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FY 1984 Annual Report
ENERGY ANALYSIS PROGRAM

May 1985

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APPLIED SCIENCE DIVISION

Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

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APPLIED SCIENCE DIVISION ANNUAL REPORT ENERGY ANALYSIS PROGRAM FY 1984

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Prepared for the U.S. Department of Energy under Contract No. DE-AC03-76SF00098

CONTENTS

Energy Analysis Program Staff 5-v

Introduction 5-1

BUILDING ENERGY ANALYSIS

Residential Energy Conservation: Microcomputer Program for Energy Analysis of Single-Family Houses
R. Ritschard, J. Huang, and J. Bull 5-2

Energy Analysis of Low-Rise Multi-Family Buildings
I. Turiel, D. Wilson, and R. Ritschard 5-6

Thermal Mass in Exterior Walls of Residential Buildings
S. Byrne, R. Ritschard, and D. Foley 5-8

Home Energy Rating Tool
Y.J. Huang, R. Ritschard, and C. Hsui 5-13

Saving Energy the Easy Way: An Analysis of Thermostat Management
E. Vine and S. Gold 5-16

Parametric Energy Analysis in Support of ASEAN Energy Conservation Standards for Office Buildings
I. Turiel, R. Curtis, and M.D. Levine 5-19

Energy Conservation in Public Housing: A Case Study
C. Goldman and R. Ritschard 5-24

Microeconomics of Residential Energy Conservation
M.D. Levine, P. Chan, and H. Ruderman 5-28

The LBL Residential Energy Model
J.E. McMahon and P. Chan 5-31

ECONOMIC STUDIES

Economic Impacts of Residential Conservation Programs on Electric Utilities
E. Kahn, C. Pignone, J. Eto, J. McMahon, and M.D. Levine 5-33

Solving the Loss-of-Load Probability Problem with Hypergeometric Approximations
E. Kahn and D. Levy 5-36

Preliminary Report on the Economic, Regulatory, and Institutional Environment Affecting Utility Energy Conservation Programs
W.Y. Wood, E. Kahn, P. Chan, and M.D. Levine 5-38

Energy Efficiency Choice in the Purchase of Residential Appliances
H. Ruderman, M.D. Levine, and J.E. McMahon 5-46

Analysis of Federal Energy Efficiency Standards for Appliances
M.D. Levine, P. Chan, J.E. McMahon, and H. Ruderman 5-49

Utility Incentive Programs for Efficient Appliances
J.E. McMahon, D.F. Dickey, and M.D. Levine 5-52

Residential Hourly and Peak Demand Model
H. Ruderman, G. Verzhbinsky, and M.D. Levine 5-57

Increased Usage of Appliances in Response to Efficiency Improvements
H. Ruderman and J. Henly 5-61

Policy Models of Natural Resource Auctions
M. Rothkopf and D. Wood 5-65

INTERNATIONAL ENERGY STUDIES

Oil Conservation in OECD Homes: Permanent or Reversible?
L. Schipper, A.N. Ketoff, S. Meyers, P. Goering, and A. Kahane 5-69

Energy Use in the Commercial Sector: An International Perspective
L. Schipper, S. Meyers, and A.N. Ketoff 5-75

Energy Use in Cities of the Developing Countries
J. Sathaye and S. Meyers 5-79

Energy Use in Developing Countries
L. Schipper, J. Sathaye, A. Ghirardi, A. Ketoff, C. Pignone, and S. Lwakabamba 5-84

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ENERGY ANALYSIS PROGRAM

INTRODUCTION

The Energy Analysis Program is engaged in interdisciplinary activities in which analysts from different fields work together on issues of national significance. The program's emphases on economics, public policy, and behavioral science distinguish it from other LBL activities. At the same time, however, engineering and technical analyses underlie its economic and policy studies, a foundation that distinguishes its work from that of most other analysis groups working on public policy issues. Virtually all of the program's research and analysis is quantitative, and much of the research staff is engaged in developing and applying mathematical models.

At present, the work of the Energy Analysis Program emphasizes the study of energy use in buildings. This subject has been stressed for a number of reasons; one of the most important is the strong research effort within the Applied Science Division on energy conservation in buildings (especially the Energy Efficient Buildings and Solar Energy programs). The Energy Analysis Program provides a rigorous and extensive capability in energy economics and analysis that complements the more technical pursuits of other groups in the Division studying energy in buildings. The program will continue to emphasize analysis of energy use and efficiency in buildings, and it is also applying techniques to other important national and international energy and resource policy issues.

The work of the program during fiscal year 1984 can be divided into the following groups of projects:

(1) Engineering and technical residential energy studies, including simulation studies and analysis of results of program survey data. This work includes extending a simple and accurate tool for approximating energy demand for residential buildings in any U.S. climate to buildings in which thermal mass is important.

(2) Economic modeling, including studies of regulatory policies to reduce energy use of appliances and of heating and cooling equipment; studies of market behavior; development of models to evaluate hourly and peak effects of conservation programs for residences; residential energy demand forecasting; analysis of the effects of energy conservation programs on electric and gas utilities; and analysis of governmental policies on transferring natural resources to the private sector for development.

(3) International studies of the structure and determinants of energy demand in developed and less developed countries.

Some of the projects described in the following pages have already provided a solid start to a systematic analysis of the issues studied. Most of them will continue to expand and evolve. They can be expected to deepen our understanding of energy use and energy conservation in buildings. In addition, the program is striving to expand its work to encompass other key energy and resource policy issues. In particular, international energy issues, critical energy price and supply questions, key resource and environmental issues, and electric utility analyses constitute some of the newest and the most promising initiatives of the program for the next few years.

Residential Energy Conservation: Microcomputer Program for Energy Analysis of Single-Family Houses*

R. Ritschard, J. Huang, and J. Bull

The purpose of this research is to develop a simplified energy calculation procedure capable of accurately estimating the energy and cost savings associated with various conservation measures. Over the past several years, the Building Energy Analysis Group has to this end created a comprehensive data base on the effects of different conservation measures on residential energy consumption. The data base, which consists of more than 12,000 computer simulations using the DOE-2.1 simulation code, served as the technical foundation for developing a set of energy-calculating slide rules. These slide rules and an accompanying homebuilders' guidebook are part of a Department of Energy program to develop voluntary performance guidelines for new single-family residences.[1]

Last year, we analyzed and tested this residential data base to develop a better understanding of the relationship of building energy use to climate, building characteristics, and occupant control conditions. Using a variety of interpolative procedures such as linear and nonlinear regressions, multivariate analysis, and other curve-fitting methods, we correlated simulated data to important climate variables. We used this data base and the simplified mathematical relationships to design a software package called PEAR (Program for Energy Analysis of Residences). PEAR is designed to be used both as a research tool by energy and policy analysts and as a nontechnical energy calculation method by architects, homebuilders, homeowners, and others in the building industry.

ACCOMPLISHMENTS DURING FY 1984

PEAR is a computerized version of Lawrence Berkeley Laboratory's DOE-2.1 residential data base. The program is written for user-friendly input and output and runs on the IBM Personal Computer with either color or monochromatic monitors. PEAR provides an easy-to-use and very fast compilation of the extensive DOE-2.1 data base for residential buildings. The current version covers five residential building prototypes (one-story, two-story, split-level, middle-unit townhouse, and end-unit townhouse) in 45 base locations, but can be extended to include multi-family buildings as well as manufactured houses. The program allows adjustments to the building prototypes for differing window area and location, as well as floor area, gross wall area, and perimeter length. It also allows for extending the data to 1000 other locations by using heating and cooling degree-day modifications. In addition to typical conservation measures such as ceiling, wall, and floor insulation, window type and glazing layers, infiltration levels, and equipment efficiency changes, the user can adjust for optional measures, such as roof or wall color, movable insulation, whole-house fans, night temperature setback, reflective or heat-absorbing glass, and two attached sunspace options (glass or opaque roof).

The user interface of the microcomputer program has six modes. INPUT consists of three screens that allow users to calculate the energy use of a typical residential building. ECONOMICS does economic calculations based on the data used in the INPUT mode. BAR CHART gives more detailed analysis of any building configuration by separating total building energy use into the contributions due to ceiling, walls, floor, windows, and infiltration. READ, SAVE, and FILE are bookkeeping options that show the status of the calculated files and create new files as needed.

The INPUT mode is organized on three screens. The left side of *Input Screen 1* contains the location (by state and city for about 800 locations) and the general house description: building prototype, foundation type, floor area, gross wall area, wall height or perimeter length, window orientation, and window area (Fig. 1). In the current version, this general input appears on the left side of all input screens for reference purposes. The right side of Input Screen 1 contains the following basic conservation measures: ceiling insulation, roof color, wall insulation, wall color, wall heat capacity (not incorporated in the current version, but equations are being developed for masonry construction), foundation insulation (basement and slab foundations), floor insulation

*This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Buildings Energy Research and Development, Building Systems Division, U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

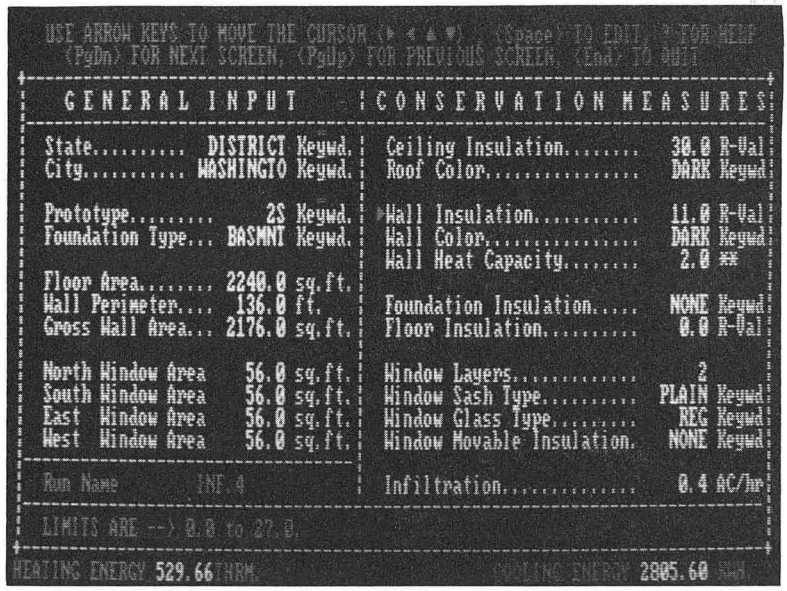


Figure 1. Input Screen 1: Location and general house description. (CBB 851-257)

(basement or crawl-space foundations), window layers, sash type (plain, wood, aluminum, or aluminum with thermal breaks), glass type (regular, reflective, or absorptive), movable insulation, and level of infiltration (0.4 ach to 1.0 ach). As the various inputs are changed, the heating energy (in therms or kWh) and cooling energy (kWh) are calculated immediately at the bottom of the screen, allowing users to assess quickly the effectiveness of different basic measures.

On-line help is available for any option on any input screen by typing "?" instead of the usual numeric or code word input. Figure 1, as an example, shows the limits for wall insulation at a particular location provided to a user who seeks help by typing "?"

The right side of *Input Screen 2* provides a selection of optional conservation measures (Fig. 2). These measures include attached sunspaces and whole house fans as well as several equipment options: heating equipment (oil/gas furnaces, electric resistance or heat pumps) and heating efficiency (AFUE, HSPF), night temperature setback, and cooling equipment (air conditioners or heat pumps) and cooling efficiency (SEER).

The right side of *Input Screen 3* contains the economic parameters (Fig. 3). In the current version, the economic input is used to calculate simple payback (in years) and the benefit-to-cost ratio. We are considering other economic indicators such as net present value and may add them in future versions. On this screen, the user can input information on the capital cost of the measures selected, lifetime of the measure, tax credit (if available), initial fuel prices for heating and cooling, real fuel price escalation rates, real discount rate, and information relevant to loans (e.g., interest rate and loan period).

For users wishing more detailed diagnosis of any particular building configuration, the BAR CHART option plots the estimated contribution to heating and cooling loads due to the following major components: ceiling, walls, floor, windows, and infiltration (Fig. 4). These graphs allow users to determine quickly which envelope components contribute most to the building load and should be improved. Heating and cooling are plotted in dollars to give the proper weighting of heating to cooling energies.

Once two or more runs have been completed (base case and any combination of conservation measures), the user can enter the ECONOMICS mode and the program will do an economic analysis. Figure 5 shows a comparison of five runs (combinations of conservation options) against the base case. A brief description of the base-case characteristics is given along the bottom of the screen as R values of the ceiling, wall, and foundation; infiltration rate; window area (square feet); number of window layers; and total yearly energy cost ($). Below the specific run names (at the top of the screen) are listed the characteristics of the individual cases chosen. The output on the ECONOMICS screen includes the following: yearly savings for heating and cooling energy

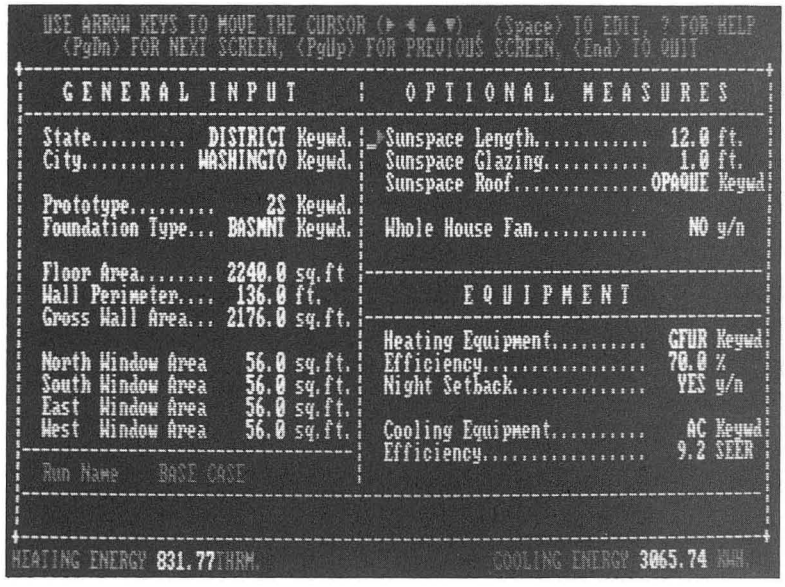


Figure 2. Input Screen 2: Selection of optional conservation measures. (CBB 851-269)

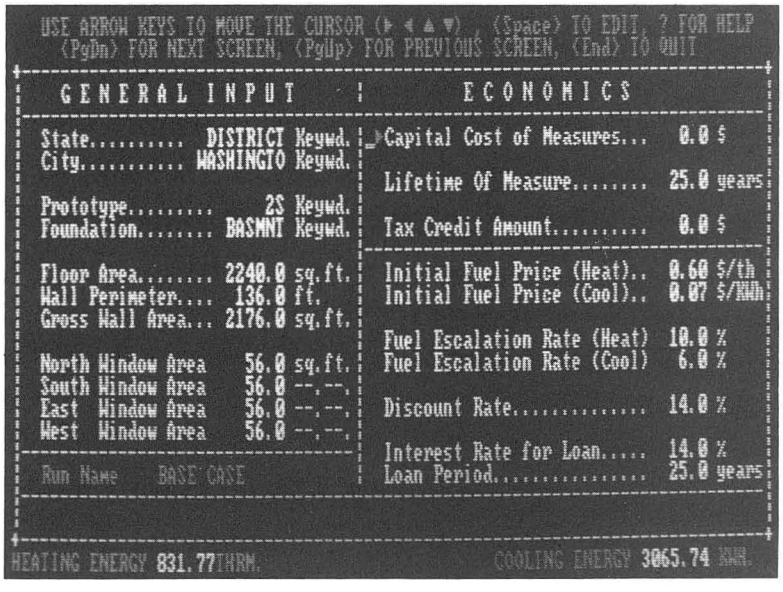


Figure 3. Input Screen 3: Economic parameters. (CBB 851-253)

($), yearly energy cost ($), a summary of economic input parameters (cost of measure, lifetime of measure, and tax credit), and two economic indicators: simple payback (years) and benefit-to-cost ratio. The user can change the economic input on this screen, such as cost and lifetime of the measure and its tax credit to see their effects on simple payback periods and benefit-to-cost ratios.

PLANNED ACTIVITIES FOR FY 1985

We plan to develop additional data that will become part of the DOE-2.1 data base supporting the microcomputer program. During FY 1985 we will:

(1) Develop and test coefficients to account for the heavy mass construction ("wall heat capacity parameter").

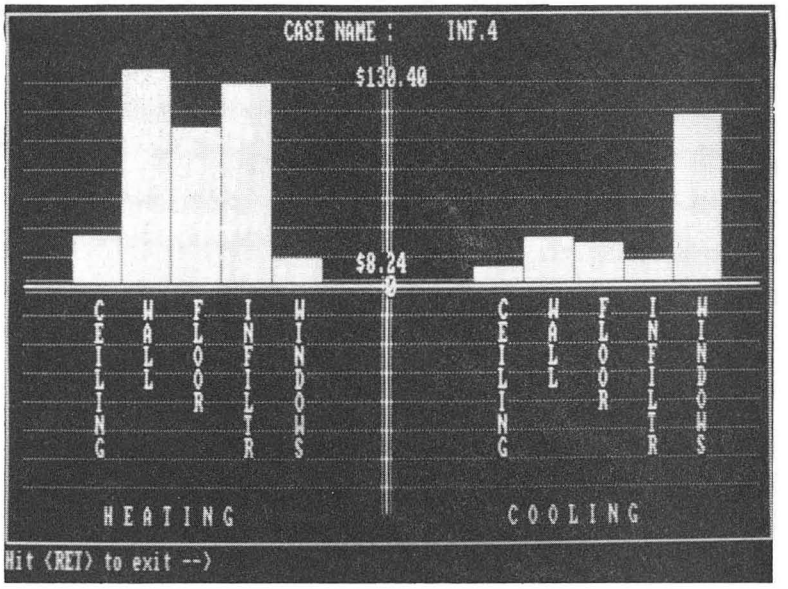
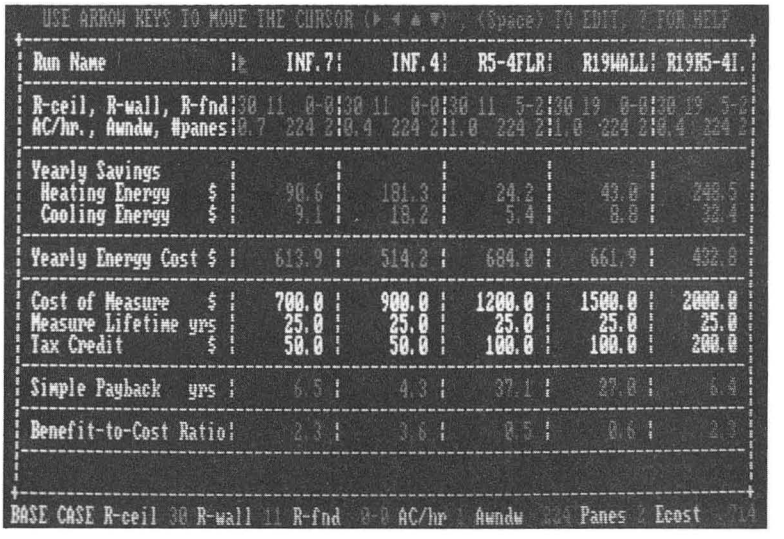


Figure 4. Bar chart option for estimating contribution to heating and cooling loads. (CBB 851-251)



Run Name	INF.7	INF.4	R5-4FLR	R19WALL	R19R5-4I.
R-ceil, R-wall, R-fnd	30 11 0-0	30 11 0-0	30 11 5-2	30 19 0-0	30 19 5-2
AC/hr., Awndw, #panes	0.7 224 2	0.4 224 2	1.0 224 2	1.0 224 2	0.4 224 2
Yearly Savings					
Heating Energy $	90.6	181.3	24.2	43.0	248.5
Cooling Energy $	9.1	18.2	5.4	8.8	32.4
Yearly Energy Cost $	613.9	514.2	684.0	661.9	432.8
Cost of Measure $	700.0	900.0	1200.0	1500.0	2000.0
Measure Lifetime yrs	25.0	25.0	25.0	25.0	25.0
Tax Credit $	50.0	50.0	100.0	100.0	200.0
Simple Payback yrs	6.5	4.3	37.1	27.0	6.4
Benefit-to-Cost Ratio	2.3	3.6	0.5	0.6	2.3

BASE CASE R-ceil 30 R-wall 11 R-fnd 0-0 AC/hr 1 Awndw 224 Panes 2 Ecost 714

Figure 5. Comparison of five runs against base case. (XBB 851-259)

(2) Simulate additional foundation types for all building types in several climates.

(3) Add to the program two "new" apartment prototypes analyzed as part of our low-rise multi-family buildings research.

(4) Select and model other multi-family building types.

(5) Develop and test new interpolative relationships for incorporation into the program.

REFERENCE

1. Huang, J., Ritschard, R., Byrne, S., Turiel, I., Wilson, D., Verzhbinsky, G., Chang, L., Hsui, C., and Foley, D. (1983), *Affordable Housing Through Energy Conservation: A Guide to Designing and Constructing Energy Efficient Homes: Technical Support Document,* LBL-16342.

Energy Analysis of Low-Rise Multi-Family Buildings*

I. Turiel, D. Wilson, and R. Ritschard

The Building Energy Analysis Group at LBL has done considerable work over the past several years analyzing the benefits of energy conservation measures for five prototypical single-family residential building types. This research effort produced a comprehensive data base that was used to provide a tool for estimating the amount of energy use for these prototypes in locations throughout the United States. The large number of buildings with two or more living units and their significant energy consumption has warranted expansion of this research to include prototypes typical of these multi-family buildings.

The objective is to gain a better understanding of the major determinants of energy use in multi-family residences and to transfer this information to the builders of such housing. The research includes data collection on the energy use and building characteristics of multi-family buildings, development of prototypical building types, simulation of prototypical buildings, and energy and economic analysis.

Of all residential units in the existing U.S. housing stock, 11.2% are in buildings with two to four units, and 14.4% are in buildings with more than four units.[1] More than 20% of the energy consumed in residential buildings (9.5 quads)[2] is used in these multi-family buildings. The present research project on multi-family housing focuses on new construction. Approximately one-third of all new residential construction is multi-family buildings.[3] This amounts to almost half-a-million multi-family units being built each year.

Low-rise buildings (one to three stories) account for 86% of all multi-family units,[3] and 75% of these units built each year are in buildings with more than four units. Our initial analysis focuses on low-rise structures with more than four units. Three states (California, Florida, and Texas) account for approximately 45% of all units built in buildings with five or more units. Because most of the new construction is in the Sun Belt,[3] it is important to stress methods of reducing cooling energy use.

*This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Buildings Energy Research and Development, Building Systems Division, U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

ACCOMPLISHMENTS DURING FY 1984

At present, data available on the construction characteristics of new multi-family buildings is limited. We met with an advisory panel of builders of multi-family residences and developed a questionnaire for gathering further information. We will analyze the responses in order to develop new prototypical buildings. We developed initial prototypes using information obtained from discussions with members of the building community and from data collected on single-family construction.[4]

Our initial prototype is a two-story building consisting of three 1200-square-foot apartment units on each floor. Because the middle and end units will behave thermally like similar units in a larger two-story building, this prototype is representative of most two-story buildings with six or more units arranged along a straight line. We performed extensive simulation analyses of this prototype, using the computer program DOE-2.1. We used the simulations to study the following parameters: ceiling insulation, wall insulation, three foundation types with variable insulation, infiltration rate, window area, glazing type (reflective and absorptive glazings as well as number of panes), floor area, roof solar absorptivity, movable nighttime insulation, nighttime thermostat setback, and building orientation.

We simulated the prototype with six separate zones, one for each apartment. We used the heating and cooling loads of the two middle units and four end units to produce average mid- and end-unit values. These average results are therefore applicable to two-story buildings only. A more detailed discussion of the methodology and assumptions used in this research is presented elsewhere.[5] We simulated most of the sensitivity studies for 45 locations throughout the United States. Previous research on climate makes it possible to extrapolate results from these 45 base locations to more than 1000 intermediate locations.[6]

An example of the type of relationships we have been developing involves the estimation of the effect of reflective glazing on cooling and heating loads. We simulated the use of reflective glazing on all windows for the six-unit prototype in 11 locations. The reflectance for this glazing was 45%, compared to the assumption of 6% for standard single-pane glass. We correlated changes in heating and cooling loads to vertical insolation during the heating and cooling periods, respectively. Figures 1 and 2 illustrate the linear relationships between the loads and the appropriate climate variable for each location. We also performed analyses for double and triple-pane windows. The correlation coefficients achieved with

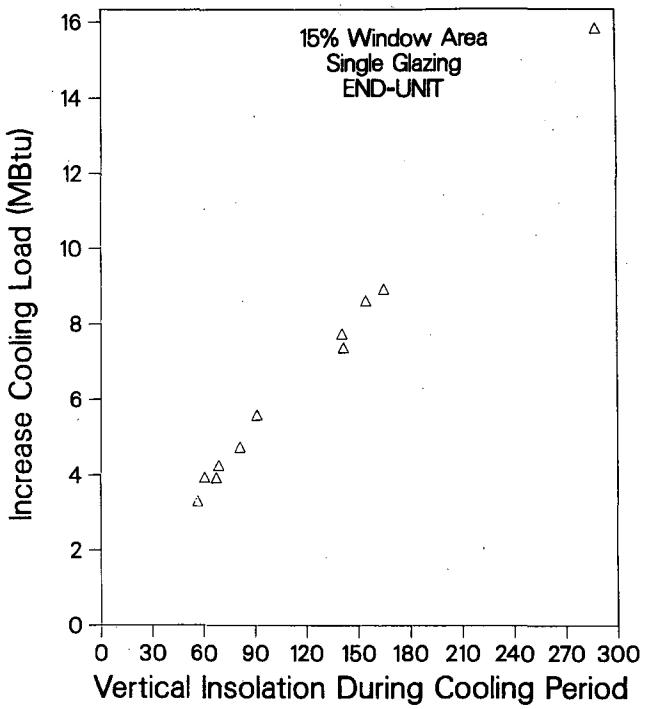


Figure 1. Effect of reflective glazing on cooling load as a function of vertical insolation during the cooling period. (XBL 851-992)

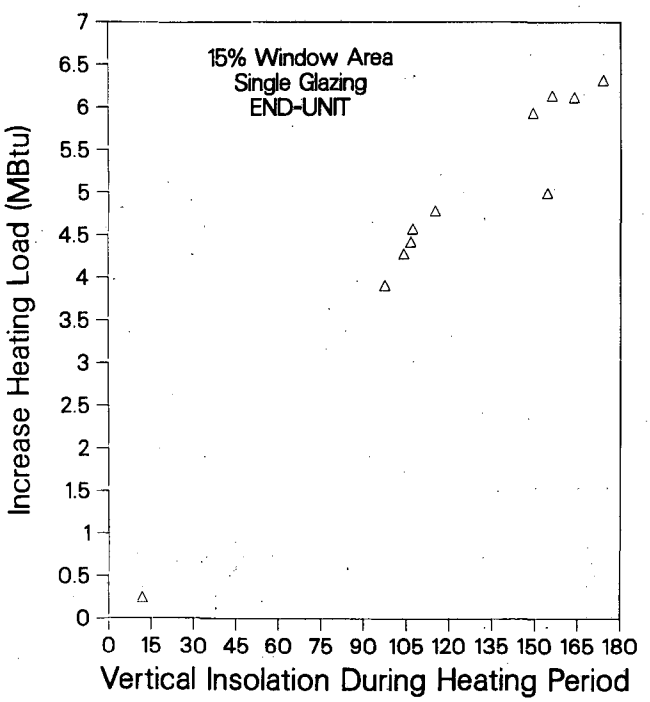


Figure 2. Effect of reflective glazing on heating load as a function of vertical insolation during the heating period. (XBL 851-991)

this regression analysis ranged from 0.95 to 0.99. We used the regression equations (see Eqs. (1) and (2)) derived from this analysis to predict heating and cooling load changes in other locations where the amount of vertical insolation is known but for which no computer simulations were performed. We used a similar methodology to analyze the effect of absorptive glazing on the building loads.

$$\Delta\text{Heating Load (MBtu/ft}^2) = 1.64 \times 10^{-3} + 2.0 \times 10^{-4} \cdot z \quad (1)$$

$$\Delta\text{Cooling Load (MBtu/ft}^2) = 2.71 \times 10^{-3} + 2.7 \times 10^{-4} \cdot y \quad (2)$$

where

$z =$ solar insolation (kBtu/ft^2) during the hours when there is a heating load.

$y =$ solar insolation (kBtu/ft^2) during the hours when there is a cooling load.

For each of the 45 cities, we developed a matrix of heating and cooling load changes that result from changes in insulation levels, foundation type, infiltration level, glazing layers, and glazing area. Preliminary results indicate that added thermal insulation, nighttime thermostat setback, decreased infiltration, and proper choice of orientation and glazing reduce space conditioning loads. The economic implications of these conservation measures must be examined in order to determine the cost-effectiveness of these load reduction strategies.

PLANNED ACTIVITIES FOR FY 1985

Energy conservation opportunities are numerous in multi-family buildings, as they are in single-family residences. In FY 1985, we will use the additional information from the advisory panel of builders and from responses to the questionnaire to develop additional apartment prototypes. We will simulate these new prototypes and perform related analyses. In addition, we will perform cost-benefit analysis to determine the cost-effectiveness of specific measures in various locations. We are developing a microcomputer program that will perform calculations for such analysis in an easy-to-use and inexpensive manner. Because two-thirds of all multi-family units are rental units, strategies for encouraging energy conservation in these buildings must be pursued vigorously if the full potential of cost-effective conservation measures are to be realized.

REFERENCES

1. Energy Information Administration (1983), *1981 Residential Energy Consumption Survey*, DOE/EIA-0314 (81), Department of Energy, Washington, DC.
2. Energy Information Administration (1983), *Consumption and Expenditures, April 1981 through March 1982*, DOE/EIA/0321, Department of Energy, Washington, DC.
3. U.S. Department of Housing and Urban Development (1984), *Characteristics of New Housing: 1983*, HUD report C25-83-13, Washington, DC.
4. NAHB Research Foundation, Inc. (1981), "Sustained Builder Survey Responses Result in Data Bank of Over One Million Houses," National Association of Home Builders Research Foundation, Inc., Rockville, MD.
5. Turiel, I., *et al.* (1985), *Low Rise Multi-Family Housing: Prototype Development and Preliminary Energy Analysis*, LBL-18823.
6. Energy Analysis Program (1983), *Affordable Housing Through Energy Conservation: A Guide to Designing and Constructing Energy Efficient Homes, Technical Support Document*, LBL-16342 (2nd draft).

Thermal Mass in the Exterior Walls of Residential Buildings*

S. Byrne, R. Ritschard, and D. Foley

The use of massive materials in exterior wall construction can be an effective means of reducing both heating and cooling loads in residential buildings. The magnitude of the savings depends on a complex interaction of parameters that include climate and the amount and physical properties of the mass. Other building design parameters, such as the area and orientation of windows, the type of window glass, the thermal integrity of the building, and the building operating conditions, also affect the performance of massive walls.

Past research has focused on the performance of buildings with a fixed ratio of mass per unit area of south-facing glazing.[1] More recent work has examined passive solar buildings with various amounts of "effective mass."[2] However, little research has been done to quantify the effects of thermal mass on cooling loads or to systematically examine a full range of commonly built massive exterior walls. This report describes a project to quantify these effects and incorporate the results into a simple slide-rule format. The research is an extension of previous work that developed a slide rule for predicting the heating and cooling loads of lightweight wood frame residential buildings.[3]

*This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Buildings Energy Research and Development, Building Systems Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

ACCOMPLISHMENTS DURING FY 1984

Methodology

Initially, we compared two detailed hourly computer simulation programs, DOE-2.1B[4] and BLAST-3,[5] to determine if the thermal mass effect would be predicted similarly even though the heat transfer algorithms in these programs are substantially different. The results indicate close agreement between the two programs for several window and wall configurations in each of three climate zones. We therefore selected DOE-2.1B for generating the complete set of parametric runs in order to maintain compatibility with earlier work on the slide-rule project.

We generated a data base of heating and cooling loads for residential buildings by computer simulation of various types of massive walls:

(1) Mass wall with insulation layer *outside* of mass (representing brick or concrete masonry).
(2) Mass wall with insulation layer *inside* of mass (representing brick or concrete masonry).
(3) Mass wall with insulation and mass well *mixed* (representing log, insulated concrete, or adobe).

Through regression analysis of these data, we developed a model equation to predict the performance of intermediate wall types. The results are a concise representation of numerous wall types, building designs, and climates.

Table 1 lists the modeling assumptions for the base-case thermal mass simulations. A full description of the prototype is included in Ref. 3. In addi-

Table 1. Modeling assumptions and parameters for base-case thermal mass stimulations.

Massive Exterior Walls
Mass conductivity:
0.50 Btu/hr·ft^2·°F (brick or concrete masonry)
0.07–0.33 Btu/hr·ft^2·°F (log or adobe)
Mass thickness:
4–8 inches
Mass heat capacity:
3.3–13.3 Btu/°F per ft^2 of wall area
Wall R-value:
5–20 hr·ft^2·°F/Btu (brick or concrete masonry)
5–11 hr·ft^2·°F/Btu (log or adobe)

Interior Mass
Furniture:
3.30 lb per ft^2 of floor area
0.30 Btu/lb
2.00 in. thick
Interior walls:
3.57 lb per ft^2 of floor area
0.26 Btu/lb
0.50 in. thick

Natural Ventilation Temperature
78 °F Winter
72 °F Summer
Spring and Autumn dates adjusted by climate

Floor
Carpet-covered 4-inch concrete slab with perimeter insulation

Ceiling
R-30 insulation

Window Glass Type
Double-pane clear glass with medium-weight drapes
Total window transmittance = 0.75
Total window reflectance = 0.16

Window Area
15% of floor area
Equally distributed in four orientations

tion to the base-case runs, we performed sensitivity studies to examine the impact of variations from the base-case assumptions.

Interaction with Building Design Parameters

The ability of thermal mass to reduce heating and cooling loads depends not only on climate and wall type, but also on the design of the building itself. In particular, any design feature that affects solar gain is likely to affect the load savings due to thermal mass. As solar gain in a building increases, the effectiveness of thermal mass also increases, because of the ability of the mass to store excess heat gains.

The results of DOE-2.1B simulations exploring this phenomenon are shown in Fig. 1. Window orientation, window glass type, window area, and drapery schedule were modified for the ranch prototype with either wood frame walls or masonry walls with insulation outside (total wall R-value = 5 hr·ft^2·°F/Btu). For each case, the difference between the frame wall and the masonry wall is plotted. Case 1 represents the slide-rule base case while in cases 2–8 a single design parameter has been changed. Case 9 represents a simultaneous change in 4 parameters.

Other design parameters that can affect the thermal mass savings include natural ventilation rate, amount of internal mass (furniture, walls, appliances, etc.), and the thermal integrity of the building. Occupant behavior and operating conditions, such as thermostat settings and night setback, also have an impact. In developing the slide rule, we have attempted to analyze typical building designs and operating conditions to quantify the thermal mass effect in average cases. However, the effect in a particular building may vary.

The Effect of Mass Conductivity

The effectiveness of thermal mass in reducing heating and cooling loads depends on its ability to dampen interior temperature swings by storing during the day excess heat gains that can, at night, offset

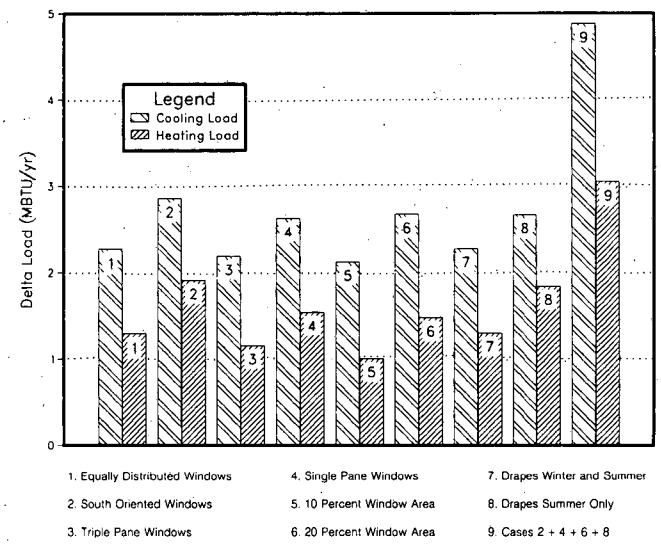


Figure 1. Delta heating and cooling loads of the ranch prototype (Pheonix, Arizona, climate). (XBL 851-984)

heating loads during the winter or be vented to the outside during the summer. The more quickly the mass can respond to surface temperature fluctuations, the more effective it will be in reducing heating and cooling loads. The conductivity of the mass has a direct impact on this response time and consequently on the load reduction.

Because of the limited ability of the slide rule format to handle multiple interactions, in the base-case simulations of massive walls with either interior or exterior insulation, the mass conductivity was held constant at 0.5 Btu/hr· ft ·°F, which is typical of uninsulated concrete. In the simulations of walls with the insulation and the mass well mixed, the conductivity is allowed to vary within the range typical of solid wood, insulated concrete, and adobe. This approach allows the results for all three wall types to be presented in a simple two-dimensional table in which the only independent variables are mass heat capacity and total wall R-value.

We ran sensitivity cases to quantify the effect of changes in mass conductivity. Figure 2 shows typical results, in this case for an R-20 wall of 8-inch-thick masonry with insulation outside of the mass. As the mass conductivity increases, the difference in load between a massive and a lightweight wall also increases. The higher the conductivity of the mass, the more effective it is in reducing loads, compared to a lightweight wall with the same total wall R-value. This effect is more pronounced in cooling than heating. Although the results shown here are climate- and building-specific, the trends are representative of any location and building design.

The Effect of Wall U-Value

We performed a sensitivity analysis for several wall configurations in which we held the mass layer constant while we varied the U-value of the insulation layer. A representative case (8-inch-thick medium-weight masonry) is shown in Fig. 3. In order to show the linear effect of wall conductance, U-value is plotted here rather than R-value.

For heating, the thermal mass effect diminishes as the U-value of the wall decreases, whereas the cooling load savings are nearly constant as the wall U-value changes. It should be noted that total heating load is more sensitive to changes in wall U-value than to changes in the amount of thermal mass, while total cooling load is impacted more by the addition of thermal mass than by wall insulation. Although the magnitude of these results changes with building design, the importance of thermal mass in cooling-dominated climates is clear.

Selection of Heating and Cooling Zones

Because of the many types of commonly built masonry and log walls, it is impractical to simulate with DOE-2.1B all possible configurations in all 45 base cities for which the slide rule was originally designed. Consequently, we ran detailed simulations for only the following wall constructions in the 45 base locations:

Wall 1 = 4-inch-thick medium-weight block with insulation outside; total wall R-value = 5 hr·ft^2·°F/Btu

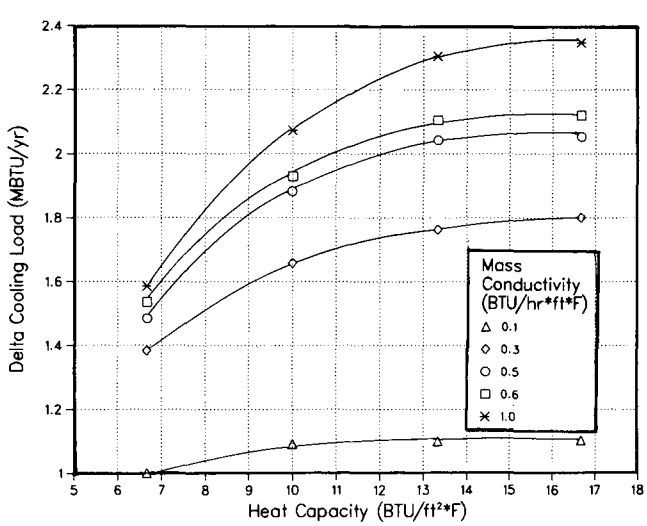


Figure 2. Effect of mass conductivity on delta cooling load (Phoenix). (XBL 851-993)

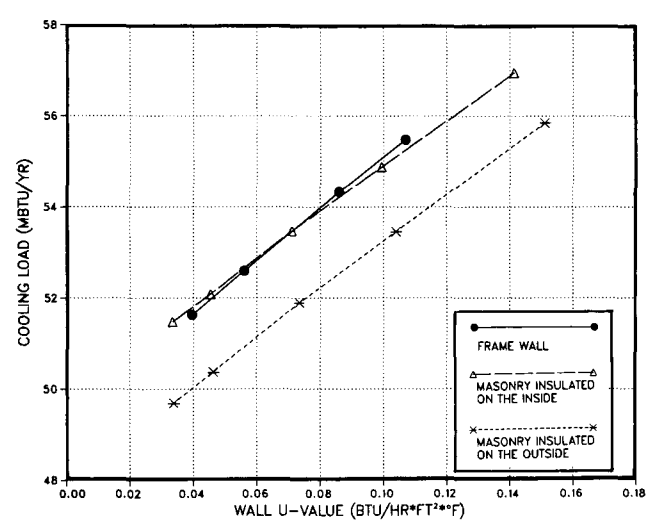


Figure 3. Effect of wall U-value on delta cooling load (Phoenix). (XBL 851-994)

Wall 2 = 8-inch-thick medium-weight block with insulation outside; total wall R-value = 5 hr·ft^2·°F/Btu

Wall 3 = 8-inch-thick medium-weight block with insulation outside; total wall R-value = 20 hr·ft^2·°F/Btu

An analysis of the results indicated that the 45 cities could be grouped into climate zones on the basis of the following dimensionless ratio:

$$\frac{\text{Load}_{(\text{wall 1})} - \text{Load}_{(\text{wall 2})}}{\text{Load}_{(\text{wall 1})} - \text{Load}_{(\text{wall 3})}}$$

This ratio separates the effects of thermal mass from the effects due to steady-state wall conductance. Calculating this ratio separately for heating and cooling loads and then sorting the results yields 12 climate zones that cover the United States. The heating and cooling loads from detailed simulations in these 12 cities were used to estimate the performance of various massive wall types in each of the 45 base locations.

Mass Wall Performance Index

In order to make the results usable in the slide-rule format, tables of Mass Wall Performance Indexes (MWPI) have been generated for each wall type and climate zone.

We produced the tables by calculating equivalent U-values for massive walls with the following equation:

$$U_{\text{eq}} = U_{\text{actual}} - \frac{\Delta\text{Load}}{\text{Slope}} ,$$

where

U_{eq} = equivalent U-value of massive wall;
U_{actual} = actual U-value of massive wall;
Slope = rate of change of load as a function of U-value of wood frame wall (obtained by regression of DOE-2.1B simulations).

