How Green Are Energy-Efficient Appliances? Calculation of End-Use Emissions Profiles from Engineering Field Data

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This paper presents initial research results to calculate hourly end-use emissions profiles undertaken for a Southern California utility in the Residential Energy Usage Comparison (REUC) Project. The REUC Project measured the field performance of comparably efficient electric and gas appliances for a large group of single-family homes in Southern California. An issue of growing awareness and importance is the environmental impact of utility demand-side management (DSM) programs, including energy-efficiency programs. This paper presents hourly end-use emissions of one program that relied on increasing the energy efficiency of residential end-use technologies. This paper uses detailed engineering field data continuously collected from these appliances and from the utility's generation facilities to calculate hourly emissions profiles for electric and gas space conditioning appliances, heat pumps and gas furnaces. Nitrogen oxide (NO_x) emissions data were measured continuously from the utility's power plants in the Los Angeles Basin. Finally, customers' environmental image of electricity and gas as appliance fuels is discussed as it relates to appliance purchases.

Introduction

An issue of growing awareness and importance is the environmental impact of utility demand-side management (DSM) programs, which include energy efficiency and load shifting programs. In this paper, we consider only energy efficiency DSM programs that focus on improving the energy efficiency of residential appliances, such as heat pumps. It is these DSM programs that are growing most rapidly and that many U.S. utilities, including those in California, are now heavily promoting. This paper presents initial results of calculating hourly end-use emissions profiles undertaken for Southern California Edison in its Residential Energy Usage Comparison (REUC) Project. The REUC Project investigated the field performance of comparably efficient electric and gas appliances for a large group of single-family homes in Southern California.

Unlike other studies that have considered environmental impacts of DSM programs, we have calculated empirical, *hourly end-use specific* emissions profiles. A number of studies have postulated methods and generated results for incorporating average annual environmental impacts in Integrated Resource Planning (IRP) and DSM programs based on projections and/or simulations; see Bernow (1992), Sisinne (1991), Tempchin (1990 and 1991) and White (1990). The need for calculating these impacts at the end-use level with empirical data has grown as the environmental consequences of DSM have been introduced into DSM program planning and utility IRP.[1]

The movement to end-use emissions analysis is supportive of the trend that utility supply-side and demand-side resources will be evaluated comparably through an IRP process. By undertaking such empirical, hourly end-use environmental impact evaluations within DSM programs' evaluation, one can better assess these programs' total cost-effectiveness. Given the market-based approach to air pollution reduction that regulators are now proffering for valuation of such reductions, the empirical evaluation of DSM program's environmental impact is especially appropriate. In addition, such environmental impacts can provide a more comprehensive foundation for assessing whether utilities' (and customers') investments in these demand-side resources are appropriate, given the present sensitivity to environmental, as well as energy efficiency impacts. This paper furthers existing research by presenting methods and results based on monitored field data by time-of-day at the end-use level that can determine how "green," that is, how environmentally benign, such energy-efficient appliances are, and how their "greenness" can be empirically measured.

The REUC Project's study area is located in Southern California, one of the most environmentally sensitive in the nation. The results presented here build on the research findings presented in Schaper (1990) and Smith (1991). This research presents initial results that examine hourly environmental profiles of nitrogen oxides (NO_x) for *both electric and gas* space conditioning appliances. It also presents hourly NO_x emissions profiles for "standard-efficiency" and "high-efficiency" electric heat pumps. The South Coast Air Quality Management District (SCAQMD), which regulates air quality in the Los Angeles Basin, has shown great interest in NO_x emissions, since NO_x is a "criteria pollutant" regulated under Rule 1135 that contributes to ozone production. Consequently, unlike many other studies, this research has focused on NO_x rather than CO_2 and SO_x. The utility's local generation mix also supports the focus on NO_x. Finally, the paper discusses customers' actual reactions to using such appliances and their environmental image of electricity and gas, which can contribute to such DSM energy efficiency programs' success.

The research results presented here emphasize the use of continuously collected field data for environmental emissions and for end-use consumption/engineering performance. It is the collection and use of these types of real-world data, rather than the use of pure simulation data, that will allow utility resource planners to make suitable decisions regarding the most effective demand-side and environmental options in which to invest. Given the changing context of air quality regulations as well as emissions monitoring technology, traditional reliance on simulation data for environmental impact evaluation may no longer be appropriate. The ACQMD regulations mandate that utilities in the Los Angeles Basin have continuous-emissions monitors installed by January 1, 1993. We believe that the methods and results shown in this paper illustrate how these emissions data, together with end-use load data, can be used for an accurate, detailed evaluation of end-use specific DSM program environmental impacts, as well as more general environmental impact analyses.

New Environmental Regulations and End-Use Efficiency

The Clean Air Act Amendments of 1990, the market-based implementation of these regulations by Federal and State regulatory agencies, utilities' compliance with these regulations, and the regulations' impact on utility resource planning have been discussed elsewhere, and will not be repeated here.[2] These regulations call for major reductions in air emissions from fossil-fueled power plants beginning in 1995. Simultaneously, there are new end-use technology efficiency standards, including those mandated by the 1992 Federal and California (Title 24) appliance standards, that will increase residential appliances' energy efficiency. The relationship between these environmental regulations and the appliance standards as well as utility energy efficiency DSM programs has been less widely considered.[3] We expect that changes in residential end-use technology efficiency will improve the end-use environmental performance as well as energy performance of these residential technologies.

