Demand Reduction through Compressed Air System Efficiency: Lessons from the Past, Questions for the Future

Mitchell Rosenberg, XENERGY Inc.

ABSTRACT

Utilities in many states have initiated programs to improve electric system reliability through highly targeted efforts to reduce electric demand. Evaluation of these programs poses a number of technical challenges, particularly in developing defensible estimates of demand reductions achieved by the program during critical costing periods. This paper examines the implications of these issues in the context of a program currently underway in California to effect significant demand reductions through improvements in compressed air system efficiency.

Introduction

This paper presents the design, operation, early results, and evaluation approach of a program to achieve rapid electric demand reductions through energy efficiency improvements to industrial compressed air systems. This effort is being carried out in the framework of Pacific Gas & Electric's Third-Party Emergency Demand Reduction Program, which was designed to achieve significant reductions in demand in the summer of 2001.

We focus on the approaches developed to address key evaluation challenges raised by reliability-driven demand reduction programs. These include the need to measure demand reductions versus energy savings and to accommodate the short time frame for program implementation and estimation of results. We also identify and discuss methods to address additional challenges posed by the nature of compressed air system efficiency improvements. These include the variety and complexity of compressed air system design and operation, the absence of broadly understood methods for establishing baseline consumption patterns, and the prominent role of on-going monitoring and maintenance in achieving and preserving energy efficient operations.

Our primary intent in presenting this material is to provide guidance in the design and evaluation of programs to capture the abundant and very cost-effective demand reductions available through plant compressed air system efficiency improvements. However, the program experience reported provides into a number of other important energy efficiency issues. These include the incorporation of market transformation elements into programs designed primarily to acquire demand-side resources **more here**

Program Objectives and Operations

Background and Objectives

In a July 2000 decision (00-07-017) the California Public Utilities Commission (CPUC) adopted the Summer Energy Efficiency Initiative (Summer Initiative) as a "rapid response procedure" to provide "measurable demand and energy usage reductions beginning in Summer 2000". The Summer Initiative was specifically designed "to provide maximum impact of demand and energy usage reductions" during the current summer energy capacity shortage and potential energy shortage projected over the next few years. In response to the CPUC Summer Initiative, Pacific Gas and Electric Company (PG&E) issued the Cross-Cutting Demand Reduction Solicitation. This solicitation sought proposals that would achieve Peak Demand Reductions by May 1, 2001 to help mitigate electric generation shortages and transmission and distribution constraints. The Summer Initiative and PG&E Energy Efficiency Programs are funded through Public Goods Surcharge funds authorized by the California State legislature under Bill AB 1890.

PG&E's solicitation called for contractors to propose programs to identify, qualify, and implement demand reduction projects in customers' facilities. The solicitation also required contractors to propose measurement and verification procedures to quantify demand reductions achieved through the projects. *Post hoc* evaluation of the demand reductions will be carried out by a third-party evaluation contractor. As part of the proposal, prospective program contractors were required to specify a measurement and evaluation approach and to identify data they would collect in the implementation process to support the *post hoc* evaluations.

Program Operations

PG&E notified XENERGY of the contract award in early September and completed contract negotiations in early October. Under the contract, XENERGY was obligated to identify and assist in the implementation of compressed air system efficiency projects that yielded a minimum of 550 KW in peak period demand reductions. The program pays for compressed air system audits, assistance in project design and implementation, and collection and reporting of post-retrofit energy use and operating data. In addition, the program pays for a portion of the cost of installing of system monitoring equipment, as well as a customer incentive of $125 per KW of verified demand reduction during system peak periods. The key elements of the program were as follows.

Customer Recruitment and Qualification. Working with compressed air equipment vendors, the contractor identified and identify and qualified customers sufficient to yield the contract target of 550 KW in peak period demand reductions. To qualify for program technical services and financial incentives, potential customers needed to:

- Have a large enough compressed air system to yield potential savings over 250 MWH per year;
- Have a total compressor load of greater than 500 horsepower per distribution system;
- Show potential for significant Peak Period Demand Reductions;
- Demonstrate willingness to invest in energy efficiency projects in the past;
- Have a straightforward process for purchasing capital improvements in the $30,000 to $200,000 price range and within the Program timeframe; and
- Have a good relationship and past project experience with the compressed air equipment vendor.