Delta loads were obtained by interpolating between actual DOE-2.1B simulations based on the regression equation shown in the following section. The MWPI values are equivalent U-values normalized from 0 to 10 so that a single table can be used with any of the five building prototypes for which the slide rule is designed. A MWPI of zero corresponds to the wall with the largest heating or cooling load, and a wall with a MWPI of 10 has the lowest load.

The user simply determines the MWPI (see example in Table 2) based on the heat capacity and R-value of the wall; this value is then used directly on the slide rule "B" tab (Fig. 4). The result is a simple and accurate method to predict the performance of most common masonry and log walls.

Table 2. Mass wall performance index for zone 1.

Zone 1 Cooling

Heat capacity (Btu/ft^2·°F)	Wall type[a]	Total wall R-value (hr·ft^2·°F/Btu) 4	6	8	10	12	16	20
4	O	2.77	4.55	5.44	5.97	6.32	6.77	7.03
	I	0.00	2.34	3.50	4.21	4.67	5.26	5.61
	M	1.23	3.04	3.94	4.49	4.85	5.30	5.57
6	O	3.06	5.08	6.08	6.69	7.09	7.59	7.90
	I	0.37	2.59	3.71	4.38	4.82	5.38	5.71
	M	1.62	3.45	4.36	4.91	5.27	5.73	6.00
8	O	3.30	5.50	6.61	7.27	7.71	8.27	8.60
	I	0.61	2.76	3.84	4.49	4.92	5.46	5.78
	M	2.01	3.85	4.77	5.32	5.69	6.15	6.43
10	O	3.49	5.85	7.04	7.75	8.22	8.81	9.17
	I	0.76	2.87	3.93	4.56	4.98	5.51	5.83
	M	2.40	4.26	5.19	5.74	6.11	6.58	6.85
12	O	3.64	6.13	7.38	8.13	8.63	9.25	9.63
	I	0.87	2.95	3.99	4.61	5.03	5.55	5.86
	M	2.79	4.66	5.60	6.16	6.53	7.00	7.28
14	O	3.77	6.36	7.66	8.44	8.96	9.61	10.00
	I	0.93	2.99	4.02	4.64	5.05	5.57	5.88
	M	3.18	5.06	6.01	6.57	6.95	7.42	7.70

Zone 1 Heating

Heat capacity (Btu/ft^2·°F)	Wall type	Total wall R-value (hr·ft^2·°F/Btu) 4	6	8	10	12	16	20
4	O	0.00	4.03	6.05	7.26	8.07	9.08	9.68
	I	0.01	4.02	6.02	7.23	8.03	9.03	9.63
	M	0.41	4.35	6.32	7.50	8.29	9.28	9.87
6	O	0.18	4.16	6.16	7.35	8.15	9.15	9.75
	I	0.16	4.12	6.09	7.28	8.07	9.06	9.65
	M	0.56	4.46	6.41	7.58	8.36	9.33	9.91
8	O	0.31	4.26	6.24	7.42	8.21	9.20	9.79
	I	0.29	4.20	6.15	7.32	8.10	9.08	9.67
	M	0.68	4.54	6.47	7.63	8.40	9.37	9.95
10	O	0.41	4.33	6.29	7.47	8.26	9.24	9.83
	I	0.38	4.26	6.19	7.35	8.13	9.10	9.68
	M	0.76	4.60	6.52	7.67	8.44	9.39	9.97
12	O	0.48	4.38	6.34	7.51	8.29	9.27	9.85
	I	0.46	4.30	6.23	7.38	8.15	9.11	9.69
	M	0.82	4.64	6.55	7.69	8.46	9.41	9.99
14	O	0.53	4.42	6.37	7.54	8.32	9.29	9.87
	I	0.51	4.34	6.25	7.40	8.16	9.12	9.69
	M	0.86	4.67	6.57	7.71	8.48	9.43	10.00

[a]Wall types: O = Mass wall with insulation *outside* of mass; I = mass wall with insulation *inside* of mass; M = mass wall with insulation and mass well *mixed*.

Regression Analysis of DOE-2.1B Data Base

In order to interpolate accurately between actual simulations in the data base of heating and cooling

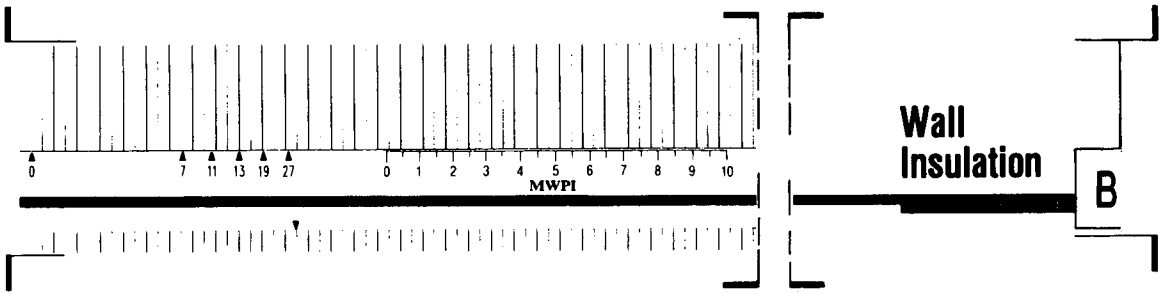


Figure 4. Wall insulation—Tab B for Phoenix, Arizona. (XBL 851-986)

loads of massive walls, we generated a set of equations using the linear and nonlinear regression procedures in *Statistical Package for the Social Sciences.*[6] We used the following linear model to predict the annual building heating and cooling loads for the case with wood frame walls:

$$\text{Load} = \beta_0 + \beta_1 U_T \quad ,$$

where

$\beta_{0,1}$ = regression coefficients;
U_T = total wall U-value (Btu/hr·ft^2·°F).

The following nonlinear model predicts the difference in load between a wood frame wall and a massive wall with the same total wall U-value:

$$\phi = e^{(\beta_0 \cdot HC)} \quad ,$$

$$\Delta\text{Load} = \beta_1 + \beta_2\phi + \beta_3 U_T + \beta_4 \phi U_T \quad ,$$

where

β_{0-4} = regression coefficients
HC = wall heat capacity (Btu/ft^2·°F)
U_T = total wall U-value (Btu/hr*ft^2·°F).

This model accounts for the exponential decay effect of wall heat capacity, the linear effect of wall U-value, and the interaction between these two effects. As shown in Fig. 5, the regression equations accurately predict the thermal mass effect of heavyweight exterior walls.

We used the results of these regressions to calculate the Mass Wall Performance Index, which is used on the slide rule. However, these equations are also useful in many other applications where it is necessary to calculate the heating and cooling loads of residential buildings with wood frame or massive exterior walls.

PLANNED ACTIVITIES FOR FY 1985

We will extend the thermal mass analysis into two important areas. First, we will add the multiple interactions between building design and mass effect to the regression equations. This will require an expansion of the data base to account for changes in window area, orientation, and glass type as well as changes in the building operating conditions. Second, we will examine the impact of climate more thoroughly to allow the results to be more broadly useful in climate zones beyond those actually simulated.

We plan to implement the FY1985 work in a microcomputer program (PEAR), that is now under development (see the article "Residential Energy Conservation: Microcomputer Program for Energy Analysis of Single-Family Houses"). PEAR will allow more flexibility and accuracy than the slide-rule format for predicting the performance of complex phenomena such as multiple-level interactions.

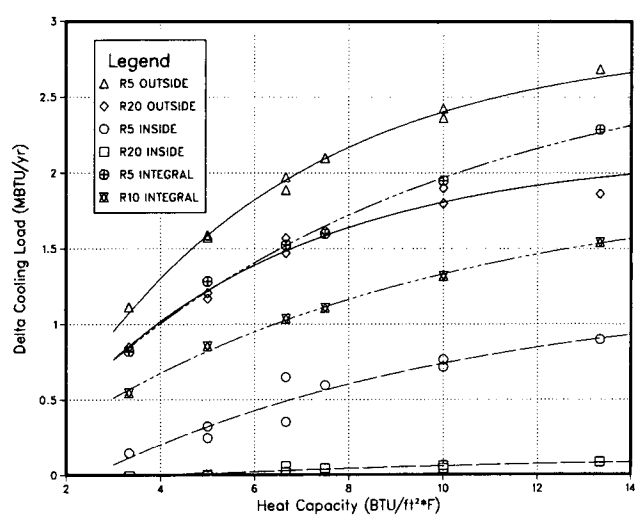


Figure 5. Heat capacity vs. delta cooling load for various massive walls (Phoenix). (XBL 851-995)

REFERENCES

1. Balcolm, J.D., *et al.* (1980), *Passive Solar Design Handbook, Vol. 2, Passive Design Analysis*, U.S. Department of Energy DOE/CS-0127/2, Washington, DC.
2. Barakat, S.A. and Sander, D.M. (1982), *Utilization of Solar Gain Through Windows for Heating Houses*, National Research Council of Canada, Division of Building Research, BRN 184, Ottawa, Ontario.
3. Energy Analysis Program (1983), *Affordable Housing Through Energy Conservation: A Guide to Designing Energy Efficient Homes, Technical Support Document*, LBL-16342 (Draft).
4. Building Energy Analysis Group (1982), *DOE-2.1B Supplement*, LBL-8706, Rev.3.
5. Construction Engineering Research Laboratory (1981), *Building Loads and System Thermodynamics Program (version 3.0)*, U.S. Department of Defense DE-AI01-79CS30301, Washington, DC.
6. Nie, H.N., *et al.* (1975), *Statistical Package for the Social Sciences*, 2nd ed.), McGraw-Hill Book Company, New York.

Home Energy Rating Tool*

Y.J. Huang, R. Ritschard, and C. Hsui

As part of a continuing effort to promote residential energy conservation,[1] the Building Energy Analysis Group is developing for the California Energy Commission (CEC) a simplified energy rating tool for existing houses to be used in a Home Labeling Demonstration Project. The labeling project will be voluntary and will assign numerical labels to houses according to their energy efficiency as calculated by the rating tool. Such labels would encourage home buyers to purchase more efficient properties and sellers to make energy improvements to their properties. In addition, if the ratings are accepted by financial institutions, they will make better loans on houses with better energy labels.

There are two major goals for the demonstration project: (1) to develop and field-test a simple and reliable tool for estimating the energy efficiency of typical existing homes and assigning ratings to them, and (2) to explore different ways of promoting home energy labels through organizations such as local energy offices, lending institutions, utilities, or real estate appraisers.

ACCOMPLISHMENTS DURING FY 1984

A key component of the Home Labeling Demonstration Project is the participation of representatives from the project communities of Roseville, Marin, and Pasadena, with each community intending to use a different process for disseminating and field-testing the rating tool. Since the success of the project will depend greatly on the degree to which its intended users (i.e., real estate agents, appraisers, or energy auditors) as well as the general public understand and accept the rating tool, we gave careful consideration to making it comprehensive and reasonably accurate, but also easy to use. We attended meetings with CEC staff and local representatives to determine local housing characteristics, typical kinds of conservation measures, and the kinds of technical data that can be gathered on a simple walk-through audit.

Although the demonstration labeling project is aimed at existing houses, the CEC staff requested that the rating tool produce energy values consistent with those from CEC calculations for new houses such as those in Title 24. We reviewed CEC methodologies and assumptions concerning building operating conditions, occupant use patterns, and domestic hot water usage and adopted them where appropriate. Test comparisons showed basic compatibility between the rating tool and earlier CEC work, although we did not achieve exact correlations (nor did we expect to) because of fundamental differences in analytical tools and methodologies.

We reduced the technical effort in developing the rating tool substantially by using analytical techniques developed in the course of earlier DOE-funded projects.† We performed parametric simula-

*This work was funded by the California Energy Commission under Contract No. 400-83-009, with facilities support provided by the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

†For details, see Energy Analysis Program Annual Reports for FY 1982 and FY 1983, in particular "Residential Energy Conservation: Developing a Guide for Homebuilders" by Ritschard *et al.* (1982) and "Simplified Energy Analysis: Slide Rules for Single-Family Houses" by Huang *et al.* (1983).

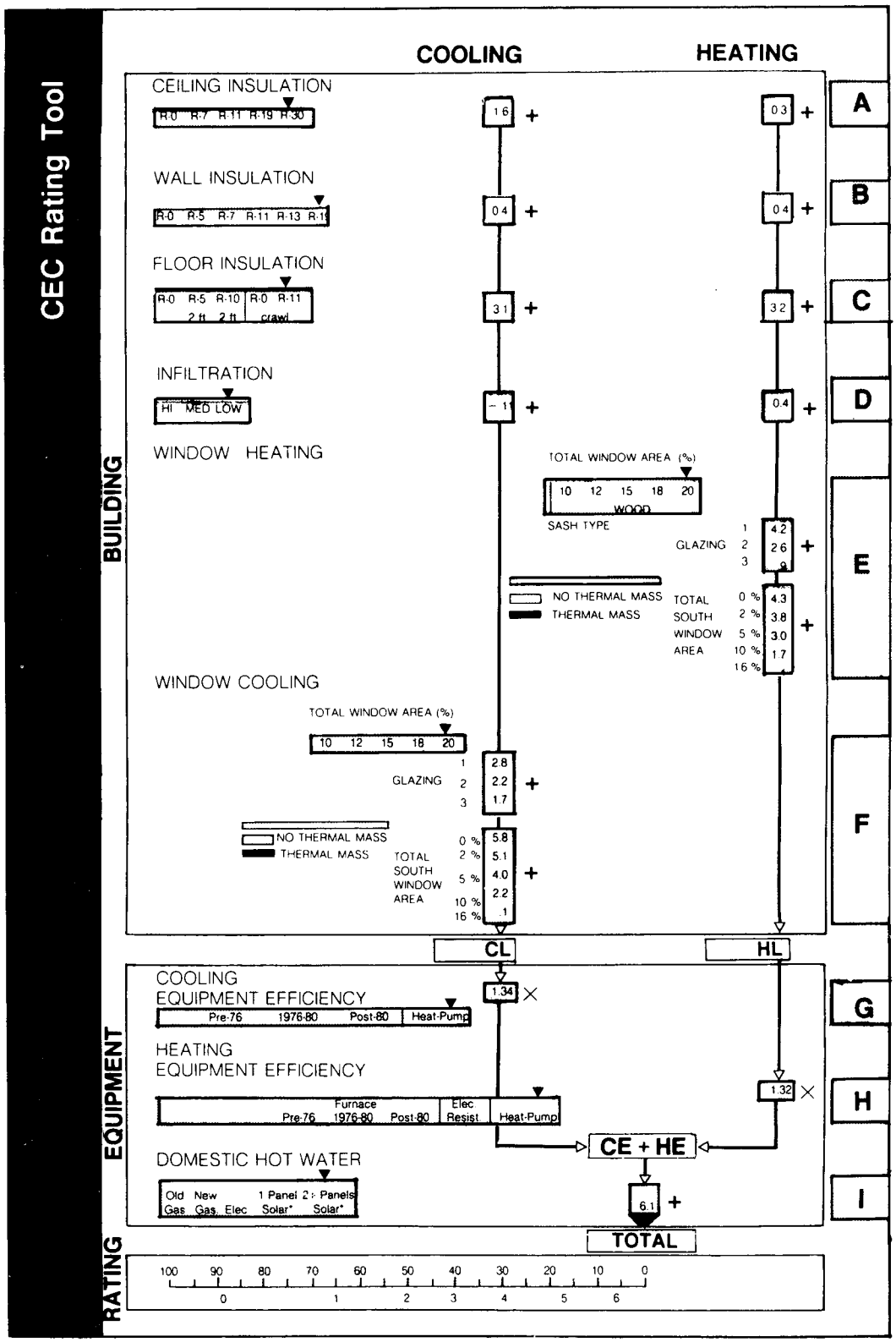


Figure 1. Draft of the home energy rating tool. (XBL 851-1027)

tions, using the DOE-2.1A computer program to calculate heating and cooling energies for two prototypical houses, a 1384-square-foot one-story and a 2240-square-foot two-story model, with differing conservation levels ranging from uninsulated houses to those substantially better than current construction practices. Because of the popularity in California of various passive solar measures, the data base also covered numerous window orientations, shading devices, and the use of thermal mass. For consistency with previous CEC work, we used CEC-designated climate zones and weather data for all computer simulations. Since the pilot cities are located in different climate zones, we made three sets of simulations, using data for Climate Zone 3 (Marin), 9 (Pasadena), and 12 (Roseville).

These computer results formed a raw data base that we then analyzed, using a methodology similar to our earlier DOE work, to derive the incremental energy savings per square foot of floor area for added conservation measures. We made the simplifying assumption that, except for thermal mass, incremental energy savings are independent and either additive for building shell improvements or multiplicative for equipment options. This assumption entails a small loss of accuracy but allows the data to be reduced to simple arithmetic operations that can be easily followed by someone without technical training.

We completed a draft version of the rating tool in late 1984 and presented working copies to the CEC for public review and comment (Fig. 1). The layout and operation of the tool are outwardly similar to those of the energy slide rules developed for DOE. The user aligns the tabs to the appropriate conservation levels and computes an energy rating by adding or multiplying the numbers appearing in the small windows to the right. These simple calculations are sequential and clearly indicated by the graphics on the rating tool. For documentation, there is an accompanying one-page rating sheet on which the user can record all calculations (Fig. 2).

The ten tabs cover variations in the following items: ceiling, wall, and foundation insulation, infiltration, windows, space conditioning system efficiency, and domestic hot water equipment. The window tables are more complex in order to cover the various window configurations found in typical houses, including total and south window areas, and the effects of thermal mass, roof overhangs, reflective glazings, and different sash types and glazing layers.

The calculation procedure is indicated by the heavy lines on the rating tool sleeve and requires only simple arithmetic. Heating and cooling energy use is calculated separately and then added to the estimated domestic hot water usage to produce a final house energy usage. This value is then converted into a rating ranging from 1 (poorest) to 6 (best). There will be a different rating tool for each pilot city because of differences in their climates.

PLANNED ACTIVITIES FOR FY 1985

Following comments from the public review period, we will make modifications to the rating tool, although we anticipate no major changes in its basic approach. We will complete final versions for all three pilot locations in early 1985 and then submit

CALIFORNIA HOME RATING AND LABELING DEMONSTRATION PROJECT
California Energy Commission (Pilot Project)
DRAFT CERTIFICATION FORM

Address of Home
Street _____
City/Zip _____

Assigned Climate Zone ____

Building Characteristics		Cooling Load	Heating Load
Number of Levels	1 2		
Ceiling Insulation	_____	_____	_____
Wall Insulation	_____	_____	_____
Floor Insulation	_____	_____	_____
Infiltration	_____	_____	_____
Thermal Mass	Y N		
Window Glazing	_____	_____	_____
South Window Area	_____%	_____	_____
SUBTOTAL		_____	_____
EQUIPMENT EFFICIENCY	A.C. x_____		Heat x_____
TOTAL		_____	_____

Total Cooling & Heating Load: _____

Domestic Hot Water: _____ + _____

HOME'S TOTAL ENERGY CONSUMPTION _____

ADDITIONAL ENERGY CONSERVATION FEATURES*

CREDIT FOR SET-BACK THERMOSTAT	Y	N	-1.0
CREDIT FOR LOW-FLOW SHOWERS	Y	N	-1.0
CREDIT FOR OUTLET GASKETS	Y	N	-1.0
CREDIT FOR WATER HEATING BLANKET	Y	N	-1.0
CREDIT FOR SHADING SCREENS/FILSM	Y	N	-1.0

FINAL TOTAL _____

ASSIGNED RATING _____

Name of Certifier (Print) _____ Signature _____

Affiliation _____ Date _____

Signature of Individual Receiving Sticker _____

*
Features and values listed only as examples.

Figure 2. User's sheet for recording home energy rating calculations.

them to the CEC for printing and use in the demonstration phase. At the same time, we plan to expand the scope of the work so as to produce a complete set of rating tools for all 16 California climate zones. We expect to begin this work during the demonstration period for the pilot rating tools and complete it in 1985.

REFERENCE

1. Energy Analysis Program (1983), *Affordable Housing Through Energy Conservation: A Guide to Designing and Constructing Energy Efficient Homes, Technical Support Document,* LBL-16342 (Second Draft).

Saving Energy the Easy Way: An Analysis of Thermostat Management*

E. Vine and S. Gold

Lawrence Berkeley Laboratory has been investigating the effects of occupant behavior on residential energy use since 1980. The principal objective has been to improve our understanding of the determinants of energy use in occupied houses. In the past year, we focused our research on thermostat management, one of the most effective and least expensive means of reducing household energy use.

ACCOMPLISHMENTS DURING FY 1984

The monetary savings of thermostat management can be substantial: it has been estimated that $5 billion has been saved annually in the United States due to changes in home thermostat use since the oil embargo of 1973.[1] Of course, this type of behavior may be merely transitory, and if people believe the energy shortage has ended, then they may start to keep their homes warmer in the winter and cooler in the summer, reducing or eliminating the $5 billion annual savings. This "rebound effect" may have already occurred for some households that have weatherized their homes; they may now feel that they can increase their indoor comfort level since the cost of their comfort is perceived to be less than before weatherization. Thus, there is a need to determine how households are managing their thermostats in order to estimate the potential for energy reduction in homes.

Another reason for examining thermostat settings in detail is to explore the amount of variability in the way people manage their indoor comfort. Although average thermostat settings may be useful for modeling energy use in unoccupied homes, estimating energy use for a large sample of occupied homes, and evaluating the impact of an energy-reducing program for a utility service area, they are not appropriate for estimating energy use in individual homes. Previous work in this area has shown that a few degrees difference can have a substantial impact on the energy consumed in the home. A difference of several degrees can affect consumers' willingness to invest in energy-efficient products. Thus, knowledge of the amount of variability in thermostat settings will be useful, for example, in performing sensitivity analyses to estimate energy- and cost-effectiveness of energy retrofits for individual households, utilities, and the nation.

Thermostat settings are also useful as indicators of the type of energy-reducing behavior being practiced by individuals. Thermostat management is usually one of the first actions an occupant takes in reducing energy in the home and is often the predecessor for more time-consuming and expensive measures such as ceiling and wall insulation. Moreover, by examining the correlates of thermostat settings (e.g., size of a dwelling, household income, and age of the respondent), one can improve the marketing of energy-reduction programs by focusing on variables that are highly correlated with thermostat management.

Ideally, one would like to monitor the indoor temperatures of residential households to determine if people are adjusting their thermostats to reduce energy use. However, the metering of thermostats is expensive and time-consuming: there have been few studies that monitored indoor temperatures.[2] A less expensive, albeit less reliable, surrogate for measuring indoor air temperature is the occupant-reported thermostat setting. In previous work, we have shown that self-reported thermostat settings do help to explain energy-use variations among households.[3,4] Relying on self-reported data, however, raises some methodological and validity issues:

*This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Buildings Energy Research and Development, Building Systems Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

without objective confirmation, one does not know the veracity of an individual's reported behavior. Anecdotal data suggest that there is a discrepancy between self-reported thermostat settings, actual thermostat settings, and indoor temperatures. So far, no one has been able to estimate accurately the relative importance of two possible sources of error—instrumentation error and respondent reactivity—to account for this discrepancy.† Until we have a more reliable method of measuring indoor temperatures, self-reported data will remain useful for improving our understanding of thermostat management.

We analyzed data on self-reported winter and summer thermostat settings and thermostat control strategies that were collected in recent surveys by utility companies and state and federal energy agencies, and in our own studies at LBL. We were interested not only in the distribution of thermostat settings but also in the dynamics of thermostat management (e.g., how people change thermostat settings during the day or from season to season). We examined how thermostat management was related to the following occupant-related features: socioeconomic characteristics of occupants (age, education, income, home ownership, and race), building characteristics (house type, size, and age), space conditioning fuel and system, climate, and energy audit programs. We also examined thermostat management over time (during the day, seasonally, and yearly) and analyzed its relationship to energy use.

We developed a conceptual model of thermostat management to examine these variables. We believe that the primary sociodemographic variables (age, education, income, and race) affect the type, size, and age of the dwelling one occupies. This, in turn, affects the type of space conditioning system and fuel used in the home. The primary sociodemographic variables also affect one's chance of owning a home. The chance of receiving an energy audit is affected by many of these variables. Winter and summer thermostat settings and thermostat control are affected by all of the above variables in addition to being influenced by climate and history (year). Similar relationships should also affect energy use during specific periods of the day. Using this model, we constructed several hypotheses on the relationship between thermostat management and its correlates. We developed these hypotheses on the basis of our experience with the energy-use literature, discussions with experts in the field, and common sense. In several cases, we included competing hypotheses (excluding the null hypothesis) to indicate alternative relationships. A complete description of these hypotheses is given elsewhere.[5]

We found that thermostat behavior (especially during the summer) is not fixed, but varies and is sensitive to some conditions (Table 1). The results strongly support three summer thermostat management hypotheses and partially support two winter thermostat management hypotheses. Certain groups—younger people, better educated individuals, audited households, multi-family households, and residents of warmer climates—reduced energy use at a greater rate than their counterparts. Households lower and raise their thermostats during the day and during different seasons and also shut off their heating and air conditioning systems when their homes are unoccupied. In fact, many households reported settings below 68° in the winter and above 78° in the summer, the standard temperatures used in many energy models and programs.

We were unable to find consistent relationships between self-reported thermostat settings and several other variables (e.g., income, home ownership, dwelling size, and race). We experienced difficulty in interpreting the relationships between thermostat behavior and its correlates for a number of methodological reasons:

1. In many cases—black households, younger households, and low income groups—the sample sizes are very small, and small sample sizes make it very difficult to obtain statistically significant relationships.
2. The results are based on responses from only one member of each household; answers on thermostat-setting activity may, therefore, be skewed and may not accurately reflect how a respondent's household is actually behaving: that is,

Table 1. Significant correlates of thermostat management.

	Winter thermostat settings		Summer thermostat settings	
Variable	Lower (cooler)	Higher (warmer)	Lower (cooler)	Higher (warmer)
Age	—	—	Older	Younger
Education	—	—	Less	More
Dwelling type	Multi-family	Single-family	—	—
Energy audit	—	—	Non-audited	Audited
Climate	Warmer	Colder	—	—

†An example of instrumentation error is changes in the calibration of a thermograph used to measure indoor temperature, producing changes in the obtained measurements. An example of respondent reactivity is when respondents seek to impress the interviewer and to give socially desirable responses.

thermostat management may be a family or household decision rather than an individual decision.

3. Self-reported data are known for their methodological limitations; without objective confirmation, one does not know the veracity of an individual's reported behavior. These methodological problems may make this kind of data unreliable for statistical analysis. In fact, the self-reported incidence of energy-reducing actions was reported in one study as uniformly (and suspiciously) high, indicating a possible upward bias.
4. Diverse methods were used to collect the thermostat data (mail questionnaire, telephone interview, and face-to-face interview), making it difficult to synthesize the findings from these studies. Different types of samples and different sampling periods also make it difficult to arrive at a consensus.

In addition to these methodological problems, we encountered an interpretation problem: the data in several studies contradicted one another, making it difficult to draw general conclusions. For example, one study reported higher summer settings in single-family houses than in multi-family dwellings, while another study found higher summer settings in multi-family homes. This indeterminacy may reflect regional differences, or it may be the result of competing hypotheses. Finally, for many of the hypotheses, the number of studies available was small, leading to greater uncertainty.

We believe we need a more reliable method of measuring indoor temperatures. Advances in metering technology and computerized data collection and analysis offer the potential of measuring occupant behavior relatively inexpensively and efficiently. The problems of intervention in the household remain, but the potential rewards are great. Metered temperature and thermostat setting data should provide a more reliable and accurate measure of indoor temperatures and thermostat management than self-reported data.

It is also important to note that one of the key differences between energy-reducing practices (e.g., lowering thermostat settings) and measures (e.g., installing attic insulation) is that the former are relatively transitory while the latter are relatively permanent. Several studies have reported an attrition in energy-reducing behavior over the last 3 to 5 years. Also, one study found that all energy-reducing practices had dropped over a 4-year period while all of the more permanent energy-reducing measures had increased. Nevertheless, there seems to be room for improvement in reducing energy through air-conditioning and heating practices.

PLANNED ACTIVITIES FOR FY 1985

Until new metering technology is used on a more widespread basis, we should continue to monitor thermostat behavior to improve the accuracy of our energy models, the effectiveness of our energy programs, and our understanding of occupant behavior and energy use. To further these objectives, we plan to conduct a multivariate analysis of self-reported thermostat settings in Davis and Lodi, California, and Pensacola, Florida, and we intend to test the sensitivity of variations in thermostat settings on energy use with computer models developed at LBL.

REFERENCES

1. Kempton, W. (1983), "Two Theories Used for Home Heat Control," presented at the Families and Energy Conference, Michigan State University, East Lansing, MI, October 1983.
2. Vine, E. (1983), *A Survey of End Use Metering in the United States*, LBL-16322.
3. Vine, E. *et al.* (1982), "The Applicability of Energy Models to Occupied Houses: Summer Electric Use in Davis," *Energy 7*, p. 909.
4. Cramer, J. *et al.*(1984), "Structural-Behavioral Determinants of Residential Energy Use: Summer Electricity Use in Davis," *Energy 9*, p. 207.
5. Vine, E. (1984), *Saving Energy the Easy Way: An Analysis of Thermostat Management,* LBL-18085, in press.

Parametric Energy Analysis in Support of ASEAN Energy Conservation Standards for Office Buildings*

I. Turiel, R. Curtis, and M.D. Levine

Energy use in commercial buildings is an important economic issue for the member countries of ASEAN, the Association of Southeast Asian Nations. In 1979, the government of Singapore, a member of ASEAN, established energy conservation standards for new commercial buildings. These standards consist of maximum allowable lighting loads and maximum allowable overall thermal transfer values (OTTV) of the building envelope and roof.[1] Owners of existing buildings may write off in one year the cost of conversion work to conform to the prescribed OTTV. Consumers of electricity in buildings that have not achieved the standard must pay a tax surcharge of 20% on electricity bills as of January 1, 1982.

Under the Second ASEAN–U.S. Energy Project, Singapore was designated the focal point for the subproject on Energy Conservation in Buildings. The U.S. Agency for International Development (AID) arranged for a project team from the Lawrence Berkeley Laboratory (LBL) to undertake this subproject in close consultation with the Development and Building Control Division of the Public Works Department of Singapore, the subproject coordinator. In the latter part of 1982, members of the LBL Energy Analysis and Energy Efficient Buildings programs initiated a joint effort with the Singapore government to assess the effectiveness of the present Singapore standards for office buildings and to update these standards where appropriate.

Commercial buildings account for about 32% of electricity consumption in Singapore.[2] In 1981, total electricity consumption reached 6.66×10^9 kWh with a demand growth rate of 7.9% and 7.5% per year in 1980 and 1981, respectively.[3] Singapore's electricity is generated with imported oil, and half of all the oil it imported in 1980 was used to generate electricity. If we assume a price of \$0.105/kWh (U.S. dollars) and an annual growth rate of 7% for 1982–1983 (so that total 1983 consumption is 7.6×10^9 kWh), the cost of electricity for operating commercial buildings (primarily cooling and lighting) in Singapore for 1983 is about:

$$\$0.105/\text{kWh} \times 0.32 \times 7.6 \times 10^9 \text{ kWh/yr}$$

$$= \$255 \times 10^6/\text{yr} \quad .$$

Therefore, a 10% reduction in energy use in commercial buildings would save \$25 million per year in energy costs. This large potential for additional energy savings and the concomitant decrease in oil imports have motivated the joint effort between the Development and Building Control Division of Singapore and LBL.

METHODOLOGY

We chose a building design based on the reference building described in the *Handbook on Energy Conservation in Buildings and Building Services*, a document published by the Singapore Public Works Department along with its building energy standards in 1979.[1] In our discussions with representatives of the Department's Development and Building Control Division (DBCD), some modifications to the design characteristics of the typical office building described in the Handbook were suggested. The final reference building design was jointly agreed upon by DBCD and LBL.

The base-case design is a 10-story office building with a total conditioned area of 5200 m^2. It has a window-to-wall ratio of 44%, and the shading coefficient of the windows is 47%. The lighting power density is 20 W/m^2 in occupied areas. A variable air volume system was modeled with a minimum air flow rate ratio of 0.5. A chiller with a coefficient of performance (COP) of 4.5 (excluding fans and pumps) provides chilled water to the cooling coils. Details of construction characteristics and occupancy and system operating schedules can be found in an LBL report.[4] The DOE-2.1B computer program for the energy-use analysis of buildings was selected because of its ability to simulate a wide variety of potential energy conservation measures in buildings and because it has been widely tested for accuracy.[5]

A Singapore weather tape for 1979 was obtained from the National Climatic Center. This tape contained hourly data for dry-bulb temperature, wet-bulb temperature, wind velocity, and cloudiness. Hourly solar insolation data for direct and diffuse radiation were obtained from data collected in Singapore.[6]

There is little seasonal variation in dry-bulb temperature. The difference between average daily max-

*This work was supported by the U.S. Agency for International Development through the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

imum and minimum temperatures varies from about 4.5° to 6°C throughout the year, a very narrow range. On an average day, the dry-bulb temperature increases from approximately 25° to 30°C. The relative humidity is very high in the early morning hours, dropping to about 74% in the afternoon (4 p.m.). These climatic data indicate that the dry-bulb temperature difference is not expected to be a driving force on building loads in Singapore. The cooling loads due to outside air moisture removal, on the other hand, can be significant.

RESULTS OF PARAMETRIC ENERGY ANALYSIS

The parameters with the greatest impact on energy use were those that affected lighting loads and solar gain. This was predicted by DOE-2.1B. (The simulated base-case heating and cooling load components are summarized in Fig. 1.) Solar gains and heat from lights together account for 50% of the cooling loads in the base-case building. The load from ventilation air is approximately 16% of the total cooling load, while heat conduction across the walls and windows together account for another 16%. The right-hand side of Fig. 1 shows the energy used for lighting, miscellaneous electrical equipment, cooling, and ventilation. The cooling energy use (36%) is the electrical energy consumed by chillers and cooling towers to remove the heat from occupied spaces. Most of the energy used to run fans and pumps (17.4%) is also for cooling. A small fraction of fan energy supplies outside air to building occupants.

In Fig. 2, we have ranked the conservation measures considered in this study. For each measure, the relevant parameter was varied from its base-case value to a value that was readily achievable in a technical sense. As can be seen in Fig. 2, the use of daylighting, lighting reductions, external shading, and window-to-wall ratio reductions produce the greatest decreases (20% to 6%, in order of impact) in total energy use. Roof and wall insulation, roof and wall solar absorptivity, glass conductance, and infiltration all affect total energy use insignificantly (<2%). Shading coefficient, cooling setpoint, and ventilation rate have intermediate (2–4%) impacts.

Lighting and three factors that affect insolation—window-to-wall ratio (WWR), shading coefficient (SC), and external shading—were among the parameters studied in detail. Total energy use decreases linearly as lighting power, window-to-wall ratio, or shading coefficient are reduced. Total energy use decreases with increased window setback ratio, but the rate of decrease is not constant. When

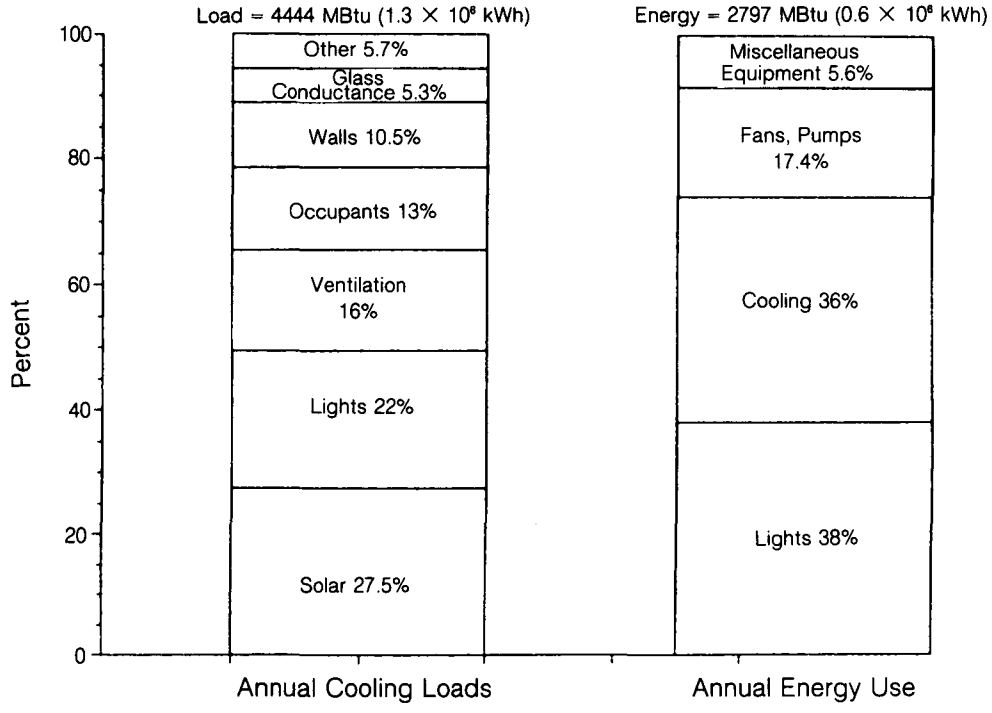


Figure 1. Base-case building cooling loads and energy use components shown as percentages of total.
(XBL 841-67)

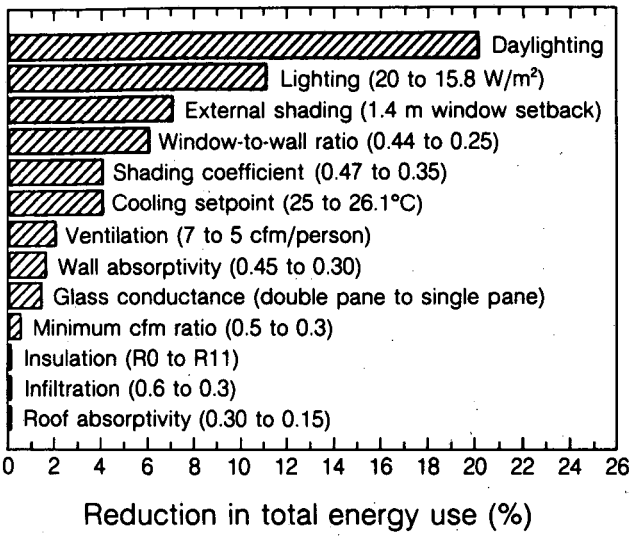


Figure 2. Conservation measures ranked by percentage reduction in total energy use. (XBL 841-68A)

two or more insolation measures are performed simultaneously, the energy-use reduction is less than the reduction predicted by simply adding the reductions resulting from each measure.

In addition to the parameters discussed above, detailed analyses were performed on the use of daylighting and the effectiveness of the OTTV formulation in reducing energy use. These analyses are discussed below.

Daylighting

Daylighting is one method of reducing lighting energy use. Photoelectric sensors in the perimeter zones of a building detect the magnitude of daylight availability. Electrical lighting in those zones is then reduced to maintain a fixed total of electric-plus-daylight lighting intensity. Since an important goal is to minimize total energy consumption, both lighting and cooling energy use must be considered.

Our parametric analysis of daylight as a substitute for artificial lighting required a large series of simulations; to make this task easier, we used a module or subroutine prepared by the LBL Windows and Daylighting Group to represent a typical floor in a multistory building. The floor has a square core zone surrounded by four identical perimeter zones, each 4.6 m (15 ft) deep. Three levels of light intensity—30, 50, and 70 footcandles (fc), from electric lighting and natural daylight in combination—are provided for at a distance of 3.08 m (10 ft) from the window all along the perimeter. Two lighting control strategies—continuous dimming and step dimming—were studied.

Eight sets of parametric runs were carried out. We modeled the single floor with and without external shading and with and without step or continuous daylighting. There were 20 runs in each set. The variables were window-to-wall ratio (WWR), shading coefficient (SC), glass conductance (GC), and wall insulation R-value. The visible transmittance was assumed to be equal to 67% of the shading coefficient, a reasonable assumption for glass with a shading coefficient around 0.50.[7] For clear glass, the visible transmittance may be 90% of the shading coefficient. Lighting energy use and chiller load are calculated for each of the five zones in the module.

Figure 3 illustrates the percentage lighting energy savings in the perimeter of the daylighting module (continuous dimming) for the case of no external shading. Three values of desired lighting intensity (30, 50, and 70 fc) were assessed. Since the lighting energy savings were very similar for all four orientations in the building perimeter, we plotted the total lighting energy savings for the whole perimeter as a function of the product of window-to-wall ratio and visible transmittance, WWR × TVIS. TVIS is equal to the fraction of solar radiation in the visible portion of the spectrum that is transmitted through the glazing. For our studies, we assumed that TVIS equals 0.67 times the shading coefficient. This is reasonable for double-pane but not for single-pane windows. Expressing the results as a function of TVIS allows the user to choose his or her values for TVIS according to the glazing selected.

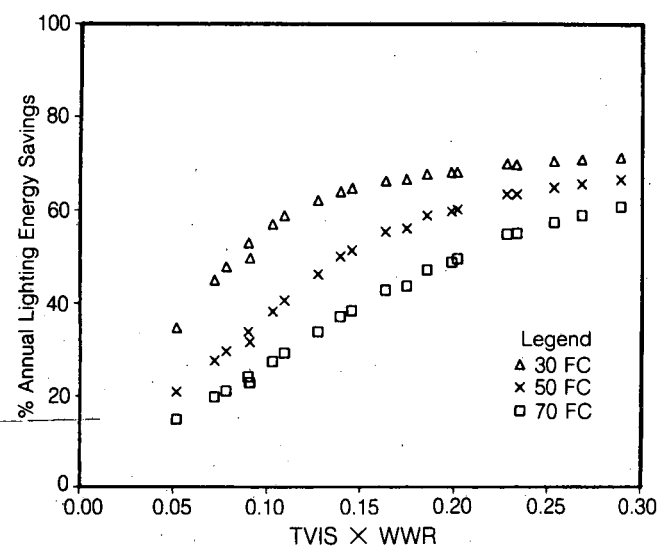


Figure 3. Percentage lighting energy savings from use of daylighting for three lighting intensities; shown as a function of TVIS × WWR. (XBL 841-69)

Smooth curves are obtained in all three cases that show lighting energy savings initially increasing linearly with WWR × TVIS and then beginning to level off. This indicates that, at high daylight levels (high WWR × TVIS), not all of the daylight can be used to reduce artificial lighting levels; i.e., during some hours the artificial lighting has already been reduced to zero, and additional daylight only adds to the cooling load. Lighting energy savings increase more rapidly with WWR × TVIS for the module without external shading. For example, at WWR × TVIS = 0.14 (base-case building), for a desired lighting intensity of 50 fc, the savings is 58% without external shading and 50% with shading. The differences between buildings with and without external shading diminish as WWR × TVIS increases. The maximum lighting energy savings can only reach about 70% because of artificial lighting during non-daylight hours. As expected, the annual savings is greatest for the lowest lighting intensity (30 fc) and least for the highest (70 fc). We have applied the results of this daylighting analysis to the reference building.

