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Getting It Right the Second Time: Measured Savings and Peak Reduction from Duct and Appliance Repairs

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Getting It Right the Second Time: Measured Savings and Peak Reduction from Duct and Appliance Repairs

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This paper reports on potential energy and peak savings in residential air conditioners, heat pumps and gas forced air furnaces. In four different pilot projects, the state of the space conditioning systems of over one thousand homes was documented. Duct leakage, air flow through the appliance and refrigerant charge on compressor systems were measured before and after repairs were made. Intensive monitoring was utilized in one project to determine the actual behavior of the system and the human occupants. In two of the pilots, sixty-one air conditioners were submetered to record use at 15 minute intervals. The pre-/post-metering took place on homes divided into three groups: random customers, high-use customers, and high-use customers that complained of high utility bills. Submetering results are compared to similar recorded peak and kWh use of a group of nonparticipants.

Introduction

Pacific Gas and Electric Company (PG&E) recently conducted a series of pilot projects evaluating potential energy savings in residential air conditioners, heat pumps and gas forced air furnaces. These studies included high-use and high bill complaint customers; high bill complaint only customers; and randomly selected customers. Common to all of these pilot studies were four main elements. First, each study worked to quantify the magnitude and extent of the problems with the space conditioning systems. Second, systems were repaired to reduce or eliminate the problems. Third, systems were retested to determine the results of implemented repairs. Finally, results were metered to determine the true effect of these repairs.

The first study was conducted in the foothills of the Sierra Nevada in the winter of 1989/90. This program, the Appliance Doctor Heat Pump (HP) Pilot Project (Proctor et al. 1990), evaluated 51 heat pumps at 48 sites which had records of high energy use and high bill complaints from customers. The second study, the Appliance Doctor Air Conditioner and Furnace (AC-90) Pilot Project (Proctor 1991), was performed in California's Central Valley in the summer of 1990. AC-90 investigated potential energy and peak savings in the residential air conditioners and gas forced air furnaces of 15 high bill complaint customers. The 1991 pilot program, Appliance Doctor Pre-Production Test (AC-91) was also conducted in the Central Valley (Jacobson et al. 1992). In the AC-91 test, 250 air conditioners of various user types were tested. The fourth pilot, the Model Energy Communities (MEC) Program (Kinert et al. 1992), started in late 1991, and has completed work on 1,000 randomly selected AC units in the Sacramento River Delta.

The same problems were evident each study: duct leakage, low airflow, inadequate charge and poor service.

Methodology

Homes were selected for these projects through various means. In AC-90, the majority of units selected belonged to high bill complaint customers with significant summer peaks (the participants averaged 3658 kWh in cooling use compared to a local average of 1650 kWh), while in the MEC study, sites were selected randomly.

While procedures were refined in each of the pilot projects, the same methodology was applied to all. Each location was visited by a team of technicians who used specifically designed forms to test, record and repair each duct system, furnace and air conditioner/heat pump. The completed forms were reviewed by the program manager to determine that the proper work had been done and that the desired results achieved. If the review determined that the unit needed additional work, return trips were made to complete the assignment. To quantify problems with the ductwork and the building shell, each of the sites was inspected and tested using a blower door and flow hood.

Ductwork Testing

Duct leakage testing was conducted by sealing all AC/furnace registers with plastic except the largest/least restricted return register. With the filter removed, the house was pressurized to 50 pascals using a blower door. At that pressure the following measurements were made:

(1) A single flow pressure was taken at the blower door. This value was used to compute the airflow into the house using a single point method.

(2) A commercial flow hood measured the airflow through the open register. This is a measure of the house duct leakage to outside.

Five of the units in AC-90 and the submetered units in AC-91 were tested for total, return only, and supply only duct leakage. For the return and supply only tests the supply system was isolated from the return by a plastic barrier at the furnace blower.

Airflow Testing

Airflow was measured by using the flow hood. After removing the plastic seals used in the ductwork test, the appliance was operated, and after steady state was reached, the flow measured at each return register. The flows from all the returns, plus the calculated return leakage, were summed for the total flow.

The resultant air flow was evaluated against the proper air flow (400 cfm/ton "wet coil" or 425 to 450 cfm/ton "dry coil").