Once customers were identified and screened according to the criteria above, they were required to sign a Preliminary Agreement before the program made further investments in their facilities. These Preliminary Agreements required participants to implement measures projected to yield a simple payback of two years or less (pending technical acceptance of the audit report), provide information required by the M&V plan, and implement maintenance activities specified in the audit.

System Audits. Compressed air system efficiency consultants conducted audits of pre-qualified facilities to estimate baseline system energy usage and demand and to identify cost-effective demand reduction measures. The methods used to estimate the baseline were negotiated as part of the contract with PG&E. They conform with procedures that PG&E is developing for its own compressed air system efficiency program targeted to smaller customers. Baseline system energy use and demand was calculated using measurements of compressor energy use and/or flow and pressure measurements. Selection of measurement techniques was based on the engineering consultant's assessment of the most appropriate and practical methods, which reflected the schedule of compressor usage, system configuration, the relationship to production volumes, and the accessibility of various system components. To facilitate adjustments in the use for potential variations in production volume pre- and post-retrofit, the consultant collected information on production levels during the baseline measurement.

Based on the results of the audit, the consultants prepared a report covering

- Estimate of the current electric use and peak demand of the system;
- Identification of measures to reduce electric use and peak demand;
- Characterization of those measures in terms of cost, energy savings and peak demand reductions, and associated non-energy benefits;
- Identification of detailed monitoring and verification procedures (M&V Plan).

Project Implementation. Once customers accepted the audit recommendations, implementation proceeded in the following steps:

- Preparation of final plans and specifications.
- Installation of recording watt meters and pressure monitoring equipment.
- Training of customer operating personnel in correct system operation, use of ultrasonic leak detection equipment, leak repair and prevention, monitoring data retrieval and interpretation. The customer pays a portion of the cost of monitoring and leak detection equipment.
- Documentation of installation and customer acceptance.
- Release of the per KW incentive to the customer.

Monitoring and Evaluation/Ongoing Technical Support. During the peak demand time period (through the end of October 2001), the program contractor will analyze system operating data for each participant on a monthly basis and provide reports of project performance to the customer and PG&E. If estimated energy or demand reductions fall more than 10 percent below projected levels for two consecutive months, the program contractor will contact the customer, assess the causes of the situation, and plan corrective action. The intervention may take the form of phone consultation, review of operating records, or an on-site inspection. Throughout the Peak Demand time period, Consultant shall provide technical support to Customer on an as-needed basis to advise on all aspects of system operation and management, proper handling of monitoring equipment and data, and use of leak detection equipment.

In this program, the data collection required for (gross) impact evaluation is collected in an on-going and systematic way during project planning, implementation, and early operation. In addition to *post hoc* evaluation, these data collection and analysis activities serve a number of key practical needs. Specifically, they support timely trouble-shooting of potential problems in measure installation and operation, and thus help to ensure that demand reduction targets are met during the critical peak period. They also serve to focus operating staff's attention on best maintenance practices and serve as a vehicle for more general training on compressed air systems.

Results to Date

As of May 1, 2001 the program had completed detailed system audits for three customers with large compressed air systems, and all three had agreed to implement the full range of demand reduction recommendations. Design engineering work was underway for two of the facilities. A Preliminary Agreement had been reached with a fourth customer, a very large auto parts manufacturing plant. With the fourth project in the program portfolio, it is likely that the goal of 550 KW reduction will be met. Table 1 summarizes details of the three projects for which audits have been completed.

Table 1. Summary of Compressed Air System Audits for Demand Reduction Program

Type of Plant	Food Processing	Food Processing	Corrugated Box Plant
Projected KW Reduction	215	265	70
Projected kWh Savings	925,400	1,897,700	573,180
Energy Cost Savings	$114,000	$142,300	$42,977
Estimated Project Costs	$128,000	$167,900	$13,140
Simple Payback Period	1.1 years	1.2 years	0.3 years
Baseline Estimation Approach	Combination of short-term KW metering and engineering estimates.	Combination of short-term KW metering and engineering estimates.	Combination of short-term KW metering and engineering estimates.
Selected Measures	• Correct capacity controls • Replace dryers and filters • Add air storage • Correct distribution piping	• Install smaller compressor for non-production uses • Reconfigure pipes to reduce pressure loss • Replace drains with level-activated models	• Correct capacity controls • Remove unneeded dryers from operation • Replace open blow end-uses with Venturi amplifiers

