SAVINGS DUE TO NEW CHILLER TECHNOLOGIES

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Introduction

In 1995 and 1996, Boston Edison (BECo), its customers and RLW Analytics implemented a comprehensive end-use metering and modeling evaluation of energy efficient chillers. The chillers were installed through a BECo pilot program to assist customers in retrofitting chillers with new, efficient systems meeting CFC guidelines. This paper addresses the systems installed, the evaluation metering and modeling methods, and the resulting energy and demand savings.

Program Description

Boston Edison's Chiller Retirement pilot program began in 1994. The purpose of the program was to assist customers with chiller replacement plans in installing properly sized high efficiency equipment, rather than standard chillers. The new chillers utilized hydrochlorofluorocarbon (HCFC) or hydrofluorocarbon (HFC) refrigerants, as opposed to chlorofluorocarbons (CFCs). Due to their ozone depleting effects, the manufacture of CFCs has been prohibited in the United States since the end of 1995, and reserve supplies are becoming increasingly expensive.

This program was designed to engage customers to *convert* or *replace* existing chillers with new, efficient non-CFC models. The pilot program assisted six customers in retrofitting chiller systems. The program process included:

- A comprehensive audit of each facility to determine the overall level of energy use and a base case for the standard efficiency chiller.
- Upgrading the building's energy efficiency, where needed and when cost-effective. These upgrades included lighting, motors, control measures, and other equipment. In addition, auxiliary systems were analyzed to determine the potential for the addition of variable speed drives and for upgrades to higher efficiency motors, fans, pumps, and other components.
- Pre-installation metering of lighting and other equipment to support savings estimates. The pre-retrofit chillers were not sub-metered because they did not represent baseline usage. The baseline usage represented the standard efficiency chiller the owner would have installed if not involved in the program. Engineering simulations were run to show what the baseline usage would have been for a standard efficiency chiller.
- The replacement of each of the chillers with high efficiency chillers or conversions. In all six cases, the size of the chillers was reduced as part of the program.
- Metering and modeling of the new chiller through at least one cooling season to measure installed performance.

The program's holistic approach involved simulation models at each participant site. The models allowed the interactions of various measures to be considered, i.e. for chiller capacity requirements to be based on internal loading following other efficiency improvements.

This study takes a look back at the six projects completed through the pilot and presents refined savings estimates for the six pilot projects based on actual operation. The potential efficiency gains which can be linked to refrigerant changeout is a critical issue, with an estimated 70,000 CFC chillers in the nation's large commercial building sector being converted from the mid-1990's to the mid-2000's (Stein and Robertson, 1995). In the Boston Edison service territory, a census survey conducted in preparation for the pilot estimated 650-700 sites with chillers (DeWeese and Hoffman, 1994).

Project Descriptions

This section describes each of the six pilot facilities, and the measures installed.

Bank Headquarters

This 422,000 square foot facility is the headquarters for a bank's computer operations, account processing and money handling activities. The facility is comprised of six buildings, all with large internal loads.

The pre-existing chiller system consisted of three 475-ton Carrier chillers and a 400-ton plate-and-frame heat exchanger. The chillers operated with R-11, with at least one machine operating at all times in order to support computer loading. The plate and frame heat exchanger was not used because of control problems with the chillers in transition from economizer cooling to chilled-water cooling. Under the Program, the three Carrier chillers were replaced with three high efficiency 475-ton Trane Centrivac units. The new units were equipped with variable frequency drive compressor modulation and extensive line protection against harmonics.

This site also included the replacement of existing fans and pumps with premium efficiency motors. Variable frequency drive fan controls were also installed on six of the existing variable air volume air handlers for one of the buildings.

Hotel

The two 350-ton primary chillers located at this 290,000 square foot hotel were replaced with two high efficiency Carrier 300-ton screw chillers. As part of the retrofit project, the chillers were downsized to 300 nominal tons each to better match the cooling requirements of the building. The two original chillers used R-11, while the new Carrier chillers were designed for use with R-123 (an HCFC refrigerant).

In addition to the two new Carrier chillers, the hotel also upgraded its primary chilled water and condenser water pumping system. The original system consisted of one 75 horsepower chilled water pump and one 50 horsepower condenser water pump, each sized and designed to meet the loads of both chillers at all times. The new system utilizes one chilled water pump and one condenser water pump for each chiller. The new pumping system allows pumping horsepower to be reduced during off-peak periods. Additionally, the cooling tower was upgraded from a single speed 700-ton tower to a two-speed 600-ton tower. The lighting throughout the facility was upgraded to energy efficient types to reduce lighting consumption and to reduce the chiller loading.

Low-Rise Office Building

This 283,000 square-foot building was constructed in 1981, and is comprised of 3 floors above ground and one lower level below grade. The facility houses a computer software manufacturer, with the majority of the building dedicated to office and computer lab areas. The computer lab areas and many smaller offices have an extremely high base equipment load, due to the nature of the business.

