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ENERGY ANALYSIS PROGRAM

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

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LBL-17074

APPLIED SCIENCE DIVISION ANNUAL REPORT ENERGY ANALYSIS PROGRAM FY 1983

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CONTENTS

Energy Analysis Program Staff 5–v

Introduction 5–1

Residential Energy Conservation: Developing a Guide for Homebuilders
R. Ritschard, Y.J. Huang, I. Turiel, G. Verzhbinsky, S. Byrne, D. Wilson, L. Chang, and C. Hsui 5–2

Simplified Energy Analysis: Slide Rules for Single-Family Houses
Y.J. Huang, G. Verzhbinsky, R. Ritschard, I. Turiel, S. Byrne, P. Chan, D. Wilson, C. Hsui, and L. Chang 5–4

Attached Sunspaces as Energy Savers
R. Ritschard, Y. Huang, D. Wilson, and J. Bull 5–7

Impact of Windows on House Heating and Cooling Loads: A Parametric Analysis
I. Turiel, Y.J. Huang, G. Verzhbinsky, R. Ritschard, L. Chang, C. Hsui, and D. Wilson 5–11

Parametric Energy Analysis in Support of Singapore Energy Conservation Standards for Office Buildings
I. Turiel, R. Curtis, and M.D. Levine 5–14

Microeconomics of Residential Energy Conservation
M.D. Levine, P. Chan, H. Ruderman, and D. Tucker 5–19

Occupant Behavior and Residential Energy Use
E. Vine, J. Cramer, P. Craig, D. Kowalczyk, S. Gold, M. Levine, B. Hackett, and T. Dietz 5–21

Energy Efficiency Choice in the Purchase of Residential Appliances
H. Ruderman, M.D. Levine, and J.E. McMahon 5–25

Improvements in Residential Energy Modeling
J.E. McMahon and P. Chan 5–29

Analysis of Federal Energy Efficiency Standards for Appliances
M.D. Levine, P. Chan, J.E. McMahon, and H. Ruderman 5–32

Effects of Utility Incentive Programs on the Energy Efficiency of Newly Purchased Appliances
D.F. Dickey and M.D. Levine 5–35

Residential Hourly and Peak Demand Model
G. Verzhbinsky, E.L. Vine, H. Ruderman, and M.D. Levine 5–39

Price Elasticity of Residential Electricity Demand
E. Kahn, J. Sathaye, and D. Robbins 5–42

Residential Energy Use and Conservation in OECD Countries
L. Schipper, S. Meyers, and J.S. Rosse 5–48

Energy Efficient Housing in Sweden
L. Schipper, S. Meyers, R. Spencer, E. Dean,
L.-G. Carlsson, and E. Vedung 5–53

Energy Demand and Energy Efficiency in the Developing Countries
J. Sathaye and L. Schipper 5-57

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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 analytical capability that complements the more technical pursuits of other groups in the Division involved in building energy research. 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 1983 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 the development of a simple and accurate tool for approximating energy demand for residential buildings in any U.S. climate and technical analysis of commercial building energy standards for Singapore.

(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; and analysis of the effects of energy conservation programs on electric and gas utilities.

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

The projects described in the following pages provide a good beginning 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 are likely to constitute some of the new initiatives of the Program over the next few years.

Residential Energy Conservation: Developing a Guide for Homebuilders*

R. Ritschard, Y.J. Huang, I. Turiel, G. Verzhbinsky, S. Byrne, D. Wilson, L. Chang, and C. Hsui

The influence of various energy conservation options on residential energy use in prototypical houses in the United States has been extensively analyzed over the past few years by the Lawrence Berkeley Laboratory. This research effort has provided technical support for the Building Energy Performance Standards (BEPS) that were mandated by the Energy Conservation Act of 1976. This Act required analysis of building energy use to develop mandatory energy performance standards. Mandatory standards were replaced in 1981 by voluntary performance guidelines, but technical support has continued in order to make the relevant information available to user groups such as the building industry.