For the reference building with daylighting, as WWR × TVIS increases in magnitude, cooling energy use increases and artificial lighting energy use decreases. Total energy use shows a very shallow minimum at WWR × TVIS = 0.10 and steadily increases with higher values of WWR × TVIS. Therefore, for office buildings without overhangs, very low values (~0.13) of WWR × TVIS are optimum as regards total energy use. For the base-case reference building, WWR × TVIS has a value of 0.14, corresponding to a WWR of 0.44 and tinted double glazing with a shading coefficient of 0.47. There is a 20% energy savings resulting from the use of daylighting in the base-case reference building. Even at high values of WWR × TVIS, daylighting gives substantial (18%) energy savings relative to the base-case building.

For the building with external shading, the total energy savings with daylighting are dependent on WWR × TVIS, but total energy use is almost independent of it. Although the maximum total energy savings (~20%) are similar for daylighting with or without fixed shading, there is a significant advantage to shading. Shading allows much more flexibility in choosing the values of WWR and SC. In particular, buildings with larger window-to-wall ratios are possible without any energy penalty if shading is incorporated into the daylighting strategy.

A daylighting analysis for step lighting as a control strategy was also performed, and two other aspects of daylighting were investigated: (1) the amount of external shading and (2) occupant behavior in the use of internal shading. The results are discussed in Ref. 4.

Overall Thermal Transfer Value (OTTV) Analysis

Thus far, we have mostly considered the energy impact of conservation measures taken one at a time. We now turn our attention to a building envelope thermal standard that considers insolation, glass conductance, and wall conductance simultaneously. Singapore's building standards currently require that air-conditioned buildings have an OTTV less than 45 W/m^2. The OTTV concept takes into account the three basic heat gains that occur through the external walls of a building:

(1) heat conduction through opaque walls;
(2) heat conduction through glass windows;
(3) solar radiation through glass windows.

The OTTV of an external wall depends upon four factors: window-to-wall ratio, shading coefficient, window U-value and wall U-value. (U-value determines heat loss or gain through various materials.) We have studied the energy-use impact of constructing office buildings with various OTTVs.

To determine if cooling energy use is linearly related to OTTV, we performed a series of simulations where OTTV was varied by altering the window-to-wall ratio, shading coefficient, and window and wall U-values. These simulations were performed with the daylighting module at the same time the daylighting parametrics were carried out. The load (in MBtu) that must be satisfied by the chiller was plotted as a function of OTTV. Separating out the simulations according to the value of α, the solar energy fraction of the OTTV, results in four separate straight lines. We define α as follows:

$$\alpha = \frac{130(\mathrm{WWR})\,(\mathrm{SC})}{\mathrm{OTTV}} \quad .$$

Another approach is to redefine OTTV so that an equation linear in OTTV can be used to fit the data thus far described by four separate equations, one for each value of α. We tried various additions to the last term in the OTTV expression, increasing the importance of solar gain relative to conductive heat transfer across the windows and opaque walls.

We found that the greater the relative importance of the last term (solar radiation) in the OTTV equation the better the correlation between cooling energy use and OTTV. This led us to determine the

correlation coefficient when a linear regression is performed for cooling energy use versus WWR × SC. That is, we eliminated the first two terms in the OTTV formulation. Figure 4 shows the result of this regression analysis. The correlation coefficient is 0.993. When a linear regression analysis was carried out using the original OTTV definition, the correlation coefficient was 0.948. The implication is that the last term of the OTTV equation is sufficient to explain 98.6% of the variation in cooling energy use, whereas the original OTTV equation (with three terms) explains only 90% of the variation. Therefore, including the first two terms in the equation worsens the ultimate prediction of cooling energy use by OTTV.

It remains to calculate the correct solar factor (SF) to be used in this new formulation of OTTV. To do this, we used the regression equation obtained from considering the chiller load (excluding fan energy) as a linear function of WWR × SC. As can be seen in Fig. 4, a straight line results. The equation of this line is:

$$\text{Chiller Load} = L_o + (B \times \text{WWR} \times \text{SC})$$

where $B = 1034$ MBtu/yr,
$L_o = 780$ MBtu/yr.

The values for B and L_o are derived from DOE-2.1B runs. B represents the slope of the line in Fig. 4 and is the amount of solar radiation (in W/m^2) incident on a vertical surface; L_o equals the chiller load from lights, people, and equipment and conductive loads

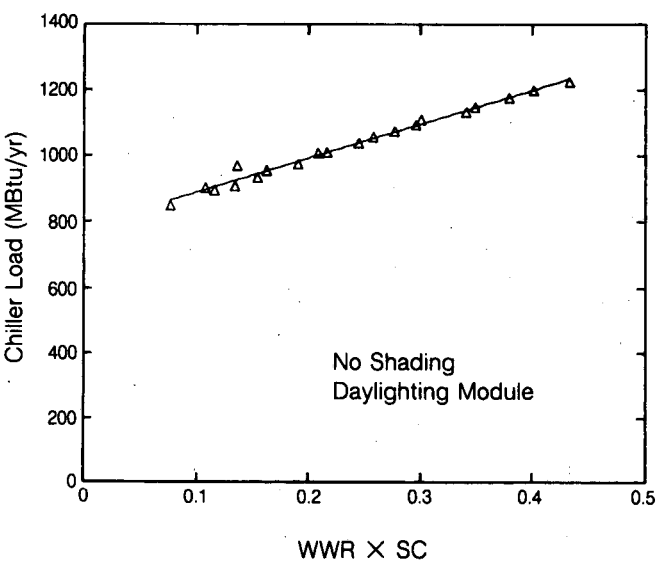


Figure 4. Chiller load plotted as a function of WWR × SC for a single-story module. (XBL 841-70)

from windows, walls, and roof. If we assume that all of the solar gain results in a cooling load for the chiller to remove, then we can equate the variable term in the equation above to the heat gain from insolation. Therefore:

$$1034 \times \text{WWR} \times \text{SC} = A_{\text{walls}} \times \text{WWR} \times \text{SC} \times \text{SF}$$

where SF is the solar factor or the average power (in watts) incident on each square meter of vertical surface. Solving for SF we find that:

$$\text{SF} = \frac{\left(1034 \text{ MBtu/yr}\right)\left(293 \text{ kWh/MBtu}\right)}{\left(454.5 \text{ m}^2\right)\left(3050 \text{ h/yr}\right)}$$

$$= 218 \text{ W/m}^2 \ .$$

We have calculated the number of cooling hours to be equal to 3050 hours per year if the chiller is on from 6 a.m. to 5 p.m., Monday through Friday, and from 6 a.m. to noon on Saturdays. The total wall area is 454.5 m^2.

The estimated value of 218 W/m^2 for the solar factor is within 10% of the values estimated from the weather tape. If the diffuse radiation is assumed to be anisotropic, weather-tape analysis gives a value for SF of 232 W/m^2 for the hours 8 a.m. to 5 p.m. and 210 W/m^2 for 7 a.m. to 6 p.m. The consistency of these two approaches to calculating the solar factor reinforces our belief that OTTV (in W/m^2) should be redefined for the Singapore climate as follows:

$$\text{OTTV} = 220 \times \text{WWR} \times \text{SC} \ .$$

ACCOMPLISHMENTS DURING FY 1984

A major symposium presenting the results of the study was held in Singapore in May 1984. The symposium was attended by more than 300 persons, including representatives of all countries of the Association of Southeast Asian Nations. We conducted analyses to relate the results of the Singapore work to other ASEAN members. We also participated in a planning exercise with ASEAN and AID participation to extend the work throughout ASEAN.

PLANNED ACTIVITIES FOR FY 1985

The effort for 1985 and beyond involves the development of commercial building energy standards or other policies for other countries within

ASEAN. The research, to be done jointly with researchers from ASEAN, will include gathering and analysis of weather data, performance of hourly computer simulations, development of procedures for energy audits, analysis of a large number of conservation options for improving energy efficiency of buildings, and the development and presentation of educational material for ASEAN researchers and policy analysts on these topics.

REFERENCES

1. Public Works Department, Building Control Division (1979), *Handbook on Energy Conservation in Buildings and Building Services,* Singapore.
2. Low Kok Hing (1979), article in *Seminar on Energy Conservation,* Science Council of Singapore, pp. 27–34; Manufacturers Association and Public Utilities Board, Singapore.
3. Public Utilities Board (1981), *Annual Report,* Singapore.
4. Turiel, I., Curtis, R.B., and Levine, M.D. (1984), *Parametric Energy Analysis in Support of Singapore Energy Conservation Standards for Office Buildings,* LBL-17427.
5. *DOE-2 Reference Manual,* Parts 1 and 2, Version 2.1B (1980), National Technical Information Service, Springfield, VA 22161.
6. Solar data was collected by Professor K.R. Rao of the Department of Building Science, National University of Singapore.
7. Technical data from Libby-Owens-Ford on single-, double-, and triple-pane glazing.

Energy Conservation in Public Housing: A Case Study*

C. Goldman† and R. Ritschard

Improving the energy efficiency of buildings will demand increasing attention from public housing officials in this decade. Rising energy costs have created an ever-widening gap between allowable expenses and rental income collected by local housing authorities. A recent review of the topic concludes that a great potential exists for energy and cost savings in public housing.[1] Over the last decade, the U.S. Department of Housing and Urban Development (HUD) and local public housing authorities (PHAs) have sponsored major retrofit projects. Savings estimates for these programs, however, have been based almost exclusively on engineering calculations; only a few evaluations of public housing retrofit efforts have relied on actual metered data. Evaluations based on metering are more desirable because they provide credibility and important feedback on the accuracy of predictions, help guide retrofit investment decisions, and often raise issues that deserve further analysis.

This article, which summarizes a more detailed LBL report,[2] describes part of DOE's long-term program to improve energy efficiency in federally assisted housing. We present a summary of a case study of one local housing authority, that of San Francisco, that developed a cooperative effort with the local utility to finance specified energy conservation measures through a zero-interest loan program (ZIP). We analyzed utility bills over a 3-year period at five housing projects, including 1 year of post-retrofit data, in order to estimate energy savings attributable to the weatherization program. These five projects represent roughly 30% of the dwelling units managed by the San Francisco Housing Authority (SFHA). The projects are occupied by families and are master-metered; thus, tenants do *not* pay utility costs directly.

Several important public policy and research issues are addressed in this study. First, there is a pressing need to determine more effective approaches for the selection, marketing, and financing of energy conservation retrofits in public housing. The SFHA is one of the first public housing authorities to fund energy-efficiency improvements by using a utility-sponsored conservation program. Such innovative financial strategies are necessary to overcome existing institutional barriers and tight budgetary constraints. Second, most of the nation's public housing units are multi-family buildings, a sector that has, until recently, received much less

*This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Buildings Energy Research and Development, Building Systems Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

†Buildings Energy Data Group of the Energy Efficient Buildings Program.

attention and research effort than single-family buildings.

ACCOMPLISHMENTS DURING FY 1984

The installation of conservation measures is just one of many factors that affect a building's energy consumption. Some factors will have a small effect, while others, such as seasonal weather variation and the number of units occupied, must be accounted for explicitly. We used the Princeton Scorekeeping Method (PRISM) to determine a weather-adjusted index of consumption, called normalized annual consumption (NAC).[3] The NAC is the energy consumption predicted for a year with average weather based on consumption data from any particular year.[4] The Scorekeeping method has been extensively used to estimate energy savings from conservation retrofits installed in single-family homes, although it has not been applied to multi-family buildings in mild climates. The data requirements of the Scorekeeping model include utility bills for periods before and after the retrofit and average daily temperatures from the local weather station during the same time intervals. The Housing Authority provided us with monthly utility bills for the period from April 1981 to March 1984. We obtained daily average temperatures from the National Oceanic and Atmospheric Administration weather station at San Francisco Airport, from which heating degree-days to different reference temperatures were computed. We estimated weather in an average year by using Test Reference Year data from the San Francisco Airport weather station.

Energy Savings

We calculated gas savings in two ways—by changes in the normalized annual consumption between the two periods and by changes relative to a comparison group (i.e., net savings). Table 1 summarizes individual project and aggregate results. Normalized annual consumption (NAC) at the five projects decreased by an average of 12 MBtu/unit after retrofit. The program achieved net energy savings of 6.6 MBtu/unit, a 6% reduction, if changes in consumption that occurred in projects with similar characteristics (Valencia and North Beach) are considered. Energy savings varied widely, ranging from 9% of pre-retrofit consumption at Alemany to 20% at the Alice Griffith site. Figure 1, as an example, shows pre- and post-retrofit normalized energy consumption at the Alemany site. Energy use actually increased by 10% after retrofit at Hayes Valley. The level of savings correlated more strongly with pre-retrofit usage levels than with the amount invested: projects with the largest savings also had the highest energy usage per unit before implementation of the program.

The disappointing results at the Hayes Valley project can be explained in part by the fact that the installed retrofit measures had lower potential energy savings. For example, at three-story Hayes Valley, only one-third of the units had direct contact with an insulated attic. This contrasts with the two-story townhouses of Alemany, Sunnydale, and Alice Griffith, where every apartment has an attic exposure. Hence, the predicted savings for attic insulation at Hayes Valley are lower, on a per-unit basis, than for other projects because of these differences in building characteristics. In addition, no hot water conservation measures were installed at the Hayes Valley sites, retrofits that appear to be quite effective at other projects. Finally, a recent on-site inspection at Hayes Valley revealed that the boiler time clocks were not operable on at least one of two boilers.

Economic Analysis

We used two indicators of cost-effectiveness in the economic analysis, simple payback period and net present value (NPV). The simple payback time is the period required for the undiscounted value of the energy savings, at today's energy prices, to equal the original investment. The net present value of an investment is the difference between the present value of benefits and costs. A worthwhile investment has an NPV greater than zero. In calculating net present value, we assumed that the real discount rate was 7%, that gas prices would increase at a real rate of 1.8% (based on California Energy Commission forecasts), and that the retrofit measures had an expected lifetime of 10 years.[5] We also assumed that incremental maintenance costs were negligible and that the ZIP loan would be paid off over eight years.

The aggregate simple payback period is either 2 or 5 years, depending on whether we use gross or net energy savings. In either case, the retrofit measures are a worthwhile investment. The Housing Authority's retrofit cost containment policy is also an important factor in the economic attractiveness of its weatherization effort. Retrofit costs, which averaged $150/unit, were only one-fifth of original utility estimates.[6] This can be explained, in part, by the competition among private contractors in the bid process, utility cost estimates that were based on experience with individual homes rather than multi-family buildings, and the apparent economies of scale from retrofitting large tracts of similar buildings.

Table 1. Summary of results for San Francisco Housing Authority's zero-interest loan program to finance energy-conservation measures.

Project name	Normalized annual consumption[a]		Savings		Cost of retro-fit (1983$)	Simple payback[b] (years)
	Before	After	MBtu/ unit/year	%		
Alemany	86.6	77.2	9.4	9	160	3.3
Potrero Terrace	134.7	113.7	21.0	16	93	0.9
Sunnydale	93.2	84.5	8.7	9	203	4.5
Alice Griffith	164.1	130.6	33.5	20	165	1.0
Hayes Valley	88.8	97.4	-8.6	-10	82	—[e]
Aggregate results[c]	111.2	99.0	12.2	11	150	2.4
Comparison Groups						
All other SFHA Projects	95.9	94.6	1.3	1		
2 similar projects (Valencia, North Beach)	122.0	115.7	6.3	5		
Net results[d]			6.6	6		4.5

[a]NAC is expressed in units of MBtu/unit/year.

[b]Simple payback period is computed as cost divided by first-year savings (gas savings multiplied by $5.10/MBtu or $0.51/therm).

[c]Aggregate results are obtained by weighting gas usage/unit before and after by the total number of units in each project.

[d]Net results are obtained by computing savings relative to the comparison group with two similar projects (Valencia and North Beach).

[e]Payback does not exist when there are negative savings.

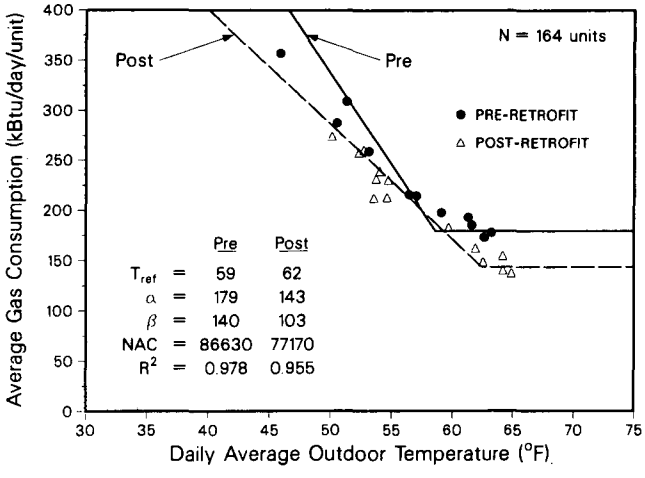


Figure 1. Plot of gas use vs. average outdoor temperature at the San Francisco Housing Authority's Alemany Project. Lines represent the best fit of pre- and post-retrofit consumption data to local weather. T_{ref} = reference temperature; α = temperature-independent or base-level usage (therms/unit/day); β = heating slope (therms/unit/°F-day); NAC = normalized annual consumption (kBtu/unit/year); and R^2 = correlation coefficient. (XCG 847-13150)

Conclusions

We have gained some insight into the process by which specific conservation measures are selected through our work with the San Francisco Housing Authority. For the most part, it appears that local authorities use whatever programs or financial arrangements are available. Often, this makes it difficult to match energy conservation efforts to the most cost-effective strategy. For example, under existing conservation programs, the SFHA cannot adequately fund several highly cost-effective retrofit options, such as lighting conversions (incandescent to fluorescent) and improved operation and maintenance practices. Yet, the Authority has recently allowed an energy management firm to install solar hot water heating systems at seven senior projects in a "shared savings" venture because existing solar and investment tax credits significantly enhance the economic viability of this effort.

The Authority also faces the institutional "barrier" of reduced maintenance budgets at the same time that it attempts to improve routine building maintenance practices. This is an important policy issue because several low-cost actions that the Authority could pursue are likely to yield highly cost-effective energy savings. These practices include repair of boiler leaks, periodic checking of heating system controls (e.g., temperature setbacks), and repair of frozen controller valves on apartment unit radiators. Given reduced operating budgets, local authorities have turned to HUD modernization funds to finance energy-efficiency investments. Modernization funds are used mostly for equipment replacement rather than retrofit. Conservation potential and reduced life-cycle operating costs are secondary criteria in the allocation of such funds. We believe that it is rather short-sighted public policy to neglect the energy and dollar savings potential of prudent energy management practices while encouraging capital-intensive equipment replacement that improves energy efficiency as a byproduct (and replaces equipment that has not been adequately maintained).

Given the limitations of existing programs, optimal results in retrofitting low-income, multifamily buildings can only be achieved through conservation programs specifically targeted at that sector. Key elements for program success include a strong technical assistance component (i.e., engineering expertise, detailed site-specific building audits), sensitivity to tenant comfort concerns and lifestyle patterns (e.g., problems of vandalism), and program design that recognizes the severe financial constraints faced by most building owners, public or private.

The San Francisco Housing Authority has clearly adopted an innovative approach in attempting to simultaneously maintain its housing stock, reduce energy consumption, and improve tenant comfort levels. Just 2 years ago, the Housing Authority faced a serious problem in obtaining funds to address any weatherization improvements. The first generation of retrofits (mostly "building shell" improvements and low-cost hot water measures) have been completed at most projects, and the Authority is currently investigating new opportunities (e.g., cogeneration, additional solar hot water systems, and heating system retrofits). The lessons learned in San Francisco can help other public housing authorities across the country that face a similar dilemma: how to regain control over spiraling operating expenses, yet still provide tenants with reasonable comfort and amenity levels in a period of tight budgetary constraints.

PLANNED ACTIVITIES FOR FY 1985

We will continue our investigation of energy conservation opportunities in the public housing sector as part of DOE's overall program to improve energy efficiency in federally assisted housing. This research topic will be coordinated among several groups within the Applied Science Division, including Building Energy Analysis, Buildings Energy Data, and Energy Performance of Buildings. In FY 1985, we will review data on the public housing building stock, energy-use trends, and previous analyses of retrofit activities in public housing. This information will help us to develop a long-range research agenda that includes the important topics in both technical and behavioral research. Finally, we plan to conduct additional case studies at selected public housing sites in order to evaluate the energy and cost effectiveness of retrofit measures.

REFERENCES

1. Ritschard, R.L. and Dickey, D. (1984), "Energy Conservation in Public Housing: It Can Work," *Energy Systems and Policy 8*(3), p. 269.
2. Goldman, C.A. and Ritschard, R.L. (1984), *Energy Conservation in Public Housing: A Case Study of the San Francisco Housing Authority*, LBL-17994.
3. Fels, M.F. (1984), *The Princeton Scorekeeping Method: An Introduction*, PU/CEES 163, Princeton, NJ.
4. Dutt, G.S., Lavine, M.L., Levi, B., and Socolow, R.H. (1982), *The Modular Retrofit Experiment: Exploring the House Doctor Concept.* PU/CEES 130, Princeton, NJ.

5. California Energy Commission (1983), *Securing California's Energy Future: 1983 Biennial Report*, Sacramento, CA.

6. San Francisco Housing Authority (1983), *Weatherization Program Report*, San Francisco, CA.

Microeconomics of Residential Energy Conservation*

M.D. Levine, P. Chan, and H. Ruderman

Considerable analysis of the costs and benefits of improving the thermal integrity of houses has been done in the past. Analysis of efficiency improvements has also been performed. However, there has been very little analysis of the combined effects of thermal integrity and improvements in appliance efficiency, even though the interactions between thermal integrity and appliance use are significant and have a marked effect on the impact of investments in residential energy efficiency. Furthermore, the potential for downsizing space conditioning equipment as a result of thermal integrity improvements in houses has not been analyzed systematically. Finally, the variation in energy prices, weather, and average thermal integrity throughout the nation requires that analysis be conducted as a function of location. This research attempts to integrate all these factors into a comprehensive analysis of the microeconomics of residential energy efficiency investments.

ACCOMPLISHMENTS DURING FY 1984

Method of Approach

Our approach uses the data base of over 10,000 DOE-2 simulations of energy use in residential buildings described in the article by Ritschard *et al.* ("Residential Energy Conservation: Microcomputer Program for Energy Analysis of Single-Family Homes"). We manipulate this data base to estimate space conditioning energy use as a function of conservation measure, house type, and weather throughout the nation.

Our approach also involves the following steps: (1) Through additional simulations using DOE-2, we evaluate the effect of different levels of appliance energy efficiency on space conditioning loads as a function of house thermal integrity and weather. (2) We collect data on the costs of downsizing heating and cooling equipment and of measures to improve thermal integrity. (3) We merge the data base on costs of appliance efficiency improvements (available from the analysis of federal appliance efficiency standards presented in an accompanying article by Levine *et al.*). (4) We construct a data base of energy prices for approximately 50 locations throughout the nation. (5) We code a computer model for using all of these data to calculate the economics of conservation measures (expressed as a life-cycle cost curve and in terms of simple payback to the investor). (6) We perform economic studies for 50 locations to arrive at a comprehensive assessment of the economics of residential conservation investments throughout the nation.

Results to Date

The project is partially completed. The computer model to evaluate the economics of residential energy conservation measures has been coded and tested. The data base on costs of conservation measures is assembled and is included in the model. Energy prices need to be assembled for individual cities to perform the economic studies.

To illustrate results of the microeconomic study, we provide results for three locations: Chicago (a cold climate), Washington, DC (a moderate climate), and Phoenix (a hot climate). We consider a typical new house with a heat pump in each of the three cities, and address the issue of downsizing the heat pump. Specifically, we performed the analysis in each location for two cases: a house with an oversized heat pump (sized for a house of low thermal integrity) and the same house with the capacity of the heat pump reduced to match the peak hourly load of the building. We used the higher of the heating or cooling hourly load to size the heat pump. In the second case, we reduced the size of the heat pump as the thermal integrity increased.

*This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Buildings Energy Research and Development, Building Systems Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

The analysis for all three cities uses a 3% real discount rate, electricity prices for each city in 1983, and a real annual escalation rate for electricity of about 1%. (The escalation rate is higher than 1% through 1985 and lower in future years). The figures shown here present the results for a series of thermal integrity options, where the options are defined in terms of the R-value of ceiling insulation; R-value of wall insulation; a number symbol representing foundation insulation; high (0.6 air changes per hour) and low (0.4 air changes per hour) rates of infiltration; and number of glazings. The symbols for foundation insulation are: 0, no insulation; 1, R-5 insulation to a depth of 4 feet; 3 and 4, R-10 insulation to depths of 4 and 8 feet, respectively.

Figure 1 shows results for Washington, DC. For both an oversized and a downsized heat pump, the mininum in a life-cycle cost curve evaluated at a 3% real discount rate has R-38 ceiling insulation, R-19 wall insulation, R-8 foundation insulation down to 8 feet, and triple glazing for houses with infiltration levels of 0.6 air changes per hour. (One example of a house of high thermal integrity and low infiltration is provided in Fig. 1 as point 13. This data point shows that reducing infiltration levels reduces both energy-use and life-cycle costs.) The conservation measures corresponding to the minimum in life-cycle costs at 0.6 air changes per hour (point 10) should be compared with those typically installed in a new house in Washington, DC, having a heat pump (approximately equal to point 6, but with more ceiling and less wall insulation). The reduction in energy use in upgrading typical construction practice to the minimum in life-cycle costs is 22%; in going from the typical house to high thermal integrity at low infiltration, the reduction in household energy use is 42%.

The downsizing of the heat pump with increasing thermal integrity does not change the set of options corresponding to the minimum in life-cycle costs. However, it does make a substantial difference in the total cost to homeowners. An effect of downsizing heat pumps not easily visible from Fig. 1 is the reduction in first costs of improving thermal integrity resulting from the credit for downsizing equipment. In adding ceiling, wall, and foundation insulation and an extra layer of glazing to a typical new house in Washington, DC without downsizing the heat pump, the homeowner would pay an extra $1900 for a new house. Downsizing reduces this incremental cost for the conservation measures to less than $1000. Because increased first costs are a significant barrier to greater investment in thermal integrity in houses, the benefits of downsizing heating and cooling equipment that results from greater thermal integrity can—if this information is provided to the purchaser of a new house—help overcome barriers associated with higher first costs.

Figures 2 and 3 present similar results for Chicago, Illinois, and Phoenix, Arizona. The same general conclusions discussed for Washington, DC apply in both colder and hotter regions: (1) Current practice in new houses (about point 5 for both Chicago and Phoenix) leads to houses consuming notably

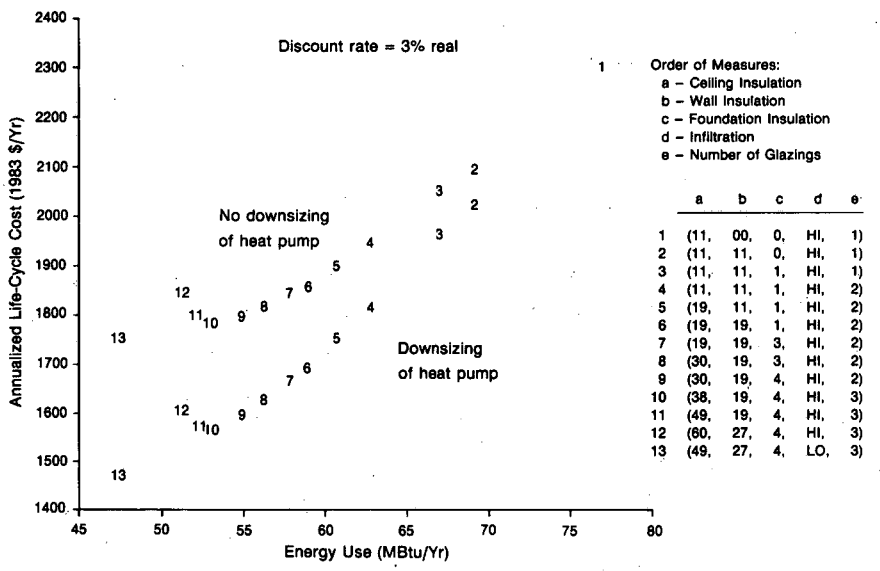


Figure 1. Annualized life-cycle cost for various conservation measures: Washington, DC, ranch house with heat pump. (XBL 851-990)

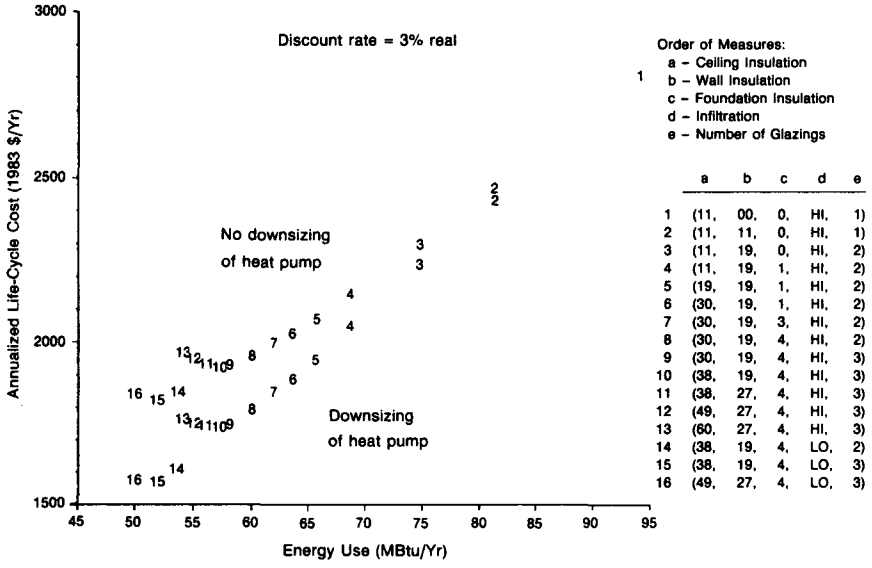


Figure 2. Annualized life-cycle cost for various conservation measures: Chicago ranch house with heat pump. (XBL 851-989)

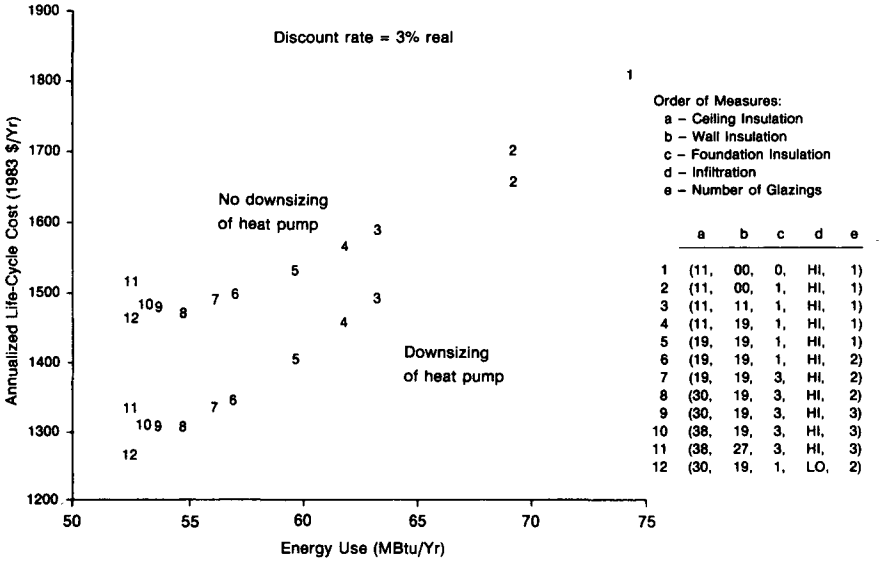


Figure 3. Annualized life-cycle cost for various conservation measures: Phoenix ranch house with heat pump. (XBL 851-988)

more energy than houses with conservation measures at the life-cycle minimum; (2) lower infiltration levels are economically beneficial and reduce energy costs in both locations; and (3) downsizing of heat pumps as thermal integrity increases is economically beneficial. For Phoenix, downsizing heat pumps makes an additional conservation measure cost effective. In Chicago, downsizing the heat pump reduces the cost of improving thermal integrity from the level of typical construction practice to the minimum on the life-cycle cost curve by over $1000 (from $2500 to $1400). In Phoenix, downsizing reduces the first cost by $500 (from $1350 to $850).

PLANNED ACTIVITIES FOR FY 1985

Continuing research will involve checking and expanding the cost data base and performing economic analyses of residential energy conservation investments that include effects of downsizing and internal load changes in appliances in representative locations in the United States.

The $900 credit cited above for downsizing heat pumps in Washington, DC refers to the benefit of reducing capacity from that for a house of typical thermal integrity (point 6 in Fig. 1) to a house with high thermal integrity (point 10). If the heat pump is equally oversized in both houses relative to peak loads, approximately the same $900 benefit occurs from the relative downsizing for the house with lower heating and cooling loads. If heat pumps are oversized in typical new installations, then the purchaser can reduce costs even further by requiring proper sizing. The availability of smaller residential heat pumps in the past several years—corresponding to an improvement in thermal integrity in new houses at a time when heat pumps are installed in 25% of all new houses—suggests that some attention is being given to sizing issues.

The LBL Residential Energy Model*

J.E. McMahon and P. Chan

Detailed forecasting models have been used since the mid-1970s to assess potential impacts on consumers of proposed federal energy conservation policies. The first such model intended as a policy analysis tool for the residential sector was the Oak Ridge National Laboratory (ORNL) Engineering-Economic Model of Residential Energy Use.[1] A version of the ORNL model was moved to LBL and adapted for an analysis of the federal government's proposed Consumer Product Efficiency Standards in 1979. Public comments during the rulemaking process and new analyses at LBL have suggested many changes in the methodology for simulating residential energy consumption. Some of those changes have been implemented and described in U.S. Department of Energy publications,[2,3] conference proceedings, and LBL reports, including previous LBL annual reports describing the analysis of mandatory appliance efficiency standards.

The accumulation of major changes to the method, including a new analysis of market behavior regarding appliance efficiencies, makes the LBL version of the ORNL model unique. The increasing availability of data and the need to analyze issues raised by interested parties in the rulemaking process have driven the transition from the ORNL to the LBL model. The major methodological differences include representation of recent equipment efficiency trends and forecasting of future appliance efficiencies, based on an analysis of market behavior during the last decade; calculation of appliance replacements, based on historical purchases and retirements; updating of the data base for equipment costs and efficiencies; and treatment of heat pumps as competitive space conditioning systems. In addition, the LBL model has been integrated with other tools for the study of individual electric utilities. (The next article, by Kahn *et al.*, describes the results of that work.) A recent description of the current model, including all changes to the original ORNL model, is available.[4]

ACCOMPLISHMENTS DURING FY 1984

During FY 1984, a panel of outside experts undertook a thorough review of the LBL model and of all components of the Consumer Products Efficiency Standards analysis. Their final recommendations for changes to the method will be published early in FY 1985. In addition, the module for forecasting future equipment efficiencies was replaced, based upon an analysis described in an accompanying article by Ruderman, Levine, and McMahon ("Energy Efficiency Choice in the Purchase of Residential Appliances"); a new method for aggregating engineering data (equipment cost and efficiency by design) across classes of an appliance was developed; and a more extensive set of sensitivity studies with regard to the range of possible input values was analyzed. We describe these changes here.

*This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Buildings Energy Research and Development, Building Equipment Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

Future Equipment Efficiencies

One major change distinguishing the LBL model from previous versions of the ORNL parent is a reformulation of the algorithm for forecasting equipment efficiencies for new appliances. Previous versions of the ORNL Residential Energy Model assumed some discount rate, then calculated the life-cycle cost for equipment designs having different efficiencies and associated purchase costs. Market imperfections were assumed to change over time in inverse proportion to energy prices. The sum of the life-cycle cost plus a distortion based on market imperfections provided adjusted life-cycle costs. The design with the minimum adjusted life-cycle cost was the long-term choice for purchase. In the year of interest, the predicted equipment efficiency choice was determined from the long-term choice and a lag factor, based on the equipment efficiency choice in the previous year.

This method for forecasting equipment efficiency was subject to several criticisms: (1) no empirical basis existed to support the method; (2) no efficiency data existed from which to infer the discount rates or lag factor used in the calculation; (3) no time-series data existed to support the assumption that market imperfections would change over time inversely with energy price.

LBL performed an analysis of market behavior for equipment efficiency in 1983 and 1984.[5] We used the national average efficiency of new appliances of each type to derive an aggregate market discount rate for efficiency choice each year. Average efficiency data were available for eight product types in selected years over a 10-year period. In brief, the equipment efficiency can be related to the current energy price through a discount rate that is roughly invariant over time. The aggregate market discount rate contains all market imperfections and lags implicitly, simplifying the methodology. (See the article by Ruderman, Levine, and McMahon for a fuller account of this research.)

The results of this analysis provide the basis for a new module for simulating the average efficiency of new appliances in the future.

Aggregation

A variety of equipment designs having different efficiencies and purchase costs must be considered when analyzing mandatory efficiency standards. For the purpose of simulating future efficiency improvements in the absence of federal policy, we need the relationship between equipment price and efficiency. For each product type (e.g., refrigerators), we define a set of classes, such as manual defrost, partial defrost, and automatic defrost models, then analyze different designs within each class. We use an aggregation procedure to represent the relationship between purchase cost and efficiency for the product type, in which all the designs are represented; we then obtain a shipment-weighted average over the classes. Because of the difficulty in exactly matching up different designs in different classes, we must interpolate between designs.

The advantages of the new aggregation method are: (1) it replaces arbitrary choices for interpolation by an explicit set of rules; (2) it bins data points to eliminate redundancies; and (3) it reduces the loss of information.

Sensitivity Studies

We performed sensitivity studies with the LBL model to determine which inputs have the greatest impact on results important to policy decisions. In previous work for DOE, the percent change in annual energy consumption for a given appliance type due to a proposed policy was a critical factor in the decision regarding the significance of energy savings. Sensitivity studies reveal that annual energy consumption is most strongly affected by the engineering relationship between equipment purchase cost and efficiency. Energy price forecasts, particularly changes in the relative costs of competing fuels, are also very important.

Market Share Elasticities

By comparing the results of the sensitivity studies with reported ownership of appliances from recent U.S. Census Bureau data, we discovered two areas requiring adjustment of the model. We compared the percent of households reporting ownership of each product by fuel used with the percent predicted by the model, after correcting the model results for reported energy costs and income. Even after these corrections, we found that, for water heaters and cooking appliances, the model failed to predict the relative market shares of electric and natural gas products as reported in the Census survey. The model *over*estimated the share obtained by electric water heaters and *under*estimated the share of electric appliances for cooking.

In both cases, the sensitivity studies in which we varied the market share elasticities provided alternative sets of inputs that gave results in better agreement with reported data. As a consequence, we replaced the market share elasticities with alternatives that gave the best agreement with the Census surveys.

PLANNED ACTIVITIES FOR FY 1985

A major focus of our work in FY 1985 will be implementing the review group's recommendations for further methodological improvements. The review group has provided an outside technical perspective on issues affecting the analysis of appliance efficiency standards. Such issues as data requirements, availability, and quality; consumer and manufacturer behavior on energy efficiency and fuel choice; and engineering/economic issues affecting availability and cost of more efficient equipment will be addressed in the recommendations of the review group, which we will receive early in FY 1985.

In addition, LBL research will address aggregation issues involving variance in weather, energy prices, and classes of appliances. The question that has been posed is: how great an error, if any, is introduced by using the products of averages to simulate the average energy consumption ?

We have started to work on improving the treatment of heat pumps as a space-conditioning alternative and will adapt the model for an analysis of proposed mandatory efficiency standards for heat pumps and heat pump water heaters. We will also substantially improve the data base for room heaters. We will make preliminary efforts to link changes in appliance efficiency to changes in space heating and cooling requirements. As they become available, we will incorporate the results of other research activities, such as new analyses of end-use efficiency elasticities. (This is discussed in the article, "Increased Usage of Appliances in Response to Efficiency Improvements.")

REFERENCES

1. Hirst, E. and Carney, J. (1978), *The ORNL Engineering-Economic Model of Residential Energy Use*, Oak Ridge National Laboratory Report ORNL/CON-24, Oak Ridge, TN.
2. U.S. Department of Energy, Assistant Secretary, Conservation and Renewable Energy, Test and Evaluation Branch (1982), *Consumer Products Efficiency Standards Economic Analysis Document*, DOE/EC-0029, Washington, DC.
3. U.S. Department of Energy, Assistant Secretary, Conservation and Renewable Energy, Test and Evaluation Branch (1983), *Supplement to: Consumer Products Efficiency Standards Engineering Analysis and Economic Analysis Documents*, DOE/CE-0045, Washington, DC.
4. McMahon, J. (1984), *The LBL Residential Energy Model*, LBL-18622 (in press).
5. Ruderman, H., Levine, M., and McMahon, J. (1984), *The Behavior of the Market for Energy Efficiency in the Purchase of Appliances and Heating and Cooling Equipment*, LBL-15304.

ECONOMIC STUDIES

Economic Impacts of Residential Conservation Programs on Electric Utilities*

E. Kahn, C. Pignone, J. Eto, J. McMahon, and M.D. Levine

Conservation programs mandated by the federal government will have economic impacts on electric utilities that may or may not be favorable to those utilities. The impact depends upon local circumstances such as the rate structure, the utility's marginal costs, and the nature of local utility regulation. To understand how these factors interact, it is necessary to model the hourly demand changes associated with particular conservation programs. Methods of economic valuation must then be developed to reflect the gains and losses associated with load shape changes.

This article describes two case studies of residential conservation programs involving utilities with substantially different marginal costs. These cases, Detroit Edison and Pacific Gas and Electric, illustrate the economic method used to estimate economic impacts. The impacts of conservation programs are unfavorable in the former case, but quite favorable in the latter.

*This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Buildings Energy Research and Development, Building Systems Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

ACCOMPLISHMENTS DURING FY 1984

Most economic analysis of conservation programs focus on the consumer perspective. It is equally important, however, to characterize the impact of conservation programs on utility earnings. To estimate these effects, we modified an accounting measure known as earnings before interest and taxes (EBIT) to include the changes in utility investment associated with particular conservation programs.