We next describe our methodology for calculating hourly emission profiles for the REUC Project's comparably efficient heat pumps and gas furnaces, as well as for standard- and high-efficiency heat pumps. The gas and electric homes in the samples were matched based on occupant and physical characteristics in order to minimize differences in energy usage patterns. More details about the design of the Project, the appliances, and the customer samples can be found in Schaper (1990) and Smith (1991).

Methodology

Residential hourly end-use emissions profiles have been produced by combining hourly emissions data by day with hourly electric and gas end-use load data by day. The load data were collected at 5-minute intervals and aggregated to hourly values for each household. In order to facilitate emissions comparisons, the electric and gas end-use load data were converted to comparable units. The NO_x emissions data used in the analysis were hourly utility system load and corresponding NO_x emissions in the SCAQMD region, which includes most of the Los Angeles Basin, during the 1991 calendar year.

We now provide a brief description of the heat pumps and gas furnaces that were used in the study. The residential space conditioning end-use data used for this analysis were developed through two separate end-use metering customer samples maintained by the REUC project between 1987 and 1989. The first sample collected data on standard- and high-efficiency electric heat pump energy usage in 31 households. The second sample collected data on gas furnace and electric heat pump energy usage in 92 households. The metered heat pumps in both samples were air-source heat pumps.

In the 31-household sample, the high-efficiency heat pumps had dual-speed compressors which operate at high speed under high-load conditions but switch to low speed under low load. The dual-speed compressor contributes to higher overall efficiency by decreasing the unit's cycling losses. These high-efficiency heat pumps have a manufacturer-rated heating season performance factor (HSPF) of 7.60, and a measured (observed) HSPF of 7.58. The standard-efficiency heat pumps had a single-speed compressor, and thus cycles more frequently during low load conditions, thereby losing efficiency. These heat pumps have a rated HSPF of 6.70, and a measured HSPF of 5.96.[4]

In the 92-household sample, 5-minute load data were collected from comparably efficient heat pumps and gas furnaces. The heat pumps had connected loads of approximately 6 kW and a resistance backup system designed to provide supplemental heat on cold days. This backup system could draw loads of up to 16 kW. These heat pumps had a manufacturer-rated HSPF of 7. The gas furnace heating systems had output capacities of 58 to 117 kBTU/hr and electric fans that had loads under 800 Watts. The gas furnaces were equipped with automatic electronic pilot ignitions. These furnaces had a manufacturer-rated annual fuel utilization efficiency (AFUE) of 80%. For this sample, measured efficiencies were not calculated.

End-use data from these two customer samples have been used to compare emissions attributable to standard- and high-efficiency electric heat pumps, as well as emissions attributable to gas furnaces and comparably efficient electric heat pumps. On-site emissions from gas furnaces are generated through the combustion of fuel in the furnace. The amount of emissions produced per BTU burned in a gas furnace is relatively constant. However, for electric heat pumps the amount of emissions produced per kWh consumed can be quite variable. This is because emissions are produced through the generation of electricity at power plants rather than combustion of fuel in the heat pump. Since plants with different thermal efficiencies are used to satisfy system demand, emissions attributable to electric end-uses are more variable with respect to time. Because we used hourly NO_x emissions data gathered continuously from each operating unit, the effect of adding (subtracting) "marginal" units as system load increases (decreases) during the day has been accounted for directly in the emissions data.

Thus, two types of continuously-collected engineering field data were used in this analysis: (1) "demand-side" end-use load data collected from customers' actual heat pumps and gas furnaces; and (2) "supply-side" data collected from actual NO_x emissions and utility system load. Both types of data are necessary to develop accurate environmental impacts of end-use specific DSM programs. This study has accounted for the energy and environmental impact due to changes in end-use load characteristics, either electric- or gas-fueled heating systems or standard- or high-efficiency heat pumps. Only the second type of data, aggregated supply-side data, would be necessary if the objective of the study were to examine the "marginal" environmental effects of changes in a utility's generation mix based on aggregate system load conditions. Such supply-side data can provide useful analyses about supply-side environmental impacts; however, it cannot accurately produce emissions impacts of energy efficiency or load shifting DSM programs without making a number of assumptions about customers' use of appliances or equipment. The need for such assumptions is removed by using demand-side field data. Furthermore, by producing hourly end-use emissions profiles, calculations can be made for virtually any time period, such as the daily peak period. With this information, cost-effectiveness calculations can include environmental as well as energy conservation impacts.

As discussed below, a number of interesting questions can be answered by using both types of data that would not be possible by using just one type of data. These questions include:

- What is the marginal emissions impact of customers switching from gas to electric heating systems?
- What is the marginal emissions impact of customers switching from standard-efficiency to high-efficiency HVAC systems?
- What are the emissions impacts of end-use specific demand-side programs?