Submetered units in AC-91 were tested for plenum pressures and register pressures. For these units the return leakage was calculated using Equation (1).

$$\text{Return Leakage} = CFM_m \times \left(\frac{pr}{pt}\right)^{.65} \tag{1}$$

where CFM_m = Measured Return Leakage
pr = Return Pressure (blower on)
pt = Return Pressure (leakage test)

In the HP and AC-90 studies a temperature rise method was also used to measure air flow. This procedure is detailed in Proctor 1991 and Proctor et al. 1990. The temperature rise method was judged to be more accurate than the method described above, but it is not as readily accomplished on a production basis.

Charge Testing

For the most common compressor based cooling system (capillary tube flow control), measuring system superheat is the preferred method of determining correct charge. Superheat is the difference between the evaporator saturation temperature and the suction line temperature. For a given set of conditions a particular superheat is specified. If the measured superheat is more than 5°F different from the specified number, the unit is incorrectly charged.

The superheat method was used to determine charge in capillary tube air conditioners that could be brought to proper air flow. Test methods for other units are described in the project reports.

Identifying the Problems

The major problems discovered in all four studies were duct leakage, low airflow, and incorrect charge. Virtually all homes had at least one problem, and many had multiple problems. In the heat pump study, for example, ninety percent of the homes had major problems. The problem that occurred most frequently was duct leakage. Thirty-one percent of the homes tested had disconnected or other "catastrophic" duct problems and 70% had diffuse duct leakage greater than 150 cfm measured at 50 pa house pressure.

The occurrence of problems in each of the samples is displayed in Table 1.

As shown in Table 1, duct leakage problems are nearly universal, occurring in three different geographical areas and overwhelmingly present even in the largest sample containing a high percentage of new construction. On the average, airflow problems occur close to half the time and incorrect charge is evident in over half the units.

Program Delivery

The pilot programs point to one crucial concept: heating and cooling inefficiency exists in most installed units, and can be remedied by informed diagnostic and repair techniques. Repair programs must, however, be carefully monitored to ensure success.

In AC-90, for example, ten of the fifteen units had been serviced within the last two years by local contractors who failed to identify or resolve the various problems. Two individuals had service agreements with local contractors who inspected the units twice a year. While one of these homes had the most efficient air conditioner of the study, it still had two disconnected supply ducts which had never been detected.

Clearly, one of the greatest problems with the current low cost, lowest-bid contractor system is that it does not promote service excellence. In the present environment, technicians are not given the time, incentive or feedback to do their work properly. That's why, in order to deliver

Table 1. Problems in Study Homes

	89-90 HP	90 AC	91 AC Submetered			91-92 MEC
Usage	High	High	High	High	Random	Random
High Bill Complaint	Yes	Yes	Yes	No	No	No
Sample Size	51	15	15	5	16	999(a)
Distribution Problem						
Duct Leakage > 150 cfm	70%(b)	93%	87%	80%	80%	98%
Heat Pump/AC Problems						
Low Air Flow (deficient by 50 cfm/ton or more)	48%	67%	50%	40%	29%	44%
Undercharge(c)	31%	27%	27%	(d)	41%	22%
Overcharge(c)	(e)	27%	36%	(d)	(f)	33%

(a) 175 air flow tests.
(b) After disconnected ducts were repaired.
(c) Tested only on units that could be brought to adequate air flow.
(d) Very small sample.
(e) Not tested.
(f) None detected.

effective service, there must be control over the program delivery.

In each pilot program, deficiencies were repaired and then retested. This feedback loop was crucial, as it enabled technicians to see reviews of their work, and helped contractors to work toward compliance. The studies demonstrate that by developing utility sponsored programs which take proactive, preventative steps to ensure proper installation and repair procedures, performance, efficiency and customer satisfaction can be dramatically increased.

Measuring the Results

In the original heat pump study, three units were monitored with data acquisition systems. This extensive monitoring gave important detailed information about every cycle of the heat pump. Among the important items established from this monitoring was the futility of asking homeowners to set their thermostats up "just a few degrees at a time". Monitored data showed that this was not accomplishing the desired goal, which was to keep the units out of the electric strip heat mode.