EBIT is simply the difference between revenues and costs. The economic value of marginal load changes is the difference between marginal revenues and marginal costs. Investment costs must be considered along with operating costs. Depending upon circumstances, the relevant investment costs may be peaking turbines or baseload facilities.

The marginal revenues associated with conservation programs are specific to particular rate schedules. Where a utility has more than one residential tariff, the conservation impact must be estimated for each rate classification. Our analysis is conducted using the LBL Residential Energy Model[1] applied at the rate class level. This means forecasting electricity sales for each tariff class with and without the conservation program. Since the LBL model is quite data-intensive, the base-case forecast (made with limited data) commonly involves some adjustment to achieve correspondence with utility estimates.

Once the quantity change associated with conservation programs has been estimated, it must be applied to the sales frequency distribution in a way that will account for the nonlinearity of the revenue response. It is necessary to know the distribution of sales over the rate tiers because tariff schedules typically have price distinctions based on the quantity consumed.[2] Marginal revenue is determined by changes in the entire sales distribution induced by conservation programs. We adopted the block-adjustment method to model these changes. Figure 1 illustrates the procedure.

Figure 1 shows two distributions, o and n. Suppose n represents the sales distribution after conservation, o the distribution before conservation, and $B_{1,o}$ = 340 kWh/month, the consumption level above which the electricity price changes from p_1 to p_2. If we know only the distribution o, its mean value μ_o, and the mean value μ_n of n, we estimate the fraction of sales below $B_{1,o}$ for the distribution n as follows. We know that n will have a larger fraction of sales below $B_{1,o}$ than o. Instead of estimating the change for the curve o to the curve n, we increase the quantity of electricity for which p_1 will be the price. This is done by defining a new price boundary, $B_{1,n}$,

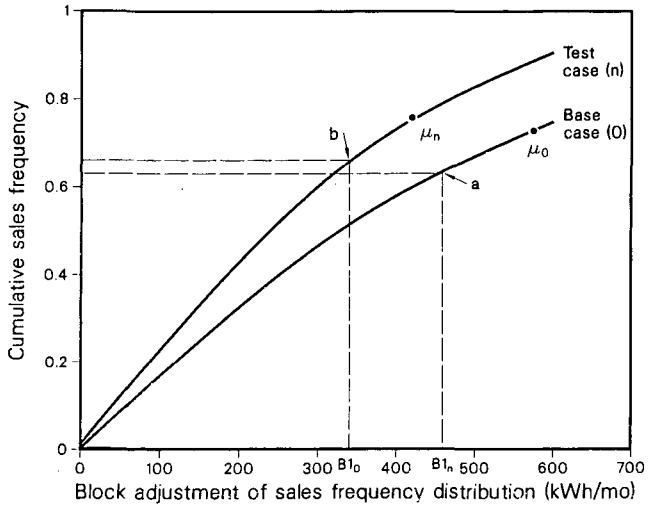


Figure 1. Cumulative sales frequency of electricity vs. block adjustment of sales frequency distribution.
(XCG 844-13045)

which is greater than $B_{1,o}$ by the ratio μ_o/μ_n. The fraction of sales at p_1 is then read off curve o at the point $B_{1,n}$. In Fig. 1, this point is labeled a.

The error of this procedure is measured by comparing point a with point b, both projected to the vertical axis. Point b is just the intersection of $B_{1,o}$ with the curve n. In this case, the block adjustment method predicts too small a fraction of sales at price p_1. The revenue impact of this error depends upon whether $p_2 > p_1$. If it is, then the block adjustment method overestimates revenue. For the purposes of case study analysis, the block adjustment method must be used until a superior alternative is developed.

Marginal costs present a different problem. Here, it is necessary to aggregate all effects up to the system level, taking due account of the diversity of load profiles across individual users. We use the LBL Hourly Demand Model[3] to perform this aggregation. Figure 2 illustrates the kind of result that comes from testing particular conservation programs. This figure shows hourly residential loads for a projected peak day in 1996. The largest load impact shown here results from a mandated efficiency standard for central air conditioners that would require a seasonal energy efficiency ratio (SEER) of 12 by 1987.

Once load impacts have been aggregated from rate classes and spread over the hours of the year, they are then valued at the utility's marginal cost. Marginal cost has two components, capacity and energy. Capacity costs are typically concentrated in those hours of the year where the utility system loss-

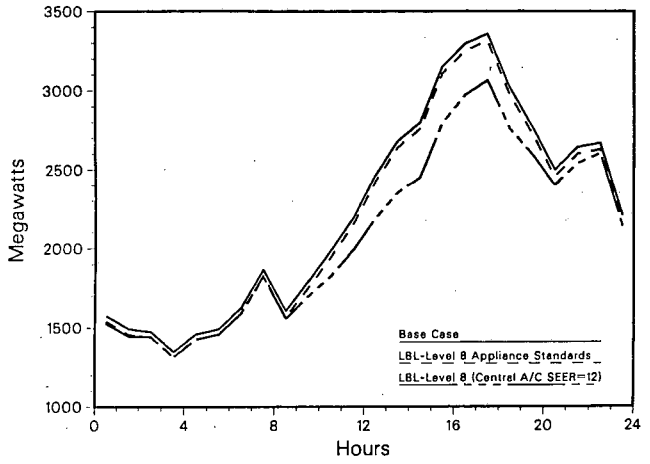


Figure 2. Projected Pacific Gas and Electric Company residential hourly load profiles for a peak summer day in 1996 (base case and two conservation scenarios).
(XCG 848-13191)

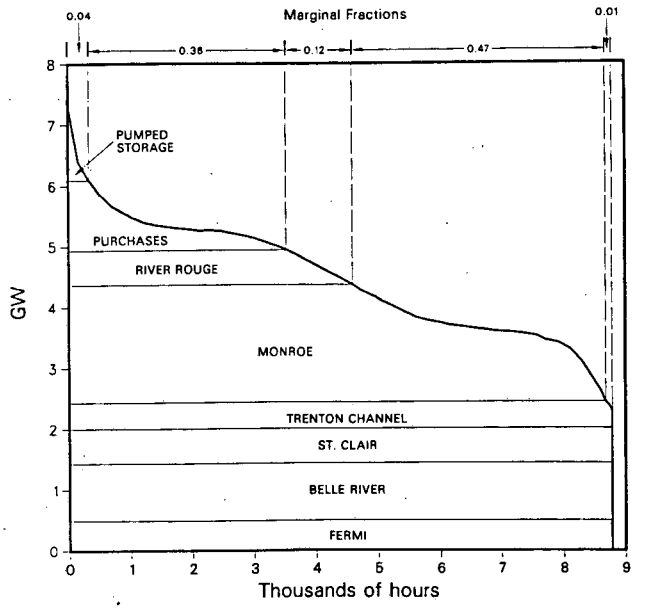


Figure 3. Fully dispatched load duration curve for Detroit Edison Company, 1988 projection.
(XCG 844-13046)

of-load probability is greatest. Simulations of Pacific Gas and Electric Company (PG&E), for example, show that the highest 10% of the load hours in July and August typically account for over 95% of the annual system reliability risk. Therefore, only these hours have capacity value.

Marginal energy costs are also estimated by system simulation methods. Typically, these methods involve load aggregation techniques that suppress the chronological sequence of loads.[4] The simulated result is summarized in the form of a load duration curve resembling Fig. 3. The monotonically declining curve represents the number of hours in the simulated period for which the system load is at a given level. Because the loads are sorted by magnitude, chronological features are lost. The supply system is dispatched to serve loads in economic order. Figure 3 shows the order in which Detroit Edison plants would serve projected 1988 loads. The plants with lowest operating costs serve the base load. These are placed at the bottom of the load duration curve (LDC). Plants that intersect the LDC are marginal producers.

Figure 3 shows how the average marginal cost over a given period can be calculated as a weighted average of the marginal costs of the plants intersecting the LDC. The appropriate weights are the marginal fractions, which are shown at the top of Fig. 3. They represent the fraction of hours for which a given plant is the marginal producer. This is the vertical projection of the points at which that plant intersects the LDC.

Applying marginal energy-cost results to a particular conservation program requires an estimate of how to translate load impacts from the hourly demand model to the more aggregated level of the LDCs. For case study purposes, we make relatively simple assumptions that result in proxies that are easy to use.

Case study results are described in detail elsewhere.[5,6] The results for Detroit Edison (DECO) are uniformly negative. Because of substantial excess capacity, DECO has low marginal costs. Therefore, the benefits of conservation in terms of the value of avoided energy production is small. There is no benefit in avoided capacity costs. The case of PG&E is more complex. This utility has high capacity costs. While its marginal energy cost is higher than DECO's, it is still less than marginal revenue. The net result of these effects depends upon the particular conservation program.

Figure 4 shows results for a conservation program corresponding to one of the two for which the effects are illustrated in Fig. 2. The positive net gain of this program is due principally to the capacity value associated with high-efficiency central air conditioners. Other programs without this component show much smaller benefits.

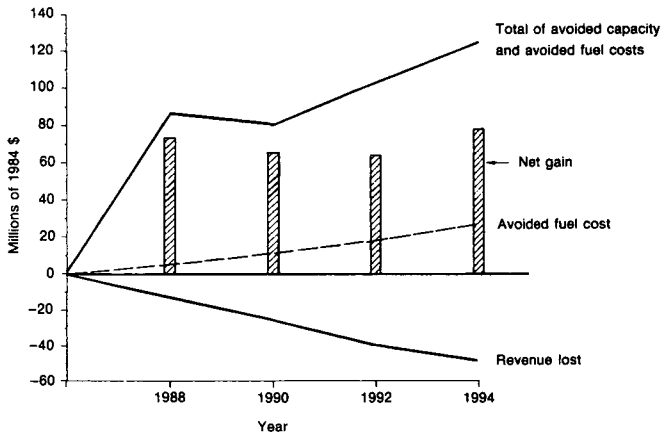


Figure 4. Economic impacts of central air conditioner standards (SEER = 12) on PG&E. (XBL 851-985)

PLANNED ACTIVITIES FOR FY 1985

We will model sales frequency distributions analytically. This will allow a substitute for the block adjustment method of revenue change estimation. We will also conduct other case studies.

REFERENCES

1. McMahon, J. (1984), *The LBL Residential Energy Model*, LBL-18622 (in press).
2. Liittschwager, J. (1971), "Mathematical Models for Public Utility Rate Revisions," *Management Science 17*, p. B339.
3. Verzhbinsky, G., Vine, E., Ruderman, H., and Levine, M. (1983), *The Hourly and Peak Demand Model: Description and Validation*, LBL-17784.
4. Bloom, J. (1984), "Generation Cost Curves Including Energy Storage," *IEEE Trans. on Power Apparatus and Systems, PAS-103*, p. 1725.
5. Pignone, C. (1984), *Financial Impact on Utilities of Load Shape Changes: Stage I Technical Report—The Detroit Edison Company*, LBL-19066 (forthcoming).
6. Eto, J., McMahon, J., and Chan, P. (1984), *Financial Impact on Utilities of Load Shape Changes: Stage II Technical Report—The Pacific Gas and Electric Company*, LBL-19067 (forthcoming).

Solving the Loss-of-Load Probability Problem with A Hypergeometric Function*

D. Levy and E. Kahn

Electric utilities may use from 20 to 220 generators to meet their load requirements. The output of each generator is characterized by a probability function—typically, a discrete on-off function. The fundamental measure of an electric power system's reliability is its instantaneous loss-of-load function. This distribution function is the cumulative probability that the aggregate power system being considered cannot satisfy the instantaneous load. Power system planners use this quantity to decide on the proper mix of generators and to determine the most efficacious way to purchase external power. For both uses, the instanteous loss-of-load quantity must be repeatedly recalculated (on the order of 10^6 times) for different loads and generation mixes. Exact recalculation of this quantity requires much computer time, since, for each configuration considered, all possible combined generator states must be enumerated. Hence, analytic, accurate, and rapidly calculable approximations of the instantaneous loss-of-load function have been sought. Until this work, however, the analytic approximations used were inaccurate and often pathological (in the sense of generating negative probabilities, probabilities greater than one, and/or nonmonotonically increasing probability distributions.)[1] These inaccuracies and pathologies arose because previous workers had applied approximation techniques that are valid only when the underlying probability distribution is continuous, whereas, in the loss-of-load situation, the probability distribution is discrete and discontinuous.

ACCOMPLISHMENTS DURING FY 1984

The case of a system with identical generators was considered and solved. Two analytic approximation formulas were derived and shown to be extremely accurate, nonpathological, and rapidly calculable. To derive these two formulas, the exact

*This work was funded by the Electric Power Research Institute under Contract No. RP-2473-3 through the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

instantaneous loss-of-load function ($LOLP^*(W)$) was expressed as a hypergeometric function. This function was then expressed in integral form, allowing the load variable to be analytically continued from discrete to nondiscrete (i.e., continuous) values. In combination with the analytic continuation, two analytic approximation formulas for the integral expression were derived. These steps can be summarized as follows:

$$LOLP^*(W) = \int_0^W P(E)dE$$

$$= L^{N-(W/c)}$$

$$\times \frac{F(N - W/c, -W/c, N - (W/c) + 1, L)}{F(N - W/c, -W/c, N - (W/c) + 1, 1)}$$

$$= \frac{\int_0^L t^{N-(W/c)-1}(1-t)^{W/c}\,dt}{\int_0^1 t^{N-(W/c)-1}(1-t)^{W/c}\,dt} ,$$

where:

- E = instantaneous output of system,
- L = forced outrage rate of each identical generator,
- W = load,
- c = capacity of each identical generator,
- N = number of generators,
- $P(E)$ = probability that output of system is E,

and the F's are the hypergeometric functions $F(\alpha,\beta,\gamma,\delta)$.[2] For completeness, one of the approximation formulas, known as LK (for Levy-Kahn), is given:

$$LK(W) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{y} e^{-x^2/2}\,dx ,$$

where:

$$y = \frac{W/c + 2/3 - (N + 1/3)(1 - L)}{|(W/c) + 1/2 - N\cdot(1 - L)|}$$

$$\times \left[\!\left[\frac{2}{1 + (1/6N)} \left\{ [(W/c) + 1/2] \ln \left[\frac{(W/c) + 1/2}{N(1 - L)} \right] + [N - (W/c) - 1/2] \ln \left[\frac{N - (W/c) - 1/2}{NL} \right] \right\} \right]\!\right]^{1/2}$$

$$\times \theta[N - (W/c) - 1]$$

$$+ 3 \frac{\left[\!\left[([(W/c) + 1]L)^{1/3} \left\{ 1 - \frac{1}{9[(W/c) + 1]} \right\} - [N - (W/c)(1 - L)]^{1/3} \left\{ 1 - \frac{1}{9[N - (W/c)]} \right\} \right]\!\right]}{\left\{ \frac{L^{2/3}}{[(W/c) + 1]^{1/3}} + \frac{(1 - L)^{2/3}}{[N - (W/c)]^{1/3}} \right\}^{1/2}}$$

$$\times \theta[(W/c) - N + 1]$$

where:

$$\theta(x) = \begin{Bmatrix} 1, x \geqslant 0 \\ 0, x < 0 \end{Bmatrix}$$

This approximation formula for the instantaneous loss of load was compared with the exact values of the instantaneous loss-of-load function for various numbers of generators and forced outage rates. Both extreme and typical cases were considered. An extreme case is one with a small number of generators and low forced outage rates. It is known that, if an approximation is going to fail, it will do so in these cases. For the extreme case $N = 5$ and $L = 0.05$, the Levy-Kahn approximation never differs from the exact values of the instantaneous loss of load by more than 12%. In this case, the exact value of $LOLP^*(W)$ varies from 9.58×10^{-10} to 1.00 as the load varies from 0 to 5 c. In a typical case where $N = 48$ and $L = 0.2$, the Levy-Kahn approximation never differed by more than 0.5% from exact values of instantaneous loss of load over the range $3.33 \times 10^{-6} \leqslant LOLP^*(W)_{exact} \leqslant 1$.

PLANNED ACTIVITIES FOR FY 1985

Currently, no work is planned.

REFERENCES

1. Levy, D. and Kahn, E. (1982), "Accuracy of the Edgeworth Approximation for LOLP Calculations in Small Power Systems," *IEEE Transactions on Power Apparatus and Systems PAS-101*(4), p. 986.
2. Abramowitz, M. and Stegun, I. (Eds.) (1964), *Handbook of Mathematical Functions*, National Bureau of Standards Applied Mathematics Series 55, Washington, DC.

Preliminary Report on the Economic, Regulatory, and Institutional Environment Affecting Utility Energy Conservation Programs*

W.Y. Wood, E. Kahn, P. Chan, and M.D. Levine

Policymakers interested in energy conservation are concerned about the situation of the electric utility industry vis-à-vis energy conservation for three reasons. First, in order to forecast the nation's future energy demand, it is critical to understand how electric utilities approach energy conservation relative to planning for new capacity. Second, the electric utility industry represents an important sector of the economy that is affected by energy conservation policies. Third, utilities may serve as a key agent for the delivery of conservation services. By lending their creditability to particular programs, local utilities can make a significant difference in the success of public conservation efforts.

The Utility Overview Study is designed to provide an estimate of both short-term and long-term utility interest in energy conservation. The objectives are to:

- characterize the economic, regulatory, and institutional environment that influences utility interest in energy conservation programs;
- provide a framework for relating to the national context the conclusions of LBL case studies of the financial impacts of energy conservation on particular utilities,[1-3] and;
- support the development of federal energy conservation policies and strategies for technology and information transfers to utilities (LBL modeling tools, Residential Conservation Seminar experience).

The financial impact of energy conservation on electric utilities consists of changes in projected revenue resulting from lost sales and changes in load shape. In the short run, if conservation reduces peak demand, it will increase the profitability of total sales by lowering average production costs where the marginal cost of power is greater than the average price of electricity. Utilities will derive a net gain from conservation efforts if savings from kW peak reduction is greater than the reduction in revenues from foregone sales (the kWh effect). Over the long term, conservation may involve load shape changes that shift the balance between peak and base load generation. Production costs for peak power are generally greater than for base load. If peak generation declines more than base load, the impact on earnings is positive because of lower average costs. Conversely, average production costs will increase if the peak-to-base ratio is higher.

ACCOMPLISHMENTS DURING FY 1984

Method of Approach

The initial focus of the Overview Study is on investor-owned utilities (IOUs); these utilities have a 77% share of electricity-generating capacity and 75.7% of total electricity sales in the United States. We included 85 utilities representing 90% of all IOUs by total generation in the Overview Study. We characterized these IOUs according to indicators that describe the economic, regulatory, and institutional environment related to energy conservation. Figure 1 shows the relative generating capacity and geographical distribution of the selected utilities.

There were five steps in our analysis of utility decision-making environments regarding conservation:

(1) Identify factors affecting utility interest in energy conservation.
(2) Define indicators for selected factors.
(3) Compile data.
(4) Compute indicators for selected investor-owned utilities.
(5) Analyze the short-term and long-term outlook for conservation.

Identification of Decision Factors

Based on a review of issues relevant to the cost and benefits of conservation from the utilities' point of view, we defined three factors to reflect the utility decision environment. They include energy supply/demand and costs, ratemaking, and political/institutional measures. These factors interact with each other and can change over time as the result of economic and other conditions. In the context of the Overview Study, we regard the energy supply/demand and cost factor as the most significant determinant of utility interest in energy conservation. The effect of the ratemaking and

*This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Buildings Energy Research and Development, Building Systems Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

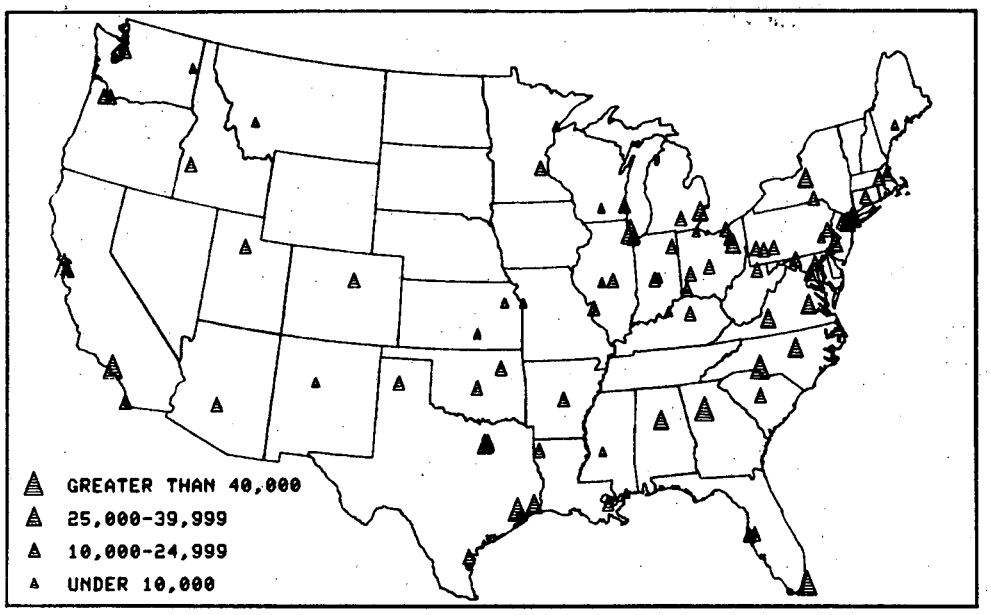


Figure 1. Geographical distribution and total generating capacity (in megawatts) of selected investor-owned utilities, 1982. (XBL 851-1043)

political/institutional factors will vary according to the availability of low-cost power and avoidable planned construction. Figure 2 shows the relationship of the 11 selected indicators to these key factors.

Data Sources

The Overview Study relies primarily on data compiled and validated by government agencies such as the Department of Energy and its Energy Information Administration[4–7] and key industry organizations such as the North American Electric Reliability Council,[8] the Edison Electric Institute (EEI),[9] and the National Association of Regulatory Utility Commissioners (NARUC).[10]

Definition of Numeric Indicators

Energy Supply/Demand Balance and Cost Factor

This factor is represented by three indicators: (1) percent excess coal capacity (PECC); (2) years until expensive power is needed (YEARS); and (3) percent avoidable construction (PAC).

Percent Excess Coal Capacity (PECC). We define potential excess coal capacity (PECC) as the potential to produce energy from all inexpensive generating facilities in excess of the utility's own requirements. Utilities with excess low-cost marginal capacity have a near-term incentive to increase revenues because the primary cost associated with selling additional kilowatt-hours is fuel cost, which is usually lower than the average cost of electricity. For this reason, they are unlikely to favor energy conservation. Utilities with little or no available cheap power will tend to favor conservation.

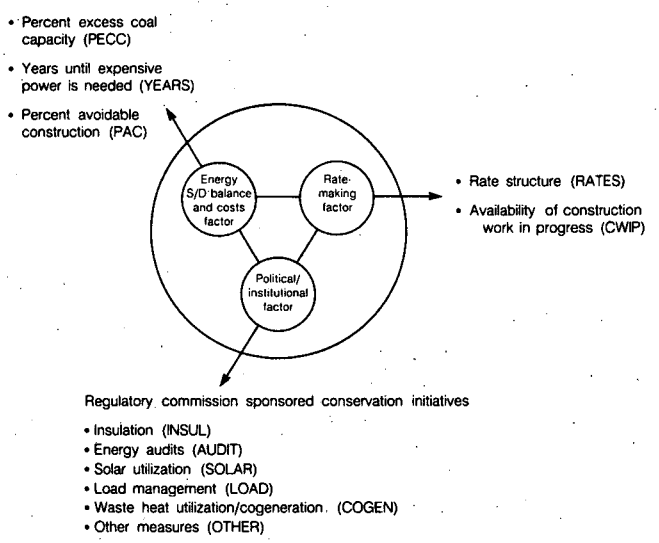


Figure 2. Relationship of three key factors to 11 selected indicators defining the utility decision-making environment for conservation programs. (XBL 851-8811)

Formally, PECC is expressed as:

$$[(C + N + H) - T]/T \quad ,$$

where:

C = coal capacity × 8760 (hrs/year) × 0.65 (estimated capacity factor);
N = actual nuclear generation (kWh);
H = actual hydro generation (kWh); and
T = total generation (kWh).

To measure potential excess capacity, we add to a utility's actual nuclear and hydro production its maximum potential coal production. This quantity is the potential low-cost production for the utility. If this number is greater than the utility's production requirements, potential excess coal capacity is said to exist. For convenience, we normalize this to total production.

Growth Rate: Years Until Expensive Power Is Needed (YEARS). The average lead time required for completion of new power plants is estimated to be 10–11 years. Availability of excess coal capacity may represent a temporary surplus, depending on the demand growth rate of the utility. If projected demand over the next 10 years or less exceeds available low-cost capacity (plus assured additions minus retirements), then energy conservation remains a long-term strategy for balancing supply and demand for those utilities with a temporary surplus of coal capacity. Utilities with more than 10 years of surplus low-cost capacity will probably not favor conservation programs.

Where PECC as computed above is greater than 0, we estimate the number of years until such low-cost power is used up, given specific growth rates for individual utilities, by using the following calculation: Find

$$n = \text{number of years} \quad ,$$

such that:

$$\text{PECC} = (1 + g)^n - 1 \quad ,$$

where g is the annual growth rate in kWh production.

Percent Avoidable Construction (PAC). Today, when new capacity investments are required, utility construction costs typically exceed revenues on the margin. Conservation can provide a way for risk-averse utilities to minimize unwanted investments. The value of such "avoided costs" varies with the timing of the need for new capacity, type of generation, and the stage of existing construction.

We define percent avoidable construction (PAC) as the ratio of two capacities: the capacity of plants under construction that are less than 20% complete to the total installed capacity. Plants at this stage of completion are often characterized as "planned" rather than "under construction." They are considered "cancellable" if major components have not yet been delivered and cancellation charges are reasonable.

Formally, for any utility i, PAC may be expressed as:

$$\text{PAC}_i = \frac{\text{Capacity of Plants} < 20\% \text{ Completed}_i}{\text{Total Installed Capacity}_i}$$

Ratemaking Factor

We have selected two indicators for the ratemaking factor. *Rate structure* (RATES) represents the short-term constraints on rate of return imposed by the tariff structure on IOUs. *Construction work in progress* (CWIP) provides a longer-term picture of the financial environment for conservation as an alternative to new plant construction.

Since 1975, a number of utilities have introduced *inverted bloc rates.* Under this rate structure, rates per unit go up with greater usage; low levels of consumption are priced below average cost in the short term, and high levels of consumption are priced above. From a social perspective, the inverted block rate consistent with an increasing marginal cost structure is a positive development because it encourages conservation by consumers, whereas declining block rates promote increased usage. However, from the perspective of utilities with inverted bloc rates embedded in a particular rate structure, conservation that affects high-level consumption severely decreases revenue because it curtails sales in the most profitable tier.

Data on rate structure at the utility level is not readily available. Work for this indicator will be completed in FY 1985.

Inclusion of construction work in progress (CWIP) in the rate base improves utilities' cash flow position during construction. If the full amount of CWIP is allowed in the rate base, the long-term competitiveness of conservation compared with new construction as a way of balancing supply and demand will decline because this treatment reduces the economic disincentive for building unnecessary capacity.

Utility-specific data for CWIP has been taken from the Wall Street firm Donaldson, Lufkin & Jenrette's *Electric Utility Statistical Reference, 1982 Edition,*[11] and from the trade journal *Public Utility Reports.*[12] We rate the availability of CWIP as fol-

lows: 0.0—not available; 0.25—minor CWIP; 0.50—case-by-case CWIP; 0.75—major CWIP; and 1.00—total CWIP.

Political/Institutional Factor

We focused on the activities of state regulatory commissions because they routinely exercise regulatory power over prices, entry, and services in the electric utility industry, and because their interest in promoting energy conservation has spurred the development and implementation of these programs by the IOUs. Overall, we consider this factor to be relatively less important than the energy supply/demand balance and cost and ratemaking factors as determinants of utility interest in energy conservation.

We used six indicators to summarize the regulatory environment for energy conservation. They include measures that have been enacted, adopted, or proposed by state law, regulation, or regulatory commission policy in the following areas: (1) insulation (INSUL); (2) energy audits (AUDIT) for residential, commercial, and industrial buildings; (3) solar energy utilization (SOLAR); (4) waste heat utilization/cogeneration (COGEN); (5) load management (LOAD); and (6) other measures (OTHER) such as revision of building codes.

We rate the availability of each conservation initiative as follows: 0—not available; 0.25—proposed measure; 0.50—test measure; 0.75—limited (means-tested) measure; and 1.00—generally available measure.

Results

The financial impact of energy conservation on utilities will differ according to their economic condition and system characteristics. During FY 1984, we defined and analyzed indicators for the energy supply/demand and cost, ratemaking, and regulatory factors for a number of the indicators. We will carry out additional work to update and refine these indicators in FY 1985. The following discussion of the utility decision environment analyses is preliminary.

In the context of the Overview Study, we considered the availability of low-cost marginal capacity (PECC and YEARS) as the most significant indicators of utility interest in energy conservation.

To test the sensitivity of these indicators to the assumed coal capacity factor of 0.65, we also computed PECC for a coal capacity factor of 0.60 and 0.70. Results of the sensitivity analysis indicates that PECC and YEARS are not very sensitive to the capacity factor except when coal is a significant percentage (>50%) of total capacity.

Table 1 presents the percent of total generation by IOUs accounted for by selected utilities at different coal capacity factors for YEARS in 1982.

To summarize:

- Depending on the coal capacity factor used, 58%–70% of IOUs by sales have 0 to 5 years of low-cost power available. (Of these IOUs, 50%–62% by sales have *no* low-cost power available.) These utilities could, under proper circumstances, be motivated to pursue a range of conservation programs in the near term.
- An additional 17%–19% of utilities by sales have less than 10 years of low-cost power available; carefully designed programs could be beneficial in the near term.
- Finally, 11%–25% of utilities by sales have more than 10 years of low-cost power available; they are not likely to be interested in pursuing conservation in the near term.

Targeting Utilities

Selected utilities in Fig. 3 are ranked by the energy balance and cost factor indicator YEARS to show their relative favorability to conservation. The darker bands show utilities that are more favorable to conservation with respect to the indicator being considered; lighter bands are less favorable. Figure 4

Table 1. Years until expensive energy is needed, as percent of total generation of selected utilities[a] in 1982.

Years until expensive power is needed	Coal capacity factor (CCF)		
	0.60	0.65	0.70
0	62%	54%	50%
0.01–5	8	11	8
5.01–10	19	19	17
10.01–15 Years	3	6	14
15.01 +	8	10	11
Total	100[b]	100[b]	100

[a]The investor-owned utilities included in this table generated 90% of all the electricity from such utilities in the U.S. in 1982.

[b]Discrepancies in totals are due to independent rounding of components.

FAVORABLE TO CONSERVATION 1982

(Coal Capacity Factor = .65)

		EXCESS COAL CAPACITY	YEAR TO BALANCE	% AVOIDABLE CAPACITY	AVAILABLE CWIP
FAVORABLE	PACIFIC GAS & ELEC CO	-.74	.00	.98	.00
	SOUTHERN CALIF EDISON CO	-.73	.00	1.48	1.00
	HOUSTON LIGHTING & PWR CO	-.73	.00	16.75	1.00
	FLORIDA PWR & LT CO	-.48	.00	.00	.75
	NIAGARA MOHAWK PWR CORP	-.61	.00	2.11	.25
	CON EDISON CO OF N Y INC	-.85	.00	.53	.25
	PHILADELPHIA ELEC CO	-.43	.00	.00	.25
	PUB SERV ELEC AND GAS CO	-.37	.00	.00	.50
	GULF STATES UTILITIES CO	-.89	.00	8.54	1.00
	TEXAS PWR & LT CO	-.88	.00	28.76	.75
	CONSUMERS PWR CO	-.06	.00	.00	1.00
	LOUISIANA PWR & LT CO	-1.00	.00	17.22	1.00
	INDIANA & MICHIGAN ELEC CO	-.01	.00	.00	.25
	ARKANSAS PWR & LT CO	-.22	.00	.00	.25
	TEXAS ELEC SERV CO	-1.00	.00	.00	.75
	OKLAHOMA GAS & ELEC CO	-.38	.00	9.85	.25
	WEST PENN PWR CO	-.30	.00	44.75	.25
	FLORIDA PWR CORP	-.76	.00	.00	.75
	BALTIMORE GAS & ELEC CO	-.28	.00	.00	1.00
	PUGET SOUND PWR & LT CO	-.92	.00	29.25	.25
	CONNECTICUT LT & PWR CO THE	-.48	.00	.00	.00
	SOUTHWESTERN ELEC PWR CO	-.16	.00	.00	.75
	PUB SERV CO OF COLORADO	-.05	.00	25.75	.50
	PORTLAND GENERAL ELEC CO	-.39	.00	.00	.00
	IDAHO PWR CO	-.22	.00	1.91	.00
	PUB SERV CO OF OKLAHOMA	-.62	.00	.00	.25
	CENTRAL PWR & LT CO	-.73	.00	36.52	.50
	LONG ISLAND LIGHTING CO	-1.00	.00	.00	.75
	JERSEY CENTRAL PWR & LT CO	-.83	.00	.00	.25
	SOUTHWESTERN PUB SERV CO	-.27	.00	16.16	.50
	DALLAS PWR & LT CO	-1.00	.00	.00	.75
	BOSTON EDISON CO	-.73	.00	.00	.00
	POTOMAC EDISON CO THE	-.94	.00	.00	.50
	SOUTH CAROLINA ELEC & GAS CO	-.02	.00	16.38	1.00
	MASSACHUSETTS ELEC CO	-1.00	.00	.00	.00
	DUQUESNE LT CO	-.10	.00	.00	.25
	NEW YORK STATE ELEC & GAS CORP	-.57	.00	.00	.50
	SAN DIEGO GAS & ELEC CO	-.99	.00	.00	.00
	MISSISSIPPI PWR & LT CO	-1.00	.00	.00	.00
	WASHINGTON WTR PWR CO THE	-.58	.00	.00	.25
	METROPOLITAN EDISON CO	-.51	.00	.00	.25
	KANSAS GAS & ELEC CO	-1.00	.00	.00	.50
	WISCONSIN PUB SERV CORP	-.03	.00	.00	1.00
	CENTRAL MAINE PWR CO	-.78	.00	.00	.50
BORDERLINE	TOLEDO EDISON CO THE	.01	.36	.00	.50
	VIRGINIA ELEC & PWR CO	.01	.49	.10	1.00
	DELMARVA PWR & LT & SUBSIDIARY	.01	.72	.00	1.00
	UTAH PWR & LT CO	.03	.83	12.56	.75
	POTOMAC ELEC PWR CO	.03	1.41	.00	.50
	OHIO EDISON CO	.04	2.82	.00	.75
	MINNESOTA PWR & LT CO	.05	2.96	.00	.25
	PENNSYLVANIA PWR & LT CO	.06	3.14	.00	.50
	MONTANA PWR CO THE	.12	4.20	.00	.00
	CAROLINA PWR & LT CO	.15	4.54	8.31	1.00
	APPALACHIAN PWR CO	.17	6.38	.00	.50
	COLUMBUS & SOUTHERN OHIO ELEC	.17	6.51	.00	.50
	COMMONWEALTH EDISON CO	.20	6.96	.00	.50
	DUKE PWR CO	.18	7.16	.00	.75
	PUB SERV CO OF NEW MEXICO	.50	7.28	.00	.50
	ARIZONA PUB SERV CO	.49	8.06	2.00	.25
	PACIFIC PWR & LT CO	.21	8.55	.00	.00
	CINCINNATI GAS & ELEC CO THE	.28	8.85	.00	.50
	OHIO PWR CO	.25	9.06	.00	.50
	NORTHERN STATES PWR CO OF MINN	.32	9.19	.00	.25
	DETROIT EDISON CO THE	.27	9.61	.00	1.00
	CLEVELAND ELEC ILLUM CO THE	.20	9.61	.00	.50
	TAMPA ELEC CO	.24	9.70	.00	.75
UNFAVORABLE	GEORGIA PWR CO	.42	11.02	23.77	.25
	ALABAMA PWR CO	.24	11.65	18.67	1.00
	INDIANAPOLIS PWR & LT CO	.38	14.65	.00	.00
	UNION ELEC CO	.42	17.13	.00	.00
	MISSISSIPPI PWR CO	.41	17.25	.00	.00
	ILLINOIS PWR CO	.37	18.27	5.06	.75
	KENTUCKY UTILITIES CO	.54	18.46	.00	1.00
	WISCONSIN ELEC PWR CO	.38	23.48	.00	1.00
	PUB SERV CO OF IND INC	1.01	28.45	.00	.00
	KANSAS PWR & LT CO	.92	34.28	.00	.00
	MONONGAHELA PWR CO	1.58	39.07	.00	.25
	CENTRAL ILL PUB SERV CO	.92	41.76	.00	.25
	KANSAS CITY PWR & LT CO	1.73	43.08	.00	.00
	WISCONSIN PWR & LT CO	.88	46.47	.00	1.00
	NORTHERN INDIANA PUB SERV CO	.35	49.82	12.59	.25
	DAYTON PWR & LT CO THE	1.16	52.87	.00	.50
	LOUISVILLE GAS & ELEC CO	1.22	63.59	.00	1.00
	PENNSYLVANIA ELEC CO	2.57	72.14	.27	.25

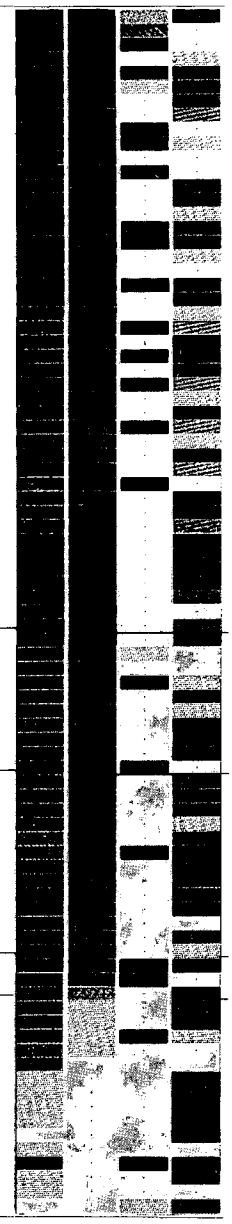


Figure 3. Eighty-five selected utilities ranked for favorability to conservation according to the indicator for the energy balance and cost factor, YEARS. The coal capacity factor used is 0.65. (XBL 851-1045A)

STATE/PUC CONSERVATION INITIATIVES (1982)

	INSUL	AUDIT	SOLAR	COGEN	LOAD	OTHER
ALABAMA	.25	.75	1.00	1.00	.00	.00
ALASKA	.00	.00	.00	1.00	.00	1.00
ARIZONA	.00	1.00	.00	.00	.25	.00
ARKANSAS	.00	.25	.00	.50	.25	.00
CALIFORNIA	.75	1.00	.25	1.00	.25	1.00
COLORADO	.00	.00	.00	.00	1.00	.00
CONNECTICU	.00	1.00	.00	.00	.00	1.00
DELAWARE	.25	1.00	1.00	1.00	1.00	.00
DISTRICT	.00	1.00	.00	.25	.25	.00
FLORIDA	1.00	1.00	1.00	1.00	1.00	1.00
GEORGIA	.00	1.00	.00	.00	1.00	.00
HAWAII	1.00	.00	.00	.00	1.00	1.00
IDAHO	1.00	1.00	1.00	1.00	.00	.00
ILLINOIS	1.00	1.00	1.00	.25	.25	.00
INDIANA	.00	1.00	1.00	1.00	.00	.00
IOWA	.00	1.00	.00	.00	1.00	.00
KANSAS	.00	.75	.00	1.00	.25	1.00
KENTUCKY	.00	.75	.00	1.00	.25	.00
LOUISIANA	.00	.00	.00	.00	.00	.00
MAINE	.00	.00	.00	.00	.25	.00
MARYLAND	.00	1.00	.00	.00	.00	.00
MASSACHUSE	.00	1.00	1.00	1.00	.00	.25
MICHIGAN	1.00	1.00	.00	1.00	1.00	.75
MINNESOTA	.25	.75	.00	1.00	.75	.00
MISSISSIPP	.25	.00	.00	.00	.25	.00
MISSOURI	1.00	.00	.00	1.00	1.00	.00
MONTANA	1.00	1.00	1.00	1.00	.00	.00
NEBRASKA	.00	.00	.00	.00	.00	.00
NEVADA	1.00	.25	.00	1.00	.25	.00
NEW	1.00	1.00	1.00	1.00	1.00	.00
NEW JERSEY	1.00	.25	.25	1.00	.25	1.00
NEW MEXICO	.00	.25	1.00	1.00	1.00	.00
NEW YORK	1.00	.75	1.00	.25	1.00	.00
NORTH	.50	1.00	.25	1.00	1.00	1.00
NORTH	.00	1.00	.00	.00	1.00	.00
OHIO	1.00	1.00	.00	1.00	.50	.00
OKLAHOMA	1.00	1.00	1.00	.00	.25	.00
OREGON	1.00	1.00	1.00	1.00	.25	.00
PENNSYLVAN	.50	.75	.50	1.00	.75	.25
RHODE	1.00	.75	1.00	1.00	.00	.25
SOUTH	.00	.75	.00	.00	1.00	.00
SOUTH	.00	.75	.00	.00	1.00	.00
TENNESSEE	.00	1.00	.00	.00	.00	.00
TEXAS	1.00	1.00	.25	1.00	.25	.00
UTAH	.00	.00	.00	.00	.75	.00
VERMONT	.00	.00	.00	.00	.50	.00
VIRGINIA	.25	.00	.00	.00	.50	.00
WASHINGTON	1.00	1.00	.00	.00	.00	1.00
WEST	.00	.75	.00	.00	.00	.00
WISCONSIN	1.00	1.00	.50	1.00	.50	.00
WYOMING	.00	.00	.00	1.00	1.00	.00

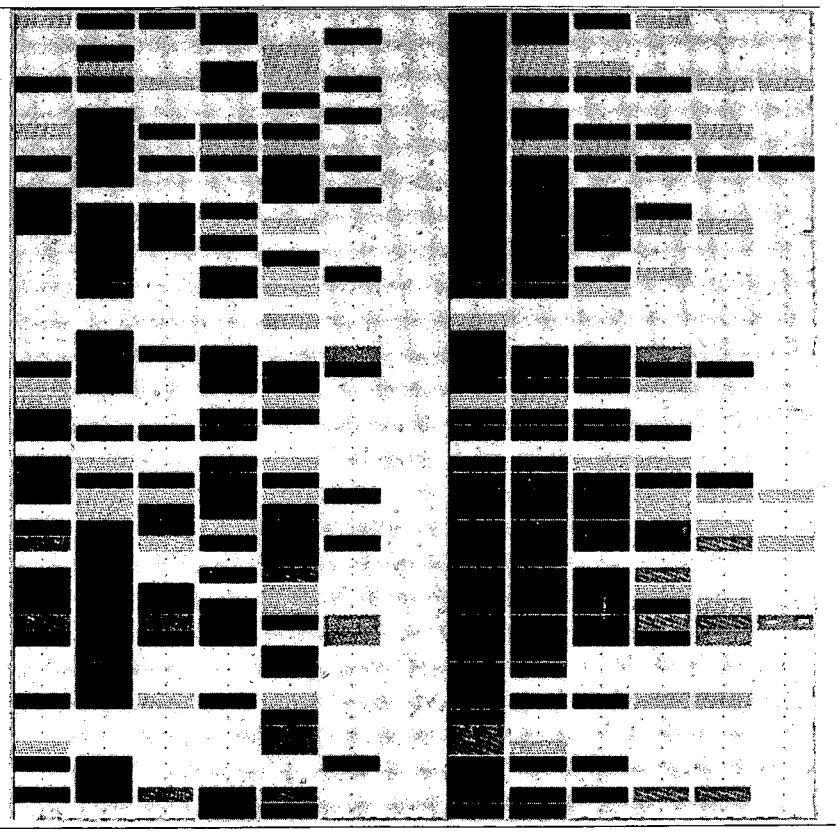


Figure 4. Results for indicators relating to the political/institutional factor, presented at the state level in terms of conservation measures supported by regulatory commissions: INSUL, insulation; AUDIT, building energy audits; SOLAR, solar energy use; COGEN, congeneration; LOAD, load management; and OTHER. (XBL 851-1044)

presents results for indicators relating to the political/institutional factor at the state level. Darker bands show the more favorable states, and lighter bands the less favorable. Values for the third factor, RATES, are not included here, as the analysis for it will not be completed until some time in FY 1985. The results for the selected indicators are interpreted using the matrix of utility decision environments presented in Table 2.

