recently completed an evaluation of operational customer-sited cogeneration systems installed during 2002 through 2004 under the Self-Generation Incentive Program (SGIP). This paper will present the results of an in-depth performance evaluation that was conducted for the SGIP Working Group to evaluate the effectiveness of useful thermal energy recovery of on-site cogeneration systems receiving incentives from the program.

In an earlier study, an initial evaluation of cogeneration system cost-effectiveness was performed for SGIP. This study raised some interesting questions regarding the actual operational efficiencies of cogeneration systems. Incorporating fuel consumption, thermal energy recovery and prime mover performance data obtained through the Program's measurement and evaluation monitoring efforts, actual measured performance was compared with the engineering estimates of performance for each project

This paper will also explore some of the key drivers behind the unexpectedly low thermal energy recovery and overall plant performance. A stepwise approach to reconciling the estimated and actual performance was implemented. If common threads were identified, they were documented in an effort to guide future cogeneration system installations. Because the performance data include the actual timing (hour and month) of cogeneration system operation, the effects of this distributed generation resource is evaluated taking into account the large differences between peak and off-peak energy costs and benefits. This program-level distributed generation analysis can help program designers and policy makers to understand the limitations of smaller cogeneration applications relative to those systems envisioned under PURPA and thus may have important policy implications for the future of cogeneration and distributed generation programs throughout the U.S.

Introduction

In response to Assembly Bill 970, which required the California Public Utilities Commission (CPUC) to initiate certain load control and distributed generation program activities, the CPUC issued Decision 01-03-073 (D.01-03-073) on March 27, 2001. This Decision mandated implementation across the service territories of California's investor-owned utilities (IOUs) of a self-generation program designed to produce significant public (e.g., environmental and energy distribution system) benefits for all electric and gas ratepayers. To meet this mandate, the California SGIP was created to offer financial incentives to IOU customers who install certain types of distributed generation (DG) facilities to meet all or a portion of their energy needs. The SGIP has been operational since July 2001.

The SGIP provides financial incentives for the installation of certain electric generation equipment on the customer side of the utility meter that meet all or a portion of the electric needs of an eligible customer's facility. Several key parties direct the SGIP design and implementation. Under the direction of the California legislature and CPUC, the SGIP is administered on a regional joint-delivery basis through three IOUs—Southern California Edison (SCE), Pacific Gas and Electric Company (PG&E), Southern California Gas Company (SoCalGas), and one non-utility Program Administrator, the San Diego Regional Energy Office (SDREO).[1]

Cogeneration Technologies in the SGIP

There are three cogeneration technologies eligible for incentives under the SGIP: fuel cells, microturbines, and reciprocating internal combustion engines (ICEs). Each of these technologies operates somewhat differently in terms of electrical conversion efficiency, theoretical heat recovery, and emissions. For each of these technologies, a description of the typical configuration and their presence in the program in terms of number of applicants, as well as capacity, is discussed. Table 1 provides a summary of installed/operating capacities of all the completed projects in SGIP.

Table 1. Number of Sites and Capacity of Completed Projects in SGIP

Technology	Number of Sites	Capacity (kW)
Fuel Cell	3	1,800
Microturbine	72	13,555
IC Engine	123	79,343

Fuel Cells

A fuel cell is an electrochemical device that combines hydrogen and oxygen to produce electricity, with water and heat as its by-product. Fuel cells hold great promise of delivering high electrical conversion efficiencies with little or no emissions. Since the conversion of the fuel to energy takes place via an electrochemical process, not combustion, the process is clean, quiet and highly efficient—two to three times more efficient than fuel burning. Heat is typically recovered via a heat exchanger and generally used for process heating at the site where the fuel cell is installed.

In addition to low or zero emissions, benefits include high efficiency and reliability, multi-fuel capability, flexibility, durability, and ease of maintenance. Their high efficiencies and reliability make them good candidates for providing base load power. Moreover, fuel cell efficiencies increase at partial load, which provides increased operating flexibility and capability for load following.[2]

Microturbines

Microturbines are small combustion turbines generally the size of a refrigerator with capacities below 300 kW. Their potential benefits include a small footprint, which allows them to be used where space is limited, lightweight, low emissions, ability to use waste fuels, and high responsiveness. In typical configurations, microturbines are fueled by compressed natural gas, methane, or propane. This fuel is ignited in a controlled combustion process and the combustion gasses are forced through nozzles that act to turn a turbine at a very high rotation (e.g., over 40,000 rpm), thereby generating electricity. Waste heat is

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[1] The San Diego Regional Energy Office recently changed its name to the California Center for Sustainable Energy.