The REUC 5-minute end-use load data from each customer sample were first aggregated to hourly loads, and then averaged by date across each monitored household. Monthly load profiles were then calculated for all households for each daytype. The daytypes used in the analysis were weekday, weekend, and peak day. The hourly system NO_x and system load data were similarly calculated for each daytype and month. The emissions were divided by system load to produce emissions profiles that represent hourly NO_x emissions per kW of demand. Each hour's electric heat pump load data for each daytype were then multiplied by the calculated hourly NO_x per kW emissions for the same daytypes. The gas end-use emissions profiles were produced in a comparable manner, except that the gas furnace load data were multiplied by the gas furnace NO_x emissions factor of 0.094 Lbs./MMBTU burned. This emissions factor is a weighted average taken from studies discussed in Weaver (1992).[5]

The combination of daytypes and end-use technology and fuel types results in the creation of 36 end-use emissions profiles. The emissions profiles can be interpreted as the emissions attributable to a given fuel and technology type for an average household represented in the REUC sample. This methodology can be used to produce emissions profiles for individual generation units as well as individual households. Also, the methodology and data available can produce annual emissions numbers.

Comparisons of emissions for gas and electric heating systems throughout the year are not meaningful in areas like the Los Angeles Basin, where the heating season covers only a well-defined portion of the year. This paper presents results for heating system emissions for the month of January, the winter season month that the utility's SCAQMD peak occurred, as well as the five-month heating season. We believe these seasonal and winter peak month numbers are most relevant for comparison of gas and electric fueled heating systems. In addition, we provide results of emissions values for standard- and high-efficiency heat pumps for the month of September, the cooling season month that the utility's SCAQMD peak occurred and the four-month summer cooling season. Annual values for the two heat pump technologies are also provided.

Results

Emissions Profiles

Figure 1 presents hourly NO_x emissions profiles for gas furnace households during January, the utility's peak winter heating month. NO_x emissions from gas furnaces are much larger than emissions attributable to electric heat pumps, which are displayed in Figure 2. On the peak day, average gas furnace emissions were calculated to be 0.0034 Lbs. per household. This is about double the electric heat pump emissions of 0.0018 Lbs. per household on the peak day. When contrasting the shape of these two emissions profiles, we see that the heat pumps' profile is less peaked than the gas furnaces' profile. This difference is based on customers' usage patterns of the appliances, as well as the characteristics of the equipment. As is mentioned below, customers believe gas heating systems provide "faster heat" than electric systems; this belief is consistent with the shape of these emissions profiles. More detailed information about the usage/load profiles of comparable electric and gas HVAC systems is provided in Smith (1991).

In considering the air quality impacts of greater use of high-efficiency heat pumps, it is important to keep in mind that the saturation of gas furnaces is far higher than the saturation of electric heaters or heat pumps in this utility's service area. This is true for virtually every metropolitan area in the US, except possibly those in the Pacific North West. In 1990 for the Los Angeles area, approximately 88% of single-family homes had gas furnaces, about 1.8% had heat pumps. Thus if heat pumps become a more prominent heating technology relative to gas furnaces, potentially significant on-site NO_x emissions