Under the performance guideline approach, builders, architects, and engineers are encouraged to develop innovative energy management schemes and designs that can substantially reduce energy requirements for new single-family houses. Homeowners will benefit from such measures through lower monthly fuel bills, with investment in energy efficiency amortized over the life of the building as well as through greater home resale values. In support of these goals, this project endeavored to develop simplified energy analysis tools capable of accurately estimating the energy savings associated with various conservation measures used in site-built single-family homes. These tools were designed to be used by a nontechnical audience such as home buyers, homebuilders, and others in the building industry.

The basic tool we have developed is a "slide rule" for estimating the energy savings that will result from adding energy conservation options to a home. It is a simple graphic representation of a comprehensive data base of computer simulations on changes in energy use as a function of building construction and location. Five prototype homes and a full range of energy conservation measures were selected. By simulating each prototype in representative weather locations with the conservation options added, changes in energy use were calculated. These changes were then converted into a simple graphic format on the slide rule. This device thus recreates the results of a complex state-of-the-art analytical procedure without substantially sacrificing accuracy and without requiring technical knowledge to operate it. The slide rule is described more fully in the next article ("Simplified Energy Analysis: Slide Rules For Single-Family Houses").

ACCOMPLISHMENTS DURING FY 1983

LBL assembled a comprehensive data base on the predicted energy consumption of five residential prototypes from a series of simulations using the DOE-2.1A computer program. Significant analysis was also done on the relationship of heating and cooling load changes to climate variables to develop a simple method for extrapolating results from 45 base locations to more than 1000 intermediate locations. For example, the climate analysis included the correlation of building conductivity and various climate parameters (Fig. 1). This work was crucial in defining climate zone boundaries and in gaining a better understanding of building physics.

To represent the energy use characteristics of site-built single-family housing, five prototype buildings were defined that encompassed the majority of new residences being built in the United States. Building types studied were one-story, two-story, split-level, mid-townhouse, and end-townhouse.

For each building prototype in any weather condition, a full range of energy conservation options was identified and simulated. These options

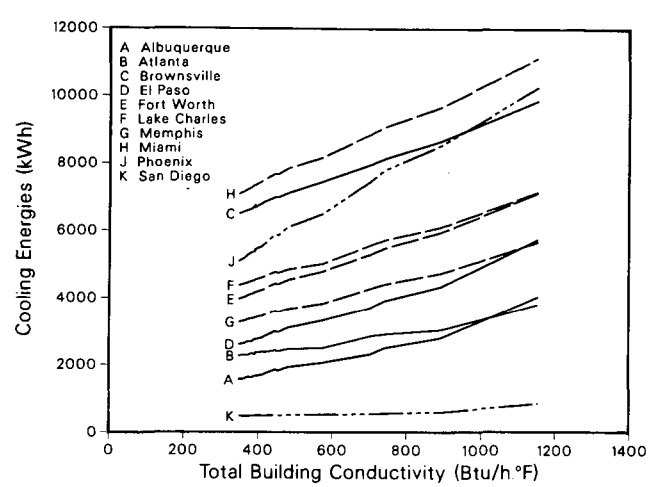

Figure 1. Plot of cooling energies vs. various conservation measures for a one-story, 1540-ft^2 ranch house in 10 cities. The x-axis corresponds roughly to increasing thermal integrity. (XCG 834-7037)

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

included various combinations of insulation (ceiling, floor, and walls), window glazing, and infiltration levels. Three types of building foundation (slab-on-grade, ventilated crawl space, and basement) were also considered, depending on the weather location.

Standard building operating conditions were defined. Thermostat settings for both heating and cooling periods were established, including night setback during the heating months. A schedule was determined for summer natural venting conditions and for the heat gains due to estimated internal loads. These conditions were generally kept constant throughout the analyses.

We also performed sensitivity analyses of the effects on building energy use of variations in building design and operating conditions. These analyses were used to extend the base case results to account for differences between individual buildings and to give accurate values for differences between conservation measures as applied to specific buildings. Our efforts in parametric analysis of building variations emphasized the development of basic scientific understanding of the parameters that determine energy use. For example, in studying the energy impact of temperature setback, we found a strong correlation between night setback and percent degree-day reductions (Fig. 2). We also conducted sensitivity studies of the following topics: building floor area; building orientation; equipment efficiencies; window size, type (wood, aluminum, etc.), and location (north, west-east, or south side); levels of air infiltration; and enhanced solar design (direct-gain and attached sunspace configurations).