The group of utilities we expect to be most favorable to energy conservation are those with less than 5 years of low-cost marginal capacity. Within this group, the environment for conservation may be uncertain in the short term if the utility has an inverted rate structure or in the long term if major CWIP is available and the public service commission is indifferent to end-use management programs. Among the utilities in the borderline category, existence of inverted rate structures will dampen interest in conservation for the near term. CWIP will render the long-term outlook for conservation unfavorable because utilities will prefer to manipulate the schedule for new capacity until such time as surplus low-cost capacity is used up.

For utilities with more than 10 years of surplus low-cost capacity, the availability of inverted rate structures, CWIP, or commission interest will mitigate or accentuate the unfavorable economic conditions but will not overcome them.

Percent Avoidable Construction (PAC)

Of the utilities with no excess coal capacity, five have less than 5% avoidable capacity, two have 5%–10% avoidable capacity, and nine have

Table 2. Utility decision environment matrix.

PECC[a]	Years	PAC	Rates[b]	CWIP	POL/INST[c]	Remarks[d]
−,0	0	0,>0	No	No	>3	S-T Fav; L-T Fav
−,0	0	>0	No	Yes	<3	S-T Fav; L-T Bord
−,0	0	0,>0	Inv	No	>3	S-T Bord; L-T Fav
−,0	0	>0	Inv	Yes	<3	S-T Bord; L-T Bord
+	<5	0,>0	No	No	>3	S-T Fav; L-T Fav
+	<5	>0	No	Yes	<3	S-T Fav; L-T Bord Unfav
+	<5	0,>0	Inv	No	>3	S-T Bord Unfav; L-T Fav
+	<5	>0	Inv	Yes	<3	S-T Bord Unfav; L-T Unfav
+	5–10	0,>0	No	No	>3	S-T Bord; L-T Bord
+	5–10	>0	No	Yes	<3	S-T Bord; L-T Unfav
+	5–10	0,>0	Inv	No	>3	S-T Unfav; L-T Bord
+	5–10	>0	Inv	No	<3	S-T Unfav; L-T Unfav
+	10+	0,>0	No	No	>3	S-T Unfav; L-T Unfav
+	10+	0,>0	No	Yes	<3	S-T Unfav; L-T Unfav
+	10+	0,>0	Inv	No	>3	S-T Unfav; L-T Unfav
+	10+	0,>0	Inv	Yes	<3	S-T Unfav; L-T Unfav

[a]PECC may be negative, zero, or positive.

[b]Inv = inverted bloc rates applicable; No = no inverted block rates.

[c]Number of measures, i.e., the indicators tabulated in Fig. 4.

[d]S-T = short-term; L-T = long-term; Fav = favorable; Unfav = unfavorable; Bord = borderline.

10%–44% avoidable capacity as percent of total installed capacity.

Construction Work in Progress (CWIP)

About 25 utilities in 17 states have received CWIP on a major or total basis. From the perspective of energy conservation, the expanded availability of CWIP in the rate base renders conservation less competitive than new power plant construction as a strategy for balancing energy supply and demand in the long term. However, CWIP is a ratemaking factor that is often influenced by both political and consumer pressures, the development of which is difficult to forecast. In evaluating the outlook for energy conservation, it is important to keep in mind that we are projecting into the future with this indicator from 1982 data.

Availability of Regulatory Commission–Sponsored Conservation Measures

Figure 4 shows that there is good awareness of energy conservation among state regulatory commissions in the U.S., as evidenced by the number of measures supported. About half of the commissions surveyed by NARUC[10] in 1983 have incentives in at least three out of six areas listed. The most popular measure is AUDIT (35), followed by COGEN (27), LOAD (23), INSUL (21), and OTHER (13).

To summarize, apart from the specific short-term impact of RATES, the utilities (in the group with 0 years of low-cost capacity) most receptive to energy conservation are: West Pennsylvania Power Company, Puget Sound Power and Light Company, Oklahoma Gas & Electric Company, Central Power & Light Company, Public Service of Colorado, and Southwestern Public Service Company. We have not included Pacific Gas and Electric and Niagara Mohawk because upon scrutiny of power plant fuel types falling under PAC (percent avoidable construction), we found that the PG&E unit that comes under this category is a geothermal steam plant and that the units under construction by Niagara Mohawk are hydro power plants. The cancellation or deferral of these plants is unlikely given the comparative cost and long-term trend toward alternate energy fuels.

It is also interesting to note that, in 1982, the availability or lack of energy conservation incentives (see Fig. 4) seems to be at odds with the economic

climate (as evidenced by the indicators for the energy supply/demand and cost factor, Fig. 3) for energy conservation in several states. Maine, Mississippi, and Louisiana are all oil-dependent states that have only minimal conservation incentive programs, while incentives for five conservation measures are offered in Wisconsin—a state with greater than 10 years of surplus coal capacity.

The geographical distribution of the sample utilities indicates that states with surplus reserves of low-cost power are adjacent to each other. For those utilities with more than 10 years of surplus low-cost capacity, power transfers may provide a way of adjusting surplus cheap power and peaking problems if transmission facilities and load requirements can be matched. If interregional wheeling is practicable on a large scale, surpluses in the Midwest may be transmitted to the East Coast deficit states. In this event, the outlook for energy conservation in the midwestern utilities may change in the long term.

PLANNED ACTIVITIES FOR FY 1985

We expect significant institutional developments in the utility industry to occur in the next few years to accommodate the need to balance energy supply and demand. We will proceed with the update and refinement of the indicators for each of the three factors in FY 1985 and develop a composite indicator of utility interest in energy conservation. We plan to carry out further analyses of rate structure, capacity savings, and regulatory treatment of construction work in progress. Also, an exploratory effort will be made to load utility-specific data tapes on a data management system to permit online retrieval and mapping of data for analysis.

REFERENCES

1. Eto, J.H., McMahon, J.E., and Chan, P. (1985), *Financial Impact on Utilities of Load Shape Changes: Stage II Technical Report—The Pacific Gas and Electric Company,* LBL-19067 (forthcoming).
2. Pignone, C. (1985), *Financial Impacts on Utilities of Load Shape Changes: Stage I Technical Report—The Detroit Edison Company,* LBL-19066 (forthcoming).
3. Kahn, E. *et al.* (1984), "Regulatory Factors Affecting the Financial Impact of Conservation Programs on Utilities," paper presented at the ACEEE 1984 Summer Study on Energy Efficiency in Buildings, Santa Cruz, CA, and in proceedings: *Doing Better: Setting an Agenda for the Second Decade,* Vol. 1 (Utility Programs/ Hood River Project), p. 144, American Council for an Energy-Efficient Economy, Washington, DC.
4. Energy Information Administration (1983), *Inventory of Power Plants in the United States, 1982 Annual,* DOE/EIA-0095(82), Department of Energy, Washington, DC.
5. Energy Information Administration (1983), *Statistics of Privately Owned Electric Utilities, 1981 Annual (Classes A and B Companies),* DOE/EIA-0044(81), Department of Energy, Washington, DC.
6. Energy Information Administration (1982), *Electric Power Annual,* DOE/EIA-0348(81), Department of Energy, Washington, D.C.
7. U.S. Department of Energy (1983), *Staff Report: Electric Power Supply and Demand for the Contiguous United States 1983–1992,* DOE/EP-0022/2, Washington, DC.
8. North American Electric Reliability Council (1983), *Electric Power Supply & Demand 1983–1992,* Princeton, NJ.
9. Edison Electric Institute (1983), *Statistical Yearbook of the Electric Utility Industry, 1982,* Washington, DC.
10. National Association of Regulatory Utility Commissions (1984), *1982 Report on Utility and Carrier Regulation.*
11. Donaldson, Lufkin, and Jenrette (1982), *Electric Utility Statistical Reference,* 1982 Edition, New York, NY.
12. *Public Utility Reports,* Arlington, VA (various reports, 1981–1984).

Energy Efficiency Choice in the Purchase of Residential Appliances*

H. Ruderman, M.D. Levine, and J.E. McMahon

This study provides a quantitative analysis of the behavior of the market for the purchase of energy efficiency in residential appliances and heating and cooling equipment. Accurate forecasts of residential energy use require quantitative assessments of market decisions about energy efficiency. The results of our investigation of market behavior can lead to a better understanding of the barriers to investment in energy conservation. Understanding market behavior over time is a prerequisite to an evaluation of the need for and the importance of policies to promote energy efficiency.

The importance of such an analysis to DOE's assessment of its proposed Consumer Products Efficiency Standards relates to its use in forecasting the behavior of the market. Most of the direct impacts of standards (energy savings, net present benefit, and cost of proposed standards) depend critically on the degree to which higher efficiency would be incorporated into new products in the absence of standards. The research will lead to improvements in the methodology and data in the base-case residential energy forecast, thereby improving estimates of the impacts of the standards.

In this study, we examine the historical efficiency choices for eight consumer products: gas central space heaters, oil central space heaters, room air conditioners, central air conditioners, electric water heaters, gas water heaters, refrigerators, and freezers. These products were selected because (1) they account for a major part of residential energy consumption, (2) data on efficiency and costs are readily available, and (3) they are under consideration by DOE for efficiency standards.

We characterize the behavior of the market for these eight products by a single quantity, which we call an aggregate market discount rate. The aggregate market discount rate quantifies the behavior of the market as a whole with respect to energy efficiency decisions. Choices by individual purchasers are constrained by the decisions made by the manufacturers of appliances, the wholesalers or retailers who distribute them, and third-party appliance installers such as builders or plumbers. The value of the discount rate reflects the actions of all these decision makers. It is determined empirically from data on the efficiency and cost of appliances purchased between 1972 and 1980. By examining the historical behavior of the market discount rate, we can better understand the factors that influence efficiency choice. Furthermore, the market discount rate can be used as a parameter in forecasting future residential energy consumption. A paper on this work has been submitted to *The RAND Journal* for publication; it is also available as an LBL report.[1]

*This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Buildings Energy Research and Development, Building Equipment Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

ACCOMPLISHMENTS DURING FY 1984

Most of the work for this study was completed during FY 1983 and was described in the previous annual report. During FY 1984, effort focused on four aspects of the study: (1) calculating payback periods as well as aggregate market discount rates; (2) recalculating discount rates based on monthly compounding rather than annual compounding; (3) examining aggregation bias in the estimation of payback periods; and (4) completing a paper for publication in a refereed journal. This article will discuss the first three aspects.

Payback Period Calculation

The simple payback period is defined as the time needed to recoup an initial investment in energy efficiency. Numerically, the payback period is equal to the increase in purchase cost divided by the decrease in annual operating cost. Assuming the operating costs change only because fuel use decreases, we have:

$$\text{Payback} = \frac{\Delta PC}{FP \cdot \Delta E} = \frac{-1}{FP}\frac{dPC}{dE} \quad , \qquad (1)$$

where PC is the purchase cost, FP is the fuel price, and E is the annual energy consumption. For a continuous cost-efficiency curve, the payback period is the present worth factor.

The purchase cost versus energy use relationship that we used was an exponential curve of the form:

$$E = E_\infty + (E_o - E_\infty)\exp[-A(C-1)] \quad . \qquad (2)$$

where:

$C = PC/PC_o$,
E = annual unit energy consumption (UEC),
E_o = highest UEC,
E_∞ = minimum UEC attainable at infinite purchase cost,

PC = purchase cost corresponding to E,
PC_o = purchase cost corresponding to E_o,

and A is a parameter determined from the shape of the curve. Using this expression, the simple payback period is:

$$\text{Payback} = \frac{PC_o}{A \cdot FP \cdot TI} \frac{1}{(E - E_\infty)} , \quad (3)$$

where we have included a factor TI to account for the possibility that the thermal integrity of the structure may change with time.†

Presenting this study's results in terms of a payback period has some advantages. First, the concept is simpler than that of an aggregate market discount rate and may be closer to what consumers use to make decisions. Second, the payback period does not depend on assumptions about appliance lifetimes and compounding periods. This point will be discussed in more detail below. Finally, discount rates are nonlinear functions of the measured parameters; hence, their values can be very sensitive to small changes in the measurements.

Average payback periods during the years 1972–1980 for the eight appliances are presented in Table 1. Except for air conditioners, the market required an average payback of less than 3 years for an investment in improved appliance efficiency, and for electric water heaters and freezers, the requirement was less than 1 year. Most of the payback periods appear to be stable over time. This supports our previous conclusions that the market for energy efficiency is not working well and that it has not shown much improvement over the past 10 years despite rapid increases in energy prices and increased awareness of energy conservation.

Monthly Discounting

The most common method for evaluating discount rates is to take the time period as 1 year. However, this will underestimate the discount rate when the payback period is shorter than 1 year. Since fuel and electricity bills are paid monthly, we chose a one-month time period for evaluating the market discount rate. It is calculated by solving the following equation for the discount rate r, given a present worth factor or payback period:

†This factor is defined as the relative energy use at different levels of thermal integrity; hence, TI decreases with better insulation and lower air infiltration.

Table 1. Payback period in years for appliances, 1972–1980.

Appliance	1972	1978	1980
Gas central space heater	2.98	2.38	2.21
Oil central space heater	2.33	1.70	1.18
Room air conditioner	5.11	4.77	5.25
Central air conditioner	4.96	4.16	5.18
Electric water heater	0.48	0.41	0.41
Gas water heater	1.50	1.07	0.98
Refrigerator	1.35	1.45	1.69
Freezer	0.60	0.67	0.72

$$PWF = \sum_{t=1}^{N} \frac{1}{(1+r)^t} = \frac{1}{r}\left[1 - \frac{1}{(1+r)^N}\right] . \quad (4)$$

The appliance lifetime N in this equation is expressed in months. An exact calculation would take into account the monthly variation in energy use by each appliance and the month in which it was bought. Since these data are not available, we average over 1 year so that the monthly energy use is one-twelfth of the annual. In presenting our results, we calculate an annualized discount rate $\bar{r}$ from the monthly discount rate r, using the relationship:

$$1 + \bar{r} = (1 + r)^{12} .$$

The revised annualized discount rates shown in Table 2 are higher than those calculated previously for a period of 1 year. The difference is largest for appliances with short payback periods. Although the values are different, our original qualitative results—that market discount rates for most appliances are higher than those expected under perfect market conditions—still hold. These results support

Table 2. Aggregate market discount rates (in percent) for appliances, 1972–1980.

Appliance	1972	1978	1980
Gas central space heater	39	51	56
Oil central space heater	52	78	127
Room air conditioner	20	22	19
Central air conditioner	19	25	18
Electric water heater	587	825	816
Gas water heater	91	146	166
Refrigerator	105	96	78
Freezer	379	307	270

the viewpoint that market forces alone are not enough to eliminate the substantial economic inefficiencies in appliance energy use.

Aggregation Bias

In calculating the payback period and market discount rate, we assume that all consumers will have an average energy use corresponding to the sales-weighted efficiency factor (SWEF). If, in fact, there is a distribution of energy consumption due to differences in efficiency choice or usage, the average market payback period of these users may be different from that calculated from the average energy use. We investigate this aggregation bias in two cases: one in which there is a distribution in energy use and a second in which there is a distribution in appliance efficiency. In the first case, the average payback period is greater than that calculated from the average energy use (and the discount rate is less). In the second case, the direction of the aggregation bias depends on the ratio of average efficiency to the maximum efficiency corresponding to E_{∞}. The amount of bias depends on the width of the energy and efficiency distributions.

To estimate the magnitude of the aggregation bias, we used data on the distribution of efficiency of central air conditioners in 1980 published by the Air-Conditioning and Refrigeration Institute.[2] The average efficiency (SEER) was 7.76, with a standard deviation of about 10%. This gives an aggregation bias of about 1%. Biases of this size are small compared to the uncertainties caused by measurement error in the SWEF and other data used to calculate the payback period.

PLANNED ACTIVITIES FOR FY 1985

Although the work on this study was completed during the past fiscal year, related research on consumer behavior is continuing. An accompanying article ("Increased Usage of Appliances in Response to Efficiency Improvements") describes some of this work. The Appliance Standards Analysis Review Group, assembled by DOE to evaluate the previous appliance standards analyses and to produce a research agenda for the reanalysis, recommended development of a household-based model of consumer behavior. Effort during FY 1985 will focus on formulating such a model and collecting data for its estimation. The model specification will utilize the microeconomic theory of consumer behavior as well as theories developed in market research. Product attributes, expectations of fuel price, uncertainty, and simultaneity in decision-making will be explicitly included as far as possible. The model will be disaggregated geographically as well as along the dimensions of product class, appliance ownership, and socioeconomic class. Several versions of the model will be tested and validated, depending on the availability of data.

REFERENCES

1. Ruderman, H., Levine, M.D., and McMahon J.E. (1984), *The Behavior of the Market for Energy Efficiency in the Purchase of Appliances and Home Heating and Cooling Equipment*, LBL-15304.
2. Air-Conditioning and Refrigeration Institute (1983), *Comparative Study of Energy Efficiency Ratios*, Arlington, VA.

Analysis of Federal Energy Efficiency Standards for Appliances*

M.D. Levine, P. Chan, J.E. McMahon, and H. Ruderman

In 1978, Congress required the U.S. Department of Energy (DOE) to develop and promulgate minimum energy efficiency standards for all major residential appliances and heating and cooling equipment. Lawrence Berkeley Laboratory's Energy Analysis Program has been deeply involved in the analysis of these standards. The major responsibility of the LBL team has been to assess the benefits and costs of standards to the consumer and to estimate the reductions in energy use that could result from them. Present DOE policy is not to set any standards for appliances. LBL is now responsible for carrying out over the next several years a reevaluation of the original standards to provide guidance in case of further major revisions in DOE policy.

ACCOMPLISHMENTS DURING FY 1984

Methodology

Our basic approach to evaluating impacts of appliance standards is to estimate the differences between a base-case forecast (i.e., the expected energy efficiency and other parameters when no federal standards are promulgated) and a standards case forecast, in which the energy efficiency and related variables are determined or influenced by the federal policy. If the efficiency of new appliances, appliance usage, first costs, and operating costs were precisely known over the time horizon of the study (as they cannot be) for both the base case and the standards case, then the direct economic impact of the standards on appliance purchasers—the difference between the two cases—would also be exactly known.

Figure 1 presents an overview of the research methodology. The general categories of data required are shown at the left: socioeconomic data for energy forecasting (e.g., projections of housing starts); economic data (demand elasticities); economic forecasts (energy prices); and the economics of appliance efficiency improvements. The model used to project the base and standards cases is a version of the Oak Ridge Residential Energy Demand Forecasting Model (ORNL).[1] This model has been substantially improved for the purpose of analyzing standards.[2] The results of the analysis, shown at the right of Fig. 1, provide direct measures of the impact of standards on appliance purchasers and on the nation: change in energy use as a function of time, change in the life-cycle cost of the appliance over time, net present benefit or cost of the standards to the consumer, and changes in shipments of products resulting from the standards. Impacts on manufacturers and on different groups of consumers cannot be evaluated directly from the model and the data. However, the analysis of direct economic impacts can be combined with other data to obtain estimates of these impacts.

The analysis requires a great deal of data disaggregated by appliance type. Only from such disaggregation can we estimate the retirement rates of individual appliances, the direct and cross price (between fuels) elasticities for energy by end use, and the cost of efficiency improvements for each appliance type.

Key Issues

Some of the most important issues in the analysis of appliance efficiency standards involve the following questions:

- What is the nature of the market for energy efficiency in residential appliances?
- What are the likely impacts of standards on consumers, manufacturers, other interest groups, and the U.S. economy?
- How will the impacts on appliance purchasers vary among different income groups and among different regions of the country?
- How do the estimated impacts vary with different products, and why? Should a government policy set different criteria for different appliances? If so, on what basis?
- What are the most important sources of uncertainty in estimates of the impacts of standards? How can such uncertainty be dealt with to improve the quality of public policy analysis?
- If standards are promulgated, might their be effects be reduced (or even eliminated) by increased usage of the more efficient products? What is the implication of such a "usage elasticity" on the analysis of policy?
- How does the interaction among end uses effect our estimates of energy savings and economic impacts?
- What is the effect on other conservation investments (e.g., thermal integrity)?

*This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Buildings, Energy Research and Development, Building Systems Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

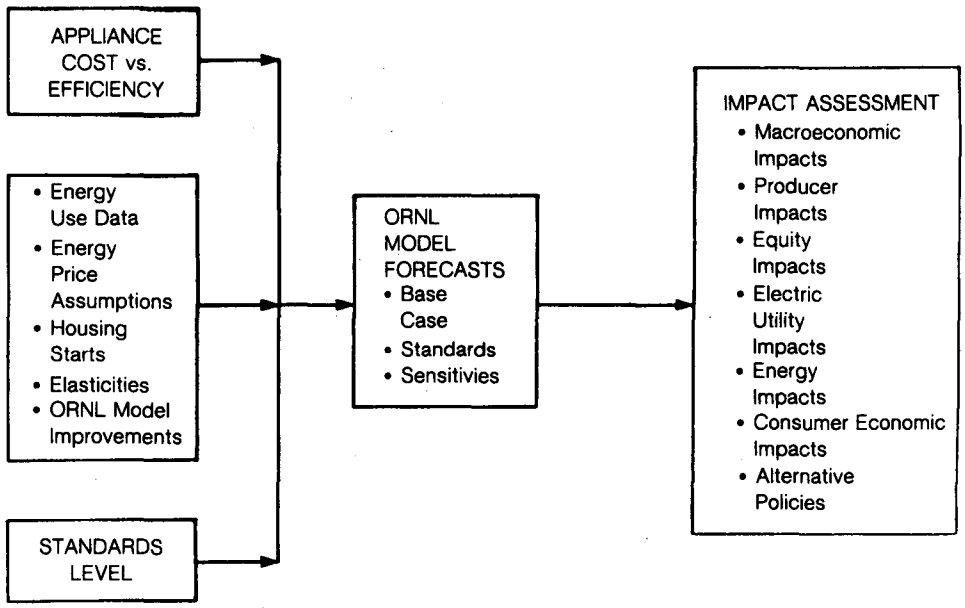


Figure 1. Overview of research methodology. (XBL 845-1963)

- How accurate are the underlying data on cost versus efficiency improvements for the appliances? How can one account for technological improvements that will take place in the future?

Results

Under various plausible assumptions, the analysis projected estimates of energy savings from the standards that ranged between 11 and 19 quads over a 20-year time horizon, with an expected value of 13 to 15 quads. While 14 quads amount to only about 5% of aggregate residential energy demand over the 20-year period, the impact on energy demand *growth* is dramatic. Figure 2 shows projected residential energy demand with and without standards. The standards originally contemplated by DOE were designed to be within present technological capabilities and to be below life-cycle cost minimums at current fuel prices; if they were to be introduced in 1986, overall residential energy demand growth would be reduced to zero for a decade. Because the legislation provided for updates to the standards, the process could lead to level residential energy demand for two decades or longer. (Other policies or higher-than-expected energy prices could result in declining residential energy demand.)

The total economic impact on consumers is significant. Absent periodic updates to and tightening of the minimum efficiency standards, energy demand is reduced by almost 0.5 quads per year within 6 or 7 years of implementation. At a cost to the consumer of $6 per million Btu, this is a reduction in fuel costs of $3 billion per year. The estimated net present benefit of minimum efficiency standards (fuel cost savings discounted at 10% real, minus the increased first cost of more efficient appliances) is $12 billion dollars, with a range between $10 billion and $16 billion under various alternative assumptions.

Figure 3 shows the estimated energy savings and net benefits of the standards for the six products that consume the largest amounts of energy. Water heaters and refrigerators yield the greatest potential energy savings. The net benefits are also greatest for these two products, both because the energy savings are largest and because the increased first cost of efficiency improvements are low. Room air conditioners and freezers also yield high net benefits per unit of energy saved.

Standards are estimated to have relatively little impact on furnaces. The major reason is that DOE originally proposed relatively low standards that would have yielded little improvement in energy efficiency over that expected without standards. Since then, condensing furnaces with efficiencies substantially higher than the trial standards have been introduced and are currently selling well. Thus, a tighter minimum standard for furnaces could show substantial energy savings; uncertainty in costs have until recently made the estimation of net benefits speculative.

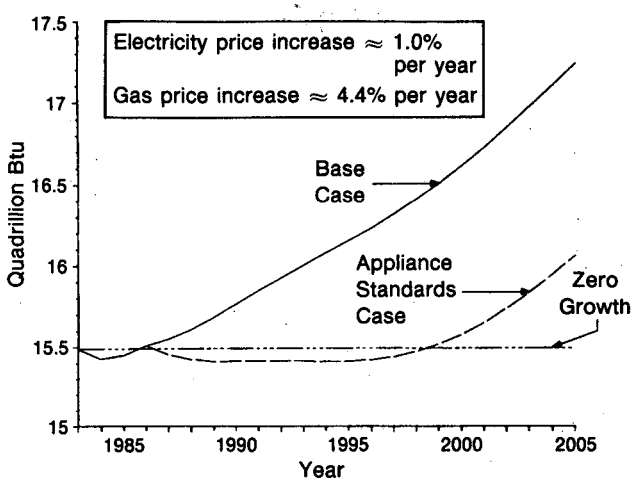


Figure 2. Residential energy demand forecasts. (XBL 845-1966)

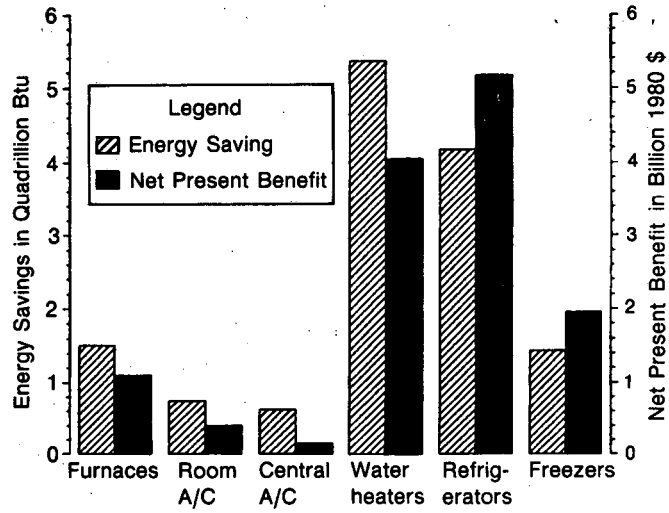


Figure 3. Energy savings and net present benefit of proposed federal standards, by product. (XBL 845-1965)

Central air conditioners show significant energy savings; however, the net benefits are not nearly so great per dollar invested, nor are the unit energy savings as much as for other products. This is because it is assumed that measures to reduce energy use are added incrementally to existing central air conditioner models, making efficiency improvements relatively expensive. If a full redesign of central air conditioners (and other products) were evaluated, the cost of efficiency improvements could conceivably be different (and lower) than the incremental approach.

Figure 4 shows the projected annual energy savings for several of the most important variables for which we performed sensitivity analyses. The reference or base case assumes a real price escalation averaging 4.4% per year for natural gas and 1.0% per year for electricity over a 20-year period. The low energy price forecast assumes real energy price increases of 1.6% per year for natural gas and no increase for electricity. The high energy price forecast is for annual real price increases of 6.1% and 2.0%. The forecast labeled "historic efficiency" does not consider energy prices explicitly; rather, it assumes that, for each appliance, the efficiency improvements of the past decade will continue. The two remaining cases (high and low market share elasticities) make different assumptions about market

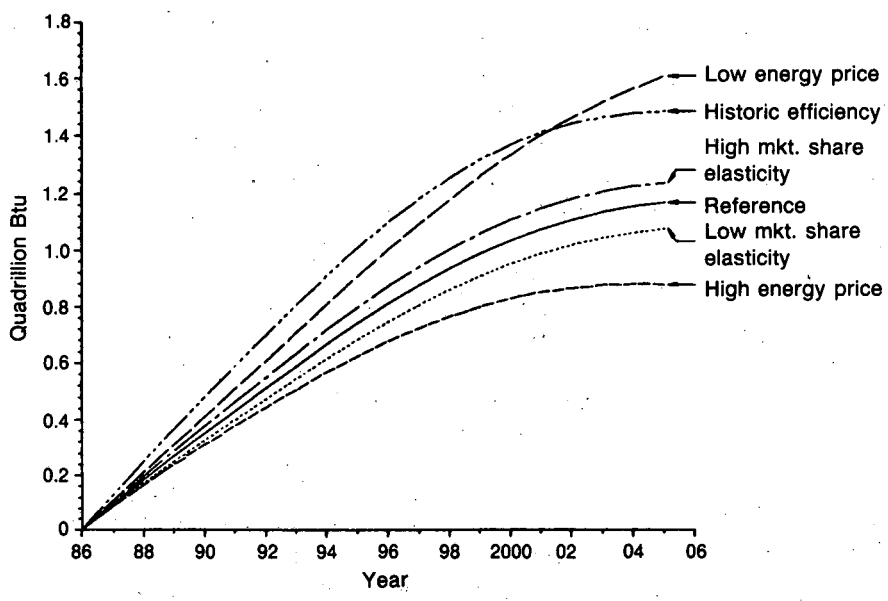


Figure 4. Projections of annual savings in residential energy use under proposed standards for appliance energy efficiency, using various base-case assumptions. (XBL 845-1964)

response to higher energy prices (in terms of the energy efficiency of new product purchases). The results of research conducted to date suggest that the reference case with a constant discount rate may best approximate reality. (This research is discussed in a preceding article on energy efficiency choice by Ruderman *et al.*)

PLANNED ACTIVITIES FOR FY 1985

The reanalysis of appliance efficiency standards is expected to take place over the next 3 years. A thorough review of all aspects of the research has been initiated by a panel of experts convened by Lawrence Berkeley Laboratory. Current work at LBL involves (1) improvements to the energy demand forecasting model (particularly in treating different classes of appliances such as frost-free and partially automatic refrigerators); (2) systematic analyses of the strengths and weaknesses of the energy demand model; (3) analysis of energy demand and usage elasticities to improve forecasting results; (4) studies of aggregation issues involved in forecasting impacts at the national level and for consumers with "average" incomes; (5) research on improving estimation of consumer fuel choice; (6) improvements in analyzing heat pump market penetration and efficiency choices; and (7) conceptual studies to begin the design of the analysis of factors affecting manufacturers' decisions regarding the energy efficiency of new product lines.

The LBL team will work closely with the research review group. Subcontracting will emphasize improved data on the distribution of energy efficiency of appliances sold both nationally and by region of the nation and a preliminary reassessment of trade-offs between cost and energy efficiency in appliances.

REFERENCES

1. Hirst, E., and Carney, J. (1978), *The ORNL Engineering-Economic Model of Residential Energy Use,* Oak Ridge National Laboratory, ORNL/CON-24.
2. McMahon, J.E. (1984), "An Improved Residential Energy Model," LBL report in preparation.

Utility Incentive Programs for Efficient Appliances*

J.E. McMahon, D.F. Dickey, and M.D. Levine

Electric utilities have traditionally been concerned with providing an adequate supply of electricity for their customers. In recent years, they have also been concerned about their ability to finance construction of additional generating stations. The costs of capital, coupled with rising fuel costs, have caused utilities to focus attention on the demand side of the problem. Many have implemented methods for limiting growth in demand (conservation) or for controlling demand during certain periods (load management).

Electric utilities are taking a variety of approaches to achieve energy conservation and/or load management. This article focuses on one of those approaches. Many utilities in the United States have programs that offer incentives, such as rebates or low-interest loans, to purchasers of residential appliances to encourage the selection of models with specified attributes, most commonly high efficiency. These programs are often justified as a means of reducing growth in peak demand or electricity consumption, or balancing seasonal loads. We have assessed the extent to which utility incentive programs, taken together, have influenced the national average efficiency of new residential appliances. We believe this is the first attempt to quantify the aggregate effect of these programs.

Utility incentive programs for residential appliances have been implemented only since 1979. Two broad surveys have provided useful compilations of information, but both have been limited in scope and therefore have not provided sufficient information to assess the effects of these incentive programs on the energy efficiency of new appliances throughout the nation. The first[1] covered only two types of equipment: central air conditioners and heat pumps. The second[2] discussed a wider range of appliances but reported on only 19 utilities. The utility industry has held workshops on measuring the effects of conservation programs,[3] but the focus has

*This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Buildings Energy Research and Development, Building Equipment Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

naturally been on individual utilities. Hartman *et al.* have described a theoretical methodology based on conditional demand analysis for analyzing conservation programs of individual utilities.[4] We are aware of one extensive evaluation by a utility.[5,6] The major conclusions of that evaluation include the following: (1) incentives cause an increase in the number of efficient appliances purchased in the service area (between 10% and 38% of annual sales), providing both energy and capacity savings; (2) many eligible purchasers do not apply for a rebate, and many who do apply indicate that they would have purchased the efficient model even without the rebate; (3) the purchase of efficient appliances provides a net benefit from the combined perspective of appliance purchasers and utility ratepayers.

In a recent LBL report,[7] we presented the results of a survey of 76 utilities. We conducted the survey in order to understand the impact of utility rebate programs on the energy efficiency of newly purchased residential appliances and heating and cooling equipment. We were interested in learning whether utility rebate programs have increased the average energy efficiency of these products; if so, by how much; and whether these utility programs will have a significant impact in the future.

This objective is important to a larger LBL effort to investigate the impact of public policies (especially appliance standards) on the energy efficiency of residential equipment. This investigation provides information useful to assessing the degree to which utility programs may result in higher energy efficiency, thus avoiding the overcounting of energy savings attributed to other policy measures and yielding information about the efficacy of existing programs in contributing to the goal of greater energy efficiency in the residential sector.

To achieve this objective, even in a preliminary way, we needed the following information:

- How many utilities are participating in incentive programs?
- Where are the utilities with programs located?
- What are the objectives of the programs?
- What appliances receive rebates?
- What has been the experience of the utilities with these programs?
- How large are the programs (how many incentives have been given)?
- Do the utilities that have programs intend to continue them?
- Are there institutional problems that might slow the implementation or otherwise interfere with the effectiveness of the programs?

In FY 1983, we made our first attempt to accumulate and assess such information. Important results for which we have obtained evidence include the following: (1) incentives are widespread, with utilities representing 67% of residential electricity sales offering incentives on some products; (2) most of the incentives are being offered for room and central air conditioners and heat pumps and are concentrated in the southern and western states; (3) most utilities expect to reduce peak load growth with these programs; (4) the aggregate effect of all the programs on national average efficiency of new products is small, because of conservative minimum efficiency requirements and the low number of incentives awarded relative to annual shipments; (5) the largest effect on efficiency is for central air conditioners, which have the largest ratio of incentives to annual shipments; (6) lower efficiency requirements are set for heat pumps, reflecting utilities' interest in promoting electricity sales in winter; and (7) these programs have the potential to increase significantly the rate of change of efficiency of new products, particularly central air conditioners, compared to the rate of change previously observed from all other factors.

ACCOMPLISHMENTS DURING FY 1984

In FY 1983, we surveyed 76 utilities to assess their incentive programs for appliances. These utilities supply 45% of the national sales of electricity to residential customers. In FY 1984, we collected data from other sources pertinent to the effects of the utilities' incentives on the national average efficiency of new appliances. The data included efficiency requirements in state building or appliance codes (from the Edison Electric Institute), and the distribution of efficiencies of appliances purchased in recent years (from the Air-Conditioning and Refrigeration Institute). We then analyzed the aggregate effects of incentives on national average efficiencies. We focused on central air conditioners and heat pumps, since these products had the largest proportion of incentives awarded relative to total sales.

Minimum Efficiency Requirements

The appliances for which minimum energy efficiency requirements most often apply are room and central air conditioners and heat pumps. The four utilities identified as offering rebate programs for gas furnaces all established minimum efficiency levels. Utilities offering rebate programs for refrigerators (in

California, Florida, and Minnesota) also placed minimum efficiency requirements on these appliances. Rebate programs for most of the other appliances did not have requirements for energy efficiency. These included solar water heaters, heat-pump water heaters, heat-recovery water heaters, electric space heating, solar space heating, gas ranges, and gas dryers. Some rebate programs can be thought of as electricity marketing rather than conservation programs.

In support of this last point, we noticed that heat pumps have consistently lower minimum energy efficiency requirements than central air conditioners—about one SEER† unit lower, on the average. However, the historical difference between the average SEER of heat pumps and unitary air conditioners is less than 0.4.[8] This might mean that sales of heat pumps to increase winter electricity demand is, for many utilities, more important than reducing summer peaking.

In the programs surveyed, 70% of central heat pump incentives required a minimum SEER between 7.5 and 8.5. The average minimum SEER for all incentives is 7.5. For room heat pumps, minimum efficiency requirements lie between 7.5 and 8.9. Central air conditioner efficiency requirements are set higher, with 62% of these incentives having minimum SEERs at or above 9.0. The average for all central air conditioner incentives is an SEER of 8.8. Room air conditioner minimum efficiencies are set at or above 7.5, with an average value of 8.4.

Number of Incentives Offered

Table 1 provides data on the total number of incentives offered for each type of appliance by the utilities in the survey. Also included is an estimate of the percent of total sales of the appliance in the residential market for which incentives were awarded in 1983, the national sales-weighted average efficiency of the appliance, and the average minimum efficiency of the utility incentives surveyed.

We surveyed two groups of utilities. Group 1 consists of 41 utilities previously identified as offering incentives for residential appliance purchases. Five of these supplied gas only, while the majority supplied electricity only or electricity and natural gas. Group 2 consists of 35 electric utilities not previously identified as offering rebates or loans. We selected large investor-owned or municipal utilities in order to expand our coverage of geographic and climatic regions, total residential electricity sales, and types of appliances.

Table 1. Estimated annual incentives and average minimum efficiencies.

Appliance	Annualized rate of incentives offered	Percent of annual shipments	National average efficiency (SEER)	Incentive average minimum efficiency (SEER)
Central heat pump[a]	32,100	5.2	8.32 (1983)	7.5
Room heat pump[a]	300	n/a	n/a	7.6
Central air conditioner	121,700	8.5	8.43 (1983)	8.8
Room air conditioner	43,200	1.2	7.06 (1981)	8.4
Solar water heater	18,300	n/a	n/a	n/a
Heat pump heater	1,100	n/a	n/a	n/a
Heat recovery water heater	3,200	n/a	n/a	n/a
Gas water heater	6,400	0.2	48.17 (1978)	n/a
Electric water heater	1,500	0.5	80.67 (1978)	n/a
Gas range	n/a	0.0	17.66 (1978)	n/a
Gas dryer	3,900	0.6	2.41 (1980)	n/a
Gas furnace	3,300	0.2	63.58 (1978)	n/a
Electric space heater	<1	n/a	n/a	n/a
Solar space heater	n/a	n/a	n/a	n/a
Refrigerator/ freezer (new)	84,600	1.5	6.12 (1982)	
Freezer			11.28 (1982)	n/a
Refrigerator/ freezer (old)	12,500	n/a	n/a	n/a

[a]Shipment and efficiency figures aggregate central and room heat pumps. Percent of annual shipments is therefore based on the aggregate totals.

The survey has identified incentives totaling 5.2% of total shipments of heat pumps to the residential sector in 1983. This number needs to be adjusted for three factors to provide a better estimate of total number of incentives as a fraction of shipments of appliances: (1) the survey accounts for 45% of utilities (by electricity sales); (2) group 1 includes utilities known to have rebate programs, and (3) group 2 shows 22% of the utilities offering heat-pump incentive programs, compared with 57% in group 1. Thus, a reasonable estimate of the percentage of heat pump sales affected by utility incentive programs is 8.2.‡ This is admittedly a rough estimate. It assumes that utilities that have not been surveyed offer the same number of incentives relative to residential electricity sales as those utilities surveyed. This may tend to cause the correction to be somewhat high. On the other hand, if utilities in the survey reported incompletely on the number of incentives awarded, then the estimate is low.

†SEER = seasonal energy efficiency ratio; the higher the ratio, the greater the efficiency.

‡For central heat pumps, 1.58% of national shipments were awarded incentives by group 2 utilities, which represent 17.4% of residential electricity sales. Using the same proportion, we estimate 3.0% of national shipments of heat pumps may have been awarded incentives by the utilities not surveyed (55% of residential electricity sales). The total fraction of heat pump shipments awarded incentives is then 5.2% (surveyed) plus 3.0% = 8.2%.

Incentives for central air conditioners identified in the survey total 8.5% of national shipments. Correcting for utilities not included in the survey yields an estimate of 10% of total shipments. For all other products, the number of incentives identified in the survey is a small fraction of total shipments. Incentives for refrigerators totaled 1.5% of shipments. Incentives for room air conditioners totaled about 1% of shipments. These and other products had few incentives compared with total national shipments.