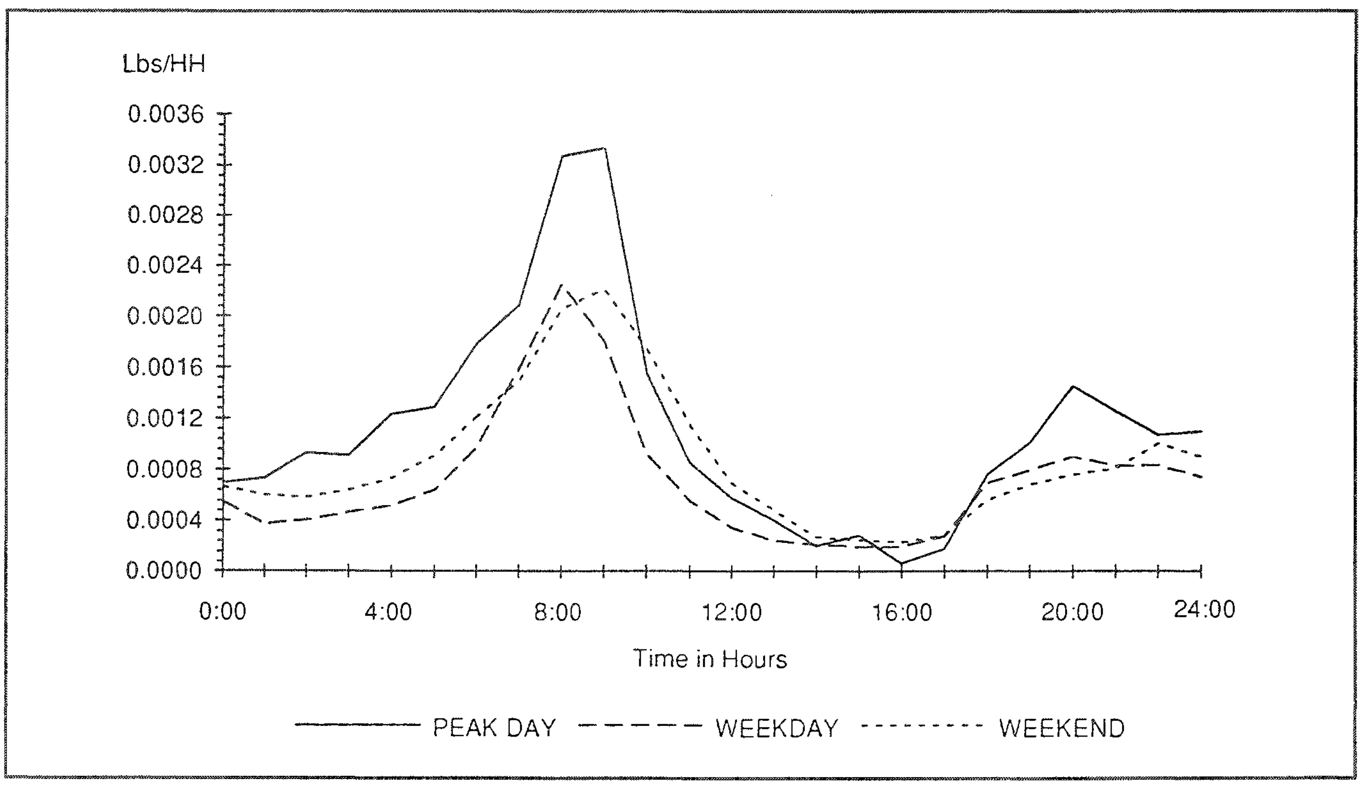

Figure 1. Gas Furnace NOx Emissions for January

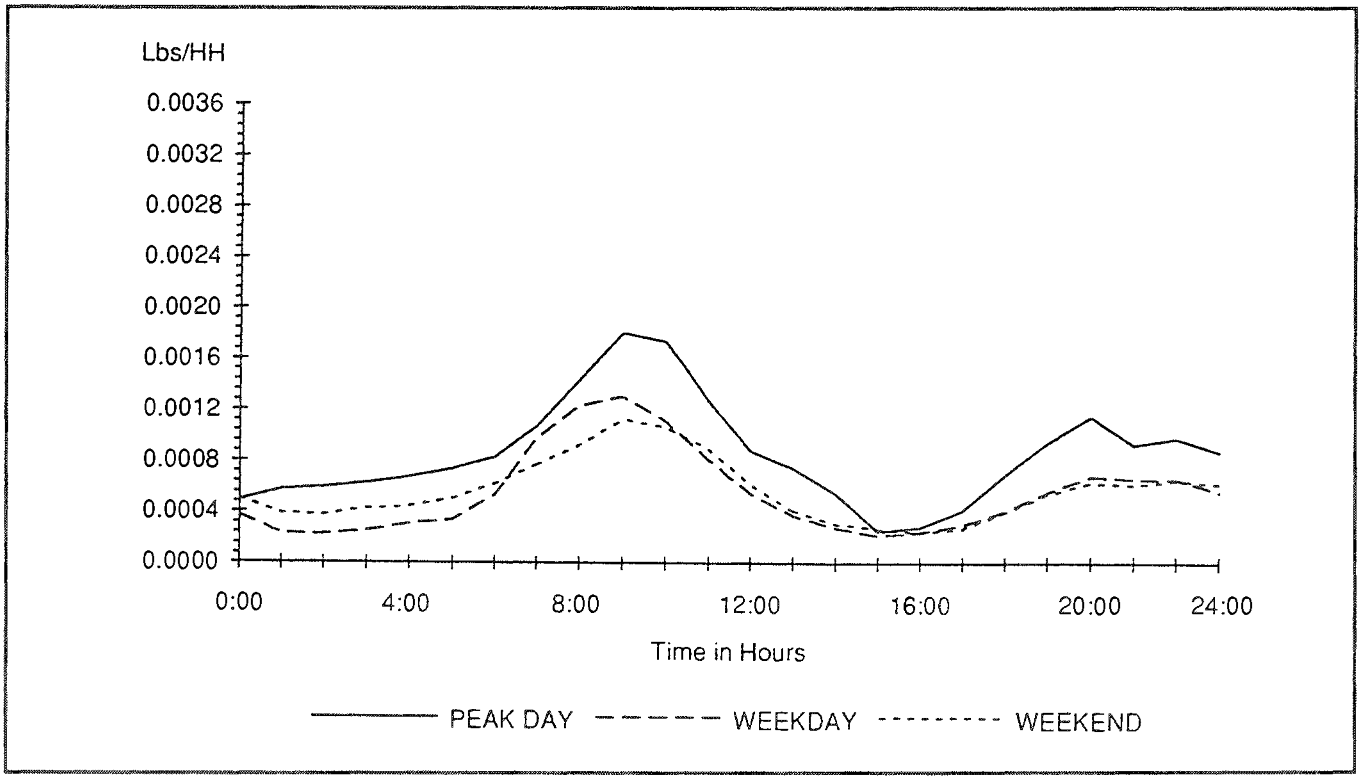

Figure 2. Electric Heat Pump NOx Emissions for January

reductions can be realized, perhaps due to electric utility DSM energy efficiency programs.

Figure 3 presents NO_x emissions attributable to high-efficiency electric heat pumps in January. Figure 4 presents emissions attributable to standard-efficiency electric heat pumps in January. As explained above, the high-efficiency heat pumps had two-speed compressors which, over the course of a day, tends to "smooth" the load profile of such heat pumps, in contrast to more "peaked" heating load profiles of standard-efficiency heat pumps with single-speed compressors. This increased energy efficiency contributes to the different shape of the emissions profiles shown in Figures 3 and 4.

As expected, standard-efficiency heat pumps produce more emissions than high-efficiency heat pumps in the Los Angeles Basin. From these initial results, we see that DSM programs that promote high-efficiency heat pumps can offer not only reduced energy usage, but consequent air quality improvements as well. Using this methodology and these results, improvements can be calculated from field data, as discussed below.

Figure 5 presents emissions attributable to high-efficiency electric heat pumps in September, the utility's peak summer cooling season month. Figure 6 presents emissions attributable to standard-efficiency electric heat pumps in September. On the peak day, standard-efficiency heat pumps produce roughly twice the emissions of high-efficiency heat pumps.