[2] Load following is defined as a generating system that adjusts its power output to match the demand for electricity.

captured from the exhaust combustion gasses and typically transferred to a working fluid, such as hot water for use in process or space heating.

IC Engines

Reciprocating ICEs have been a preferred means of electricity generation for the past hundred years or more. Power is produced when a mixture of air and fuel is ignited, causing expansion of pistons connected to a crankshaft that turns a generator. ICEs typically range in capacity from a few kilowatts to over 5 MW. While ICEs can consist of diesel or spark-ignited systems, only spark-ignited engines are used in the SGIP. Spark-ignition engines are predominately fueled with natural gas, but can be fired using propane, gasoline, and waste fuels such as landfill gas. Currently, ICEs are more commonly being used for combined heat and power applications due to their rapid start up and good load following capabilities. Waste heat can be recovered from the engine exhaust and cooling systems to produce either hot water or low pressure steam.

Waste Heat Recovery and Efficiency Goals for Cogeneration Projects

Federal Guidelines/Requirements (FERC)

In 1978, Congress passed the Public Utility Regulatory Policies Act (PURPA) to help increase generation of electricity from non-utility sources, termed “qualifying facilities.” At the time, PURPA established sets of operational guidelines for qualifying facilities including fuel use, size, fuel efficiency, and reliability. Under the efficiency guidelines, qualifying cogeneration facilities are required to have the useful power output of the facility plus one-half of the useful thermal energy output equal to no less than 42.5% of their total energy input. PURPA became the guiding set of requirements for cogeneration systems installed across the nation.

The Federal Energy Regulatory Commission (FERC) is currently considering modifying PURPA. Among the proposed changes is increased emphasis on ensuring that recovered waste heat is used for “productive and beneficial” purposes at industrial, commercial, or institutional facilities. In particular, FERC proposes to examine individual qualifying facilities to make certain that recovered waste heat usage is “productive and beneficial” and not a “sham.” FERC is considering similar provisions to ensure that electricity production from qualifying facilities helps offset the electrical needs of the industrial, commercial, or institutional facilities at which they are located. Within this context, FERC intends to critically examine facilities where the thermal output only minimally meets its thermal input requirements. In these instances, FERC is concerned that such facilities are essentially designed to provide most of their electrical output to the utilities rather than meeting the intent of PURPA.

State Guidelines/Requirements

California Public Utilities Code Section 218.5 covers efficiency and useful waste heat recovery from cogeneration facilities installed under the SGIP as follows:[3]

“218.5. ‘Cogeneration’ means the sequential use of energy for the production of electrical and useful thermal energy. The sequence can be thermal use followed by power production or the reverse, subject to the following standards:

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[3] Since the preparation of this report PUC 216.6, has been implemented to govern efficiency and waste heat recovery requirements.

(a) At least 5% of the facility's total annual energy output shall be in the form of useful thermal energy.

(b) Where useful thermal energy follows power production, the useful annual power output plus one-half the useful annual thermal energy output equals not less than 42.5% of any natural gas and oil energy input."

Evaluation of Performance and Possible Problems

Electrical Conversion Efficiency

Electrical Conversion Efficiency is a particularly important element of the PUC 218.5(b) system efficiency, because in the equation electrical energy (kBtu) is credited at a rate of 100%, whereas heat energy is credited at the much lesser rate of 50%. It is also important because it represents a significant efficiency component that can be used to compare actual performance against expected performance.

Electrical conversion efficiencies are calculated using the following equation:

$$ElecEff_t = \frac{ENGO_t kWh \times 3.412 \, {}^{kBtu}\!/_{kWh}}{FUEL_t kBtu} \quad \text{where:}$$

$ElecEff$ = Electrical Efficiency
t = time period of interest
$ENGO$ = Electric net generator output, in kWh
$FUEL$ = Fuel input, in kBtu

Overall System Efficiency

Overall system efficiency is the sum of electrical conversion efficiency and rate of useful thermal energy recovered by the system. This measure is important because it represents a significant performance benchmark that can be used to compare cogeneration system performance against the performance of alternative technologies.

Overall system efficiencies are calculated using the following equation:

$$OverallEff_t = ElecEff_t + \frac{HEAT_t kBtu}{FUEL_t kBtu} \quad \text{where:}$$

$HEAT$ = Useful thermal energy recovered, in kBtu
$FUEL$ = Fuel input, in kBtu

Useful Thermal Energy Recovery

Cogeneration systems are subject to certain heat recovery and system efficiency requirements during the implementation stage of the SGIP. A variety of means is used to recover heat for useful purposes, and to apply that heat to provide various forms of onsite heating and cooling services. Heat recovery is typically accomplished through:

- Engine block via water-to-water heat exchanger,
- Exhaust via air-to-water heat exchanger,
- Exhaust via air-to-air heat exchanger,
- Exhaust via heat recovery steam boiler, or
- Exhaust directly.