Two of the three chillers located at the facility were retrofitted with high efficiency refrigerant conversion packages. The two original Carrier chillers were rated at 750 nominal tons each and used R-500. These chillers were retrofitted with refrigerant conversion packages to replace the existing refrigerant with R-134a (an HFC refrigerant). The compressors and condenser tubes were also replaced through the project. The compressors were replaced to derate the capacity of the chillers to 500 nominal tons each to better match the cooling requirements of the building. The condenser tubes were replaced with new high performance tubes to improve the operating efficiency of the chillers. The third chiller was taken off line. Along with the chiller upgrades, an effort was made to reduce the cooling load on the chillers. This included pumping upgrades and high efficiency lighting retrofits throughout the facility.

High School

This four-story high school was constructed in 1973, and has a gross floor area of approximately 450,000 square feet. In addition to classroom, lecture hall and administrative office space, the building hosts a library, pool, indoor track, auditorium, gym, automotive, electrical, and carpentry shops. Summer school is in session June through August.

The larger of the two primary chillers located at the high school was retrofitted with a Trane Tri-Star compressor replacement package. The two original Trane chillers were rated at 740 and 459 nominal tons each and used R-11. The Trane package replaced the existing compressor with a new three-stage compressor specifically designed for use with R-123 (an HCFC refrigerant). During the retrofit project, the chiller was downsized from 740 nominal tons to 600 nominal tons to better match the cooling requirements of the building. The 459-ton chiller was decommissioned because the 600-ton chiller was able to meet summer peak day loads.

In addition to the Trane compressor conversion package, the high school also upgraded its air handling motors to high efficiency motors. Primary chilled water and hot water pumps were upgraded to high efficiency motors with variable frequency drives. The energy management system was upgraded to a more user friendly PC based version. Lastly, the high school replaced all exit signs with new LED technology.

High-Rise Office Building

This high-rise office building is located in Boston's Financial District. The building was constructed in 1982, with all floors at least partially occupied at the time of the evaluation. The three chillers involved in the program serve floors three through forty-six of the facility, which are tenant-occupied.

The two primary chillers located at the facility were retrofitted with a high efficiency refrigerant conversion package. The Trane chillers, rated at 1,100 nominal tons each and using R-11, were retrofitted with Trane Bi-Star (2 stage) conversion packages. The Trane package replaced the existing compressor with a new two stage compressor specifically designed for use with R-123 (an HCFC refrigerant). The chillers inefficient evaporator tubes were also retrofit through the project. These tubes were replaced with new factory enhanced tubes to improve the operating efficiency of the package. During the retrofit project, the chillers were downsized to 1,000 nominal tons each to better match the cooling requirements of the building.

Three variable speed drives were installed as part of the program. These drives were installed on the two chilled water supply pump motors for the primary chillers and the chilled water supply pump motor for the secondary chiller. The primary pump motors are rated at 150 horsepower each, and the secondary pump motor is rated at 50 horsepower.

College

This college campus is located outside of downtown Boston. The project involved the Administration Building, Library Building, and Science Building. The four story Administration building was built in the 1890's, and the East and West Wings of this building were added in the 1930's. The Library Building was constructed in 1961, and consists of two connected sections, one with two floors and one with five floors. The Science Building was constructed in 1972, and consists of four floors. The total area of these buildings is approximately 363,000 square feet. These buildings are cooled primarily by two main centrifugal chillers.

The two original chillers were a 550-ton York chiller and a 250-ton Carrier chiller. These original units used R-11. They were replaced with two York chillers which are rated at 500 and 200 nominal tons, respectively. The York chillers use R-123 (an HCFC refrigerant).

Evaluation Methodology

To measure the program's performance, RLW and Boston Edison implemented an integrated metering and simulation modeling effort. The comprehensive analysis of the program included in-person interviews, end-use metering, total load data and DOE 2.1E simulation modeling. The end-use metering was used to develop part load curves and other chiller specifications for the model. The model was then calibrated to total load data using the RLW's Visualize-IT™ DOE-2.1 Calibration Tool. Baseline and post-retrofit runs were conducted to accurately estimate the savings due to the chiller installations. Logger metering and detailed on-site audits were used to estimate the savings for other measures, such as lighting and motors.

Data Collection

Each on-site visit collected detailed participant specific data, including occupancy patterns, thermostat settings, and building characteristics that drive the actual savings that occur at each individual site. Intensive end-use metered data were collected to measure chiller performance under a variety of load conditions. AEC Micro Dataloggers were used to collect much of the data. Energy management system data and customer metering were also used in the analysis for some sites. The metered points for each chiller included:

- kW of the chiller compressor,
- Flow rate of the chilled water through each chiller, and
- Entering and exiting temperature of the chilled water at each chiller.