Table 1 presents the total emissions attributable to gas furnaces and heat pumps during the winter heating season, which we have defined as the months of November, December, January, February, and March. As discussed above, annual emissions comparisons should not be made between these technologies, since they do not perform the same functions over the year. Comparisons should be limited to the winter season. However, Table 1 also presents summer and annual emissions for completeness. We have defined the summer as the months of June, July, August and September. As shown, during the winter heating season these heat pumps are shown to produce 32% less NO_x emissions than the gas furnaces.

Table 2 presents the total emissions attributable to standard- and high-efficiency heat pumps during the winter and summer seasons as well as the entire year. Table 2 shows that over the entire year, high-efficiency heat pumps' NO_x emissions per household are about 15% lower than the standard-efficiency heat pumps. It is also

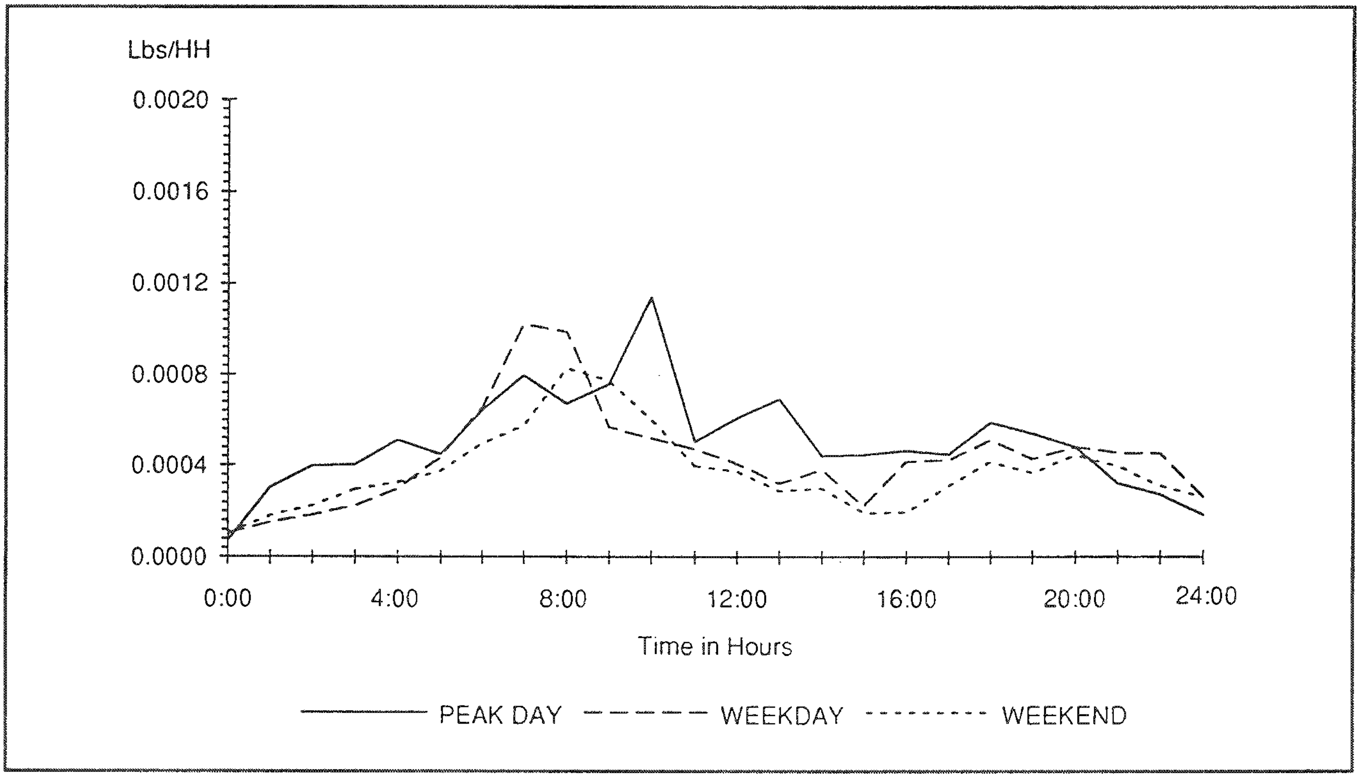

Figure 3. High-Efficiency Electric Heat Pump NOx Emissions for January

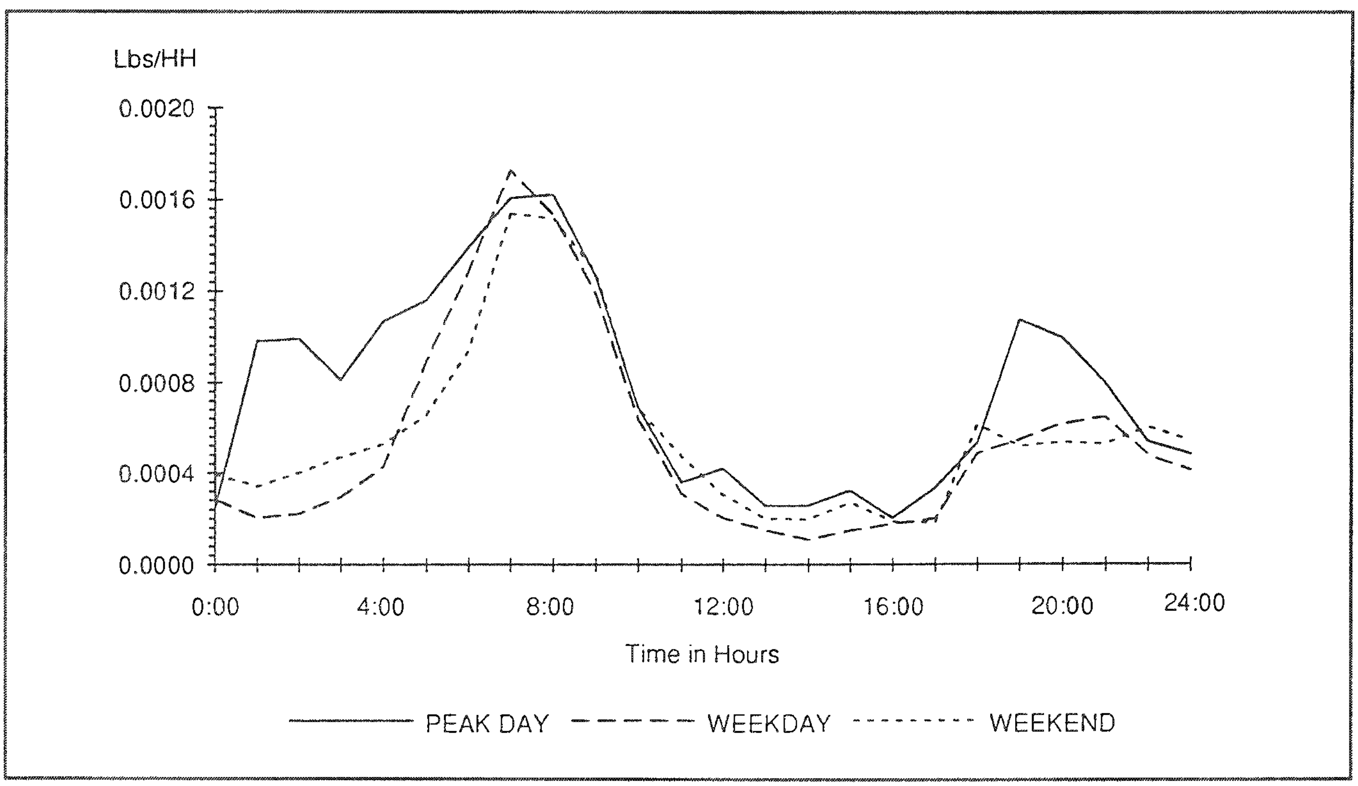

Figure 4. Standard-Efficiency Electric Heat Pump NOx Emissions for January

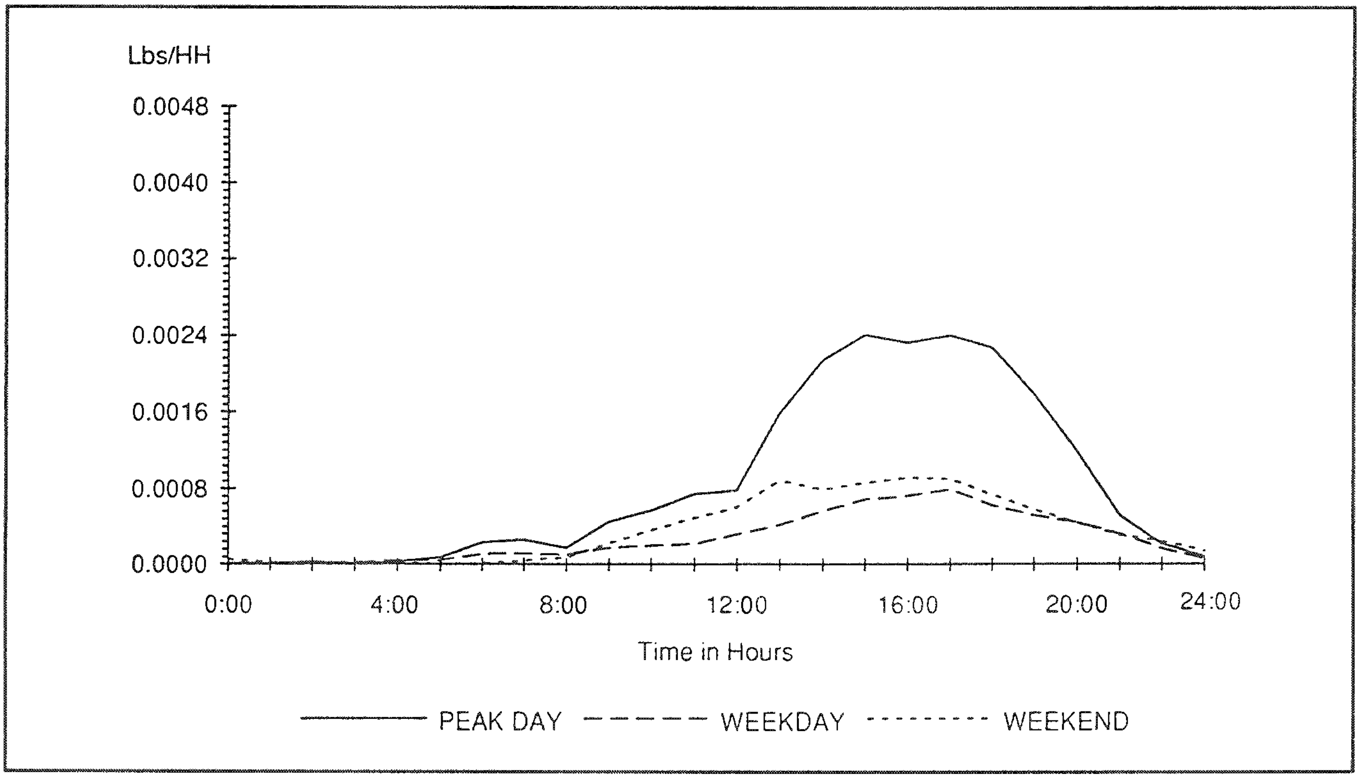

Figure 5. High-Efficiency Electric Heat Pump NOx Emissions for September

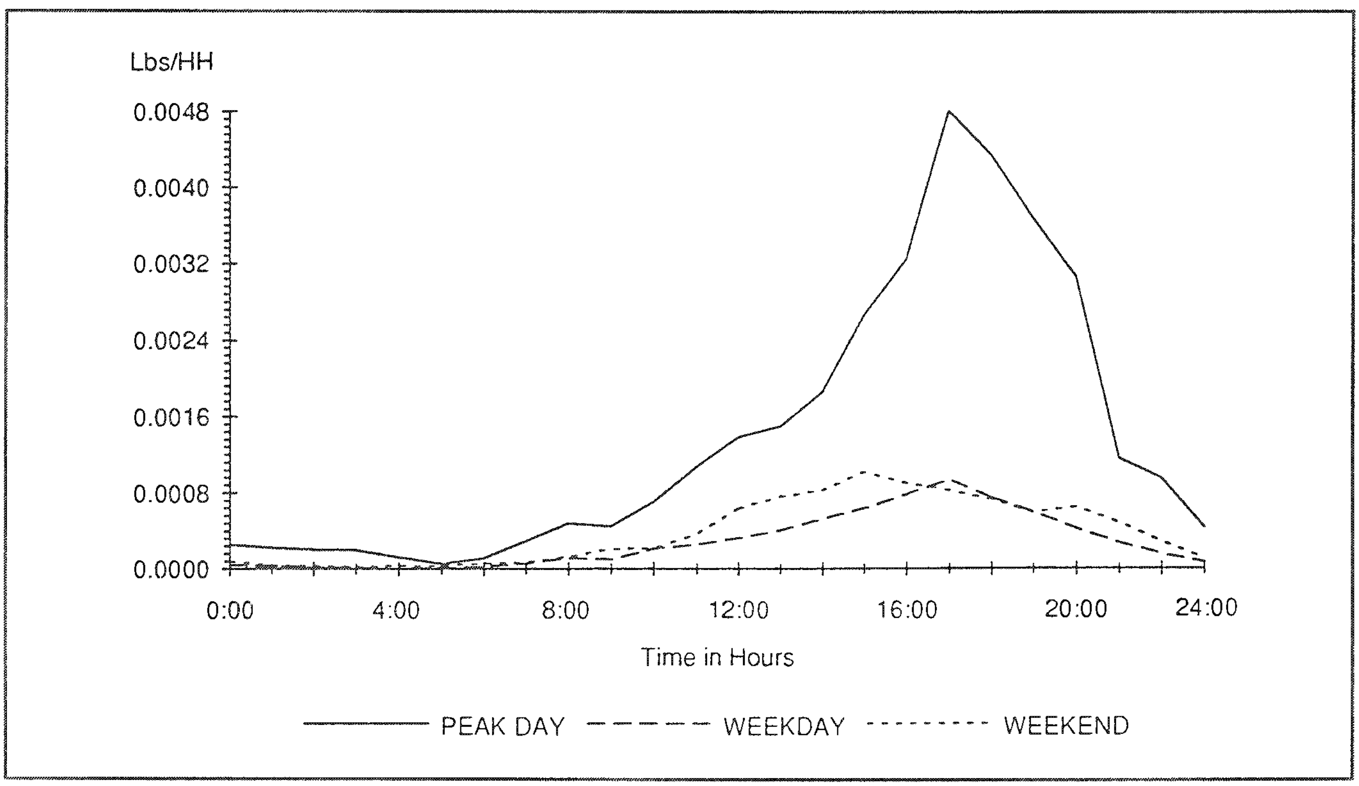

Figure 6. Standard-Efficiency Electric Heat Pump NOx Emissions for September

Table 1. Total NO_x Emissions by Fuel Type and Season (lbs. per Household)

Technology	Winter	Summer	Annual
Gas Furnace (AFUE: 80%)*	1.75	0.03	1.89
Electric Heat Pump (HSPF: 7)	1.33	0.62	2.13

*Manufacturer-rated performance in parentheses.

Table 2. Heat Pump Total NO_x Emissions by Season (lbs. per Household)

Technology	Winter	Summer	Annual
Standard-Efficiency (7.58)*	1.57	1.15	2.96
High-Efficiency (5.96)	1.09	1.13	2.56

*Manufacturer-rated performance in parentheses.

interesting to note that virtually all of the improved environmental performance of these heat pumps comes during the winter season. During the winter, the high-efficiency heat pumps produced 44% less NO_x emissions than the standard-efficiency heat pumps. During the summer cooling season, the NO_x emissions are virtually identical. This may be due to differences in the utility's generation mix across the seasons as well as the customers' operation of the heat pumps.