Recovered heat must be applied to a useful purpose to be credited to PUC 218.5 and other efficiency measures. Heat utilization is typically accomplished via:

- Use of recovered heat for space heating, water heating, or process heating, and/or
- Use of recovered heat to operate a heat recovery absorption chiller (HRAC).

The evaluation of the performance and identification of possible problems involves an investigation into why the system was designed as it was, how the host is using the heat recovered, and what technologies or situations are present to maximize (or minimize) thermal energy recovery.

Range of Electrical, Overall System, and 218.5 Efficiencies at SGIP Facilities

Microturbines

Electrical system efficiencies for microturbines are significantly below manufacturer claims of approximately 30% but are very consistent. Table 2 presents summary statistics for electrical and overall system efficiencies.

Table 2. Electrical, Overall System, and 218.5 Efficiencies at SGIP Microturbine Facilities

	Min.	**Max.**	**Median**	**Ave.**
Electrical Efficiencies	0.15	0.25	0.23	0.22
Overall System Efficiencies	0.20	0.73	0.45	0.46
218.5 (a) Efficiency	0.22	0.71	0.49	0.49
218.5 (b) Efficiency	0.18	0.47	0.34	0.34

Electrical efficiencies of microturbine systems are relatively flat with fairly widely distributed overall system efficiencies, showing that the source of variation is not on the electrical conversion side but rather on the useful waste heat recovery.

Examination of the two components of the PUC 218.5(b) calculation is provided in Table 3. Even if the electrical efficiencies were increased to manufacturer's claims, our analyses indicate many systems would fall below the required 42.5% levels required by PUC 218.5(b). This indicates that there are operational issues on both sides of the cogeneration system.

Table 3. Breakout of Electrical and Thermal Components of PUC 218.5(b) for Microturbines

Elec. Eff	Waste Heat	218.5(b)
21.90%	12.28%	34.18%

IC Engines

Observed electrical conversion efficiencies for IC Engines cogeneration systems were higher than the Microturbine systems. There is a wide range of electrical efficiencies present in the program, as indicated in Table 4.

Table 4. Electrical, Overall System, and 218.5 Efficiencies at SGIP ICE Facilities

	Min.	Max.	Median	Ave.
Electrical Efficiencies	0.17	0.34	0.26	0.27
Overall System Efficiencies	0.31	0.69	0.47	0.49
218.5(a) Efficiencies	0.15	0.68	0.38	0.40
218.5(b) Efficiencies	0.28	0.48	0.37	0.38

In general, ICE cogeneration systems perform closer to PUC 218.5(b) than microturbine systems. This is in part due to the way PUC 218.5(b) is calculated, in that electrical efficiency counts twice as much as thermal efficiency. That being said, ICEs overall do not meet PUC 218.5(b). As shown in Table 4, the average PUC 218.5(b) level achieved was only 38%, and the minimum level achieved was only 28%, compared to the minimum requirement of 42.5%. Fuel cells were not included in this analysis for two primary reasons. First, the higher electrical efficiency of fuel cells is typically sufficient to meet PUC 218.5(b) without recovering waste heat. Second, there were only three completed fuel cell projects through 2005. These two factors combined did not warrant additional analytical effort.

Problems Encountered with Waste Heat Recovery

Many times the calculations at the design stage had significant flaws that overstated the achievable efficiency. In addition to flawed design assumptions, there are many cases of equipment failures that contributed to poor performance. In some cases, the failure causes complete system shutdown, which does not impact overall efficiency calculations. Other times, however, only part of the system is disabled (i.e., the heat recovery loop) and the generator continues to produce electricity without recovering heat, causing overall system efficiencies to plummet. Some examples of mechanical equipment problems are presented below.

- Heat exchanger failure due to unexpected reactions with working fluids.
- Recuperator failure causing poor electrical power output.
- Gas compressor failure.
- Absorption chiller failure.
- Poor fuel quality leads to part-load operation (this applies to renewable-fueled projects but has a significant negative impact on operations).

- Operating temperature has an effect on system electrical efficiency.

Comparison of Performance between Microturbines and IC Engines

Figure 1 presents a comparison between 218.5(b) efficiency by technology. As shown in the figure, 218.5(b) efficiency for microturbines is significantly lower than the ICEs. Most of the difference in efficiency is because of electrical efficiency. When compared against one another, microturbines seem to have a better level of waste heat recovery than reciprocating engines. This is partially due to their lower electrical conversion efficiencies, leaving more heat available for energy recovery in the exhaust system.