These metered inputs were used as inputs to DOE 2.1E simulation models to estimate "as-built" loads. The primary purpose of the end-use metering was to have better information on the performance of the chiller and other measures for use in the modeling. While many factors affect the model inputs, e.g., construction and other equipment characteristics, it was most important to focus on the installed measures to which savings were attributed.

End-uses and equipment not covered in the metering were addressed by examining information collected prior to the installation, facility blueprints, customer interviews and/or detailed post-installation audits. These data, together with the metered datapoints, were used to construct the simulation models. Total load data was used to check the accuracy of the inputs through calibration to total load data for monthly peak demand, monthly energy consumption, monthly weekday and weekend loadshape data.

Modeling and Calibration

Modeling Tools. Of the six sites evaluated, three utilized DOE-2.1E for the pre-installation analysis. The remaining three sites were analyzed utilizing other packages for the pre-installation work. DOE 2.1E is generally considered the most comprehensive of the three modeling packages applied. Table 1 compares and contrasts the different simulation packages used to justify measure installation and to predict savings. As the table indicates, DOE 2.1E offers the benefits of custom weighting of loads and algorithms as well as hourly simulation and output. The final evaluation models had the benefit of all being done in DOE-2.1E, of being based on as-installed measure conditions and end-use metered data, and of being calibrated to post-installation end-use metered and total load.

Feature	DOE 2.1E	Trane Trace	Carrier HAP
Simulation Method	8760 hrs	48 days	8760 hrs
Loads Wtg Factor	Custom	Standard	Custom
Hourly Output?	Yes	No	Yes
Customizable Algorithms?	Yes	No	No
Parametric Operation?	Yes	No	No
# Terminal System Types	28	26	21
# Primary Equip. Types	22	33	13

Table 1: Comparison of Modeling Programs

DOE 2.1E Modeling and Calibration. The post-installation DOE 2.1E models in the evaluation were developed from the pre-installation DOE 2.1E models available for three sites, and as custom models for the remaining three sites. The pre-installation models were of varying levels of accuracy. Some were calibrated to within 10% of metered total demand, while others were calibrated more loosely to energy consumption only.

Careful calibration based on as-built conditions and metered data were key to the integrity of the evaluation results. To enhance the accuracy of each model, the DOE-2.1E building simulation results were informed with total load (15 minute demand) and chiller load data. The chiller load data obtained through metering was used to define the actual part load performance characteristics of each chiller. This chiller performance curve information was included in the DOE-2.1 model to assist in the calibration of the model and to achieve more accurate savings results.

Load profiles from each simulation run were studied using RLW's Visualize-IT™ DOE-2.1 Calibration Tool. Adjustments to DOE-2.1 inputs and assumptions for each building were made in an iterative fashion. Some sample DOE-2.1 Calibration Tool screens are shown below to illustrate the calibration approach and the need for the proper tools to post-process the DOE-2.1E output.

Following calibration, the six building models were run using as installed measure conditions found during the on-site survey. Each site had a run for the base case, and sequential and incremental runs for each measure type. All runs were executed with actual and Typical Meteorological Year (TMY) 8,760 Boston weather data.

Comparing Pre and Post Installation Models. Comparing the pre-installation and post-installation models underscores the value of careful calibration using as-built conditions and metered data. Figure 1 and Figure 2 depict the monthly calibrations in the pre and post-installation case, respectively, for the high-rise office building. Each figure depicts the monthly metered and modeled peak kW (on the left) and the monthly metered and modeled kWh (on the right). The dashed lines bounding the actual metered demand and consumption numbers represent a ±10% error band for reference purposes.

In Figure 1, the pre-installation model was run, without modification, with actual weather data for the 1996 calendar year. The error observed in the demand numbers indicate that monthly kWh was used alone for calibrating the pre-installation model. In Figure 2, the modeled values represent the post-installation DOE-2.1E model results after the iterative calibration using the Visualize-IT™ DOE-2.1 Calibration Tool. This model was also run with actual weather data for the 1996 calendar year, with dramatic improvements in the calibration to metered peak demand data.

The monthly calibration shown in Figures 1 and 2 are typical for spreadsheet calibration analysis. However, theses simplified graphs leave out valuable information on the sources of error in monthly values. Daily load shapes are much better tools to analyze sources of error. However, developing and comparing daily load shapes for metered and modeled results can be cumbersome.