In order to provide some initial case studies with measured data, the AC-90 and AC-91 studies implemented submetering on a variety of units. Sites were submetered with a Domestic Automation Company Type SM-DAC, Model TMC kilowatt hour meter on the air conditioning circuit. This meter is capable of recording and storing the total kWh for various time increments, and downloading the information to a laptop computer. The meter was programmed to record the total kWh use for every 15-minute period. All meters were downloaded by PG&E personnel. This data is being analyzed for peak use, hourly use, occupant strategy and daily use.

Initial Submetering Results

Submetering data from the 15 units in AC-90 was used to investigate occupant control behavior, and to predict peak reduction and seasonal efficiency improvement for each unit.

Occupant Control Strategies. When the air conditioner is controlled by a constant thermostat setting in the range 75°F to 85°F, a large percentage of the cooling hours are characterized by the unit cycling on and off.

While cycling operation is usually controlled by the thermostat, continuous operation is usually due to human intervention. When an occupant moves the thermostat to a lower setting the air conditioner runs continuously for a significant period of time. If the occupant frequently adjusts the thermostat, a large percentage of the operating hours will show continuous operation rather than cycling operation. A similar pattern could be produced by a severely undersized unit.

The percentage of cooling hours exhibiting cycling operation is a good measure of the control method of the occupants. Figure 1 shows cycling operation percentages for the air conditioners in AC-90.

The occupants of the 1991 test houses utilized a similar variety of thermostat control strategies:

(1) Fifty percent of the AC-91 houses used off/on control - manually switching the thermostat on when the occupant wants it cooler and off when s/he considers it cool enough. This is accomplished with the off-cool switch on the thermostat or by adjusting the set point of the thermostat up/down.

(2) Twenty four percent of the AC-91 houses used daily set up/set down control - a consistent pattern of setting the thermostat up in the evening and down at some time during the day, with only occasional minor adjustments of the thermostat.

(3) Twenty six percent of the AC-91 houses used constant temperature setting control - setting the thermostat at one temperature and nearly always leaving it untouched.

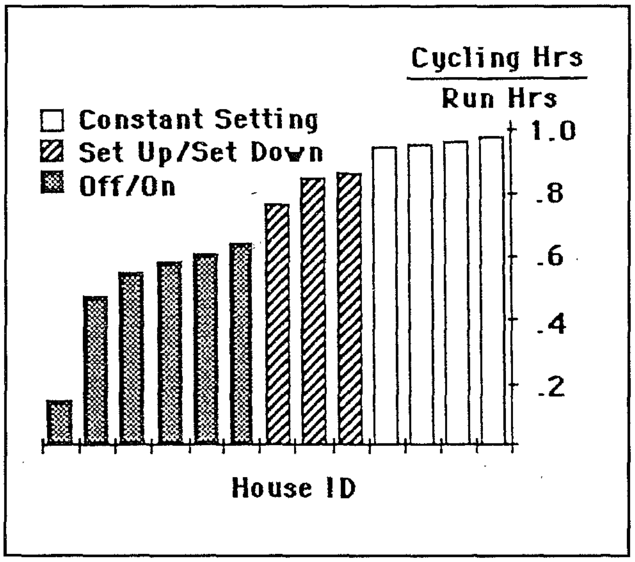

Figure 1. Thermostat Control Strategies

This series of tests found that the mix of occupant thermostat behavior makes prediction of energy savings or peak reduction more difficult. Regression against outside temperature alone will be accurate for less than one third of the units in service. For example in a home where the occupants return from work and set down their thermostat, use will be more closely correlated to time of day than to outdoor temperature.

Aware of the limitations imposed by a linear regression that assumes constant temperature setting, an empirical model was built to aid understanding of the data.

Peak Reduction Model. The design of the simplified model is detailed in Proctor (1991). It can be summarized in the following manner. For each house, the 15-minute consumption data was sorted and averaged over time to provide the proper resolution (ability to see cause/effect relationships). A linear regression correlating maximum air conditioner input to hourly outdoor temperature data was calculated and is shown in Figure 2. Similarly, another regression line describing the air conditioner use when the unit is cycling was computed and is shown in Figure 3. The intersection of these two lines is the onset of continuous operation and indicates the temperature above which the air conditioner will run continuously.