Effect on Efficiencies of New Appliances

The efficiency of appliances has generally increased over the time utility incentives have been in place.[8] In spite of the rapid and extensive penetration of these incentive programs throughout the nation, it is difficult to determine how much of the change in efficiencies can be attributed to them. State efficiency standards, increasing energy prices, federal labeling programs, and the possibility of federal efficiency standards also could have contributed to manufacturers' and consumers' decisions regarding appliance efficiencies. Insufficient data exist to separate these effects at this time. Furthermore, we cannot determine whether the participants in utility rebate programs would have purchased efficient products even without the incentive, and simply took advantage of the cash rebate without changing their efficiency choice. Alternatively, the utility incentives may have motivated manufacturers to produce and distributors to stock, or people to buy, more efficient products than they would otherwise have done. Obviously, additional data collection and analysis would be valuable. For now, we confine our quantitative analysis to a comparison of the average efficiency required by surveyed incentives in 1983 with the national sales-weighted efficiency (SWEF) for 1982. The calculated percent change attributable to incentives is compared to the reported change in average efficiency from 1982 to 1983.

In addition to any change in national average efficiency, the incentives may shift electrical demand among regions by influencing the efficiency distribution available in each region. If the models shipped to regions with incentives have higher efficiencies while the remaining lower-efficiency models are shipped to regions without incentives, then demand is effectively wheeled from the regions with incentives to those without. The extent to which this occurs depends upon manufacturer and distributor decisions. This effect would be hidden in a national-level analysis of changes in efficiency, but it could play a role in shifting demand away from utilities with lower reserve margins (and incentive programs) toward utilities with excess capacity (and no such programs).

Efficiency Effects: Central Air Conditioners

For central air conditioners, we have examined the level of state efficiency standards, the national distribution of shipments according to efficiency, and the utility incentive programs surveyed. We draw two conclusions:

(1) Most states' requirements for air conditioner efficiency (in building codes rather than specific appliance efficiency regulations) are based upon ASHRAE standards, which are relatively low.[9]

(2) Utility incentive programs to date have increased the national sales-weighted efficiency by only a small percentage, both because the number of incentives is small relative to total sales and because the minimum efficiencies are near the average efficiency already being sold. On the other hand, this effect might be comparable in magnitude (within a factor of 2 or 3) to the annual percent change observed in recent years due to *all other factors combined.*

Figure 1 shows the distribution of state requirements for minimum efficiency of central air conditioners, weighted by average number of units shipped per state. It compares the state require-

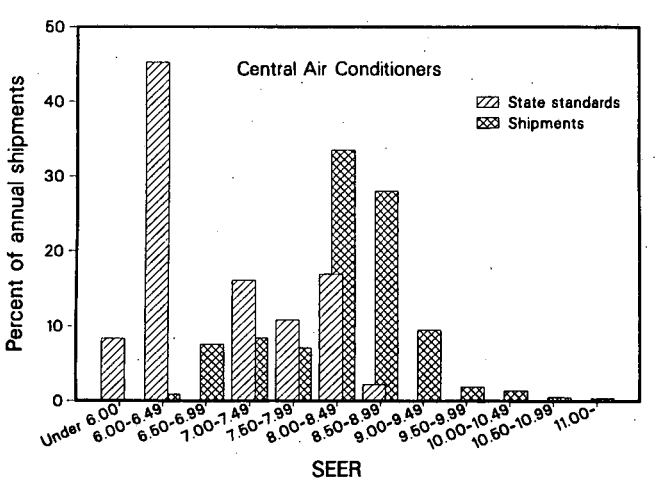


Figure 1. Distribution of state minimum energy efficiency requirements (by SEER) for central air conditioners, weighted by average number of units shipped per state (percent of annual shipments), compared with the 1982 distribution of units shipped (by SEER). (XCG 849-13249)

ments, expressed as percent of annual shipments, to the 1982 distribution of units shipped. The national sales-weighted efficiency (SWEF) is 8.20 SEER; the weighted average of the state requirements is 7.07 SEER. Only 12% of national shipments were under 7.0 SEER in 1982, and only 7 states, representing less than 20% of shipments, have efficiency requirements at or above 8.0 SEER. Yet 70% of national shipments are at or above 8.0 SEER. The state requirements appear only to provide a floor for efficiencies, not to force the implementation of new technologies.

Our minimum estimate, based on our survey, is that more than 121,700 utility incentives were awarded for central air conditioners in 1983. Figure 2 shows the breakdown according to minimum efficiency requirement. The percent of incentives by efficiency requirement is displayed, along with the 1982 distribution of shipments by efficiency. While only 11% of shipments in 1982 were at or above 9.0 SEER, 62% of the incentives required 9.0 SEER as a minimum in 1983. Thus Figure 2 indicates that purchasers who received incentives bought central air conditioners having efficiencies higher than the average unit manufactured. The number of incentives (75,000–90,000 above SEER 9.0) is less than the number of units that would have been bought at high efficiencies anyway (194,000 above SEER 9.0). From 1982 to 1983, total shipments of central air conditioners increased by 40%, but sales of units at SEER 9.0 and above increased by over 90%. The total number of incentives corresponds to about half of that increase. However, it is clear that the incentives operate at the high end of the existing sales distribution.

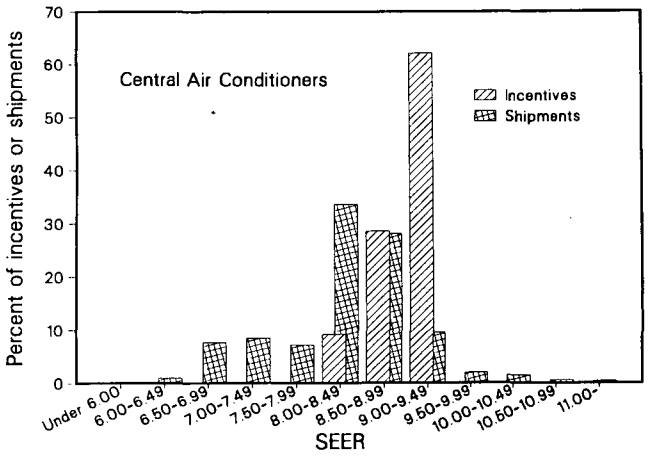


Figure 2. Percent of incentives awarded in 1983 according to minimum efficiency requirements, compared with 1982 national distribution of shipments by efficiency.

(XCG 849-13250)

The average minimum SEER of air conditioner incentives is 8.8. The sales-weighted SEER for central air conditioners was 8.4 in 1983. However, 62% of all incentives require an SEER of 9.0 or above. Assuming that the incentives promote an average SEER of 9.2, and that consumers in these programs would have purchased at the national average of 8.4, the effect of the utility programs is to increase the SEER by: 0.8 (increase in SEER) $\times$ 0.12 (fraction of central air conditioner sales impacted by utility programs) = 0.1. This is an increase of about 1.2%. Historical annual increases have ranged from 1.1 to 6.8% since 1976.[7] The change from 1976 to 1980 comprises 1.8%/year on average due to all factors combined. From 1981 to 1982, the change was 6.8%, and the change from 1982 to 1983 was 1.4%. By comparison, the change apparently due to incentive programs alone is substantial.

Utility incentive programs have not yet significantly affected the national average SEER for two reasons: (1) recipients represent a small proportion of the total population of purchasers; and (2) the minimum efficiency requirements in the incentive programs are not forcing the development of new designs. According to data from Northern States Power Company's evaluation of its program, only 54% of purchasers eligible for rebates applied for them. That is to say, the minimum efficiency requirements are well within the universe of available models, so that sufficient numbers of these models are available to the public even without the rebates.

Many of the participants in the utility incentive programs are "free riders." According to a survey by Northern States Power, 39% of applicants for central air conditioner rebates said they would not have bought an efficient model without the rebate. Many purchasers said they would have made the same selection even in the absence of incentives. This supports the view that the minimum requirements are not technology-forcing.

Limitations of the Analysis

This analysis is limited by several factors: (1) the survey does not include all utilities; (2) some responding utilities with incentive programs did not divulge the results; (3) the minimum efficiency requirements of the incentives, not the actual efficiencies of models purchased, were used when estimating effects on average efficiency; (4) many of the participants in the incentive programs would have made the same appliance choice anyway; and (5) we have assumed that appliance sales to nonparticipants are unchanged by the incentive programs.

The first three of these factors cause us to underestimate the effects of the incentive programs. The fourth factor may cause us to overestimate their effect. The effect of the fifth factor on our estimate is indeterminate. We believe our estimate of the effect of incentives on average efficiency is low and recommend further survey work to refine the present estimates.

PLANNED ACTIVITIES FOR FY 1985

No further work is planned in FY 1985.

REFERENCES

1. Air-Conditioning and Refrigeration Institute (1982), *Utility Incentive Programs for Central Air Conditioners and Heat Pumps*, Arlington, VA.
2. American Council for an Energy Efficient Economy (1983), *Utility Rebate Programs: An Overview* (draft), Washington, DC.
3. Hirst, E., Ed. (1982), *Workshop Proceedings: Measuring the Effects of Utility Conservation Programs*, Electric Power Research Institute, EPRI-EA-2496, Palo Alto, CA.
4. Hartman, R.S., O'Keefe, J.C. and Jensen, K.A. (1984), "Measuring the Effects of Utility-Sponsored Conservation Programs: Do the Programs Work?," *Energy Systems and Policy 8*, p. 213.
5. "Rebates Push Sales of Efficient Appliances," *Electrical World 198*, p. 83 (January 1984).
6. Northern States Power (1983), "Northern States Power Company's Evaluation of the Appliance Rebate Program," prepared for the Minnesota Public Utilities Commission, Minneapolis, Minnesota.
7. Dickey, D., Levine, M.D., and McMahon, J.E. (1984), *Aggregate Effects of Utility Incentive Programs on the Average Efficiency of New Residential Appliances*, LBL-18339 (in press).
8. Air-Conditioning and Refrigeration Institute (1984), *Comparative Study of Energy Efficiency Ratios*, Arlington, VA.
9. Edison Electric Institute (1984), *State Codes for Energy Conservation in New Buildings*, Washington, DC.

Residential Hourly and Peak Demand Model*

H. Ruderman, G. Verzhbinsky, and M.D. Levine

For the past few years, we have been developing a model of hourly and peak residential electricity demand in utility service areas. The model enables us to examine the effects of various energy conservation policies on utility load shapes. Changes in peak load and load factor can affect the financial picture of an electric utility by reducing or increasing the need for new generating capacity. Knowing how conservation policies affect electricity sales and load shapes is crucial for understanding whether utilities will support the policies and assist in their widespread adoption. Application of the model to two utility service areas is described in another article ("Economic Impacts of Residential Conservation Programs on Electric Utilities").

The model operates by disaggregating projections of annual residential electricity consumption for 12 end uses to each hour of the year. The disaggregation is accomplished with the aid of hourly load profiles for the temperature-insensitive end uses and by fraction-in-use matrices for the temperature-sensitive end uses. The latter contain data on the fraction of the installed appliance capacity in use for each hour of the day, versus temperature or a temperature-humidity index. At present, the annual consumption projections are provided by the ORNL/LBL Residential Energy Use Model.[1,2] Because of the high level of disaggregation in both the hourly and annual consumption models, utility and government policies targeted at specific appliances and building characteristics can be evaluated. Details of the construction, operation, and validation of the residential hourly and peak load model may be found in an LBL report.[3]

ACCOMPLISHMENTS DURING FY 1984

Work this year was primarily directed toward (1) adding a new heat pump module, (2) calibrating and

*This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Buildings Energy Research and Development, Building Equipment Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

validating the model, and (3) completing the documentation.

New Heat Pump Module

This year, we wrote a new module to calculate heat pump loads in the heating mode. The key part of this effort was an analysis of the difference in performance of heat pumps and electric resistance heaters. Using the DOE-2 program, we simulated hourly electricity loads in residential buildings heated by heat pumps or resistance heaters in four locations: Detroit; Washington, DC; Phoenix; and Minneapolis. For each location, we recorded the heat pump electricity demand for heating for each hour of the year in a matrix by hour of the day and outdoor dry-bulb temperature. Each element in the matrix represented the average heat pump demand for the corresponding hour and temperature. We constructed a similar set of matrices for the operation of electric resistance heaters under the same conditions. Dividing each element in the heat pump matrix by the corresponding element of the resistance heater matrix gives a matrix of heat pump efficiencies.

In examining these efficiency matrices, we noticed that they were nearly the same for all locations, except for missing elements in the warmer locations that represented combinations of temperature and hour of day that did not occur. Furthermore, there was little diurnal variation in the efficiency. Thus, we concluded that the average heat pump efficiency depended only on temperature. A code was incorporated in the peak load model to construct the heat pump fraction-in-use matrix by multiplying elements of the corresponding electric resistance fraction-in-use matrix by the heat pump efficiency at that temperature.

The heat pump module was tested by simulating a winter peaking utility based on data from the Detroit Edison Company (DECO). DECO was changed from a summer to a winter peaking utility by increasing the saturation and market penetration of electric heating systems relative to gas and oil systems. With these changes, the peak residential load occurred in January. We compared projections of annual energy use and peak load for space heating for two cases: (1) all-electric heating was supplied by resistance heaters operating at 100% efficiency, and (2) 10% of the electric heating systems were heat pumps with an average coefficient of performance (COP) of 1.88.

The results showed both qualitative and quantitative agreement with what would be expected if heat pumps were substituted for electric resistance heaters. The average COP of heat pumps was higher than the COP at peak load because peaks occur during periods of low outdoor temperature. The average COP calculated from the ratio of annual energy use was 1.89. The peak load COP of 1.13 calculated from the ratio of peak loads was slightly different from the value of 1.11 calculated from the DOE-2 simulations of resistance heaters and heat pumps discussed above. This small discrepancy is due to the normalization to annual energy consumption in the model. We believe these results demonstrate that the module is operating correctly, but the final test will be to compare heat pump loads with measured utility data when they become available.

Model Validation

A major effort took place during this year to validate the LBL residential hourly and peak demand model, using data from DECO. We compared historical residential loads in the service area with the loads calculated by the model. This allowed us to calibrate the model to account for some of the residual demand diversity not included in the original matrices. We used the Detroit Edison service area because this utility provided us with the most complete set of data.

Before comparing the simulated loads with actual measurements, we made adjustments to the data in the ORNL/LBL and peak load models. First, to estimate building thermal integrities, we compared utility data on annual energy consumption for space conditioning with results from the DOE-2 energy model for single-family detached houses. Second, we modified the fraction-in-use matrices for several end uses in order to match the observed daily load shapes.

The data provided by DECO for annual heating and cooling requirements of existing single-family homes are used in the ORNL/LBL and hourly load models. However, DECO did not have data on the heating and cooling requirements of new houses. We used the relative values obtained from DOE-2 simulations, scaled to the data for existing houses, to obtain the annual energy requirements of new houses. We then calculated the ratio of energy consumption for new and existing houses from DOE-2 heating and cooling loads to obtain the thermal integrity factors needed in the ORNL/LBL model.

We made some adjustments to the original fraction-in-use matrices to get better agreement with the historical load shapes. For example, the hourly load curve for freezers contained an obvious typographical error. In another instance, the original curve for clothes dryers showed a sharp dip in energy

use during the evening. There seemed to be no obvious explanation for this result, so we increased the load during these hours to give a smooth variation. Another problem was that the load curve for cooking peaked between 6 and 7 a.m. and again between 4 and 5 p.m. Better agreement with measured load shapes was obtained when the cooking curve was shifted 1 hour later.

The most significant change was made in the shape of the miscellaneous load. The original data for this load shape came from single-family homes in Southern California, where the miscellaneous load varied by more than a factor of 20 from its minimum in the middle of the night to its maximum at 9 p.m. We believe the miscellaneous load varies greatly between service areas because of differences in the mix of appliances that contribute to this component of demand, so that the Southern California data are not typical of residences in the DECO service area. For example, electric swimming pool heaters are commonplace in Southern California, whereas electric blowers on gas furnaces are important in Detroit. Additional research is needed to characterize this end use properly. It may be necessary to further disaggregate the miscellaneous load to reproduce accurately its time and temperature dependence in the model. As a first approximation, we used flat summer and winter miscellaneous loads (taken at the average of the daily load curves). These gave good fits to the hourly load shapes, so we made no further adjustment.

Figure 1 compares the annual residential electricity sales for 1977–1982 in the DECO service area with the results of the ORNL/LBL model. The model results have been corrected for year-to-year differences in weather. We derived unit energy consumptions for space conditioning equipment from DOE-2 runs using a Temperature Reference Year (TRY) tape. We adjusted space heating and cooling annual electricity use for actual weather in proportion to heating and cooling degree days, respectively. The calculated residential sales are about 1% lower than the actual sales over the 6-year period, which gives us confidence that the ORNL/LBL model is responding properly to changes in housing stock, appliance saturation and efficiency, and economic conditions.

A direct comparison of simulated peak residential loads with actual loads was not possible because DECO reports the residential load on the system peak day rather than on the residential peak day. Figure 2 compares the calculated and actual maximum residential load on the system peak day during the period 1977–1982. Except for 1981, the two agree to within 10%. The 1981 point was calculated using a temperature of 98°F from a weather tape for that year. Detroit Edison, however, claims the maximum temperature on the peak day was 92°F, which would bring the calculated load down to about 2400 MW, closer to the actual value of 2185 MW. We are investigating the possibility that we used the wrong weather tape in the calculations for 1981.

Figure 3 shows a comparison of the hourly loads that occurred on the peak days of each month during 1982 with the predictions of the hourly load model after the adjustments described above were made. The agreement is quite good for most months. There appears to be some tendency for the evening

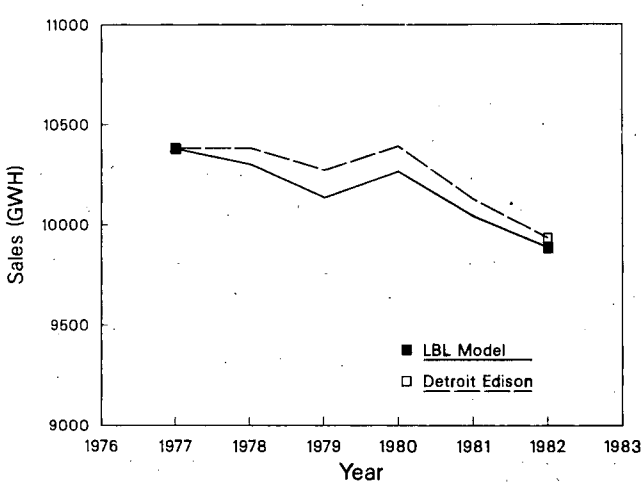


Figure 1. Comparison of annual residential electricity sales, 1977–1982, in Detroit Edison service area with results of the ORNL/LBL Residential Energy Use Model. (XCG 851-7)

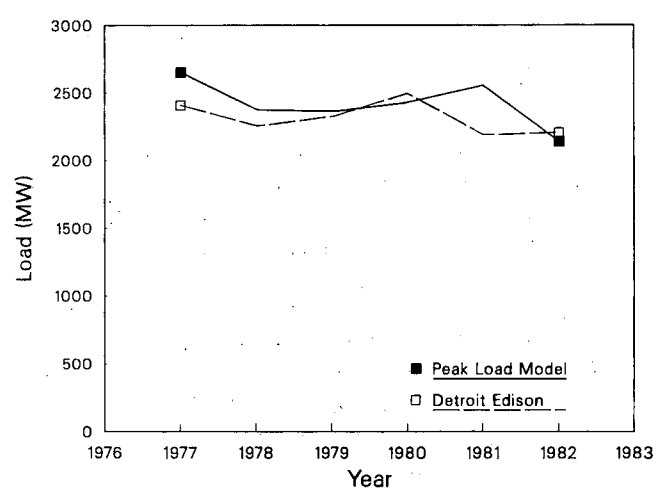


Figure 2. Comparison of the calculated and actual maximum residential loads on DECO's system peak day for each year of the period 1977–1982. (XCG 851-8)

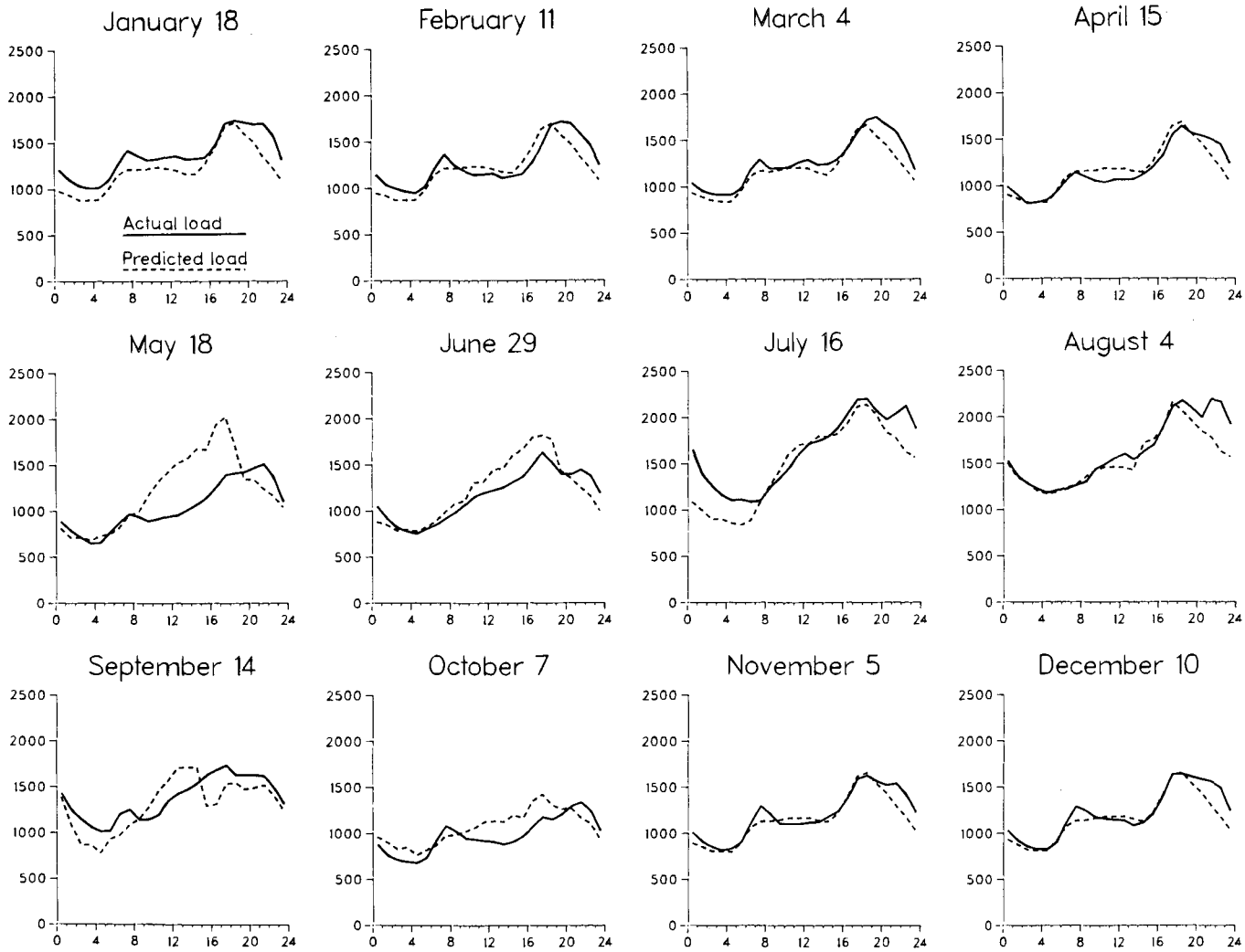


Figure 3. Hourly DECO loads (in MW) on monthly peak days of 1982, compared with predictions of the LBL hourly load model. (XCG 851-6)

peak to be too short and for the early morning minimum to be too low. Because the agreement of the hourly load shape is good over the whole year, we believe the model can accurately forecast load-duration curves as well as peak residential loads.

The largest discrepancy occurs on May 18th, when the temperature exceeded 80°F for the entire afternoon. That the model predicted a load much larger than the actual load may be due two factors, one technical and one behavioral, that it does not capture. First, the model calculates the air conditioner load based on the current temperature; it does not explicitly take into account thermal lags. Rather, thermal lags are implicit in the data used in constructing the fraction-in-use matrices. If the days preceding May 18th had lower temperatures so that the heat stored in buildings did not increase as is typical during summer months, then the model, because its matrices are based on typical summer days, would predict too high an air conditioning load. The behavioral explanation is that people do not run air conditioners as much on the first warm day of the year as they would in midsummer, especially if some effort is needed to get them operating after they have been turned off for the winter.

PLANNED ACTIVITIES FOR FY 1985

With the installation of the new heat pump module and the validation of the model, emphasis has shifted from developing the model to applying it to specific utilities. However, we will continue with

a low-level effort to correct deficiencies and improve the quality of the fraction-in-use matrices based on our experience in using the model.

With additional funding, we will add the capability to assess the effects of load management and time-of-day pricing on residential load shapes. This task involves building two new modules integrated with the existing module. One, the load management module, will modify the fraction-in-use matrices and hourly load profiles on the basis of information about the nature and impacts of specific utility load management programs. The other, a time-of-day pricing module, is more complex, as it involves the assessment of all available data on elasticities of electricity demand as a function of time of day and weather conditions.

The inclusion of time-of-day pricing and load management will yield a model of more general applicability to virtually all major end-use management programs utilities are likely to undertake. The main benefit of performing this work is that its completion will give the model the ability to address a much greater range of utility programs affecting residential loads.

REFERENCES

1. Hirst, E. and Carney, J. (1978), *The ORNL Engineering-Economic Model of Residential Energy Use,* Oak Ridge National Laboratory Report ORNL/CON-24, Oak Ridge, TN.
2. McMahon, J.E. (1984), *The LBL Residential Energy Model,* LBL-18622.
3. Verzhbinsky, G., Ruderman, H., and Levine, M.D. (1985), *The Residential Hourly and Peak Demand Model: Description and Validation,* LBL-18698 (in press).

Increased Usage of Appliances in Response to Efficiency Improvements*

H. Ruderman and J. Henly

The National Energy Conservation Policy Act of 1978 required the U.S. Department of Energy (DOE) to promulgate minimum efficiency standards for 13 home appliances "to achieve the maximum improvement in energy efficiency which the Secretary determines is technologically feasible and economically justified." The legislation also requires DOE to conduct a reanalysis of the standards within 5 years of their issuance to determine if they should be amended. Lawrence Berkeley Laboratory has been actively involved in DOE's analysis of the appliance standards program since 1979, and this work is continuing during the reanalysis. Our analysis has focused on the energy savings and economic benefits to consumers as major considerations in the justification of standards. Quantitative estimates of savings and benefits depend on how households use more efficient appliances. Because efficient products cost less to operate, they tend to be used more than inefficient ones. Hence, the energy savings and monetary benefits to consumers will be less than those calculated when this behavioral phenomenon is ignored, although consumers would enjoy other benefits of the increased usage.

The issue of increased use of more efficient appliances has been raised in studies by Khazzoom[1] and by the Regulatory Analysis Review Group (RARG) of the Council on Wage and Price Stability.[2] Both argue that increased usage of more efficient appliances purchased because of standards could result in an *increase* in energy consumption. The purpose of our work during FY 1984 was to evaluate previous estimates of how large this "rebound" effect is and to determine whether the methodology used is applicable to our analysis of appliance efficiency standards. We also began examining the more fundamental question of how to model consumer decision-making in the choice and utilization of household appliances.

ACCOMPLISHMENTS DURING FY 1984

During the past year, we began a more intensive effort to understand and model consumer decision-making on the purchase and operation of appliances and space conditioning systems. A major portion of this effort was addressed to the question of increased use of more efficient appliances. We looked at economic models of consumer behavior and empirical data on appliance usage. Our general conclusion

*This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Buildings Energy Research and Development, Building Equipment Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

was that the existing models and data are inadequate for analyzing policy relating to appliance efficiency. In a second phase of this effort, we investigated possible formulations and data requirements for such a model. A preliminary survey was initiated to estimate the magnitude and cost of a full-scale data collection effort.

Energy is consumed in a residence by appliances to provide services to the occupants. Thus, the amount of energy consumed and its cost depend not only on the level of service desired, but also on the characteristics of the appliances used. The short-term decisions on level of service depend on long-term choices of appliance ownership, capacity, and efficiency. For space conditioning end uses, the short-term usage decisions are also conditional on the level of insulation, amount of glazing, air infiltration rate, and other thermal integrity measures incorporated in the structure. These long-term factors must be considered in modeling end-use residential energy consumption.

The change in energy consumption with appliance efficiency can be characterized by an efficiency elasticity. In analogy with price elasticity, the efficiency elasticity is defined as the percentage change in an appliance's energy consumption for a 1% change in its efficiency. If there is no change in behavior, energy consumption is inversely proportional to efficiency; hence, the efficiency elasticity is -1. Increased usage, or "rebound," implies that the elasticity is algebraically greater than -1.

The argument that increased appliance efficiency could lead to increased energy consumption is based on a simple relationship between price and efficiency elasticities and on estimates of appliance price elasticities. Under the assumption that the demand for the service provided by energy depends on energy price p and appliance efficiency e only through their ratio p/e, it can be shown that the efficiency elasticity n_e is given by

$$n_e = -1 - n_p \quad , \tag{1}$$

where n_p is the price elasticity of energy consumed by the appliance. Thus, if the price elasticity is algebraically less than -1, as some studies of air conditioning indicate,[3] the efficiency elasticity will be positive, implying that efficiency improvements will increase energy consumption.

There are several reasons for believing that, even in the short run, the demand for energy services is a more complicated function of fuel price and appliance efficiency than simply their ratio. Many parts of the country have a block rate structure in which the price paid for electricity depends on the amount consumed. When the efficiency of an appliance such as an air conditioner is changed, its electricity consumption and hence the price of electricity may change. In other words, price is a function of appliance efficiency.

Another basic limitation is that possible informational problems are ignored. Households respond to the *perceived* rather than the *actual* operating cost, and perceptions of changes in the efficiency of a particular appliance may be inaccurate. Individual appliances are not separately metered. As a result, it may be difficult for a consumer to trace the effects of a change in the efficiency of a particular appliance on his or her electric bill to that appliance. This is particularly true if the efficiency of several appliances changes at the same time, or if the thermal integrity of the dwelling changes contemporaneously with the change in efficiency of the space conditioning system, either of which is likely when a family changes dwellings or remodels.

A third limitation of the assumption that the demand for appliance services depends only on p/e is that it rules out any direct consumer preferences about energy conservation independent of concerns the consumer has about the cost of appliance services. Said another way, the assumptions made by RARG and Khazzoom imply that energy is not an argument in the consumer's utility function; only appliance services are. This does not seem consistent with survey data indicating a consumer desire to save energy apart from the desire to save money.

Furthermore, Eq. (1) does not hold in the long run. Attempts by others to derive a relation similar to Eq. (1), where n_e and n_p are interpreted as long-run elasticities, have omitted crucial elements in the characterization of long-run behavior. In particular, they have neglected the fact that appliance purchase decisions depend on appliance price which, among other things, depends on appliance efficiency. They also ignore the dependence of efficiency choice on energy price. As a result, long-run energy demand elasticities, by themselves, are not capable of yielding long-run rebound estimates. Rebound will, in fact, be smaller than indicated by the long-run elasticity of energy demand.

This discussion of the limitations of the simple approach to estimating efficiency elasticities is somewhat theoretical. The important question is whether an alternative estimation approach in which Eq. (1) is not imposed would yield different estimates of elasticity. We are aware of only two studies that provide data for this experiment, in neither case as a direct object of the study. In both cases, limitations of the data or of the methodology seem to preclude a good test of the relationship.

Hausman[4] estimates an electricity demand model for room air conditioners that rejects Eq. (1) at only the 70% level. However, Hausman's test lacks sufficient power since his cross-sectional regression is based on only 46 observations.

Adams and Rockwood estimate the effects of differing levels of thermal integrity on HVAC energy consumption.[5] As Table 1 indicates, whether the efficiency elasticity is estimated independently from the coefficient of their thermal integrity variable ("Direct estimate") or from their price elasticity ("Indirect estimate") affects its value considerably. The direct estimates show a larger rebound effect than the indirect ones. Neither the Hausman nor the Adams and Rockwood study provide a solid test of Eq. (1). However, they seem to indicate disturbingly large differences between efficiency elasticity estimates based on Eq. (1) and those estimated directly.

More recently, Hirst *et al.* examined the "rebound" effect in improving the thermal integrity of residences.[6] Their study compared energy use for heating during the winters of 1981/82 and 1982/83 by 79 households in the Bonneville Power Administration service area that had been retrofit in 1982. They observed an average decrease in electric heating energy use of 4700 kWh (weather-corrected) in the year following the retrofit. They claim that the occupants of the retrofit homes increased the indoor temperature by an average of 0.8°F, resulting in a reduction in electricity savings of 570 kWh. In other words, the "rebound" effect was 13%.

Taken at face value, their results imply $n_e = -0.87$. This value, however, should not be given much weight for several reasons. First, the magnitude of the effect depends on a model for separating heating energy demand from total residential demand (electric heaters were not separately metered). Second, other factors such as changes in electricity prices and income, which are known to affect demand, were not considered in the analysis.

Table 1. Efficiency elasticity estimates based on Ref. 5.

Weather zone	Indirect estimate	Direct estimate
1	−0.92	−0.58
2	−0.93	−0.35
3	−0.85	−0.27
4	−0.71	—[a]
6	−0.46	—[a]
7	−0.49	—[a]

[a]Estimate not significantly different from zero at 10% level.

A similar study of energy demand in houses that were not retrofit could clarify this point. Finally, according to Table 1 of Hirst *et al.*, the "rebound" effect may not be statistically significant.

Even if Eq. (1) were the correct relationship between price and efficiency elasticity in the short run, mis-specification of the equations used to estimate the short-run price elasticity could lead to biased estimates of the efficiency elasticity. We examined two general types of specification error: (1) the omission of an appliance efficiency variable from the regression equation, and (2) restrictions imposed on efficiency elasticity by Eq. (1) when efficiency *is* included in the regression equation. The usefulness of existing electricity demand studies for determining efficiency elasticity appears to be limited by either one or the other of these two factors.

Suppose the demand for the services of a particular type of electrical appliance can be written as:

$$s = f(x, p, e, u) \quad , \tag{2}$$

where s represents demand for appliance services, p is the price of electricity, e is appliance efficiency, x is a vector of other observed variables affecting demand for appliance services, and u represents the total effect of unobserved variables on demand for appliance services and is uncorrelated with x, p, and e.

The first type of specification error occurs when appliance efficiency is omitted from the set of regressor variables. That is, instead of estimating (2), an equation of the form

$$s = g(x, p, v) \tag{3}$$

is actually estimated, with efficiency now subsumed in the error term v representing the effect of unobserved variables. If efficiency is correlated with electricity price, which will be the case if operating costs are a factor in appliance purchase decisions, then econometric estimates of the effects of electricity price on appliance utilization will be biased as a result of the omitted efficiency variable.

The second type of possible specification error occurs if an equation of the form

$$s = h(x, p/e, w) \tag{4}$$

is estimated, where w represents the effect of unobserved variables. This functional form leads to the simple relationship (Eq. (1)) between the estimates of price and efficiency elasticity. Equation (4) may not adequately describe the relationship between efficiency and the demand for appliance services, for the

reasons discussed previously. If it does not, biased estimates of both price and efficiency elasticities will result.

The preceding analysis leads us to conclude that using Eq. (1) with existing data on price elasticity does not provide meaningful estimates of the rebound effect. We have shown that there are theoretical reasons for not believing this simple relationship is correct in the short run and that there is some empirical evidence to support this theory. Moreover, it is not a valid description of long-run consumer behavior because it ignores the long-term capital choices that affect appliance utilization. Even if Eq. (1) were correct in the short run, using currently available estimates of price elasticity will give biased estimates of the efficiency elasticity. Another approach is needed to model appliance usage. We believe such a model should be part of a larger model of consumer decision-making.

A household's decisions on appliance use depend not only on short-run factors such as energy price, family income, and weather, but also on the long-run decisions concerning appliance capacity and efficiency and, for some end uses, the thermal integrity of the residence. One approach is to model separately the short-run usage decision conditional on appliance efficiency and possibly additional long-run capital choice variables that could influence usage. Such a model could be used to estimate the short-run price, income, and efficiency elasticities.

A more general approach is to model usage jointly with the long-run capital choices. The capital choice equations could include market segment and socioeconomic variables. An equation representing supply constraints on appliance availability could also be incorporated. This framework contrasts with most prior efforts in appliance utilization modeling in two major respects: (1) it separates the short-run usage model from the long-run capital choice models, and (2) it includes efficiency variables.

The data requirements for such a joint choice model are extensive, and existing data sets are inadequate. Most of them do not include any measurement of appliance efficiency, which is critical to an analysis of standards. In addition to efficiency, other capital choice variables needed include the capacity and purchase price of the appliance, the size and thermal integrity of the residence, the tenure and socioeconomic class of the occupants, and the climate and energy prices where the house is situated. The short-run variables could include energy price, income, weather, and occupancy. And, of course, data on energy consumption by end use is necessary. It appears that a new survey will have to be performed to collect the required data.

As a first step in developing a method for collecting data on appliance purchase and utilization decisions, we contracted with the Roper Organization to add two questions to one of their periodic surveys. They asked the 2000 people surveyed if they had a room or central air conditioner in their home and, if so, whether they would participate in a more detailed survey. A total of 429 people agreed to participate. We obtained from Roper the names, addresses, and telephone numbers of the potential participants as well as demographic and social data for the entire sample. These data will be analyzed during FY 1985.

There are several questions still to be answered before the model structure and data requirements can be specified fully. One issue is how to separate energy consumption by individual end uses from the overall residential consumption in the absence of end-use metering. Another is the proper energy price variable for the model when there is block pricing, as is typical for electricity in most parts of the country. A practical issue that must be resolved is whether it is possible to separate the effects of appliance efficiency on energy use from the inverse relationship: the effect of expected energy use on appliance efficiency choice. Another issue is how to focus on the behavior of those households that would be affected by appliance standards; i.e., those that would have purchased appliances with efficiencies below the standard. Finally, issues in data collection center around the need to procure a sufficiently large and representative sample to produce statistically significant results for a variety of regional, socioeconomic, and market segments of the nation.

PLANNED ACTIVITIES FOR FY 1985

Activities during FY 1985 will focus on developing a model of consumer decision-making with respect to appliance purchase and operation and on collecting data to construct such a model. The starting point of the model development will be a thorough survey of the theory of consumer demand for energy and previous efforts to model appliance choice and usage decisions. We will formulate approaches of varying complexity and different assumptions to analyze household data. To the extent possible, tests will be performed with small data sets to determine the variables most likely to be important and to identify sources of error or bias in the estimating procedure. The most important issue in model formulation is the ability to identify the role of energy efficiency as distinct from other factors involved in the choice and utilization of appliances.

There are two basic methods of obtaining efficiency and cost data: surveys of existing households and surveys of consumer decisions at the point of purchase. Surveying existing households has the advantages that it is a familiar technique, is relatively inexpensive, and can, in principle, allow the assessment of nonresponse biases. The problem is that surveys of households may have difficulty identifying model numbers (and thus efficiencies) and will almost certainly be unable to identify purchase prices of the appliance and alternative models of differing efficiency available to the consumer. On the other hand, a household survey could also provide information on other factors that influence energy consumption such as house size, thermal integrity, etc. Both household and point-of-purchase surveys would need a further effort to acquire and correlate monthly energy bills and weather data.

To collect data on appliance choice, it will probably be necessary to perform a consumer survey at the point of purchase. This will also provide information on the other choices considered and rejected by the purchaser. This work will be carried out by (1) preparing a complete description of the intent of the survey and the basic data to be obtained; (2) holding a series of meetings with survey research firms, retailers' associations, and other groups to define possible options for obtaining the data; (3) identifying and tasking one or more firms with sufficient expertise to evaluate alternative approaches to obtaining the data; (4) reviewing the evaluations and detailed survey design by the group proposing the most promising approach to the survey; (5) developing a survey instrument; (6) pretesting the survey instrument; (7) performing the survey in selected locations; and (8) analyzing the survey results to determine accuracy of the data.

This effort will be carried out with the assistance of a review group, whose task it will be to provide ideas on different model specifications. The judgment of the review group will be particularly valuable in the design of the survey and the estimation of the model.

REFERENCES

1. Khazzoom, D.J. (1980), "Economic Implications of Mandated Efficiency Standards for Household Appliances," *Energy J. 1* (4), p. 21.
2. Regulatory Analysis Review Group (1980), *Department of Energy's Proposed Energy Efficiency Standards for Consumer Appliances,* Council on Wage and Price Stability, Washington, DC.
3. Lawrence, A.G., and Parti, M. (1984), *Survey of Conditional Energy Demand Models for Estimating Residential Unit Energy Consumption,* Electric Power Research Institute Report EA-3410, Palo Alto, CA.
4. Hausman, J.A. (1979), "Individual Discount Rates and the Purchase and Utilization of Energy-Using Durables," *Bell J. Economics 10* (1), p. 33.
5. Adams, R.C., and Rockwood, A.D. (1983), *Impact of Improved Building Thermal Efficiency on Residential Energy Demand,* Battelle–Pacific Northwest Laboratory Report PNL-3733, Richland, WA.
6. Hirst, E., White, D., and Goeltz, R. (1984), *Indoor Temperature Changes in Retrofit Homes,* Oak Ridge National Laboratory, Oak Ridge, TN.

Policy Models of Natural Resource Auctions*

M. Rothkopf and D. Wood

Each year, the federal and state governments transfer natural resources worth billions of dollars to the private sector for development. These resources include oil, gas, coal, timber, and minerals such as uranium. Many transfer mechanisms are used, including claim staking, lotteries, and many different kinds of auctions. Auction mechanisms used include oral and sealed bidding for lump sums, unit prices, royalty percentages, or profit shares. In addition, there are many different rules and practices that affect the conduct and results of natural resource auctions. Among these rules are restrictions on joint bidding by potential competitors, choice of bid variables, restrictions (such as minimums) on acceptable bids, and criteria for rejecting all bids. The state or federal government in choosing its rules has several objectives; these may include increasing government

*This work was supported by the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

revenue, the economic efficiency of the transfer and resource development process, fairness, and avoiding the appearance of unfairness.