Visualize-IT standardized and accelerated the process of developing daily load shape calibration comparisons. Figure 3 presents daily load shape comparisons for the pre-installation model. The graphs are based on an extended ten-month period due to the duration of the available total load data, although daily load shapes can be developed for any desired length of time and time of year. Figure 3 clearly demonstrates that the pre-installation model was missing the base load occurring at the facility, and over-estimating daytime demand. Figure 4 depicts the correction of the problem in the final evaluation calibrated model. Moving from Figure 3 to Figure 4 was an iterative process which required examination of the on-site and blue print data, review of reported schedules, and a number of viusal checks through automated re-generation of daily load shape comparisons in Viusalize-IT.

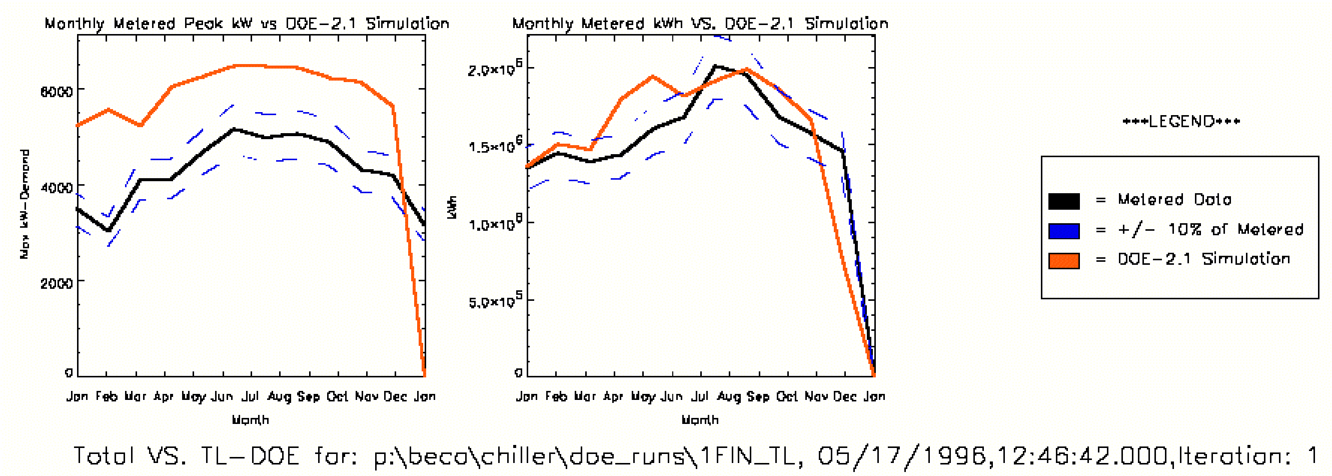

Figure 1: High-Rise Office Initial Monthly Calibration

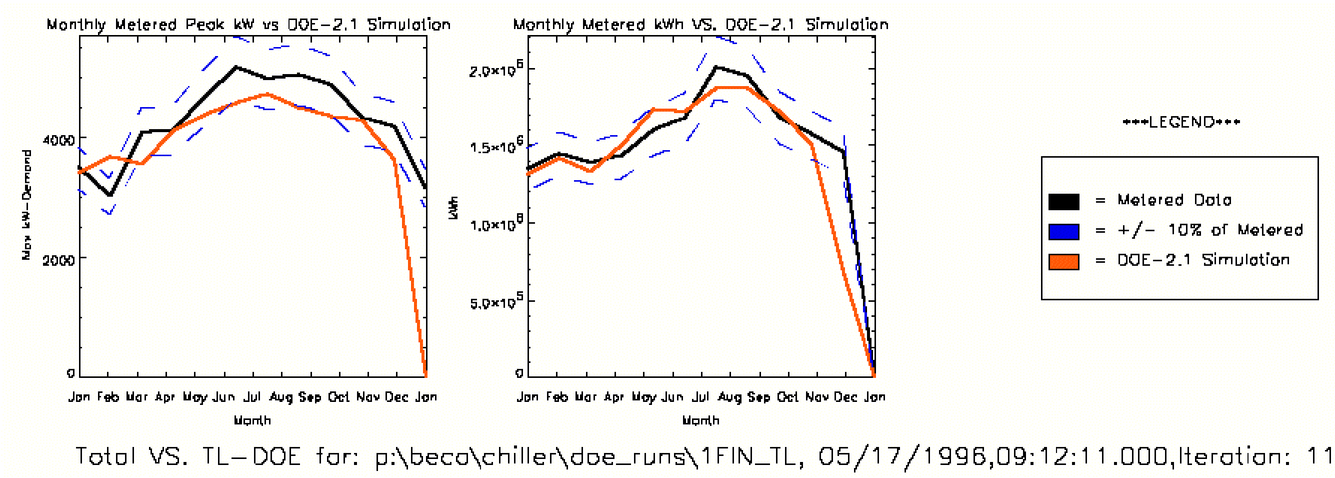

Figure 2: High-Rise Office Final Evaluation Monthly Calibration

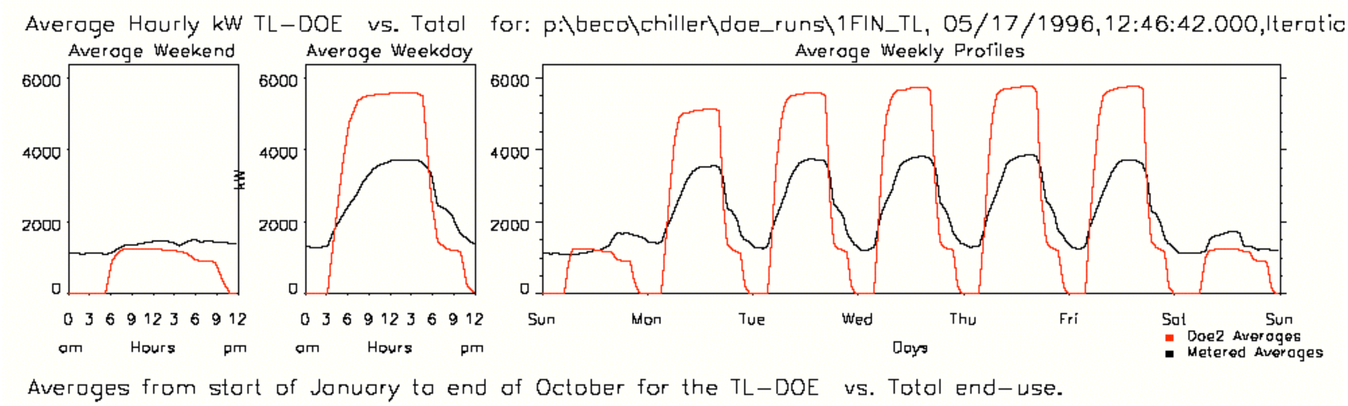

Figure 3: High-Rise Office Initial Daily Load Shape

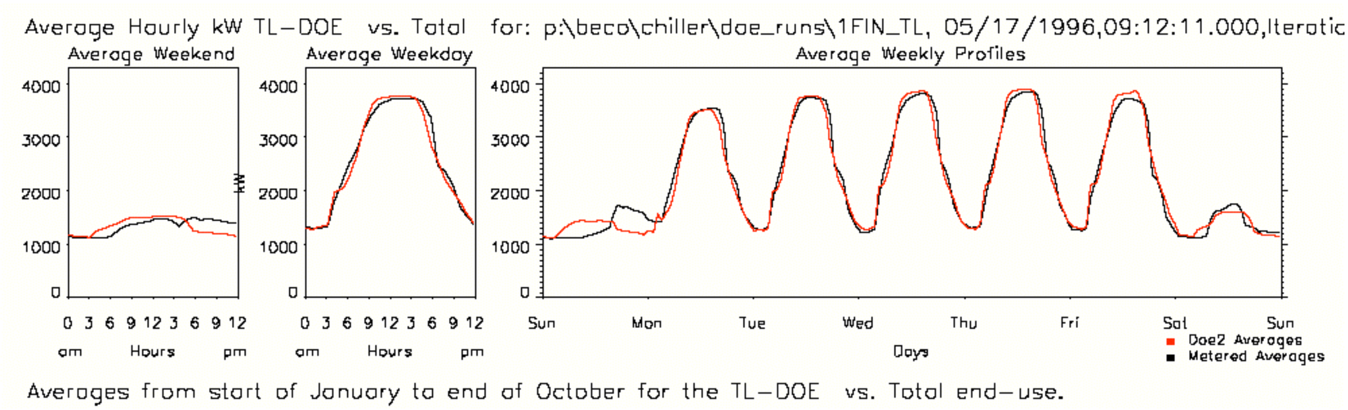

Figure 4: High-Rise Office Evaluation Daily Load Shape

The Iteration Process. The calibration of each model was an iterative process, involving numerous runs for each site to pinpoint daily load shapes by month. This detailed calibration process was greatly facilitated by the use of the Visualize-IT software. This productivity-enhancing software allowed average daily load shapes for modeled and metered results to be easily developed and compared for numerous periods, e.g., by month, and viewed on a single screen.

The low-rise office building is used here to demonstrate the iterative calibration process. Figure 5 presents the summer daily load shape comparison for a version of the model a third of the way through the iterative process. In this model, it is clear that the summer peak kW is being over-estimated. In examining the end-use metered data for the site, it was clear that only one chiller was on-line at any time during the course of the year. Iteration 7 of the model had two chillers enabled in some peak hours in the summer months. This problem was solved by enabling only one of the two chillers in the DOE 2.1E model. The result was the improved summer daily load shapes in Figure 6.