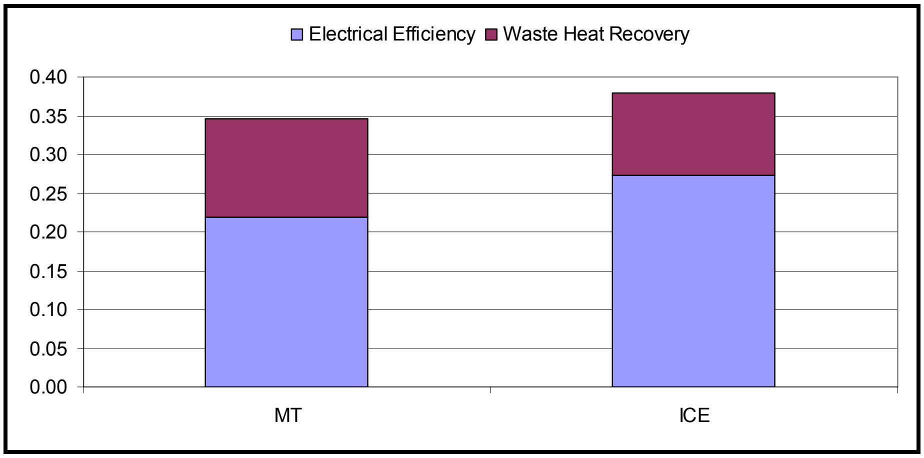

Figure 1. Comparison of 218.5(b) Efficiency by Technology

Figure 2 compares the performance parameters by technology. As shown in the figure, microturbines generally have higher 218.5(a) and lower 218.5 (b) values when compared to ICEs. This is because ICEs have higher electrical efficiencies and microturbines have higher thermal efficiencies when compared to each other.

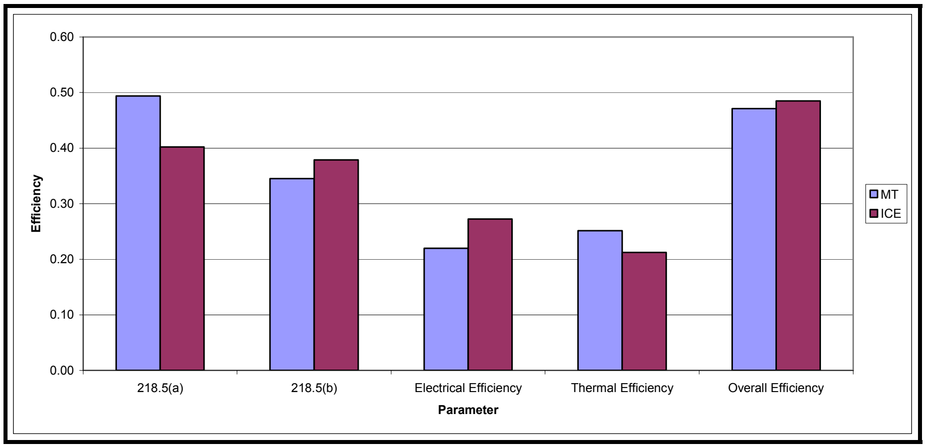

Figure 2. Comparative Parameters for Microturbines and ICEs

Conclusion

Customer-sited cogeneration systems have promise for helping to meet the electricity needs of utilities. However, the expectations for electrical generation and heat recovery should be well understood. Proactively addressing some of the identified issues during the design phase will help to mitigate some of the performance issues. Careful design will also help to improve performance. We have already seen second generation equipment that addresses some of the performance issues. As the program matures, technology should be further refined to continually improve performance. With the recent adoption of PUC 216.6 rather than 218.5, it will be interesting to revisit this study in a few years to evaluate whether performance improvements were realized.

Concurrent to this analysis, the SGIP Working Group refined the Waste Heat Utilization Worksheet to include monthly electrical and thermal demand information in an effort to encourage a better coincidence between electrical and thermal loads. Further refinements were suggested to the Working Group and may be incorporated in future versions. As an independent evaluator, we are prohibited from biasing the program and, therefore, do not provide direct suggestions for improvement to system owners. In many cases, we have provided information to the Program Administrator so that they can attempt to contact the system owner to discuss ways to improve operation of their cogeneration system.

Acknowledgments

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California Public Utility Code Section 218.5.

Fuel Cell operational information: http://www.fuelcells.org.