For simplicity, we designed the slide rule to contain only part of the sensitivity work—namely, insulation, infiltration and window options, and different equipment efficiencies, all scaled to the appropriate floor area and location. Additional energy conservation measures such as movable night insulation, building orientation, exterior roof and wall color, enhanced solar design, and night thermostat setback were considered as modifiers to the values displayed on the slide rule. More complete descriptions of the study methodology, assumptions, and results have been presented elsewhere.[1,2]

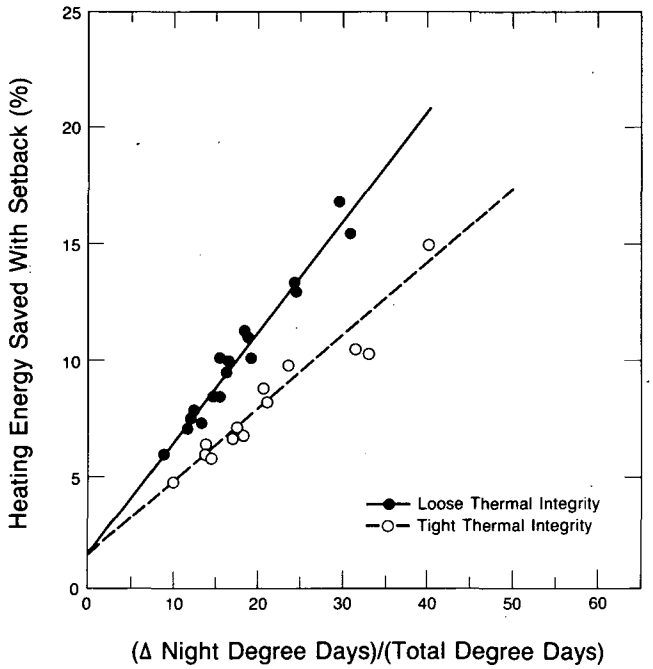

Figure 2. Plot of temperature-setback savings vs. degree-day differences, for a 1540-ft^2 house with loose and tight thermal integrities. (XBL 836-2754)

PLANNED ACTIVITIES FOR FY 1984

This work will continue, with the major emphasis on completion of a full set of slide rules for 45 climate zones and five building prototypes. We will begin to extend this analysis to other prototypical buildings, including garden apartments and other multi-family residences. In addition, we will develop a microcomputer program and software package as the next version of the Homebuilders' Guide.

REFERENCES

1. Energy Analysis Program (1983), *Affordable Housing Through Energy Conservation: Technical Support Document,* LBL-16342 (Draft).
2. Energy Analysis Program (1983), *Affordable Housing Through Energy Conservation: Data Base for Simplified Energy Analysis,* LBL-16343 (Draft).

Simplified Energy Analysis: Slide Rules for Single-Family Houses*

Y.J. Huang, G. Verzbhinsky, R. Ritschard, I. Turiel, S. Byrne, P. Chan, D. Wilson, C. Hsui, and L. Chang

As part of a project sponsored by the Department of Energy ("Affordable Housing Through Energy Conservation"), a Homebuilders' Guide was developed for new, site-built, single-family houses. The Homebuilder's Guide consists of (1) a set of slide rules with sets of interchangeable tabs and (2) a user's manual with tables for optional correction terms. With these tools, users can analyze the energy effectiveness of a large range of conservation measures in single-family residences without detailed calculations.

The slide rules are graphic representations of a comprehensive data base of over 10,000 DOE-2.1A computer simulations covering five building prototypes (one-story, two-story, split-level, and two types of townhouses) and three foundation types (slab, basement, and ventilated crawl space) in 45 climate regions. There is a separate slide rule for each prototype, with interchangeable of tabs for different locations, equipment, and fuel types. By inserting the correct tabs in the appropriate slide rule, users can recreate with good accuracy any portion of a DOE-2.1A data base that covers the range of conventional housing in the United States.[1]

The user's manual includes climate data that extends the data base to nearly 1,000 secondary locations and "modifier tables" that delineate the energy effects of measures such as building color and orientation, window orientation and shading strategies, thermostat controls, and attached sunspaces. This additional information extends the range and utility of the slide-rule calculations.