Errors in winter peak demand were also observed. The winter peak demand was too low in earlier versions of the model. It was determined that the model had simulated no reheat coils in the variable volume system, although it was obvious that the site had reheat that was obvious from the winter morning total load demand peaks. In addition, heating load was not satisfied in the model. The solution was to enable the reheat coils in the model and increase air supply temperature. However, this lead to an over-estimation of heating energy in the model. Figure 7 depicts this over-estimation, displaying the average daily load shapes for January through March in Iteration 17 of the model.

Figure 8 adds further information, moving from average loadshapes for a specified period to a snapshot view of loadshapes *for every day*. Figure 8 is an example of another calibration tool used in the analysis – the EnergyPrint™. The EnergyPrint is a 3-dimensional plot of interval (15 minute, half hour, or hourly) energy related data. In the graph, the three dimensions are the time of day (on the Y axis), the day of the period (on the X axis), and the demand for each interval (represented using color). Lighter colors represent higher intensity of energy use and darker colors represent lower intensity of energy use. Reviewing the 3-D image in Figure 8, the over-estimation of loads in both day and evening hours from November through April is clear. The EnergyPrint allows allowed the adjustment of heating parameters to calibrate to metered total load on an hourly basis.

In addition to the use of Visualize-It to calibrate to total loads, the evaluation benefited from extensive and detailed on-site and end-use metered data on specific as-built equipment and operating conditions. For the low- rise office building, the following modeled parameters were matched to metered values to further enhance the calibration:

- Chiller kW,
- Chilled water supply temperature,
- Condenser water supply temperature,
- Chiller tower approach temperature,
- Free cooling operation parameters, and
- Chiller tower fan controls.

Figure 9 presents the final monthly model calibration, with metered peak demand and kWh within ±10% for all but one month.