The audit results summarized in Table 1 suggest that the projects identified will be very cost-effective. This result contributed to the relatively rapid pace of project development and customer acceptance. One of the audits identified and quantified non-energy benefits. Under existing conditions at one of the food processing plants, pressure regulation controls had been inoperable for some time. The specific operations powered by the system required pressure in a very narrow band to operate correctly. This problem prevented the plant from using all production stations simultaneously and contributed to fairly serious quality control problems. Correction of the pressure control problems will restore all production stations to operability and significantly reduce waste. The customer estimates the value of these improvements at $112,000 per year.

The Compressed Air Resource

Review of the fairly sparse literature on documented energy savings from compressed air system efficiency projects suggests that the significant savings and positive project economics displayed in Table 1 may be typical of similar projects in other jurisdictions. Moreover, verified patterns of compressed air system use suggest that industrial compressed air systems present an attractive target for "resource acquisition" demand-reduction and energy efficiency programs. To summarize:

- ***Industrial compressed air systems consume huge amounts of electricity.*** Air compressors use 16 of all electricity used to power motor driven processes in US industries. (XENERGY 1998)
- ***Most industrial compressed air systems are hugely inefficient.*** Well-engineered efficiency improvements yield verified savings in the range of 15 to 30 percent of system energy consumption. Some case studies have documented savings of more than 50 percent.

- ***Savings from compressed air measures are coincident with electric system peak periods.*** Plant air systems[1] tend to run long hours, 5,000 to 8,000 hours per year. Thus energy and demand reductions are very likely to occur at system peaks and contribute to system reliability.
- ***Compressed air system efficiency improvements are highly cost-effective.*** Many verified projects and studies have identified significant energy and demand reduction projects with paybacks less than one year. Most projects yield savings sufficient to amortize investments in two years or less.

Industrial Plant Air System Energy Consumption

The results of the motor system inventory conducted for the 1998 *United States Industrial Electric Motor Systems Market Opportunities Assessment* (or *Market Assessment*) indicate that compressed air systems use 15.8 percent of all process motor drive energy in American factories. In physical terms, this is over 90,000 GWH per year. The *Market Assessment* did not distinguish between air compressors that power a variety of machines and tools distributed throughout a factory (plant air systems) from air compressors that drive only one process (process air systems). Generally, process systems are simpler than plant systems and offer fewer energy savings opportunities. Industry observers believe that plant air systems account for 60 – 70 percent of total compressed air usage.

Compressed Air System Energy Savings Opportunities

In a recent poll of compressed air system efficiency consultants reported that, in their experience, the energy consumption of a typical plant air system could be reduced by 15 to 20 percent through a combination of capital, maintenance, and operating improvements. (XENERGY 1998) This rule of thumb is borne out by the results of post hoc verification of energy savings and demand reductions achieved by projects that received assistance custom rebate programs offered by San Diego Gas & Electric in 1997. The field research on which these savings estimates are based was carried out in 1999. Thus, in most cases, a full year had elapsed since installation of the measures. Table 2 summarizes the results of savings analysis. For each facility, the table furnishes verified estimates of pre- and post-retrofit demand for the compressed air system, the gross change in demand associated with the retrofit, the demand reduction expressed as a percentage of the baseline KW, and a brief description of the measures implemented.

- In most of the cases presented in Table 2, pre- and post-KW estimates were based on in-depth consultant studies conducted before and after project implementation. KW estimates were generally based on short-term (2 – 4 weeks) monitoring of compressor amperage or wattage under normal and peak operating conditions. In some cases, recording wattage meter data were available for post-retrofit operations for a period of 12 months or more. Wattage measurements were in most cases combined with measurement of operating pressure at various points in the system and detailed description of system operations from plant personnel to arrive at an operating profile of the system that included baseline energy and demand estimates, as well as air flow estimates. In some cases, baseline conditions

[1] Throughout this paper we will use the term "plant air system" to refer to compressed air systems that deliver motive power to a variety of machines and tools distributed around a factory versus compressors that serve a single process such as mixing or aerating.