Maximum input limit (connected load) is probably the most critical factor in peak use. Continuous running

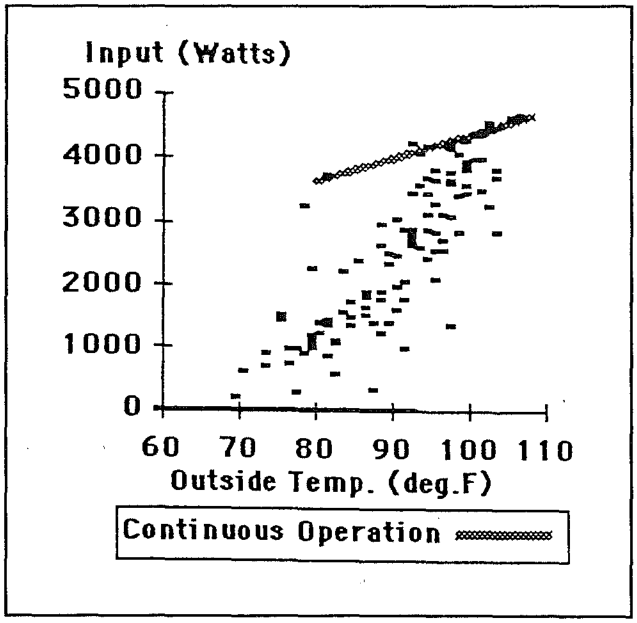

Figure 2. Maximum AC Demand Continuous Operation

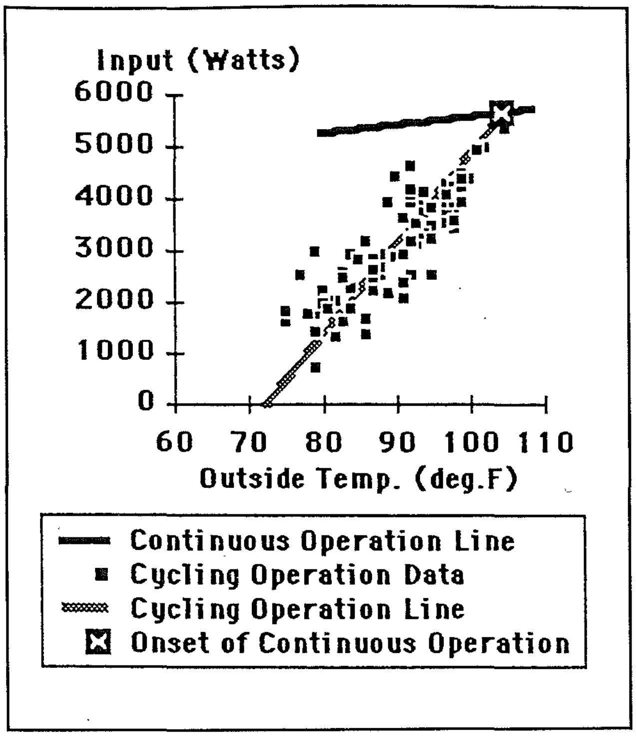

Figure 3. Cycling AC Operation and Onset of Continuous Operation

creates the maximum sustained demand that an air conditioner will put on the utility system. Under these circumstances the input is dependent on the outside temperature. As the outside temperature rises, the compressor head pressure elevates and the watt draw of the unit increases. Continuous running conditions form a readily distinguishable limit line on the plot of hourly use vs. hourly outside temperature. This is shown in Figure 2.

The cycling air conditioner input line is highly dependent on occupant behavior. The cycling energy input for any outdoor temperature was described by selecting data that contained no continuous running, averaging over the two hour interval following the temperature reading, and then regressing the average use against the outside temperature. This process eliminated start cycles, stop cycles, hours with no use, hours with continuous use, and segregated rising and steady temperature periods from falling temperature periods. The two hour average furnishes some compensation for the lag time between outdoor temperature and cooling demand.

The determination of a cycling input regression line is shown graphically in Figure 3.

The intersection of the regression lines for cycling and for continuous operation was labeled the Onset of Continuous Operation (OCO). When the temperature exceeds the OCO, the air conditioner is likely to run continuously and the house temperature will not fall to the set point of the thermostat. This may result in occupant comfort complaints.

In order to estimate the effect of tested modifications on lowering peak demand, the model described above was developed for both pre- and post-repair conditions. The outside temperature in Fresno at the time of the 1990 system peak was input to both models. The resulting one-hour demand was calculated for both conditions. The reduction in energy use from pre- to post-repair is the estimated peak reduction for that house. This is illustrated in Figure 4.