ACCOMPLISHMENTS DURING FY 1983

The cornerstone of the Homebuilder's Guide is a large computer-generated data base of residential energy use compiled by this project over the past 3 years using the DOE-2.1A building simulation program (see the Energy and Environment Annual Reports for 1981 and 1982). This data base quantifies the savings possible with more energy efficient homes and supports DOE's goal of promoting "affordable housing through energy conservation."

In 1983, we developed a mixed format of slide rules and tables to make this technical data usable and appealing to a nontechnical audience, specifically homebuilders. The slide rules provide a flexible and quick method for comparing energy savings for standard conservation measures, while the "modifier tables" in the manual permit more detailed comparisons of optional measures. The refinement of this format required solving numerous technical and graphic-design issues, with a final result that is visually attractive but maintains close correspondence to the technical data base.

Working slide-rule prototypes and draft copies of the modifier tables were submitted to DOE in late 1983 for public review. (Printing and manufacture of the draft and final versions will be done by DOE.) Because of the large number of tabs required for the complete Homebuilder's Guide package, a computer program was written that automatically plots the slide rules, using a commercial graphics package.

Methodology

The public review version of the slide rule (see Fig. 1) allows users to estimate energy savings from the *addition* of conservation measures to a base-case house design. A slightly different design also allows the user to calculate a building's total energy consumption.

The slide rule gives energy savings associated with standard conservation measures such as insulation, number of window glazings, and reduced infiltration. These savings are then adjusted for differences in house size, equipment efficiencies, and climate variations from the base-case locations.

The data base was first analyzed extensively to derive the change in loads for the prototype house due to incremental changes in conservation, such as switching from R-11 to R-19 wall insulation.[2] These load differentials ("Δloads") are then translated graphically onto the slide rule as either linear or logarithmic scales, depending on their functional relationships.

The first five tabs (A through E) correct for differences in building loads due to differing ceiling, wall, and foundation insulations, window sizes and glazings, and infiltration rates. Since analysis showed these Δloads to be basically additive, they were plotted on linear scales. In setting the tabs to the correct conservation measures, the user is actually subtracting Δloads from a highest possible value. For legibility, Δloads from the data base were normalized so that the subtotal always gives an unadjusted building