Table 2. Examples of Verified KW Reductions from Compressed Air Efficiency Projects
San Diego Gas & Electric, 1997

Type of Facility	Pre KW	Post KW	Δ KW	% KW Reduction	Project Description
Electronics Assembly	42	20	22	52%	• Converted 100 HP compressor from primary to back-up. • Sequenced 3 20 HP compressors for primary service. • Reduced end pressure from 125 to 100 psig.
Heavy Electric Equipment Manufacturer	935	638	297	32%	• New piping configuration to supply high pressure receivers and isolate peak demand events from the supply components; Leak repair. • Removed 2 compressors from service.
Sheet Metal Forming Plant	319	240	79	25%	• New piping configuration. • Installed additional air receivers. • Reduced end pressure from 125 to 90 psig.
Electronics Manufacturer	564	499	65	12%	• Leak reduction, installation of low-loss drains, added controls, storage. • Elimination of inappropriate end-uses.
Circuit Board Manufacturer	318	224	94	30%	• New piping configuration; installed additional air receivers. • Reduced end pressure from 105 to 85 psig.
Metal working facility	109	61	48	44%	• Replace one 150 HP compressor with 50 HP primary and 25 HP trim units. • Add storage to isolate high demand events; lower overall system pressure..
Aircraft Parts Manufacturer	353	199	154	44%	• New piping configuration; installed additional air receivers.. • Reduced end pressure from 120 to 90 psig.
Shipbuilder	419	269	150	36%	• Replace 350 HP compressor with 200 HP primary and 100 HP trim units. • Add storage; lower overall system pressure.
Metal Working and Aerospace Manufacture	509	147	362	71%	• Consolidate three separate systems into one. • Add storage capacity, controls, reduce distribution system pressure.
Plastic Injection Molding Facility	344	202	142	41%	• Replace inappropriate end-uses with vacuum pumps and motor drives. • Expand storage; reduce distribution system pressure. • Install higher efficiency hand tools.
Plastic Extrusion Plant	325	141	184	57%	• Same measures as project above.
Average			**145**	**40%**	

were inferred or altered from the initial studies to account for new information about plant operations gathered for the *ex post* study. The information in Table 2 suggests the following.

- ***Significant KW reductions can be achieved through compressed air system improvements.*** The average demand reduction achieved though the eleven verified projects summarized in Table 1 was 145 KW or 40 percent of the baseline. Large percentage savings were achieved in relatively modest compressed air systems (under 500 HP or 375 KW connected capacity) as well as in the larger facilities. To provide a sense of scale, the demand reduction associated with constructing an ENERGY STAR qualified home versus a baseline model is about 1 KW.
- ***The range of efficiency improvements is broad and must be carefully tailored to the configuration of the existing system, as well as the production requirements of the facility.*** The list of measures in the far right hand corner suggest that very few compressed air system efficiency strategies involve simple substitution of an efficient component for a standard model. Rather, the strategies involve a number of related capital, maintenance, and operating changes. They require a fairly sophisticated grasp of the interaction between the system and its loads and among the various components of the system.

Coincidence of savings with system peaks

Table 3 summarizes information on monitored operating hours, estimated energy savings, and demand reductions by time of use periods for the 11 projects summarized in Table 2. Where the plant air systems included two or more compressors, annual operating hours in the table reflect operations of the baseload machine. We can infer the following points from Table 3.

- ***Most plant compressed air systems have very long duty cycles.*** Six of the eleven systems in the program were operating at all times (8,760 hours per year); two others recorded annual operating cycles over 8,000 hours.