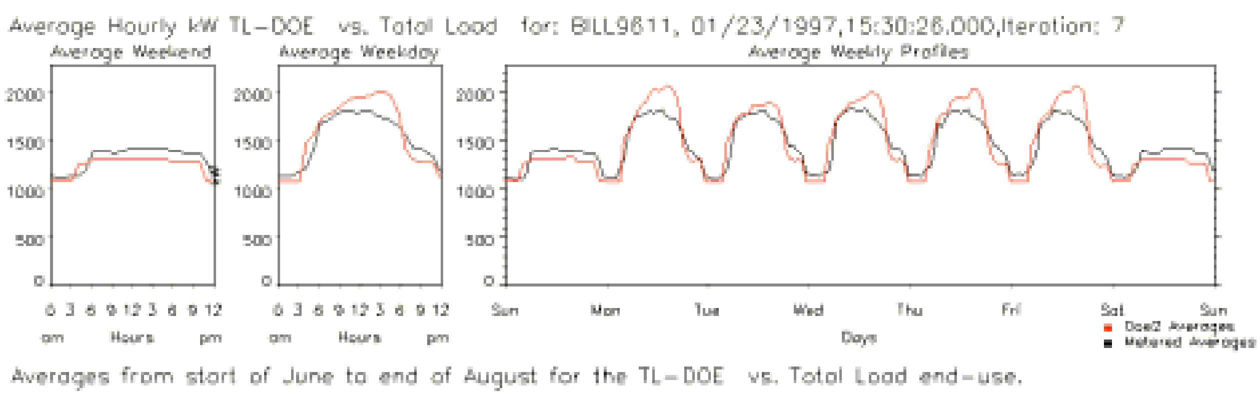

Figure 5: Low-Rise Office Summer Daily Load Shape Calibration 7

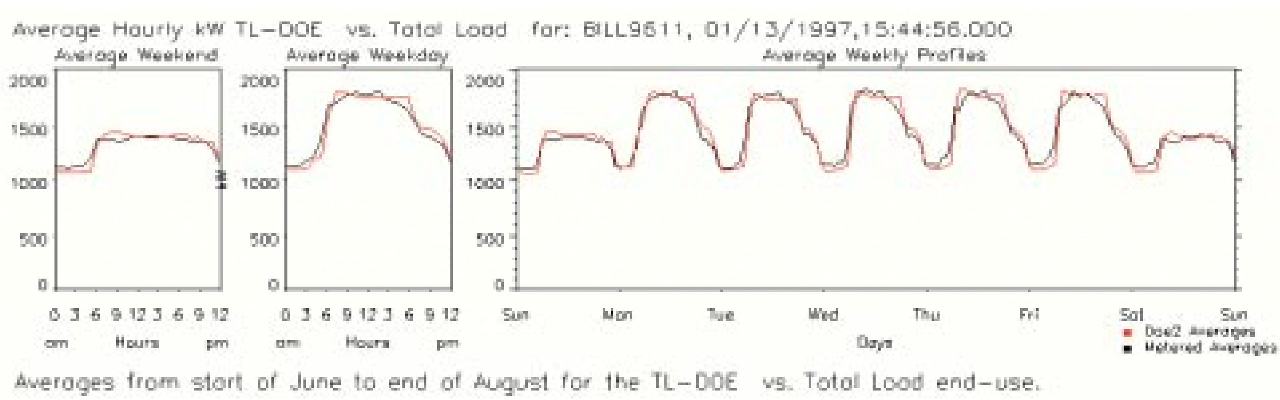

Figure 6: Low-Rise Office Summer Daily Load Shape Calibration 17

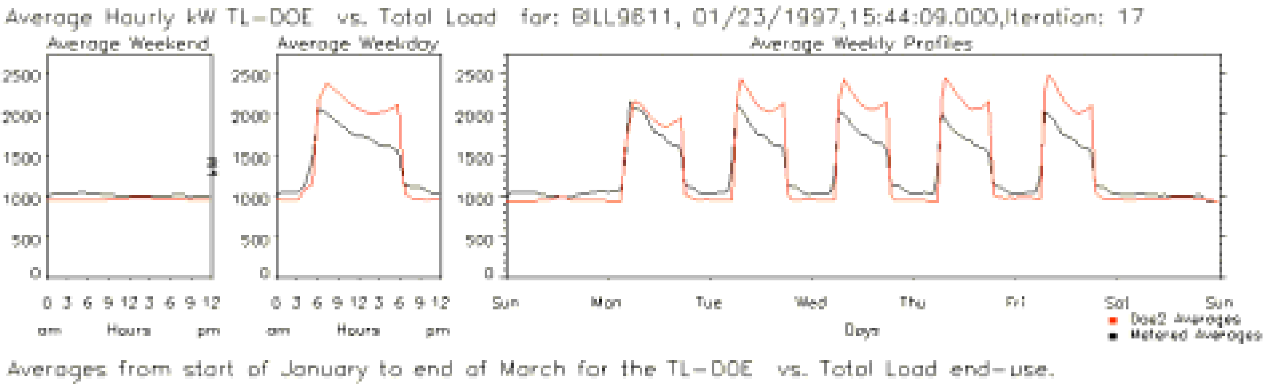

Figure 7: Low-Rise Office Winter Daily Load Shape Calibration 17

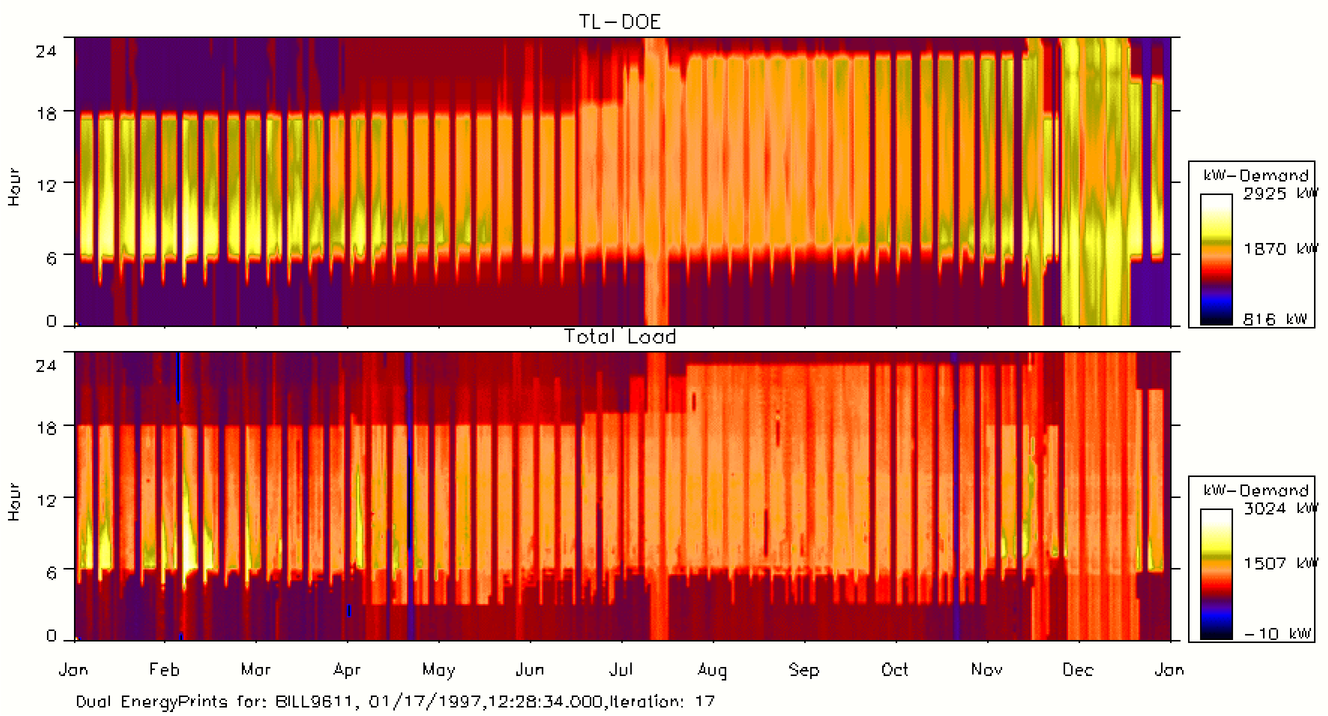

Figure 8: Low-Rise Office EnergyPrint Calibration 17

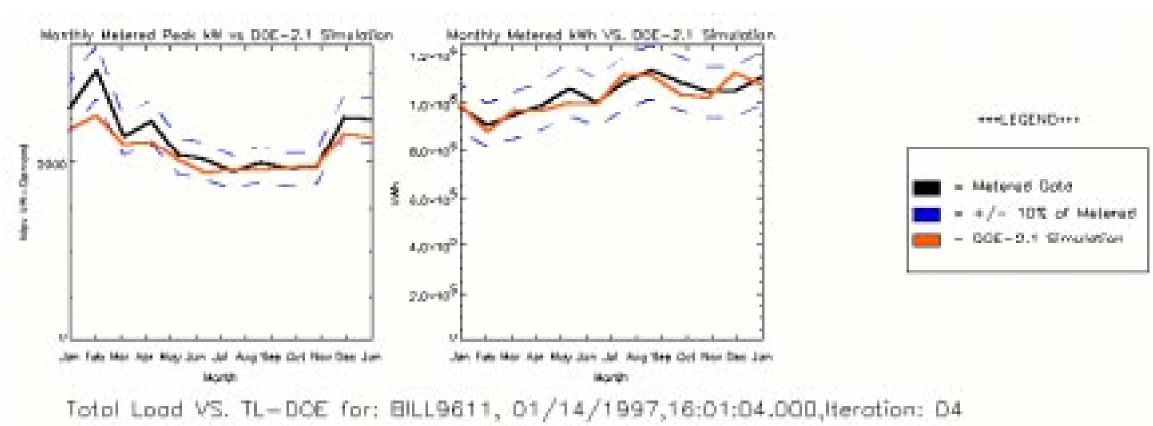

Figure 9: Low-Rise Office Final Evaluation Monthly Calibration

Savings Results

The final results for each site included actual and normalized energy savings, on-peak energy savings, and coincident peak demand savings. Table 2 describes the annual energy savings results for the chillers installed at each site, while Table 3 describes the annual energy savings for other measures installed under the comprehensive approach.

The total energy savings for the program were 2,301 MWh for chillers and 4,704 MWh when considering all measures installed. As shown in Table 3, these energy savings resulted in an estimated cost savings to customers of $314,226 annually. Summer peak demand reductions were estimated to achieve an additional $117,031 per year.

Facility	Summer Peak kW Savings	kWh Savings	Tons	kWh Svg/ Ton
High-Rise Office	239	1,046,431	1,800	581
Bank Headqtrs	105	589,571	1,200	491
Low-Rise Office	219	431,884	1,000	432
Hotel	40	120,784	600	201
College	85	79,529	600	133
High School	23	32,654	600	54
TOTAL	711	2,300,853	5,800	397

Table 2: Chiller kW and kWh Savings