The general purpose of the research reported here is the analysis of policy issues related to the designs of resource transfer auctions and the development of a simulator and other tools to support such analyses. A particular objective has been the development of a simulation model to analyze a particular form of auction used by the U.S. Forest Service to sell logging rights in national forests of the western United States. Currently, this auction is a progressive oral auction in which bids are vectors of unit prices for each marketable species of tree on a tract. The total amount of a bid is the inner product of the bid vector with a vector of Forest Service estimates of the quantities of each marketable species. The whole tract is awarded to the high bidder figured on this basis, but the payment by the winner is made at the time the trees are cut and is based upon the actual, not estimated, quantity harvested. Bidders have discovered that they can profit by "unbalancing" or "skewing" their bids to take advantage of perceived Forest Service estimating errors—especially an overestimate of a minor species. The Forest Service has been criticized for sales in which this occurred,[1] and is considering rule changes to limit skewed bidding.[2,3] The bidding literature contains insightful analysis of how bidders can best bid in such unit-price auctions,[4,5] but only a little analysis of how bid takers can best manage them.[6]

ACCOMPLISHMENTS DURING FY 1984

While our major effort was directed at constructing a bidding simulator capable of handling unit-price auctions, two other activities received attention. These are briefly described. The first was an analysis of a model of information pooling in joint bidding. The second was work on developing indices of auction competitiveness.

Information Pooling Critique

We reviewed the model by DeBrock and Smith of information pooling in joint bidding for offshore oil tracts.[7] DeBrock and Smith make four implicit assumptions that affect their conclusions. These assumptions are:

(1) The winning bidder always pays the fixed cost of exploring the tract. In particular, the winner makes no use of the information contained in the bids of his competitors or in the failure to bid of potential competitors.

(2) There is no optimization nor, indeed, any variation in the amount of information a bidder obtains irrespective of the size of his or her coalition and irrespective of the number of competitors.

(3) There is no information exchanged or cost incurred in the coalition formulation process, and coalition partners are selected independently of members' views about the value of the tract.

(4) The net value of unsold economic tracts is lost forever.

We found that these assumptions are not fully met and that, therefore, DeBrock and Smith's policy conclusion that "the government and society at large can benefit significantly from joint bidding" is not adequately supported by their model. We have documented this analysis.[8]

Competitiveness Indices

The second accomplishment not related to the unit-price auction simulator is the construction of two families of continuous measures of auction competitiveness that depend primarily on the amounts of the losing bids.[9] Such indices are potentially useful in evaluating auctions and in helping make bid rejection decisions. The indices are dimensionally analogous to the "number of serious losing bids," but they are continuous functions of the amounts of the losing bids in that they avoid the discontinuous jump associated with a cutoff level at which a bid will be regarded as not "serious."

The first of these families of indices is given by the formula:

$$C_{mnk} = [(n - 1)/(n^{1-k/m} - 1)] \sum_i x_i^k \quad ,$$

where

C_{mnk} is the index of competitiveness,
x_i is the amount of the ith losing bid normalized by the high bid,
n is the number of bids,
m is a parameter determined by the mean to standard deviation ratio of the distribution of serious bids, and
k is an arbitrary parameter.

When $k = 1$, the index is linear in the amounts of losing bids. When $k > 1$, the index is nonlinear in assigning relatively great importance to losing bids close to the high bid. For any positive value of k, the index is normalized in such a way that its average will approximate the number of losing bids when

all bids are serious. The approximation is based, in part, upon an assumption that the bids are drawn from a limiting distribution (Gumbel's third) of extreme-value statistics.[10]

The second family of indices requires and takes advantage of prior information on the likelihood and distribution of nonserious bids. The index amounts to the sum over all losing bids of the probability that that bid was "serious." The indices are given by

$$C_p = p \sum_i f_s(x_i)/[pf_s(x_i) + (1 - p)f_n(x_i)] \quad ,$$

where

C_p is the index,
$f_s(x)$ is the probability density of serious bids,
$f_n(x)$ is the probability density of nonserious bids,
x_i is the ith losing bid, and
p is the prior probability that a losing bid will be serious.

Unit-Price Auction Simulator

Our unit-price auction simulator models the quantity and value estimating processes of the seller and of each bidder, and each bidder's strategy choice. It performs a Monte Carlo simulation of the auction to evaluate a variety of measures of auction performance, including the probability that at least one acceptable bid is received, the expected revenue received by the seller, and the probability that each bidder (including each less efficient one) wins. These simulations can be repeated for different sets of auction rules to estimate the effects of rule changes.

Several kinds of bidding strategies can be treated by the model. The model will handle bidders who skew their bids in the manner suggested by Stark[4] and those who do not skew their bids. The model characterizes a bidder's strategy in terms of two factors: the maximum fraction of his or her total value estimate the bidder is willing to bid (if competing bids make this necessary) and, for skewing bidders, the additional fraction of the estimated additional profit from skewing that the bidder would "give back" in the form of further bid increases (again, if competing bids make this necessary). Bidders' strategies characterized in terms of these two fractions may either be prespecified or be classified as "optimal." For bidders with "optimal" strategies, the model adjusts the two fractions that compose the strategy so that (within tolerances) no further adjustments could increase that bidder's expected profit. If there are two or more bidders with "optimal" strategies, then the strategies of each must be adjusted to find (to within tolerances) a Nash equilibrium set of strategies in which no optimizing bidder can unilaterally improve his or her own expected profit.

Stark's original work on skewed bidding[4] showed that the optimal pattern in skewing bids is the solution of a linear programming problem and, furthermore, that in certain situations the optimal pattern of skewing could be determined without resorting to interactive calculations (such as the simplex method). We have used this result and extended our ability to obtain essentially noniteractive solutions to two additional kinds of constraints, including those proposed by the U.S. Forest Service.[2,3]

Finding optimal or equilibrium strategies is computationally difficult because each evaluation of the objective functions of the bidders for a given set of strategies requires a Monte Carlo simulation. Such evaluations involve a substantial computational effort, one that increases as the square of the required precision.

We have used three different methods for equilibrium calculations. The first method involves running a set of Monte Carlo simulations in a pattern suggested by experimental design considerations, fitting quadratic surfaces to the results, finding the equilibrium on the quadratic surfaces, and iterating with a new pattern centered around this point. This method is related to an approach discussed by Glad and Goldstein.[11] The second approach is specialized, applying only to situations in which all optimizing bidders are identical for strategic purposes. It looks for symmetric sets of equilibrium strategies by varying one bidder's strategy and using the results to make a damped adjustment of all bidders' strategies. The third method is more general, applying to both symmetric and asymmetric auctions. It determines each bidder's best strategic response for several fixed values of the opponents' strategies, and fits functional forms to these values. We find the equilibrium strategies by locating the intersection of these functions.

Of the three methods, the third is generally superior, and was used to produce most of our results. The first approach is the most direct, but our problem seems to require strong curvature of the fitted surfaces or unreasonably good initial guesses for convergence. The second method (when it can be used) converges quite quickly for reasonably good initial guesses, but provides no direct way to estimate the uncertainty of the equilibrium except by replicating the entire algorithm. This replication, if required, would make it more costly than the third method. Versions of all three methods have been implemented on the CDC 7600 and/or LBL's MIDAS parallel processor computer.

The second and third approaches both require finding a bidder's "best response strategy" to opponents' fixed strategies. We have tried two different approaches to this subproblem: an iteractive application of simplex search[12] and a fairly straightforward application of classical response surface methodology. Of these, the second method has been more useful.

Preliminary results using the simulator lead to the following conclusions:

(1) Nondegenerate equilibrium sets of strategies exist and can be found even when optimizing bidders have moderately different relative values for the timber.

(2) For some auction conditions, near-optimal strategies for a bidder (given the strategy of his competitors) cover a wide range of "givebacks" of anticipated profits from skewing. Hence, little is lost by assuming that "giveback" is arbitrarily fixed rather than optimized. This significantly eases the calculation burden of finding equilibrium strategies.

(3) To the extent that equilibrium strategies can be relied upon, it appears that if there are two or more optimizing bidders (who are also skewing bidders), then much of the apparent revenue gain by winning bidders who skew will be competed away.

(4) In these auctions, equilibrium bidding strategies are more aggressive with fewer bidders. Unlike sealed-bid, first-price auctions, this is true in comparing two-bidder auctions with three-bidder auctions.

(5) At equilibrium, expected government revenue increases and the expected profit of the winning bidder decreases with the number of symmetric bidders.

PLANNED ACTIVITIES FOR FY 1985

We will complete simulator documentation and, if funding permits, analyze the nature of fair market value in competitive sales of "captive" coal tracts. We also hope to obtain support for work on the theory of optimization when evaluation of the objective function involves a Monte Carlo simulation.

REFERENCES

1. General Accounting Office (1983), "Skewed Bidding Presents Costly Problems for the Forest Service Timber Sales Program," GRAD/RCED-83-37, February 9, Washington, DC.
2. U.S. Forest Service (1983), "National Forest Timber Sales; Control of Skewed Bidding; Procedures," *Federal Register 48* (128), pp. 30417–30420, July 1.
3. U.S. Forest Service (1984), "National Forest Timber Sales; Control of Skewed Bidding; Procedures," *Federal Register 49* (137), pp. 28748–28749.
4. Stark, R.M. (1974), "Unbalanced Highway Contract Tendering," *Operational Research Quarterly 25,* p. 373.
5. Deikman, J.E., Mayer, R.H., Jr., and Stark, R.M. (1981), "Coping with Uncertainty in Unit Price Contracting," Preprint 81-541, ASCE Meeting, St. Louis, MO, October.
6. Rothkopf, M.H. (1983), *Comment on Proposed Policy on Procedures for Control of Skewed Bidding in National Forest Timber Sales,* LBL-16571.
7. DeBrock, L.M. and Smith, J.L. (1983), "Joint Bidding, Information Pooling, and the Performance of Petroleum Lease Auctions," *Bell J. Economics 14,* p. 395.
8. Rothkopf, M.H. (1984), *On Joint Bidding and Information Pooling in Petroleum Lease Auctions,* LBL-17933.
9. Rothkopf, M.H. (in preparation), "Continuous Measures of Auction Competitiveness," LBL-18158.
10. Gumbel, E.J. (1958), *Statistics of Extremes,* Columbia University Press, New York.
11. Glad, T. and Goldstein, A. (1977), "Optimization of Functions Whose Values Are Subject to Small Errors," *BIT 17,* p. 160.
12. Nelder, J.A. and Mead, R. (1965), "A Simplex Method for Function Minimization," *Computer J. 7,* p. 308.

Oil Conservation in OECD Homes: Permanent or Reversible?*

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Since FY 1979, the Energy Analysis Program has carried on an in-depth study of energy use in homes in countries belonging to the Organization for Economic Cooperation and Development (OECD). The 10 countries in this LBL study are Canada, Denmark, France, West Germany, Italy, Japan, Norway, Sweden, the United Kingdom, and the United States. We have assembled a data base and published analyses of individual countries and intercountry comparisons.[1–7]

Our method has been "bottom-up," assembling data on the structure of households and homes, such as size and equipment ownership, and data on consumption per home of each fuel. An extensive summary of the first 5 years of our work will be published in FY 1985.[1]

ACCOMPLISHMENTS DURING FY 1984

This report summarizes recent findings from our special study of oil use.[8] During the past year, we assembled detailed data on the structure of the oil-using housing stock in seven of the 10 studied countries (Denmark, Canada, France, West Germany, Norway, Sweden and the U.S.), and on unit and total oil consumption in these countries. We considered heating oil, liquified petroleum gas (for heating and hot water), and kerosene, and also studied the use of supplementary fuels in homes heated with oil.

The Structure of Oil Use

During the period preceding the first oil shock, residential oil use in seven major OECD countries increased from around 3600 petajoules (10^{15} J) to nearly 6500 PJ (Table 1). The proportion of dwellings heated with oil (Fig. 1) increased almost everywhere, falling only in North America, although the number of homes using oil did increase there. In addition to the growing proportion of oil-heated homes, the average size of these homes increased, and the share of homes with central heat and hot water increased continually, so that, between 1960 and 1972, oil use increased by 40% to 500% in West European countries. This *structural* increase was driven primarily by rising incomes. Falling oil prices, however, certainly contributed to the switch to oil. Oil use in North America increased much less because this structural growth was slower and was decreasing by the early 1970s.

After 1973, the pattern changed radically. Consumers in single-family dwellings switched from oil to gas, first in Sweden and Norway, then in the U.S. and Canada, and, in the late 1970s, in Denmark, Germany, and France as enormous investments in gas networks brought this substitute to detached homes. Consumers in apartments in virtually all countries, through the owners or administrators of their buildings, also converted to gas and district heating. But the intensity of *structural* consumption in homes still using oil increased, as size, central heat and hot-water penetration, and the share of single-family dwellings among all residences increased everywhere.

In Germany and France, the increase in living standards was great enough to offset almost half of the oil savings per home with central heat and hot water. Moreover, the number of homes using oil increased 22% in Germany and remained virtually constant in Denmark and France. In Sweden, Canada, Norway, and the U.S., by contrast, the number of homes using oil as the principal fuel decreased by 15%–30%, driving oil use downward even further. By 1980, the share of oil-heated homes was decreasing in every country, as Fig. 1 shows, although the total number of homes using oil still was greater than in 1973 in most countries.

Figure 2 summarizes these changes in oil use, showing the Federal Republic of Germany as an example. The upper part shows total oil use and the number of oil-heated homes over the 1960–1983 period, indexed to their 1960 values. Up to 1972, oil intensity—the expanding shaded area between dwellings and use—crept up slowly, mostly as a result of increases in the number of homes using oil and the share of single-family dwellings, central heating, and hot water among these homes. These are indicated in the lower part of the figure. After the first oil

*This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Buildings Energy Research and Development, Building Systems Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098. We also acknowledge the support of the Swedish Council for Building Research.

Table 1. Changes in oil heating in seven OECD countries, as indicated by substructure, intensity, and total use.

Country & Year	No. of dwellings w/oil (10^6)	Dwelling type,[a] in %				Weight factor[a]	Oil-based hot water, %[b]		Oil use	
		SFD		MFD						
		CH	Non-CH	CH	Non-CH		in SFD	in MFD	Per Dw. (GJ)	Total (PJ)
CANADA										
1961	2.67	70	30	←	←	0.75	—	—	145	387
1971	3.47	59	10	31	←	0.80	17	38	172	597
1976	3.23	61	6	33	←	0.80	22	39	173	560
1981	2.75	65	4	31	←	0.85	25	42	137	376
DENMARK										
1965	0.75	43	9	33	15	0.69	32	26	125	93
1972	1.16	58	5	29	9	0.78	55	27	153	177
1977	1.19	62	3	30	5	0.80	61	30	131	156
1982	1.18	65	2	30	3	0.82	65	30	83	102
FRANCE										
1962	2.14	10	27	36	27	0.51	7		50	107
1973	9.05	26	19	35	19	0.59	14	18	87	785
1978	9.09	34	14	38	14	0.64	20	21	79	722
1981	8.63	38	12	38	12	0.67	23	22	74	640
GERMANY										
1960	2.08	21	26	27	26	0.56	7		77	160
1972	10.35	35	19	31	14	0.64	30	15	99	1031
1978	12.40	44	13	33	10	0.70	34	18	92	1193
1982	12.60	46	11	34	9	0.71	58		73	913
NORWAY										
1960	0.14	6	16	46	32	0.48	2[c]	28[c]	83	14
1967	0.34	8	50	23	18	0.51	2[c]	10[c]	—	—
1973	0.70	8	55	16	20	0.51	2[c]	10[c]	59	41
1980	0.50	16	52	17	15	0.55	2[c]	6[c]	57[d]	27[d]
1983	0.41	18	58	21	3	0.59	2[c]	6[c]	—	—
SWEDEN										
1963	1.56	27	5	64	4	0.63	22	58	92	144
1972	2.23	41	1	56	2	0.70	40	56	116	260
1978	2.06	44	0.3	55	0.2	0.72	44	55	96	198
1982	1.63	44	0.2	56	0.2	0.72	44	56	85	138
USA										
1960	19.6	—	—	—	—	—	37		144	2813
1970	20.5	62	10	24	4	0.80	37		142	2818
1973	21.5	—	—	—	—	0.81[c]	37		150	3223
1978	20.0	65	10	23	4	0.82	34		140	2790
1981	18.3	65	10	22	4	0.82	47		107	1951

Sources: LBL data base and references herein.

[a]The weight factor measures the intensity structure, giving a single-family dwelling (SFD) with central heating (CH) a weight of 1.0, an SFD with non-CH or a multi-family dwelling (MFD) with CH a factor of 0.5, and an MFD with non-CH 0.33. For France and Canada, we assume that half of the dwellings labeled "noncentral systems" by our sources are SFD, half MFD. An arrow (←) denotes that the information is contained in the adjacent column.

[b]Fraction of homes with oil heat that also have oil-based hot water. The breakdown into SFD and MFD, where known, is shown. The sum of these two gives the total penetration of oil-based hot-water systems among oil-fired dwellings. (Figures between the two columns are totals that could not be disaggregated.) In almost every case, oil-based hot-water systems are found only in homes with central heating, and with oil as the principal fuel. Hot-water figures are estimated from surveys that include questions about hot water (Germany, Canada, U.S., France) or from penetration of hot water overall and known penetration of oil-based central heating (Sweden, Denmark, Norway).

[c]Figures very approximate or interpolated.

[d]Figures for unit consumption and total consumption are for 1981.

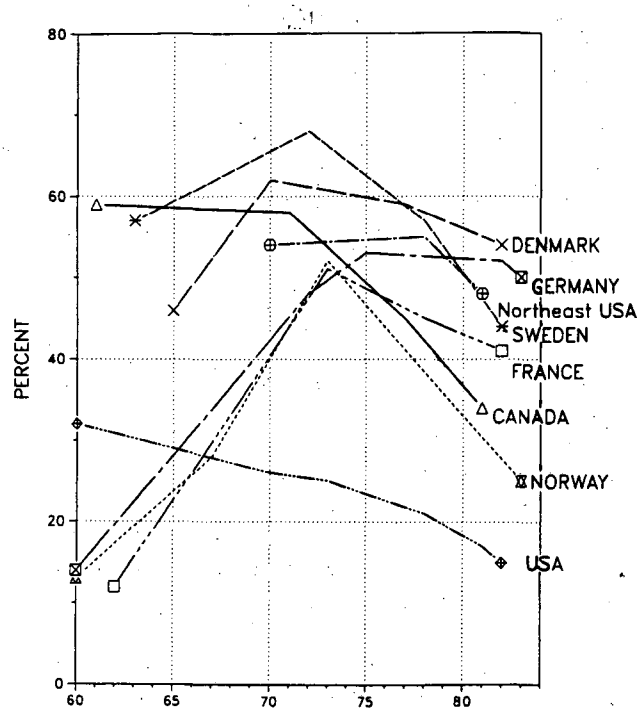

Figure 1. Share (in percent) of dwellings with oil heating (including LPG and kerosene) in seven OECD countries, 1960–1983. (XBL 851-1040)

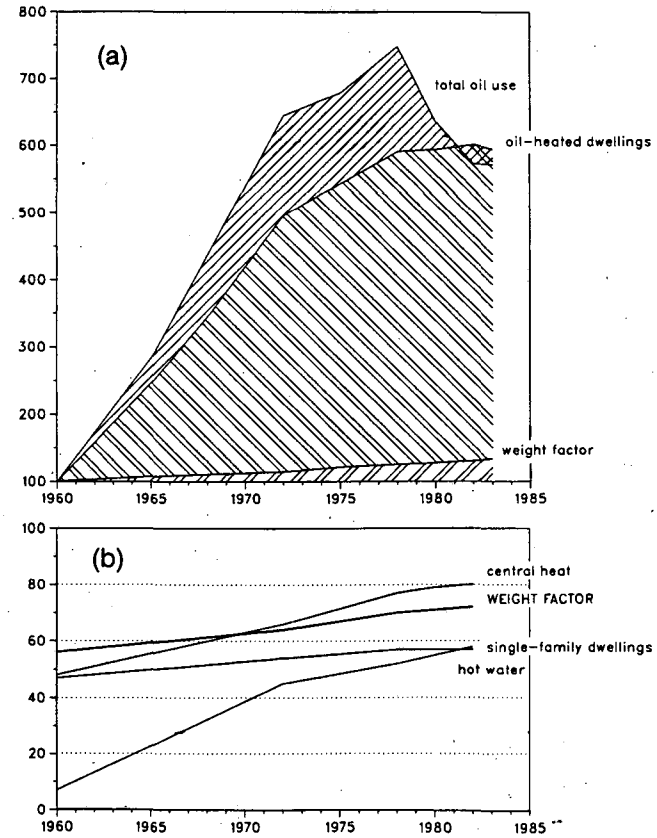

Figure 2. Factors driving residential oil use in West Germany, 1960–1983. (a) Number of oil-heated homes and total oil use, indexed to 1960 values (1960 = 100). (b) Share of single-family dwellings and increases in homes with central heating and hot water. The weight factor is explained in note to Table 1. (XBL 851-1041A)

embargo, households reduced oil intensity, but much of the reduction disappeared by 1978. The effects of the 1979 oil shock were far more permanent. Homes converted from oil to other fuels for heating and hot water in increasingly greater numbers, and oil intensity (in 1982–1983) was lower than it was in 1960, as indicated by the fall in the oil-use curve below that for the number of oil-heated dwellings. This means that German households had reduced oil use so much that the impact of a 300%-plus increase in central heat and hot water penetration and a greater than 20% increase in area per home was more than offset by conservation.

The experience of Germany is similar to that for the other countries we have studied, although the components are different,[8] and the rates of change before and after 1972 varied. Because the continued change in the structure of oil use after 1973 obscured conservation by consumers, we examine these changes separately.

The Intensity of Oil Use

A decline in unit oil consumption means improved efficiency, changes in behavior, or use of a supplementary fuel to provide some of the heat previously provided by oil. Figure 3 shows oil intensity for space heating, per degree-day and square meter, in single-family dwellings. Before 1973, there was a great difference in intensity among countries, with Sweden the lowest. Intensity dropped in every country in 1974–1975, rebounded in most countries after 1975, then fell by about 20% after 1979, except in Sweden, where consumption had fallen continuously after 1973. In most countries, unit consumption eventually fell to less than two-thirds of its pre-embargo value, and the differences among countries shrank. Consumption in 1983 remained near this level; in spite of a leveling of oil prices, there was no rebound as in 1976–1977.

We found that oil intensity in apartments also fell between 1972 and 1982. Since the use of secondary fuels appears to be far less important than in single-family dwellings, the decline represents a real decrease in space heating intensity. Sweden, with the greatest number of degree-days and the largest apartments, had the lowest intensity (in kJ/deg-day/m^2), which declined slowly, lying about 20% lower in

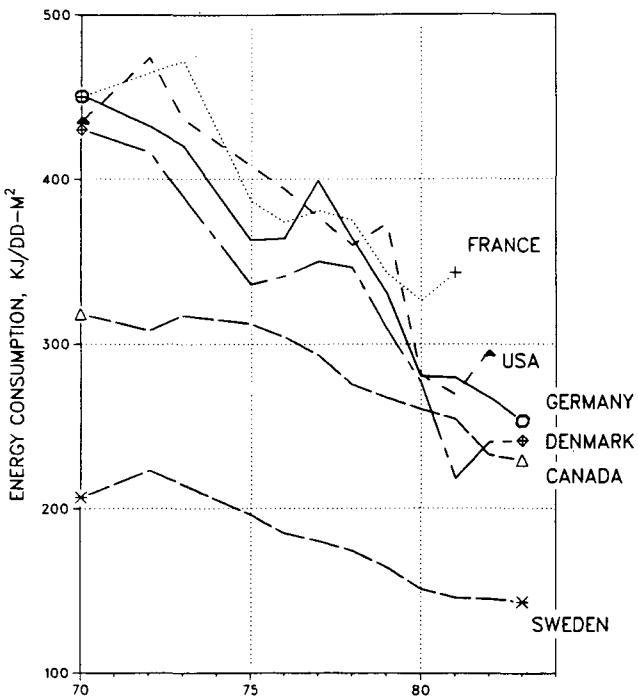

Figure 3. Oil-use intensity in single-family dwellings for space heating, by kilojoules per degree-day per square meter, in six OECD countries, 1960–1983.

(XBL 851-1042)

1982 than in 1972. Intensities in France, Germany, and Denmark fell by 25%, 35%, and 45%, respectively, in part because of a much larger incidence of direct metering of heat to individual apartments. This also caused greater fluctuations of use with energy prices than in Sweden. But the drop in Sweden is remarkable, considering the absence of direct metering. For all countries, then, oil intensity in apartments fell, even in those heated by kerosene or oil stoves.

Secondary Heating Fuels

Secondary fuels, whose local use allows occupants to turn off or turn down a central system, became more prevalent after 1978 and could account for a significant drop in oil intensity, without necessarily representing increases in efficiency or changes in comfort. Their use is concentrated in single-family dwellings, where the consumer saves money directly by using them; in collectively metered apartments, no such savings would accrue. After examining the reported saturation of secondary heating equipment, including the use of such equipment in homes where oil was the principal fuel, and noting estimated or measured fuel use, we concluded that secondary fuels accounted for as much as one quarter of the change in unit consumption in Norway and 15% in Sweden and parts of Canada and the U.S., but far less in Denmark, Germany, and France. The most commonly used secondary fuels is wood, with electricity important in Norway and Sweden.

The Total Oil Decline

The oil savings between 1972–73 and 1981–82 were appreciable—from 11% (for Germany) to 47% (for Sweden), as shown in Table 2. These savings arose from different components, however. In Sweden and Canada, the absolute number of oil-heated dwellings dropped 27% and 21% respectively, causing close to half of the change in oil use. In the U.S., intensity dropped considerably more than the number of dwellings. In Norway, the number of homes using oil as the principal fuel decreased greatly, but the effect of two- and three-fuel homes blurs the details of the change and makes it equally difficult to state the reduction in unit consumption. Nevertheless, there, as in Sweden and North America, oil use decreased markedly by 1981, and this decline continued rapidly through 1983.

In the other countries, the situation is quite different. In Denmark, the number of oil-heated dwellings barely changed, and in France, it increased through 1978 and then reversed, falling slightly below its 1973 level in 1982. In Germany, the

Table 2. Oil savings, 1972–1982.

Country/ period	Structural change (%)	Weight change (%)	Intensity change (%)	Total oil reduction from 1971–73	
				PJ	%
CANADA 1971–1981	−21	+3	−20	−218	−37
DENMARK 1972–1982	+2	+5	−43	−79	−44
FRANCE 1973–1981	−5	+13	−15	−145[a]	−18
GERMANY 1972–1982	+22	+14	−27	−116	−11
NORWAY 1973–1981	−31	+16	−3[b]	−14	−33
SWEDEN 1972–1982	−27	+3	−28	−122	−47
USA 1973–1981	−15	+3	−29	−1272	−39
TOTAL[c]	—	—	—	−1966	(−32)

Note: Structural change gives the percentage change in the number of dwellings using oil. *Weight change* refers to change in weight factor (see note to Table 1). *Intensity change* gives the change in oil use per oil-heated dwelling. All changes refer to the years shown for each country.

[a]Excludes 10 PJ reduction in "other" oil (hot water and cooking);

[b]Figure uncertain because of oil use in mixed systems where oil was not the predominant fuel.

[c]Note that the initial and final years are not the same for every country.

number of homes with oil was 22% higher in 1982 than in 1972. Unit consumption, however, fell in all three countries, most sharply in Denmark (43%), but significantly in Germany and France (~35% and 30%, respectively, in all dwellings with central heat). Thus, in these three countries, the oil drop has been caused mostly by a rapid decrease in intensity, in both new and older homes, but in Germany and France, the weight index of the housing stock (Table 1) increased by 13%–15%, cutting appreciably into the total savings.

The reductions in total oil use in Scandinavia and North America are significantly greater than those in Germany and France. We attribute this to both the greater availability of less-costly substitutes (Sweden, Canada, the U.S.) and the higher standards of heating and hot-water use prevalent before 1973 (in Denmark, Sweden, Canada, and the U.S.), which yielded to great savings after that year. By the late 1970s, however, oil use was falling rapidly in these countries as well.

Causes of Oil Savings

What caused these reductions? First, oil prices shot up. This immediately depressed unit consumption in single-family dwellings and in apartments with meters (or individual heating units). From 1972 to 1982, real heating oil prices increased by 8.5%–9.5% per year in the U.S. and Canada, 12%–15% per year in Norway, France, Denmark, and Germany, and 17.3% per year in Sweden. The differences were caused both by differing initial prices (although prices were close in all countries at 1972 exchanges rates), different increments of taxation, and changes in domestic prices caused by fluctuations in each country's dollar exchange rate. The decline in *residential* oil consumption over this period, whether caused by structural or by intensity changes, was greatest in Sweden, which had the greatest proportional change in oil prices. There is considerable scatter among other countries; the decreases in oil use in Canada, Norway, and the U.S. were greater than 35%, even though the price increases were least in these countries. Similarly, drops in unit consumption alone, or changes in the number of oil-heated homes, cannot be sorted out by looking at price changes alone. This suggests that, while prices are unquestionably important, other factors—including the structural factors already discussed, as well as incomes, government policies, etc.—must be taken into account.

Incomes, for example, grew more slowly after 1973 than before, and two or more recessions gutted most pocketbooks. These changes, however, had only a minor effect on total oil use, because (1) the changes in oil use were much greater than the fractional changes in incomes; (2) the price increases for oil were also fractionally much greater than income changes. While it is possible that the extended recession in Denmark did push oil use down somewhat, it still appears that the income effect was minor, although higher oil prices may have hit apartment-dwelling families harder than those in single-family dwellings (the incomes per capita of the former tend to be lower than those of the latter). The overall picture still suggests that incomes were only a minor factor in the oil savings we have reported.

We briefly reviewed the impact of government oil-saving programs and concluded that these had the greatest impact in Sweden, followed by Canada, where a special subsidy is offered for households to switch away from oil. In all countries, however, it is difficult to measure the marginal impact of such programs, i.e., to show how many households reduced or eliminated oil use only because of them. However, the rapidity of reductions in unit consumption in all countries except Sweden suggested that most of the savings were owing to household actions caused not by programs but by the rapid increase in prices.

Changes in Oil Use: Permanent or Reversible?

Will the savings shown in Table 2 persist? Conversions away from oil usually involved substantial investments with long payback times, so we classify these savings as permanent, except in Sweden and Norway, where about 20% of today's wood or electricity users still have oil boilers that could easily be returned to use. We therefore classify 80% of the fuel change in those two countries as permanent.

To evaluate changes in unit consumption, we classify modifications to the building stock (and heating equipment) that increase efficiency as virtually permanent. It is unlikely that falling oil prices would cause occupants to reverse these measures, particularly those with long lifetimes, except for changing fuels in dual-fired equipment. We classify behavioral changes (popularly called "sacrifices") as reversible, in the sense that they could disappear ("wear off") if prices fell. Similarly, improved maintenance of systems might be abandoned if oil prices decrease, so these also belong to the "reversible" category.

Unfortunately, it is difficult to determine exactly the permanent and the reversible components of the drop in unit consumption. However, several facts allow a *rough* partitioning of the changes in oil use. In Sweden, the drop in unit consumption has been slow but steady. Indoor temperatures are still high,

and the number of homes that undertook substantial retrofits is among the highest. We estimate, therefore, that 75% of the drop in intensity there is permanent. The rest was caused by lower temperatures, reduced hot-water use, and switching to secondary fuels, all of which we deem reversible. In the other countries, the rapid drops in unit consumption suggest that, altogether, only 25% of the change is permanent, with the rest reversible if oil prices fall.

We can now transform the components of structural and intensity changes into "permanent" and "reversible." Our results, shown in Table 3, indicate that in Sweden the oil savings are overwhelmingly permanent. The Norwegian figure also indicates a similarly great permanent change, but this is uncertain because of the heavy use of secondary fuels. In the U.S. and Canada, the permanent component is over 50% of the total savings. In the remaining three countries, reversible savings dominate, particularly where the number of oil-heated homes increased. The number of such dwellings is now decreasing in all seven countries, however, so residential oil use will probably slide downward for several years to come, as more homes convert away from oil and as retrofitting penetrates farther into those homes remaining with oil.

CONCLUSIONS

We conclude that oil is on the way out of the residential market in the developed countries, after a dramatic increase between 1955 and 1972. The conditions for each country studied often differed significantly in 1973, yet the oil backout is continuing everywhere. In all, consumers saved a great deal of oil. Some 33% of the 1972 oil consumption in homes in these seven countries—about 2000 PJ—was saved by 1982. Higher oil prices appear to be the principal reason, but the impact of government programs, particularly in Sweden, cannot be overlooked. Most important, the savings appear to be continuing in the mid-1980s, principally because the number of homes heated with oil continues to decrease.

Table 3. Estimates of permanent and reversible oil savings.

Country	Permanent (PJ)	Share of savings (%)	Reversible (PJ)	Total savings (PJ)
CANADA 1971–1981	−146	67	−72	−218
DENMARK 1972–1982	−17	21	−62	−79
FRANCE 1973–1981	−63	43	−82	−145
GERMANY 1972–1982	+139	−120[a]	−255	−116
NORWAY[b] 1973–1981	−11 to −13	79–93	−1	−14
SWEDEN 1972–1982	−95	78	−27	−122
USA 1973–1981	−678	53	−594	−1272
TOTAL SEVEN	−873	44	−1093	−1966

[a]Because of the great increase in the number of oil-heated dwellings (structural consumption), the permanent reduction in oil use from reduction in intensity is far less than the increase from structure, thus giving the minus sign.

[b]Uncertain because of the domination of mixed systems; range shown is our estimate.

PLANNED ACTIVITIES FOR 1985

We will update the oil-use study to include the effects of the recent decrease in world oil prices, study changes in residential electricity use patterns, and, with assistance from the Norwegian Statistical Office, study residential and commercial gas uses as well. Furthermore, our 10-country study will be expanded to include other kinds of information, and we will extend our analyses to the Netherlands and Belgium. Finally, a parallel analysis will examine changes in energy use in industry in OECD countries.

REFERENCES

1. Schipper, L., Ketoff, A., and Kahane, A. (1985), "Explaining Residential Energy Use: The International Bottom Up Approach," *Annual Review of Energy,* No. 10, Annual Reviews, Inc., Palo Alto, CA.
2. Ketoff, A. (1985), *Residential Energy Use and Conservation in France,* LBL-19412 (Draft), forthcoming.
3. Meyers, S., and Schipper, L. (1984), "Energy in American Homes: Changes and Prospects," *Energy—The International Journal 9,* p. 495.
4. Schipper, L. (1984), *Internationella Jämförelse av Bostädernas Energiförbrukning (International Comparison of Residential Energy Use), R131,* p. 84, Swedish Council for Building Research, Stockholm (includes appendix in English, "Reconstruction and Analysis of Residential Energy Use in Sweden, 1960–1982").
5. Ketoff, A. (1984), "Facts and Prospects of the Italian End Use Energy Structure," in J. Goldemberg, T. Johansson, A. Reddy, and R. Williams, Eds., *Global Workshop on End Use Energy Strategies* (in preparation).

6. Schipper, L. (1984), "Residential Energy Use and Conservation in Sweden," *Energy and Buildings 6*, p. 11.
7. Schipper, L. (1983), "Residential Energy Use and Conservation in Denmark," *Energy Policy 11* (4).
8. Schipper, L., and Ketoff, A. (1984), "Oil Conservation: Permanent or Reversible? The Example of Homes in the OECD," submitted to *Science*.

Energy Use in the Commercial Sector: An International Perspective*

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The International Energy Studies Group of the Energy Analysis Program has been collecting and analyzing data on the energy consumption patterns of the residential sectors of 11 countries in the Organization for Economic Cooperation and Development (OECD).[1] Recently, we began to collect similar data on the commercial sector. In FY 1984, we developed a comparison of the most important trends in commercial energy use, which we describe here.

In the last decade, there has been considerable progress toward understanding the changes in energy use in the residential, industrial, and transportation sectors of the OECD countries. Much less work has been done on the commercial sector. This has probably been due in part to lack of interest, the commercial sector being the smallest energy consumer of the four end-use sectors. But the lack of adequate data on energy use in the commercial sector has also stymied efforts to better understand how its consumption has been changing over the past 10 years. Additionally, the commercial sector is frequently lumped with the residential sector and certain other uses into a residual that defies analysis.

The commercial sector has become more important in recent years because it has shown the strongest growth, particularly in the use of electricity. Because many U.S. utilities have experienced peak-load problems, often related to cooling in commercial buildings, many efforts are now under way to understand this sector. The work discussed here represents our preliminary findings from FY 1984.

*This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Buildings Energy Research and Development, Building Systems Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

ACCOMPLISHMENTS DURING FY 1984

Defining the Commercial Sector

In a general way, the commercial sector corresponds to the provision of services by public and private entities (in contrast to the production of goods or the transportation of people and goods). It follows from this that a wide array of activities are lumped together in the commercial sector. "Commercial" activities range from caring for the sick to treatment of sewage. A reasonable definition of commercial activities includes activities in wholesale trade; retail trade; finance, insurance, and real estate; services; public administration; transportation and communication; and electricity, gas, and sanitary services. What we refer to as commercial-sector energy consumption includes energy consumed by commercial activities, with the exclusion of energy consumed in transportation and in electricity and gas production.

A large part of energy consumption in the commercial sector, but by no means all of it, is associated with building functions: heating and cooling, ventilation, lighting, and other electrical operations. It should be kept in mind, however, that services like street lighting and waterworks are also part of the commercial sector, and in some countries certain industrial and agricultural activities are counted in it as well. Finally, the statistics compiled by some countries put energy use in large apartment buildings into the commercial sector because of the way in which the energy, usually electricity or gas but possibly oil or district heating, is billed. Thus, understanding the commercial sector requires much in-depth analysis of the nature of the sector itself and how it is defined by different sources or countries. We found that little of this work had been done in a way that permits international comparisons.

Commercial-Sector Energy Use in Context

Compared to residential energy consumption, delivered energy consumption in the commercial sector ranges from 40% (in the European countries) to

about two-thirds (in Canada) of residential use. The mix of fuels in the commercial sector (Table 1) also differs from the mix in the residential sector in that electricity is much more prominent. Its use accounts for between 26% (Germany and the United Kingdom) and 38% (Sweden) of total delivered energy consumption, compared with 15% to 29% in the residential sector. The share of oil is generally less in the commercial sector, while gas tends to have about the same share in both sectors. (The United Kingdom, however, is an exception in both cases.) Use of solid fuels (coal, wood) is less common in the commercial sector.

Some General Trends, 1972–1982

We have assembled a time series of commercial-sector energy consumption for six countries: Canada, Denmark, France, Germany, Sweden, and the United States. In most cases, we took data already aggregated into the commercial sector directly from official in-country sources. In other cases, we assembled commercial-sector electricity consumption data ourselves. For France and Germany, where the official statistics include energy consumption for users not properly part of the commercial sector, we were able to exclude all or some of this consumption. The time series for Germany, however, still includes a considerable amount of energy (20% in 1982) that should not be classified in the commercial sector.

Table 1. Commercial and residential sectors: shares of delivered energy, 1982 (%).

Country	Oil	Gas	District heat	Electricity	Solids
CANADA					
Commercial	21	46	—	33	—
Residential	27	41	—	29	3
DENMARK					
Commercial	37	1	28	34	—
Residential	55	2	22	15	6
FRANCE					
Commercial	47	22	[6][a]	29	2
Residential[b]	48	23	3	16	10
GERMANY					
Commercial	43	21	7	26	3
Residential[b]	48	24	3	16	9
SWEDEN					
Commercial	39	—	23	38	—
Residential	41	—	18	29	11
UNITED KINGDOM					
Commercial[c]	34	31	—	26	9
Residential[c]	7	54	—	19	21
UNITED STATES					
Commercial	17	44	3	34	2
Residential	15	49	—	26	9

[a]In France, fuel inputs for district heat are counted with oil, gas, and solids.

[b]1980.

[c]1981.

Commercial-sector *delivered* energy consumption has either declined or grown slowly since 1971–72 in the six countries for which we have reliable time-series data; this is shown in Table 2, which lists the average annual growth rates over the periods given. Denmark has seen the largest total decline (8%), while Sweden has seen the biggest (but still modest) increase (7%). Delivered energy consumption *per capita* has fallen or stayed the same in all cases. All indications are that commercial-sector energy use grew faster than the residential sector before 1971–72; after this time, both sectors grew more slowly, but commercial still outpaced residential, or at least contracted more slowly.

Part of the decline in delivered energy consumption may be attributable to structural changes that led to the use of fuels that are more energy-efficient in terms of delivered energy—i.e., district heat and electricity. Unlike oil and gas, they do not have combustion losses at the building site. Counting primary energy shows all of the energy resources that go into district heat and electricity production for the commercial sector. Since electricity production in particular has high energy losses, increasing use of electricity in the commercial sector (discussed below) has led to growth in primary energy consumption. This growth ranged from 0.9% per year in Canada to 2.4% per year in Sweden.

The result of differing growth rates has been a considerable shift in the shares of the fuels used in the commercial sector. *Oil* accounted for 55% (Denmark) to 72% (France) of total delivered energy consumption in the early 1970s. By 1982, the oil share had fallen to between 37% (Denmark) and 47% (France). In Canada and the United States, where oil shares in the early 1970s were 33% and 25%, respectively, substantial drops occurred as well.

The *electricity* share of total delivered energy consumption has grown to over 25% in all six countries: from 16% to 33% in Denmark, from 16% to 29% in France, from 14% to 26% in Germany, from 25% to 38% in Sweden, from 23% to 35% in the United States, and from 29% to 34% in Canada. *Gas* consumption has taken on a major share of total delivered energy consumption in France (22% in 1982), Germany (21% in 1982), and the United Kingdom (31% in 1980), and has risen to nearly half of total consumption in Canada and stayed at that level in the U.S.

Table 2. Commercial-sector energy consumption: average annual growth rates (%).

	Canada 1973–81	Denmark 1972–82	France 1974–82	Germany 1971–83	Sweden 1972–82	U.S. 1971–82
Delivered energy						
Total	0.6	−0.9	−0.1	0.0	0.7	0.4
Per capita	−0.7	−1.1	−0.5	0.0	−0.4	−0.6
Primary energy						
Total	0.9	1.3	1.8	1.5	2.4	1.8
Per Capita	−0.4	1.0	1.4	1.5	2.2	0.8

On a per-capita basis, commercial-sector energy consumption (Table 3) is some 50% to 100% higher in the United States and Canada than in the European countries, which are roughly in the same range, once the colder Swedish climate is taken into account. This finding does not account for differences in the amount of commercial-sector floor area per capita. The accuracy and comparability of floor area estimates among countries is difficult to assess. Using the estimates available to us, we found that the higher level of floor area per capita in the U.S. explains some of the difference in per-capita energy use. Energy use per square meter of floor area remains considerably higher in the U.S., however. This may be attributable in part to the nearly universal use of air conditioning.

The Structure of the Sector

Energy use in the commercial sector is shaped by what we call its structure: the *physical* attributes of the sector, such as the various activities that take place within it, the nature of the building stock, and the type of fuels used to support its activities. All of these attributes change over time, and these changes affect the evolution of energy use.