Table 2. Operating Hours, kWh Savings, Average and Peak KW Reductions Compressed Air Efficiency Projects SDG&E and PG&E, 1997

			KW Reductions		
Type of Facility	**Annual Op Hours**	**En. Savings kWh/Year**	**Average**	**Summer Peak**	**Winter Peak**
Cleanroom Laboratory	8,760	192,287	22.0	20.4	20.1
Turbine Manufacturer	8,760	2,777,300	317.0	302.2	266.7
Sheet Metal Forming	8,760	699,740	79.9	79.3	79.3
Electronics Manufacturer	4,640	431,006	92.9	77.4	67.5
Plastic Injection Molding	8,424	906,184	107.6	141.1	142.1
Circuit Board Fabrication	8,760	145,419	16.6	18.3	20.6
Fabricated Metals	8,760	561,212	64.1	66.9	67.3
Aerospace Manufacturer	8,760	1,777,021	202.9	199.8	199.1
Shipbuilder	4,725	1,254,460	265.5	72.6	253.0
Aerospace Manufacturer	8,193	1,496,568	182.7	173.8	176.7
Plastic Extrusion	5,898	673,165	114.1	115.1	111.3
Average	**7,676**				

- ***Savings from compressed air measures are generally coincident with electric system peak periods.*** To estimate the coincidence of demand reductions with system peak, the evaluation analysts estimated the distribution of energy (kWh) savings across time-of-use costing periods: on-peak, semi-peak, and off-peak for both winter and summer. Average KW reductions (short-term metered reductions/annual system operating hours) were adjusted according to the ratio of the percentage of total annual energy savings/the percentage of total hours for each of the time periods. Thus, for example, if a costing period accounted for 20 percent of all hours in a year, but for 30 percent of all energy savings, KW reductions for that period would be 1.5 * average KW reductions for the project. The results in Table 2 show that KW during the summer and winter peaks exceeded average KW reductions in 3 of 11 cases. Peak KW reductions were 93 – 99 percent of average KW reductions in an additional 5 cases.

Cost-effectiveness of compressed air projects

Table 4 presents projections of costs and savings from detailed compressed air system assessments conducted for nine customers of Central Vermont Public Service Company. Without taking into account the value of demand reductions, the "simple payback" periods for these projects ranged from 0.74 to 3.28 years, with an average of 0.86 years.[2] Even without financial incentives to reduce "first costs", seven of the nine projects have payback periods shorter than 2 years. Many market

[2] Savings and cost estimates have not been verified by *post hoc* evaluation. Informal communications with project participants suggests that most of the projects are performing as projected in the plant assessments.

observers believe that a two-year payback is the typical investment criterion that industrial managers use in assessing energy efficiency investments.

Table 4. Project Costs and Energy Savings
Nine Projects in Vermont

Type of Facility	Annual KWh Savings	$ Savings @ $0.054/kWh	Project Costs	Simple Payback (Years)
Food Products	444,714	$24,015	$35,060	1.46
Printing	1,091,548	$58,944	$52,355	0.89
Wood Products	186,152	$10,052	$33,000	3.28
Plastics	566,000	$30,564	$27,560	0.90
Health Products	1,418,529	$76,601	$56,700	0.74
Auto Parts	392,079	$21,172	$21,300	1.01
Food Products	202,969	$10,960	$20,446	1.87
Electrical Products	465,524	$25,138	$36,700	1.46
Ceramics	285,559	$15,420	$34,500	2.24
Average per site	**631,634**	**39,703**	**$ 34,108**	**0.86**

Compressed air system efficiency projects often provide a number of customer benefits in addition to energy cost savings. These include improved consistency in air supply, reduced downtime for unscheduled repairs and maintenance, and reduced levels of moisture and contamination in the air supplied. These are significant values for industrial facility managers. A recent national survey of plant managers found that their factories were idled due to unscheduled maintenance of compressed air systems for a median value of 2 days per year, with some experiencing as much as 10 days of unscheduled downtime. (XENERGY 2001)

Uncertainty of Gross Impact Estimates

Due to the complexity of compressed air systems, the interrelated nature of efficiency measures, and the importance of diligent maintenance in realizing savings, actual savings and demand reductions can vary significantly from engineering productions. Among the eleven projects reviewed, KW savings measured one to two years after installation averaged 61 percent of the levels projected by engineering studies, with a range of 21 percent to 168 percent. The deviations on the low side resulted primarily from failure to realize planned system pressure reductions, which in turn required that high levels of connected horsepower be maintained. Most of the more successful projects succeeded in reducing system pressure, which enabled operators to take one or more compressors off line. The design of the PG&E program takes this experience into account by paying for the metering equipment and training needed to monitor project performance on a continuous basis and by linking contractor payments to submission of monthly results.