When an efficiency improvement occurs, the slope of the cycling operation line is reduced. This simply means that less input power is needed to maintain the house at the same temperature. For certain modifications the continuous operation line will also be changed. For example,

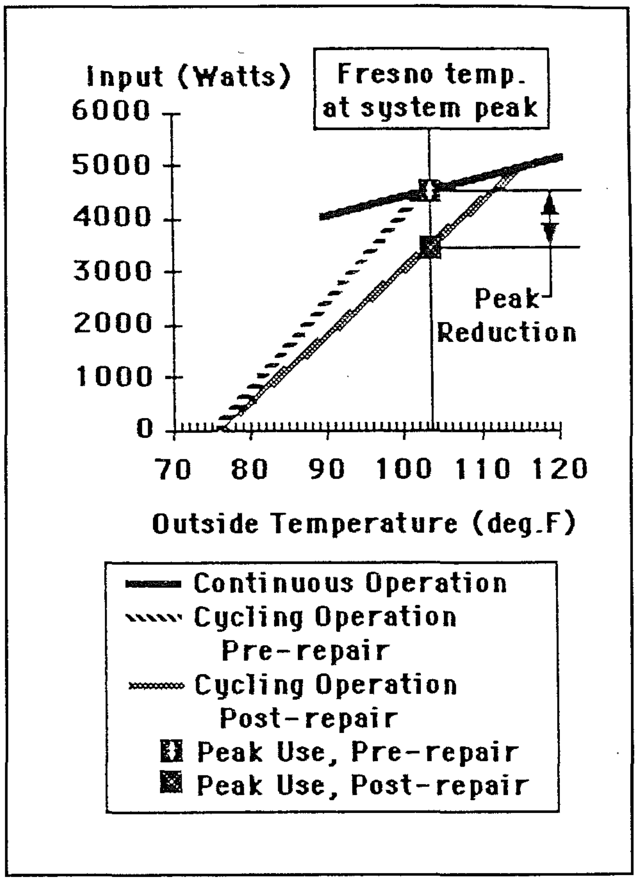

Figure 4. Estimated Load Reduction at Peak Temperature

adding charge will raise the continuous operation line, while removing charge will lower it.

Energy Savings Estimation. The energy savings expected from each individual measure was estimated from published empirical field and laboratory data and is detailed in the Appendix to Proctor 1991. Savings for the measures applied to the house were combined accounting for interaction.

Model Predictions of Savings and Peak Reductions. The data from the 15 units submetered in AC-90 produced the first order savings predictions shown in Table 2.

These predicted savings were tested by the submetered units in AC-91.

AC-91 Submetering Results

The AC-91 case studies came from two classes of customers, high use/high bill complaint customers and randomly selected customers in a stratified sample. Potential study participants were stratified based on billing history. Base use (nonweather dependent use) was estimated from the spring and fall. Base use was calculated for the summer period and subtracted from the total summer electrical usage. The resultant temperature dependent use indicator was used to stratify the sample of customers. As was expected, few customers in the lower half of the stratification had central air conditioning. The submetered random group consisted of four customers in the upper quartile, five customers in the second quartile, and five customers in the lower two quartiles. Fifteen high use/high bill complaint AC customers were submetered. All of the submetered units were treated with the appropriate retrofits.

The comparison group used in this analysis consisted of 25 untreated random customers in the study area that are submetered as part of the PG&E Appliance Metering Project (AMP). The comparison group was analyzed in the same manner as the experimental group.

This submetering does not have sufficient units to prove or disprove the savings and peak reduction available for a large population. However, it provides the first measured savings on units that are operated at the discretion of the occupant. Previous studies (Cummings et al. 1990) were limited to units with constant temperature settings.

Energy Savings. Submeter data for each house was summed for each day and was regressed against the average outdoor temperature from the Fresno airport for that day. Days with no use were excluded from the analysis. Regressions were run for pre-repair and post-repair periods for both the experimental houses and the comparison houses. These regressions were corrected by bin analysis to the Fresno Typical Meteorological Year. The energy savings was calculated based on normalized use. The resultant raw and corrected energy savings are shown in Table 3. The comparison group showed substantial increase in energy use in between the pre- and post-time periods. This accounts for the sizable correction in the raw data.