We have been able to characterize the composition of the stock of commercial buildings for four

Table 3. Commercial buildings energy consumption.[a]

	Canada 1982	Denmark 1982	France 1980	Germany 1982	Norway 1982	Sweden 1982	U.K. 1980	U.S. 1979
Delivered energy								
Total (PJ)	743	69	552	765	64	150	706	5540
Per capita (GJ)	30	14	10	12	16	18	13	25
Per m^2 (MJ)	1895[b]	870	835	765	1250	1120	—	1325
Primary energy								
Total (PJ)	1197	120	787	1155	143	270	1209	9620
Per capita (GJ)	48	23	15	19	36	32	22	43
Per m^2 (MJ)	3024[b]	1500	1185	1120	2870	2015	—	2300
Climate index	107.8	94.8	92.9	95.8	104.0	100.7	99.8	102.7
DD normal (18°C)	4581	3122	2450	3116	4025	4010	2917	2680

[a]Probably includes some nonbuilding energy consumption in Canada, Denmark, and Germany. Residential consumption has been removed from U.S. data.

[b]1981.

countries: Denmark, France, Sweden, and the United States. It is difficult to make conclusive comparisons between countries, however, for the categories used are different from one country to the next. Nevertheless, it is striking that the share of floor space for education and health-related activities is significantly lower in the U.S. than in the European countries.

Space heating does not dominate commercial sector energy use as it does in the residential sector, but it is nonetheless the most significant end use, and the one for which users have the most choice with respect to fuels. We found data on the heating fuels in use in commercial buildings for three countries: Denmark, Sweden, and the United States. Denmark and Sweden have a similar structure: oil heat accounts for nearly half of the commercial floor area, district heat for most of the rest (Table 4). In the U.S., gas heating (at 49% of floor area) and electric heating (at 19% of floor area) are more prominent.

Energy Intensity in the Sector

The commercial sector has grown in all countries in our study. The stability or decline in total energy consumption is thus not a consequence of lack of growth in energy-demanding activities. The data suggest that energy-conserving measures have had an effect.

Probably the most useful indicator of energy intensity is energy use per unit of floor area. Tracking changes in this indicator over time allows an assessment of progress in energy conservation. Intensity—as measured by dividing total sectoral energy consumption by the total floor area of commercial buildings—declined 27% between 1972 and 1982 in Denmark, 17% between 1972 and 1982 in Sweden, 18% between 1970 and 1980 in the United States, and 7% between 1975 and 1980 in France. (The years chosen had comparable weather.) We have been able to assemble this indicator on a subsectoral level for a recent year for three countries: Denmark (for oil), France, and the U.S., but only for Sweden do we have data for more than one year (see Table 5). Although the period covered is short (1977–1981), the decline in energy intensity is evident. Note that the oil intensity varies significantly among building types; this is true for the other countries as well, and for buildings of the same type built in different periods.

Table 4. Heating fuels used in commercial buildings, 1979–1981 (by % of floor area).

Fuel	Denmark	Sweden	U.S.
Oil	45	44	17
District heat	38	42	—
Electricity	2	6	19
Gas	—	—	49

Conclusions

Differences among countries in per capita commercial-sector energy use can can be partly explained by differences in commercial building area per capita. Differences in energy intensity also play a role. The United States has both the most area per capita and the second highest energy intensity (after Canada). The share for different fuels varies among countries and within a country over time. In most cases, these fuel shares are significantly different from those in the residential sectors of the same countries. Energy intensity varies among the subsectors, and countries also vary in the shares of floor space held by different subsectors. This variation, coupled with the differences in subsectoral energy intensity, accounts for some of the differences in overall commercial building energy use in the countries we have studied. In the countries for which survey data exist, there is clear evidence that energy use per unit area has decreased since 1973. If pri-

Table 5. Oil intensity in Swedish commercial buildings (MJ/m^2).[a]

Subsector	1977	1981	% Change
Theaters	1360	1290	−5%
Hospitals	1290	810	−37%
Other care	1250	1065	−15%
Lodging	1215	1215	0%
Religious	1140	955	−16%
Schools	1140	920	−19%
Other assembly	1140	920	−19%
Retail/wholesale	1065	775	−27%
Banks/insurance	1030	1180	+15%
Other office	1065	845	−21%
All comm. buildings	1140	920	

[a]Intensities are for buildings in which oil is the principal heating fuel and include oil used for hot water.

mary energy is counted, this decrease is less, because of increased use of electricity. For all countries, however, total delivered and primary energy use has grown more slowly than total floor area, indicating conservation. Oil intensity and the use of oil as the principal heating fuel have both decreased more than other fuels.

PLANNED ACTIVITIES FOR FY 1985

We will analyze the data collected so far in order to (1) characterize end-uses in the commercial sector, (2) aggregate over the various subsectors into a meaningful sectoral total, (3) find indicators of activity and conservation in this sector, and (4) investigate the role of electricity in the commercial building sector. We will attempt to measure changes in sectoral energy use by examining changes at the subsectoral level, including changes in fuel mix, changes in subsectoral energy intensity, and changes in the shares of floor space in each of the subsectors. Additionally, we will try to relate total energy use to macroeconomic indicators, such as gross domestic product generated in the "services" sectors. Activities will include an international workshop, at which the issues raised herein will be discussed.

REFERENCE

1. Schipper, L., Meyers, S., and Rosse, J. S. (1984), "Residential Energy Use and Conservation in OECD Countries," in *FY 1983 Annual Report, Energy Analysis Program*, LBL-17074. See also the references in the preceding article.

Energy Use in Cities of the Developing Countries*

J. Sathaye and S. Meyers

The movement of people from the countryside to cities is a significant feature of the recent development process of many Asian, African, and Latin American countries. In many of the poorest countries (mostly in Africa), the growth rate of the urban population averaged more than 6% per year during the 1970s. Together, the developing countries now contain more than 250 cities with populations over 500,000. Urbanization brings with it changes in the ways resources are collected, distributed, and used. In rural areas, people are more directly involved in these activities. In cities, there is greater dependence on a supply network. With many cities growing very rapidly, there is increasing pressure upon these networks and, in many cases, concern about whether they will be able to cope with the growing demand. Understanding the nature of urban resource consumption—in particular, the changes that take place as a country's population becomes more urban—is an important element in planning supply networks that will be able to accommodate future demands.

ACCOMPLISHMENTS DURING FY 1984

Although the rural energy situation in developing countries has been the object of much study, there has been comparatively little research on the nature of urban energy use. Because of its importance to understanding energy demand in the developing countries, we undertook a review of the literature on urban energy use in these countries.

Urbanization has brought with it a transition from traditional energy sources to modern ("commercial") ones like petroleum fuels and electricity. Income growth in urban areas has also facilitated demand for new services, such as refrigeration, air conditioning, and personal vehicle transportation, that require modern fuels. In most countries, the use of such fuels is highly concentrated in the cities, and urban growth and rising demand for modern fuels are highly correlated.[1]

The patterns of energy use in the cities of developing countries exhibit great variety across socioeconomic groups. There are pockets of affluence where energy-use patterns are similar to those found in warm-climate European cities. There are also areas where the patterns more closely resemble those of the rural areas from which many urban dwellers have recently arrived, with the important difference that energy resources are rarely available for free in urban areas, and the need to purchase energy creates problems for the urban poor.

*This work was supported by the Assistant Secretary for Policy, Safety and Environment, Policy, Planning and Analysis Branch of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098; by grants from the Exxon Corporation, Standard Oil Company of California, Standard Oil Company of Ohio, and Statoil of Norway; and by the International Development Research Centre, Ottawa, Canada.

The information we found in our literature review dealt largely with energy use by households, either in the home itself or in personal transportation. We discuss our findings in these areas below.

Energy Use in the Home

As households take on a more modern way of life, demands for new services arise, and there are changes in the way old services are performed. In some cases, a new demand arises that traditionally did not exist (such as refrigeration of food). In others, a traditional service (such as lighting or space cooling) is performed more adequately by a modern device/fuel combination. Replacement of human labor by nonhuman-powered machines is also a characteristic of the transition (especially in clothes care). Convenience, the desire for more service (e.g., more cooling than ventilation provides, more entertainment than radio provides), and considerations of style and image have led to growing use of electric appliances and changes in cooking habits in urban homes. Such changes are very much dependent on household income. Most Third World urban households combine traditional and modern methods. The mix varies widely among cities, but in most, there are probably more households living in a largely traditional manner than in a fully modern one.

Cooking

Cooking is the primary energy-consuming activity in most Third World homes in both rural and urban areas. Results from a survey of semi-urban households in India show that over 90% of total energy use in both low and middle-income homes went for cooking.[2] A survey of households in three Chinese cities found an even higher share of energy use for cooking.[3]

The predominance of cooking is a result of both the absence of other energy demands and the low efficiency of energy conversion by traditional cooking fuels. As household income rises, these conditions change. Households are able to purchase new energy-using devices to meet new demands and to acquire different, more energy-efficient devices for cooking.

The choice of cooking fuels depends on preference, ability to afford a particular fuel, and the availability of fuels and devices. Urban areas are a fertile setting for change in cooking fuels both because of their income-earning opportunities and the availability of different fuels. The type of fuel used for cooking is usually a good indicator of economic status. As income rises, the main cooking fuel tends to move from firewood or charcoal to kerosene to liquefied petroleum gas (LPG) or electricity. One pattern that emerges is a rise in the use of kerosene along with income in the poorer groups. As income increases further, however, use of kerosene gives way to use of LPG and/or electricity.

A recent survey of 1800 households in Hyderabad, India,[4] found that, as expected, firewood consumption fell (by 8%) as income rose (by 10%). For LPG, the income coefficient was almost 1. Kerosene use showed a less continuous pattern than wood and LPG. As noted, its use rose very sharply from the lowest income group and then fell off as income increased further.

Availability of fuels plays a key role in shaping patterns of change. It strongly influences the use of firewood, which remains a common fuel for the urban poor in many places. Where it is cheap or free, it tends to be used—because of habit as well as cost. Recent surveys of energy use in Kenya found that fuelwood accounted for 60% of total energy consumption among the lowest income group of urban households.[5] In the Philippines, reliance on wood is much higher among households in the poorer socioeconomic class in provincial urban areas, where wood is relatively cheaper and more available than kerosene and LPG, than it is in Manila, the primary city.[6] Lack of wood resources around urban areas has become a serious problem in many places, particularly in Africa. Scarcity of wood contributes to the shift to charcoal, which has become a common cooking fuel for the poor in many African cities. Lack of wood can also accelerate the transition to modern fuels, especially where they are locally available at a low price. This has been the case with kerosene in Indonesia, and with coal in China.

Ownership and use of more than one cooking device is common in urban areas, partly because different kinds of food are best prepared with different types of fuel. Households generally do not discard their old cooking device when they acquire a new, more modern, one. Among upper-income households in Kuala Lumpur, 87% used LP gas, 45% used electricity, 23% used kerosene, and 19% used charcoal. In Hyderabad, the proportion of households using both wood and kerosene ranged from 24% in the lowest income group to 7%–9% in the upper-income groups. The proportion using both kerosene and LPG ranged from 1% in the lowest income group to 35%–40% in the upper-middle-income groups. The percentage dropped for the highest income groups, since use of only LPG becomes very common. Use of more than one cooking device and fuel is not restricted to middle and upper-income households. Among the Hyderabad lower-income

households, 21% used wood and kerosene, and 10% used kerosene and LPG.

Fuel switching can be either temporary or permanent. Households that own more than one cooking device have flexibility in responding to changes in the cost or availability of particular fuels. The acquisition of new cooking devices when poorer households gain more income may lead to a more permanent change, although going back to the old fuel often remains a possibility. The initial cost of new cooking devices can be an important barrier to the use of a new fuel, even when the price of the fuel itself is comparatively attractive.

The amount of energy that households use for cooking depends very much upon the efficiency of energy conversion, which can vary greatly, depending on the kind of fuel and device used. In the Hyderabad survey, average monthly energy use per person for cooking fell from 0.239 million Btu among very low income households, who rely heavily on wood, to 0.165 million Btu in the highest-income households, who mainly use LPG. The effect of using more efficient devices can also be seen in Chinese households. Average monthly cooking fuel consumption per person was lowest in homes where town gas was used (180 MJ) and highest where bituminous coal was used (630 MJ). It is possible to use measured or estimated conversion efficiencies to calculate the approximate amount of energy that is actually providing the cooking service. Among the Hyderabad households, "useful" energy consumption per person for cooking increased only slightly as income rose.

Lighting

The use of electricity for lighting is now widespread in urban areas. Where electrification has not yet reached—in the peripheral areas of large cities and the small cities and towns—kerosene is still used for lighting in many homes. The quantity of lighting demanded by households varies considerably. Wealthier families, living in larger homes, demand much more lighting than low-income households, who often only have one or two bulbs.

Appliances

A key feature of the urban scene is the growing ownership of electric appliances. Three activities in particular could have a major impact on residential electricity demand in Third World cities: refrigeration, water heating, and air conditioning. The percentage of urban homes with refrigerators varies from almost zero in China to over three-fourths in the wealthier cities of Asia (Table 1). A refrigerator is usually the first electricity-intensive appliance acquired when urban families have sufficient income to buy one. (Black-and-white television sets, often the first major electric appliance purchased, use much less electricity.) Data from the Philippines and Malaysia show that ownership of refrigerators increases sharply from the lowest income group to the next highest. In the upper-income groups, refrigerator ownership is nearly universal.

Water heating for hygiene is similar to refrigeration in that it is usually not found in a traditional setting. In the Third World, most modern water heaters use electricity. Malaysian survey data, which show low levels of water heater ownership for most income groups, indicate that it is a lesser priority for households than refrigeration. This is no doubt a consequence of the warm, humid climate of most Third World cities. The tropical climate works in the other direction with respect to home cooling, the demand for which could have a major effect on electricity use. At present, air conditioning is uncommon except among the wealthiest households. Determining the income level at which households tend to acquire air conditioning is an important task for electric utility planning.

Other home appliances are mostly not heavy electricity users. In places where household electri-

Table 1. Ownership of major electric appliances in urban areas of Malaysia and the Philippines, by percent of households in each income group.

Income group	Appliance		
	Refrigerator	Air conditioner	Water heater
Malaysia (1980)[a]			
150–299	13	0	0
300–599	50	0	0
600–999	65	1	6
1000–1999	79	10	14
2000–4999	87	23	31
5000+	96	79	50
Philippines (1979)			
Low	15	0	—
Middle	66	2	—
High	93	20	—

Source: Ref. 7.

[a]Kuala Lumpur and Kajang; income figures in dollars per month.

city use is very low, however, increasing use of appliances such as TV sets and clothes washers could have a significant proportional effect on electricity demand. While ownership of TV sets has become common in many cities and is nearly universal in the more modernized cities of Asia, clothes washers are still relatively rare.

Increased use of electric appliances and of more efficient devices for cooking as income rises have opposing effects on overall energy consumption. In urban areas where the modernization process is not so far along, the result may be only a small increase in overall household energy use as income grows. Greater efficiency of energy use in cooking by middle-income families balances their use of more electric appliances. As overall income levels increase, and as the middle and upper classes become wealthier, the situation changes. The use of very inefficient device/fuel combinations for cooking declines among the poor, and ownership of electric appliances by wealthy households becomes significant. In this situation, there is greater increase in energy consumption from the lowest to the highest income groups.

The growth rate in residential demand for modern fuels will depend largely on the movement of families to cities, the rate at which poor households move from traditional methods of meeting services to modern ones, and the extent to which middle-class households expand their appliance holdings. The fastest growth is in the use of electricity, and room for growth in its use exists at nearly all income levels.

Energy Use in Transportation

Energy use in transportation is influenced both by the spatial environment in which people live and by the activities that entail movement, such as work, shopping, social interaction, and distribution of products. While the traditional human- and animal-powered forms of transportation predominate in rural areas of developing countries, the use of motor-powered vehicles—motorcycles, cars, buses—has become an important feature of urban life. A wide range of transport options is often available in cities, and the amount of energy used to accomplish the movement of people and goods is very much dependent on the transport mode chosen.

The various transport modes provide different types of service, measured in terms of speed and comfort of movement, and also require differing amounts of economic resources to make use of them. Walking, the least expensive mode of travel, remains important in cities of developing countries. In Lae, Papua New Guinea, it was estimated that walking was the major mode for 20% of the people, compared to 15% for cars.[8] Where longer distances are involved, buses are the primary transport mode for the urban poor and middle class.

The mode of personal transport varies with household income. As average income has grown, the use of personal automobiles has risen. In Kuala Lumpur and Kajang in Malaysia, 40% of the surveyed households reported the car as their mode of travel to work. Among the poor households, very few used a car, but in the wealthiest group, over 90% did so (Table 2). Philippines data also show that automobile ownership is very dependent on household income. In the upper 9% of households, 44% owned a car, 19% owned a jeep, and 13% owned utility vehicles. In the middle-income group, only 5% owned a car and 6% owned a jeep. In the two lowest groups, comprising half of the sampled households, there was no car ownership at all.

Car ownership also varies between large and smaller cities. In Manila, 11% of households owned a car. In provincial urban areas of the Philippines, the number was 3%–4%. Higher incomes, a well-developed road system, and the greater distances to be traveled for daily activities probably account for this phenomenon. Once a car is owned, the household tends to use it for much of its transport needs. In Nairobi, the share of total travel mileage accounted for by automobile travel increased from 3% in the lowest income group to 90% in the highest group.[9]

Cars have an important effect on energy use because they are an inefficient mode of urban trans-

Table 2. Mode of travel to work in Kuala Lumpur and Kajang, Malaysia, in 1980, by percent of households in each income group.

Monthly income[a]	Car	Taxi	Bus	Motor-cycle	Others[b]
150–299 (3%)	—	—	27	13	60
300–599 (20%)	8	2	30	22	39
600–999 (28%)	3	2	27	19	18
1000–1999 (29%)	48	4	11	18	18
2000–4999 (15%)	73	1	3	15	9
5000+ (5%)	92	—	—	—	8
Total	40	2	18	18	22

Source: Ref. 7.

[a]Income figures in dollars; figures in parentheses refer to percentage of sample population.

[b]Bicycles, walking, etc.

port. In three Latin American countries, for example, automobiles are responsible for 65%–75% of energy use in passenger transportation, but carry only 25%–35% of the total volume of traffic.[10] Energy efficiencies calculated for Hong Kong show the automobile to be some 10 to 15 times more energy-intensive than buses.

The amount of energy used in a particular mode depends largely on the number and length of trips taken. Studies of energy use in Nairobi and Mexico City[11] show that the number of trips per day increases rapidly with rising incomes. Average trip length is affected by particular features of the urban landscape, such as the degree of sprawl. Automobile ownership encourages the undertaking of longer trips: the average car trip in Nairobi was almost twice as long as the average foot or bicycle trip. Traffic conditions also affect the duration of trips. Congestion, which has become severe in many Third World cities, leads to slower travel and less efficient operation of fuel-powered vehicles.

Because of the differences in mode choice, trip length, and number of trips, energy use in transportation varies enormously among income groups. In Hong Kong in 1974, Newcombe[12] found a 40-fold increase in per capita energy use for transportation between the lowest and highest income groups (Table 3). Most of this increase was accounted for by purchases of gasoline and diesel fuel for private use. Consumption in this category showed a big jump from the second highest to the highest income group, reflecting frequent car use by the wealthiest families.

Table 3. Transport energy use in income in Hong Kong (1974).

Monthly income[a] (HK$/cap.-month)	Public	Private (MJ/capita-day)	Total
<100 (3%)	0.13	0.13	0.26
101–150 (11%)	0.07	0.25	0.32
151–200 (18%)	0.21	0.05	0.26
201–250 (16%)	0.34	0.60	0.94
251–300 (10%)	0.49	1.38	1.87
301–350 (7%)	0.67	1.11	1.78
351–400 (4%)	0.49	1.58	2.07
401–550 (9%)	0.92	3.52	4.44
550+ (18%)	1.78	9.26	11.04

Source: Ref. 12.

[a]Figures in parentheses refer to percentage of sample population.

Estimates of transport energy use by households in Nairobi and Mexico City show a similar trend. In Nairobi, research indicated a 60-fold increase in energy use per household from the lowest to the highest income groups. As in Hong Kong, most of the increase was related to car travel, accounting for 30% of the energy used in the lowest income group compared to 95% in the highest. For Mexico City, there was a 40-fold increase in energy use per household across the income scale, the automobile again emerging as the major contributor.

If households are at a point where automobile ownership is a possibility, moderate increases in household income may lead to very substantial growth in the consumption of transport fuels. The price and availability of automobiles, the proportion of city dwellers able to purchase them, and the existence and adequacy of alternatives to private automobiles—all will be major determining factors of energy use in urban passenger transportation.

Conclusions

Patterns of energy use in the cities of the developing countries have undergone considerable change during the past two decades. These changes are closely linked to growth in household income, which has allowed the acquisition of devices that use modern fuels. A major area of change has been in cooking, where traditional fuels like wood have given way to kerosene, LPG, and electricity. The other key development in homes has been the growth in ownership of electric appliances. These include devices, like refrigerators, water heaters, and air conditioners, that substantially increase household electricity demand.

A striking feature of energy use both in the home and in transportation is the large difference in the amount used by households at different socioeconomic levels. Major segments of the urban population in many cities own few appliances and use most of their purchased energy for cooking. For transport, they either walk or use mass transit. In many cities, a small proportion of the households accounts for a large share of the use of modern fuels, especially electricity. The extent to which lower-income households move into more electricity-intensive lifestyles will depend very much upon both general income growth and income distribution.

PLANNED ACTIVITIES FOR FY 1985

The International Energy Studies Group will continue to investigate urban energy demand as part of its Less Developed Countries Project.

REFERENCES

1. Sathaye, J. *et al.* (1984), *Summary of Results and Progress Report for the Study of Energy Use in Developing Countries,* LBL-17842.
2. Gupta, C.L., Rao, K., and Vasudevaraju, V. (1980), "Domestic Energy Consumption in India (Pondicherry Region)," *Energy 5,* p. 1213.
3. Zhu, H., Brambley, M., and Morgan, R. (1983), "Household Energy Consumption in the People's Republic of China," *Energy 8,* p. 763.
4. Alam, M., Dunkerley, J., Gopi, K., and Ramsay, W. (1983), *Fuelwood Survey of Hyderabad,* Resources for the Future, Washington, DC.
5. Beijer Institute (1984), *Energy and Development in Kenya: Opportunities and Constraints,* Stockholm.
6. Philippines Ministry of Energy (1982), *Energy Sectoral Survey Series: 1979 Urban Household Energy Demand,* Manila.
7. Socio-Economic Research Unit (1981), *The Use of Energy and Attitudes towards Energy Conservation among Urban Households,* Kuala Lumpur, Malaysia.
8. Newcombe, K. (1980), *Energy for Development: the Energy Policy Papers of the Lae Project,* Australian National University, Canberra.
9. McGranahan, G., Chubb, S., Nathanns, R., and Mbeche, O. (1979), *Patterns of Urban Household Energy Use in Developing Countries: The Case of Nairobi,* Institute for Energy Research, Stony Brook, NY.
10. Inter-American Development Bank (1982), *The Impact of Energy Costs on the Transport Sector in Latin America,* Washington, DC.
11. McGranahan, G. and Taylor, M. (1977), *Urban Energy Use Patterns in Developing Countries: A Preliminary Study of Mexico City,* Institute for Energy Research, Stony Brook, NY.
12. Newcombe, K. (1979), "Energy Use in Hong Kong: Part IV," *Urban Ecology 4,* p. 179.

Energy Use in Developing Countries*

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The International Energy Studies Group is conducting a detailed study of the patterns of energy demand in the less developed countries (LDCs) that are likely to have the biggest impact on the configuration of world energy demand during the next decade.

Since the mid-1970s, there has been a worldwide trend toward less reliance on petroleum-based energy sources. This trend was clearly noticeable among developing countries. Faced with a severalfold increase in their energy-import bill, LDCs were unable to increase their exports amidst a generalized international recession. Hence, they experienced rapid deterioration of their domestic economies as inflation and external debts soared to record levels.

Despite efforts to develop alternative energy sources, LDCs still rely heavily on petroleum products; in many cases, these products account for most of their energy supply. The share of petroleum in primary energy use is higher in LDCs than in industrialized economies, and LDCs account for most of the net growth in world petroleum demand. Much of the urban and industrial development now taking place in LDCs will further increase demand for petroleum products for industrial processes, urban transportation, and household use.

The conflict in LDCs between continued economic development and the need to reduce petroleum imports adds great uncertainty to future energy (and petroleum) demand. Therefore, in order to estimate future trends in world energy markets, it is essential to understand the structure of energy demand in LDCs. We plan to study 16 countries that account for 75% of energy use in LDCs. They are Argentina, Brazil, Mexico, Venezuela, Colombia, Peru, Korea, Indonesia, the Philippines, Malaysia, Singapore, Taiwan, Thailand, India, Bangladesh, and Pakistan. We have completed most of the analysis for Argentina, Brazil, Venezuela, Korea, the Philippines, Taiwan, and Thailand.

*This work was sponsored by the Assistant Secretary for Policy and Evaluation, the Assistant Secretary for Fossil Energy, and the Assistant Secretary for International Affairs and Energy Emergencies, Energy Emergencies Branch, of the U.S. Department of Energy under Contract No. DE-ACO3-76SF00098; it was also supported by grants from the Exxon Corp. (and Esso Eastern), the Standard Oil Company of Ohio, Chevron Inc., and Statoil of Norway. The project also received assistance from Scallop Corp., NY, and from the International Development Research Centre, Ottawa, Canada.

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In light of the substantial reduction in petroleum demand achieved by many LDCs during the last decade, this analysis addresses one of the main issues for the future use of energy in developing economies: How permanent will be the effects of changes in the composition of industrial output, of energy conservation, and of fuel substitution measures, especially under conditions of renewed economic growth?

Our analysis is based on a sector-by-sector disaggregation of energy use. It associates the trends in energy demand with the observed changes in the levels of sectoral activity.[1–7] Other commonly used approaches such as building detailed econometric models or studying aggregate economic trends are not as well suited to developing countries because the aggregation hides quantities and trends of interest and because the broad market assumptions underlying econometric models may not apply. The approach adopted in this study takes advantage of specialized knowledge of individual countries while mitigating the problem of data imperfections by examining energy use at a sectoral level.

ACCOMPLISHMENTS DURING FY 1984

Some Observations of Changes in Oil Use

During FY 1984, our analysis concentrated on changes in oil use in the studied countries. The observed reduction in the use of petroleum is a consequence of energy conservation, fuel substitution, and economic recession. Both the private sector and government institutions in developing countries reacted to higher energy prices by promoting energy conservation and by replacing imported petroleum products with domestic sources of energy. In addition, the low level of economic activity throughout the world in the late 1970s and early 1980s caused a widespread slowdown in industrial production and fuel use, especially in the most energy-intensive sectors such as steel and cement.

Other factors, however, combined to increase energy and petroleum demand. The changes in the composition of the manufacturing sector in developing economies seem to have increased the use of energy (and petroleum) as these countries work to establish their own basic industries such as metals, chemicals, food, and paper and pulp, most of which are more energy-intensive than the traditional activities that make up the bulk of output in some developing economies. At the same time, high rates of population growth combined with migration to urban centers have created additional demand for commercial fuels for transportation and household use.

Although the effort to reduce the use of imported petroleum products and increase reliance on domestic energy resources is noticeable in all economies, the trends in energy use have been somewhat different in oil-importing countries than in those that possess abundant energy sources.

In countries with sufficient resources to supply the domestic market (e.g., Argentina and Venezuela), substitution has been more marked than conservation, with electricity and natural gas replacing oil in industrial applications, and with natural gas, hydropower, and coal displacing fuel oil and diesel for electricity generation. Some of these self-sufficient countries, most notably Venezuela, have experienced an increase in the overall energy intensity of value added in manufacturing during the past 10 years.

All of the oil-importing countries studied so far have shown a noticeable decline in the energy intensity of value added in manufacturing. In these countries, conservation has exceeded fuel substitution; it has been promoted both by the private sector (e.g., changing to dry process for cement production in Thailand) and by government policies (e.g., closing gasoline stations on Sundays in Brazil).

Oil Use in the Near Future

The evidence collected so far shows that most of the reduction in the use of petroleum products has taken place in industry and in electricity generation, especially through substitution away from fuel oil. It appears that most of these changes will have an effect lasting at least through the end of the decade.

By comparison, the residential and transportation sectors seem less amenable to fuel substitution, and their demand for light petroleum products is expected to continue growing at rates comparable to those observed in the 1970s, especially in the absence of a substantial increase in the real price of petroleum. Most reductions in energy use in the residential and transportation sectors are more easily reversible, as they are associated either with mandated conservation or with short-term responses to higher prices or lower incomes.

The evolution of energy use in Taiwan and Venezuela (Fig. 1) provides a general example of the differences between oil-importers and self-sufficient countries over the past decade. Many of the self-sufficient countries show an increase in the relative use of energy in every sector of the economy, even following the price increases of 1979. When that is the case, energy use in industry usually outpaces growth in both the transportation and the residential sectors.

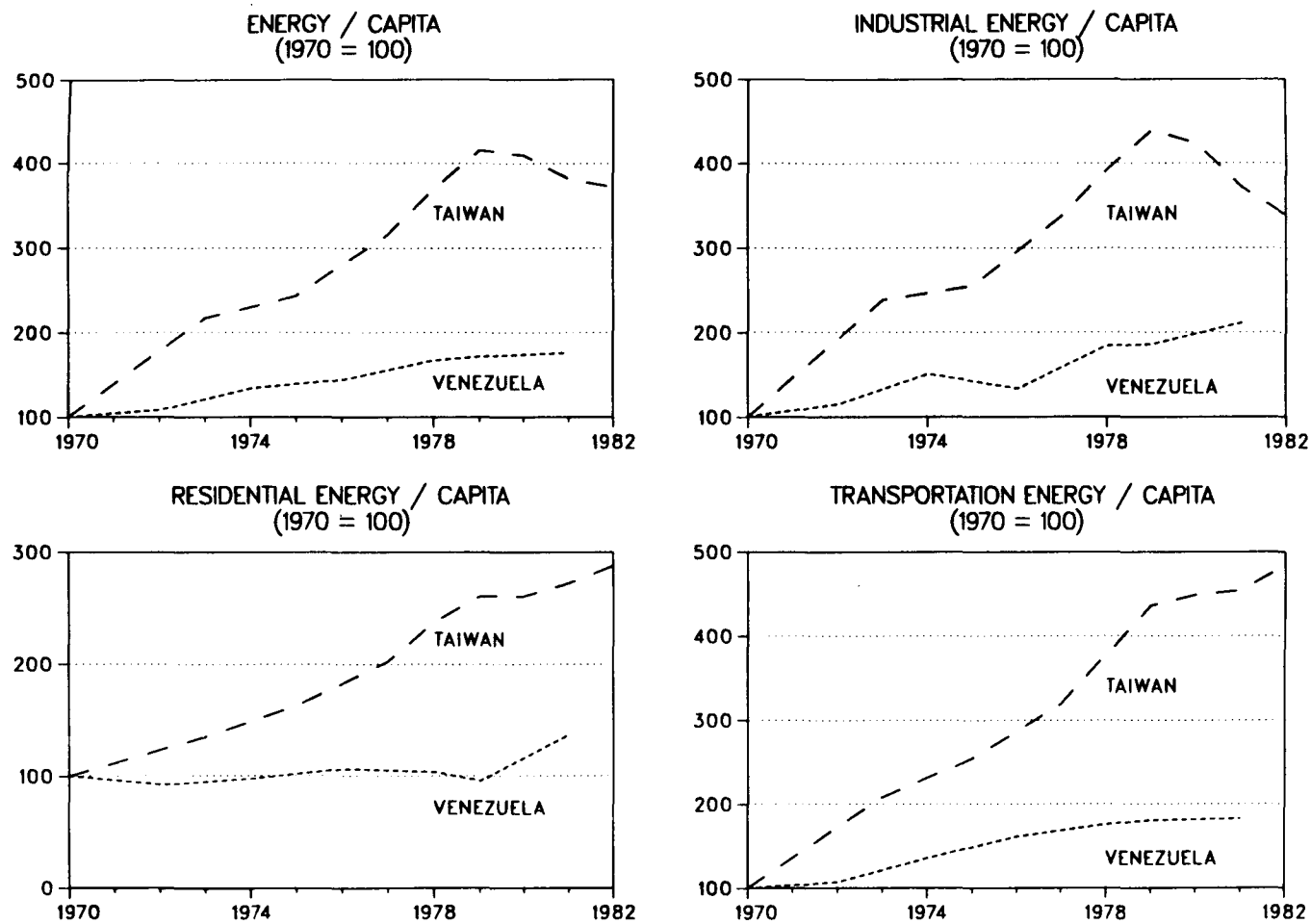

Figure 1. Energy indicators for Venezuela and Taiwan, 1970–1982. Taiwan is an oil-importing country, while Venezuela is self-sufficient. (XBL 851-987)

On the other hand, all the oil importers managed to curb energy use after 1979, and did so primarily by reducing industrial energy use. There are indications that, because of high rates of population growth and increasing urbanization, the aggregate use of petroleum products in the transportation and residential sectors will continue to grow, creating additional demand for gasoline, diesel oil, and LPG, despite economic recession.

Permanence of Changes in Energy-Use Patterns

Whether the degree of petroleum savings thus far achieved can be maintained is contingent upon: (1) the level of economic growth, and (2) a combination of petroleum prices and the nature of the energy-saving measures adopted by each sector. Renewed economic growth will rekindle demand for all products. At the same time, however, renewed growth will spawn investment in new equipment that should embody greater efficiency and contribute to the decline of energy intensity of value added.

In order to assess their stability, we have grouped these changes in petroleum use into two categories: permanent and reversible.

Permanent Changes

We identified the following changes as permanent:

(1) All substitutions away from fuel oil and diesel in electricity generation in favor of hydro, nuclear, geothermal, natural gas, and coal. Typical examples are the increased use of natural gas and hydroelectricity for power generation in Argentina; the increase in nuclear and coal-fired generation in Taiwan; and the rapid increase in the share of natural gas for power generation in Thailand.

The expansion of hydroelectric generation is particularly noticeable in Argentina; there, the share of

hydroelectricity in total generation has increased to nearly 50%, compared to 10% in the early 1970s. Hydroelectric generation has also increased in Asia; in Thailand, its share of total generation has increased from 11% in the early 1970s to 23%.

(2) Technical innovations and change in the composition of industrial output. The main examples in this class are:

- The conversion of cement plants from wet to dry process (Thailand and Argentina).
- the conversion from oil to coal burners (nearly half the cement plants in Brazil, and all in the Philippines).

(3) Increase in the number of cars and motorcycles per capita in transportation. Even though gasoline use per vehicle showed some response to prices, the aggregate use did not decline as much, because the total number of cars kept increasing.

(4) The switch from kerosene and noncommercial fuels to electricity for lighting in the residential sector in all countries studied.

(5) The switch from noncommercial fuels to LPG for cooking in the residential sector in Latin America, due to the development of rural areas. The exception is Argentina, where natural gas has nearly completely replaced LPG for household use, a change that can also be regarded as permanent.

Most countries have singled out industry and electricity generation for investing in reductions in the use of fuel oil. These two sectors are the most suitable for energy conservation and fuel substitution for three seasons: (1) fuel oil is the most widely used petroleum product in those sectors; (2) there are direct substitutes for fuel oil in most of its applications (e.g., natural gas, coal, and wood for steam generation); and (3) the use of energy is easier to monitor, since most of it is concentrated in a few large users.

Reversible Changes

The changes we classified as reversible are:

(1) Industrial fuel substitution. The main examples are:

- Increased use of domestic coal, charcoal, and wood briquettes in industry in Brazil. These are conditional not only on prices but on regional availability; industrial use of wood briquettes in Brazil is by and large restricted to one state.
- The replacement of imported fuel oil with imported coal in Korean industry, in plants with dual fuel capability.

(2) The short-term response to gasoline and diesel prices, which reduced driving but did not increase fleet efficiency.

(3) The increased use of commercial fuels for cooking in Asia. Most households in Asia (except Taiwan) are equipped to use a variety of fuels (commercial or not) for cooking. Variations in the relative price and availability of fuels affects the types and quantities of fuels used.

These changes were motivated by the oil price increases of the late 1970s, which enhanced the competitiveness of other fuels (e.g., imported coal for Korea) and made viable reserves that had been uneconomic in the past (domestic coal in Brazil).

Also among the reversible changes is a fuel substitution that is likely to revert to petroleum in the near future. This is the sale of electricity at subsidized prices to displace fuel oil for steam generation in Brazilian industry. Because of the economic recession, the use of electricity in early 1982 in Brazil did not reach the levels previously anticipated, causing a surplus of generating capacity. Starting in 1981, hydroelectricity has been offered at subsidized rates to industries willing to replace oil-fired boilers with electric ones. The subsidized rates will be in effect through 1986; thereafter, in the absence of economic incentive, it is likely that many users will revert to fuel oil for steam generation. If that happens, it will cause a rapid escalation in the demand for fuel oil in Brazil before the end of the decade.

In Taiwan, Taipower is planning to provide a similar subsidy, but it is not yet implemented.

Forces Driving Future Demand

Industry and Electricity Generation

The replacement of fuel oil in industry was achieved through increased use of coal (primarily in steel and cement production), natural gas, and electricity. Additionally, because of improved management of energy use, intensity of fuel oil use declined in most of the manufacturing sectors. These accomplishments were motivated by a combination of high prices and government incentives.

In electricity generation, fuel oil was replaced with coal, natural gas, nuclear fuel, hydropower, and geothermal steam. The incentive to avoid new oil-fired plants will remain strong in this sector.

A factor that may reduce the incentive for further conservation of fuel oil is its relative abundance in the world market. Most developing countries have reduced their use of fuel oil, but not that of lighter petroleum products. To reduce the surplus

of fuel oil, various countries may: (1) export the surplus, all or in part; (2) reduce crude oil imports and import some of the light products needed, rather than refining it all domestically; (3) use higher quality (lower density) crudes; and (4) restructure refineries to produce a larger fraction of light products. Which of these alternatives will be implemented will depend on each country's evaluation of its security and vulnerability to disruptions in petroleum supply.

Transportation and Residential Sectors

Energy use in the residential and transportation sectors is dispersed and relatively more difficult to monitor. Prices are the only instrument capable of a global effect in these sectors; nevertheless, their effect on aggregate use has been relatively small. The trend in the aggregate growth of energy use in the transportation and residential sectors is ultimately dictated by a combination of population growth and urbanization, both of which have been rapid in most of the countries studied.

In all of these countries, transportation is the most critical sector in terms of petroleum substitution. It typically accounts for 70%–90% of gasoline and diesel use and is the least amenable to fuel substitution.

At least two main factors promote the continued increase of energy use in transportation: (1) the lack of alternatives to petroleum products for individual transportation; and (2) the growth in car and motorcycle fleets (even with stagnant or decreasing income per capita, the real price of cars has declined in many countries).

In homes, two factors contribute to the nearly continuous increase in energy use: urbanization and population increase. In most countries studied, and especially in Latin America, there is an intense and continuous transfer of population from rural to urban areas. This migration is accompanied by the substitution of LPG and electricity for the kerosene and noncommercial fuels used in rural areas (in some Latin American countries—e.g., Venezuela—rural areas use kerosene for both cooking and lighting). The conversion to commercial and more efficient fuels often leads to a decline in the total energy use per household or per capita as the use of LPG and electricity per capita increases. The higher efficiency of the commercial fuels often causes the growth of total energy use in the residential sector to proceed at a lower rate than in the rest of the economy.

In Latin America, urbanization has also reduced the ability to switch among cooking and lighting fuels; if the price of LPG increased, most urban households would not be able to switch to another fuel (e.g., wood or charcoal) because these alternative fuels and the equipment to use them are often not available.

Also contributing to the growth in residential energy use is the more widespread use of electricity, favored both by urbanization and by the expansion of transmission networks. In their levels of urbanization, Taiwan and Thailand are studies in contrast (80% and 15% respectively), but both show rapid growth in electricity use. In Taiwan, there has been a continued increase in income per capita accompanied by a rapid growth in the ownership of electrical appliances. In Thailand, despite the low level of urbanization, the number of customers served by electricity has increased steadily as a result of extending transmission lines to serve rural areas.

Conclusions

In this study, we measured critical changes in oil use in seven less developed countries by examining oil use per kWh in electricity generation, oil use per output in industry, and oil use per capita in transportation and in the residential-commercial sector. We found that if activities in these countries in 1982 had proceeded at 1978–1979 oil intensities, oil use would have been 13% higher than the 2.36 million barrels per day actually consumed.

In contrast with that decline, 1982 oil use was up from that in 1981. We believe that structural growth will cause a gradual increase in oil use during the next 5 years, despite greater efficiency and continued fuel substitution that will reduce petroleum consumption (and total energy use) per unit of activity.

PLANNED ACTIVITIES FOR FY 1985

We will quantify in more detail the nature of recent trends in oil demand, extending the analysis to Indonesia, Mexico, India, Pakistan, and Bangladesh, as well as some of the smaller West African countries. We will also combine the results of individual country analyses to compare energy use profiles of the four oil-producing countries in the study (Indonesia, Venezuela, Mexico, and Nigeria) and to compare energy use in transportation among all countries. In addition, we will update information on energy demand to show end-use patterns in all sampled countries during 1983.

REFERENCES

1. Schipper, L., Sathaye, J., and Meyers, S. (1984), *Energy Demand in the Developing Countries:*

Toward a Better Understanding, Energy Research Group Manuscript Reports, ERG-MR2e, The Energy Research Group, Ottawa, Canada.

2. Ghirardi, A. (1984), *Trends of Energy Use in Brasil: Is Self-Sufficiency in Sight?* LBL-18422.
3. Pignone, C. (1984), *Energy Demand and Fuel Supply in Indonesia,* LBL-19025.
4. Schipper, L., *et al.* (1985), "The Directions of Oil Demand," Annual Review on the Study of Energy Demand in Developing Countries, International Energy Studies Group, Lawrence Berkeley Laboratory Report LBID-1013 (Draft).
5. Ghirardi, A. and Ketoff, A. (1985), *The Structure of Energy Demand in Argentina,* LBL-19410 (Draft).
6. Ghirardi, A. (1985), *Energy Demand in Venezuela,* LBL-19411 (Draft).
7. Schipper, L. and Meyers, S. (1983), "Energy Use and Conservation in Kenya's Modern Economy," *Energy Policy 11*(3), p. 225.

This report was done with support from the Department of Energy. Any conclusions or opinions expressed in this report represent solely those of the author(s) and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory or the Department of Energy.

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