Evaluation Challenges

Evaluation of demand-side programs designed to enhance system face a fundamental challenge of matching technique to the program objectives. Program objectives require that demand reductions be accomplished during specific time periods. To meet the basic summative requirements of evaluation, the approach must yield results by critical costing periods. To provide guidance in program implementation, the approach must yield those results quickly, if not in real time. In the current period of demand crisis (at least in some states), the pace of program activity required to meet reliability objectives raises additional challenges. Finally, the complex nature of compressed air systems and measures to increase their efficiency adds yet another layer of complications. We believe these issues will apply in some degree to virtually all programs that target rapid demand reductions to enhance system reliability.

The following paragraphs outline some of these challenges in terms of concepts that are commonly applied in conventional energy efficiency programs.

Selection of time periods for program planning and performance measurement. Programs that (by design) cost many hundreds of dollars per KW reduction make economic sense only in markets with severe capacity constraints. By now, most persons active in energy efficiency and supply are familiar with the "hockey stick" price duration curve that characterizes wholesale power markets in California and the Northeast. Under current conditions, a very small number of hours account for a very large percentage of the total dollar volume of wholesale power transactions. Demand reductions during those hours have a very high value because, under current market rules, the resulting lower prices (and lower expenditures) are experienced by all customers in the market.

The periods of very high costs are generally of shorter duration than the 8 or 12 hour peak periods used for structuring demand and other time-related rates. This raises the question: should reliability programs be planned to target reductions to periods shorter than typical costing periods? If so, do their results need to be measured accordingly?

Data required to demonstrate demand reductions during system peaks. Once program planners settle on appropriate periods in which to measure program performance, the next question becomes the determination of appropriate approaches to measurement. In the case of the compressed air program, the solution to this question was fairly straightforward. Given the relatively small number of projects involved, the high level of potential savings, demonstrated uncertainty in savings estimates, and short payback periods, it made sense to pay a portion of the cost for the installation of monitoring equipment that could yield hourly demand readings in each site. The added expense was partly covered by the program, and the customers found the remainder unobjectionable due to the positive economics of the projects.

One can easily imagine programs that offer potentially significant demand reductions that are very difficult to verify. For example, a number of analysts have identified HVAC and lighting retrofits in residential and small commercial buildings as strong candidates for demand reduction programs due to the volume of these end uses and their coincidence with system peak. However, the potential demand reductions at any one site are rather small. Verification of savings for these kinds of programs would require a sampling approach due to the relatively high cost of metering. In such cases an application of load research to stipulated energy savings might be the more attractive approach. However, if the programs are relatively expensive, program administrators may feel the need for more direct forms of performance verification.

Net v. gross. Methods are available to estimate net impacts for complex, custom industrial process projects. These methods involve the administration of complex interview scripts to one or more decision makers for each participant and the reconstruction of the role of the program in the implementation decision. For the SDG&E project we used these methods and came up with free ridership ranging from 0 to 20 percent at the project level. The broader question here, however, is whether adjustments to gross impacts should be considered at all. In the case of the compressed air program, one could argue that free ridership should be ignored. The purpose of the program was to achieve quick, verifiable demand reductions during specified periods. In order to meet the short deadline, it was necessary to identify customers who were predisposed to make potentially sizable investments on an accelerated schedule, as indicated by previous activity. Thus the program designed in a fair amount of self-selection bias. On the other hand, if the customer would have made the investment in the absence of the program *during the required time frame*, common sense suggests that free ridership should be measured and taken into account in estimating program effects. In this case the concept of deferred free ridership has merit because of the time-limited nature of the program benefits.

Market effects. At the moment, the infrastructure of consultants and technicians required to deliver compressed air efficiency projects is very thin. There are perhaps two-dozen individuals across the country with the engineering skills required to identify and design successful large-scale compressed air efficiency improvements. Programs are underway at both the federal and state level to increase the awareness of compressed air opportunities and basic technical skills among plant operators and system vendors. This program is likely to have some market effects to the extent that participating vendors and customers have their awareness of the benefits of compressed air efficiency measures raised, as well as their skill levels in realizing such opportunities. Thus, at leas at a conceptual level, the example of the compressed air program demonstrates that resource acquisition programs in their most urgent form are not incompatible with market transformation efforts.

References

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