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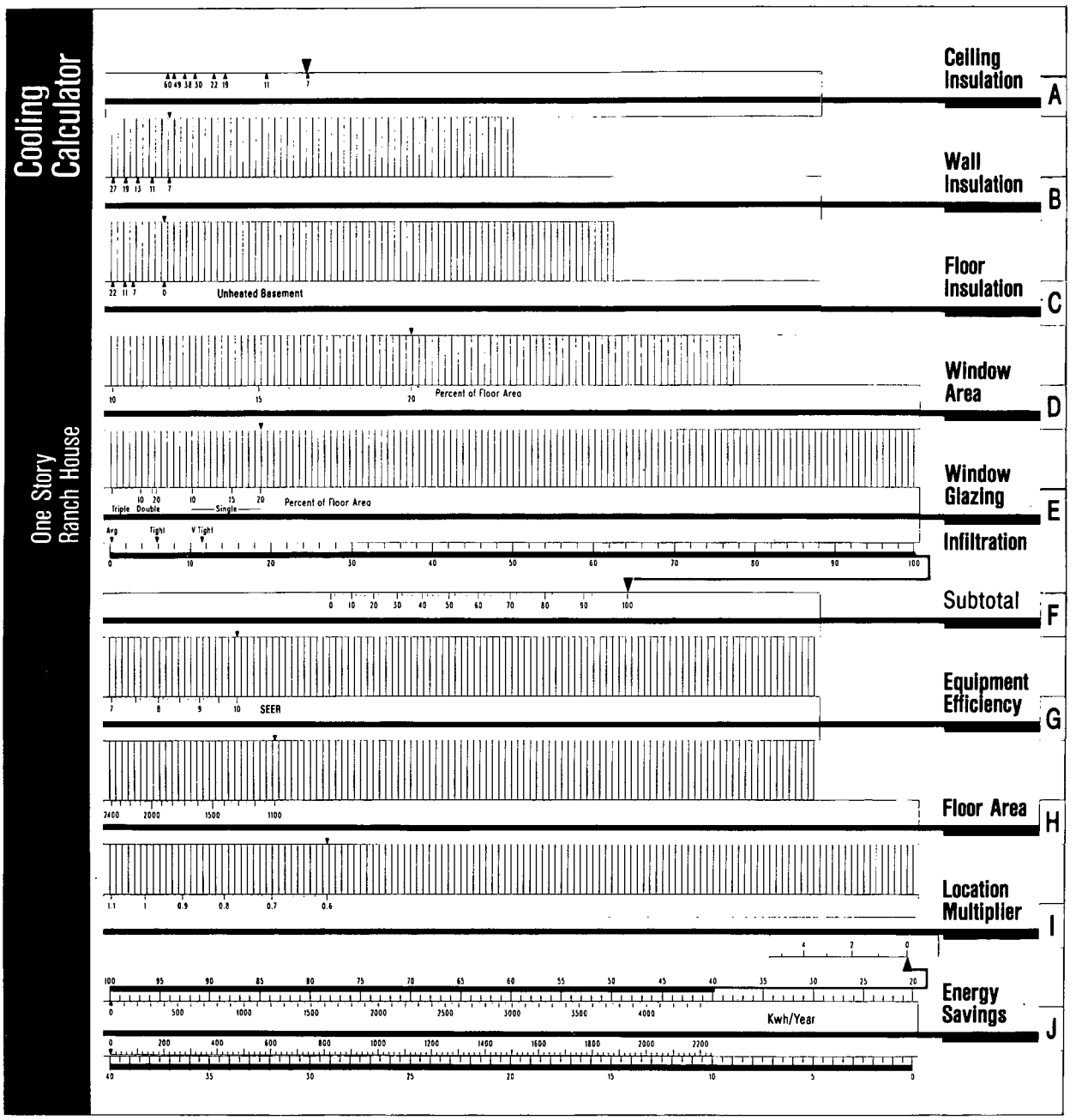

Figure 1. Slide rule ("Cooling Calculator") for one-story ranch house. There are corresponding slide rules for the other prototypes, and a similar set for heating calculations. (XBL 8312-2462)

load for the prototype house—from 0 for the highest to 100 for the lowest possible load.

The next four tabs (F through I) adjust the subtotal from the prototype house and base-case location for differences in floor area, equipment efficiency, and climate. These corrections are based on the functional relationships established in the data base analysis.[3] Since these adjustments are multiplicative, logarithmic scales are used. The detailed simulation work is sometimes hidden by the simplicity of the scales. For example, the scale for air conditioner efficiency on Tab G is based not on the nominal SEER values (Seasonal Energy Efficiency Ratios) indicated, but on the net seasonal efficiency from the DOE-2.1A simulations incorporating the effects of both performance curves and part-load

degradation. Tab I corrects for degree-day differences from the base city to other locations and allows the slide rule values to be extended to 1,000 other locations listed in the user's manual. The resultant total from setting Tab I gives the adjusted total building energy use, again normalized to range from 0 to 100.

The final tab (J) indicates the savings in fuel between two sets of conservation measures. The difference in total building energy use between the two sets is calculated and then converted to standard units of fuel such as therms/year or kWh/year.

In developing the slide rule, it was necessary to compromise between ease of use and accuracy. For example, interactions between window sash types and window sizes, and between air conditioner efficiencies and house thermal integrities have been ignored. The relatively small errors resulting from these approximations are preferable to the complexity of more precise procedures, since this guide is intended to be used by a fairly nontechnical population.