Customer Reactions

We have shown that heat pumps, especially high-efficiency heat pumps, can provide much reduced NO_x emissions for the Los Angeles Basin. To realize such air quality improvements ultimately requires customers to purchase these appliances rather than gas furnaces or standard-efficiency heat pumps. How can this occur? It is beyond the scope of this project to delve too deeply in answering this question; however, we provide below a summary of information about how the REUC Project participants reacted to using their heat pumps and gas furnaces that can be instructive in how to design DSM programs that address this question.

The participants were asked to respond to several surveys, one of which included questions that were used to develop images of electricity and gas. These images, as well as customers' experience with energy-efficient appliances, can be used to design DSM programs that have environmental and energy efficiency benefits. Figure 7 shows the results of the participants' image of these two fuels, as rated on a unit-less index from 1 to 7. As can be seen, participants on average considered electricity a "cleaner" and "safer" fuel, and they perceived gas as an "inexpensive," "fast heat" fuel. These customers' image of electricity as a "cleaner" fuel appears consistent with the results discussed above.

In another set of survey questions, participants were asked to compare their new space heaters with their old space heaters. The gas furnace customers stated that their new systems heated more quickly, heated more evenly, were less noisy, and turned on and off less frequently than their old heaters. Conversely, the heat pump recipients agreed that their new appliances provided sluggish heat, were more noisy, and turned on and off (cycled) more frequently than their old heaters. In addition, gas furnace systems are more likely to have proponents than heat pump systems. This result may have been caused by quality problems with the new heat pumps that were installed in 1987-88. In order for more utility customers to purchase higher-efficiency heat pumps, equipment vendors will need to address these customers' operational concerns and installers will need to be properly trained.

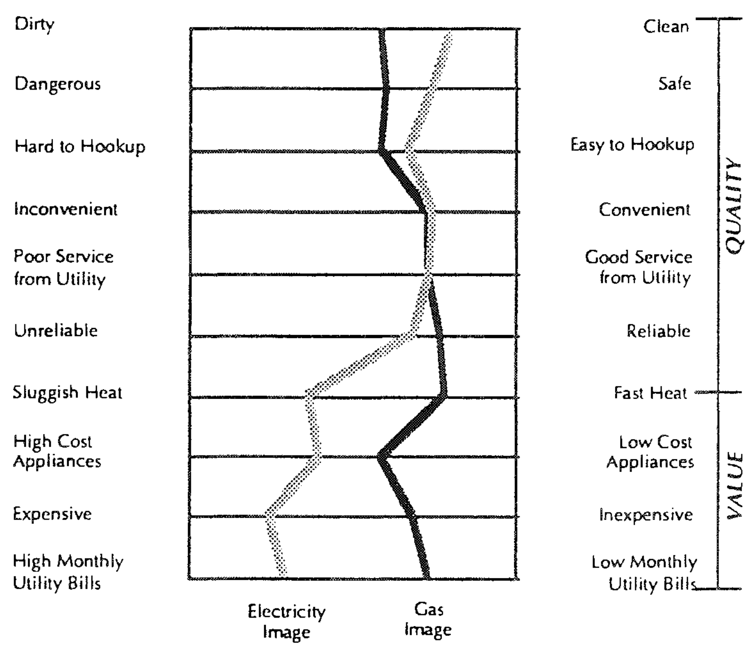

Figure 7. REUC Participant Images of Electricity vs. Gas

These customer responses illustrate that DSM program marketing activities may be able to take advantage of customers' attitudes and images about heating fuels, appliance characteristics and environmental issues in promoting the environmental *and* energy benefits of high-efficiency appliances.

Findings

Initial research into calculating hourly end-use NO_x emissions profiles with continuously-monitored field data in the Los Angeles Basin has produced information that can be used in evaluating the environmental impacts of end-use specific energy efficiency DSM programs. The principal findings are summarized below.

- During the winter heating season, electric heat pumps produced 32% less NO_x emissions than comparably efficient gas furnaces.
- During the winter heating season, high-efficiency heat pumps produced 44% less NO_x emissions than standard-efficiency heat pumps.
- The annual NO_x emissions of high-efficiency heat pumps were 15% less than the standard-efficiency heat pumps.
- During the winter peak day, electric heat pump NO_x emissions were about 50% of those of gas furnaces.

Taking these results and findings into consideration, the "green-ness" of these energy-efficient appliances' NO_x emissions can be ranked as follows:

- Forest Green Appliance: REUC High-Efficiency Heat Pump; represented "quantitatively" as Pantone color #336.
- Kelly Green Appliance: REUC Standard-Efficiency Heat Pump; Pantone color #340.
- Lime Green Appliance: REUC Gas Furnace; Pantone color #366.

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Endnotes

1. See Ganji (1991), Harper (1990 and 1992), and Weaver (1992) for several studies that discuss end-use technologies' environmental impacts.

2. The reader is referred to Sissine (1991) for a useful bibliography, as well as to Tempchin (1990 and 1991), Weaver (1992), and White (1990), for worthwhile research studies on this topic.

3. Several studies worth reviewing in this area are: Harper (1990 and 1992) and Sim (1991).

4. See Schaper (1990) for a description of how these measured energy performance calculations were made from the appliances' metered data.

5. This factor was taken from Weaver (1992), Table 2, p. 162.

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