Facility	Summer Peak kW Savings	Demand Charge Savings ($)	kWh Savings	Energy Charge Savings ($)
High-Rise Office	261	$38,398	1,733,683	$121,993
Bank Headqtrs	166	$20,458	1,288,698	$81,910
Low-Rise Office	257	$31,673	553,325	$35,440
Hotel	77	$9,489	332,974	$21,549
College	70	$8,627	526,448	$34,754
High School	57	$8,386	269,328	$18,579
TOTAL	888	$117,031	4,704,456	$314,226

Table 3: Total kW, kWh, and Cost Savings

Conclusions

The pilot and the subsequent performance measurement activity were aimed at testing a concept for a full-scale program to encourage energy efficient chiller conversions. The evaluation was an integrated portion of the pilot, aimed at measuring savings based on actual and using a comprehensive, state-of-the-art approach to reliably estimate savings. The use of a single modeling tool allowed the development of more accurate and consistent results than was possible with a variety of tools.

Meaningful savings results were achieved through DOE-2.1E models which utilized end-use metering inputs and were calibrated to total load for the facility. The calibration of DOE 2.1E using Visualize-IT revealed that significant model enhancement could be achieved using on-site, customer interview, and available total load data. In this case, the availability of detailed end-use metered data served to further enhance the model. The evaluation indicated that the six pilot projects resulted in significant savings for the customer.

Acknowledgments

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