The high use/high bill complaint group saved less than the 24.4% predicted from the 1990 AC data. This appears to be partially due to problems associated with repairing undercharged units. While proper leak detection and repair is possible, it is a time consuming job. These units often do not show a savings for two known reasons. In some cases the occupant knew that the unit was low on charge and prior to repair was refraining from using the unit except when it was very hot. That behavior changed after repair. In other cases the leak was not found and not repaired, the refrigerant continued to leak to the atmosphere, and energy savings did not occur.

Table 2. Savings Estimates

Repair Measure	Cooling (kWh)	1 Hour Peak (watts)	Heating (therms)
Correct Low Airflow	7.7%	101	1.9%
Repair Overcharge	11.5%	314	
Repair Undercharge	11.8%	183	
Repair Duct Leakage	18%	527	12%
Total Program	24.4%	691	12%

Table 3. Energy Savings

Test Group	Raw kWh Cooling Savings	Corrected Cooling Savings
High Use/High Bill Complaint (n=15)	8.4%	16.2%
High Use/High Bill Complaint excluding undercharged units (n=11)	13.8%	21.6%
Random Units (n=11)	1.4%	9.2%
Top Quartile of Random Units (n=3)	15.6%	23.4%
Second Quartile of Random Units (n=4)	-2.0%	5.8%
Bottom Two Quartiles of Random Units (n=4)	-5.7%	2.1%
Comparison Group Savings (n=25)	-7.8%	

When the undercharged units are removed from the high use/high bill complaint group, the corrected savings is near the 24.4% savings projected from the 1990 data. (See Table 2.) In addition, high use customers in the random group (the top quartile) saved 23.5%, which is very near the predicted numbers from the 1990 analysis.

The lower use customers (customers in the bottom three quartiles) do not appear to have near the savings potential that the high use customers have.

Peak Reduction. A number of analytical approaches to determination of the peak effect of these repairs are in process. If peak reduction occurs, it is not sufficiently large to be adequately characterized by a sample of this size. Initial results do suggest that to obtain the peak reduction made possible by duct sealing, repairing low air flow, and correcting improper charge some additional steps may be necessary. These additional steps are discussed below.

Submeter data shows that peak electrical use is driven primarily by occupant behavior, the capacity of the unit and the EER at peak temperature.

One method of obtaining peak reduction is to limit the maximum watt draw on the unit. This theoretically can be done with some load shedding or cycling device. However such a strategy runs the risk of customer complaints, sabotage of the controller, and other negative effects such as shortened, less efficient cycles.

Another strategy would harvest the peak reduction made possible by efficiency improvements. First the cooling load would be reduced by improvements to the system through duct sealing and insulation. Following those improvements, a new high efficiency unit of a smaller capacity could be installed. This new smaller high efficiency unit would "lock in" the peak reduction that the customer could previously override. For example, consider replacing a unit delivering 40,000 btu per hour at an EER of 6 at peak with a new unit downsized 25% because of efficiency improvements that has an EER of 10 at peak.

Initial Peak Watt Draw:

40,000 btu/6 btu per watt hr = 6667 Watts

Final Peak Watt Draw:

30,000 btu/10 btu per watt hr = 3000 Watts

The actual peak reduction will depend on the diversity factor (which is high on peak hours). Importantly, selection of a replacement unit should not depend on SEER. Replacement selection should consider the air conditioner's peak temperature kVA, latent capacity, and total capacity.

Summary

In four pilot studies it has been determined that many existing heating and cooling systems were not properly installed or maintained, due to a system which does not recognize or address quality control. This has lead to high energy bills and inadequate comfort for numerous customers. By "getting it right the second time," through specialized programs, past deficiencies in contractor infrastructures can be addressed.

When these deficiencies are repaired, high use customers experience improved comfort and lower bills. From the utility perspective, "getting it right the second time" improves customer relationships, can provide a substantiative response to high bill complaints, and is a potential source of peak load reduction.

The pilot projects have identified a significant source of untapped electrical and gas savings which can be achieved by bringing existing equipment up to their designed efficiency, while at the same time addressing the needs of energy users, providers, and regulators.

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