The "modifier tables" permit more detailed calculations of energy savings for the following optional strategies: building and window orientations, reflective and absorptive glass, movable night insulation, temperature setback, building color, and attached sunspaces. Figure 2 shows a typical example. The tables are based on correlations of the DOE-2.1A data base with various climate parameters.[3] Since they are designed to be used in conjunction with the slide rule, the modifier tables also use normalized units.

Results

The slide rule and modifier tables give users a complete, simplified calculation technique based on

Night Setback Modifiers

Table 1

Location Number	Setback Factor: Ranch, Two-Story, Split-Level	Setback Factor: Townhouses	Location Number	Setback Factor: Ranch, Two-Story, Split-Level	Setback Factor: Townhouses
1	4.1	3.6	23	4.5	4.7
2	4.6	3.9	24	4.8	5.1
3	4.9	4.6	25	10.2	13.2
4	2.9	1.7	26	4.2	4.0
5	3.5	3.0	27	4.2	3.9
6	3.7	3.0	28	0.0	0.0
7	6.2	7.5	29	2.4	1.9
8	3.3	2.5	30	3.8	3.7
9	2.7	1.8	31	4.1	3.1
10	5.1	5.2	32	3.9	3.4
11	3.6	2.9	33	3.4	2.5
12	3.4	3.0	34	3.8	3.1
13	3.7	3.0	35	5.9	6.8
14	4.0	3.4	36	3.6	2.8
15	4.7	4.7	37	3.8	2.8
16	4.5	4.6	38	5.0	4.8
17	5.1	5.9	39	3.5	3.1
18	3.3	2.5	40	3.4	2.6
19	0.0	0.0	41	4.0	4.3
20	4.3	4.8	42	9.1	11.0
21	2.3	1.6	43	7.2	9.5
22	3.1	2.6	44	4.5	4.7
			45	3.2	2.7

Figure 2. Example of a "modifier table" from the user's manual.

a large, well-documented data base created using a state-of-the-art computer program. A prototype slide rule, modifier tables, technical support document, and the DOE-2.1A data base were submitted to DOE in November 1983 for release during the public review period beginning in early 1984.

PLANNED ACTIVITIES FOR FY 1984

At the close of the 6-week DOE public review period, LBL will review all public comments and incorporate suggested improvements into the final slide rules and modifier tables. LBL will also incorporate into the slide rules results from its current research on masonry walls. After all these changes are made, a complete master set of slide rules and tabs will be produced and sent to DOE for final printing and distribution. It is anticipated that the entire package will be completed during FY 1984.

REFERENCES

1. DOE is concurrently funding a similar project to produce energy calculation slide rules for manufactured houses. This work is being conducted by Steven Winter Associates, Inc., with technical support from the Building Energy Analysis Group at LBL.
2. Energy Analysis Program (1983), *Affordable Housing Through Energy Conservation, Data Base for Simplified Energy Analysis,* LBL-16343 (Draft).
3. Energy Analysis Program (1983), *Affordable Housing Through Energy Conservation, Technical Support Document,* LBL-16342 (Draft).

Attached Sunspaces as Energy Savers*

R. Ritschard, Y.J. Huang, D. Wilson, and J. Bull

One response to higher energy prices and the widespread popularity of solar technologies has been increased interest in passive solar buildings, including isolated gain systems such as attached sunspaces. Although many new homes incorporating passive solar designs have been constructed and other houses have been retrofit, little analytical work has been done to determine the effect of these additions on space conditioning loads. In support of a comprehensive Department of Energy effort to develop guidelines for construction of energy-efficient single-family houses, we conducted sensitivity analyses using a modified version of the DOE-2.1A code to model the effects of sunspace options attached to the south side of a one-story ranch house in 11 cities. The results, presented below, are compared to a base-case house without a sunspace but with similar thermal properties. The analysis provides homebuilders with general information on the energy performance of a sunspace option.

*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 1983

Approach

We modeled the attached sunspace as an extension to the south wall of the building, covering as much as 44% of the wall's surface area. The sunspace constituted a separate thermostatic zone, thus allowing heat transfer into the house to reduce the heating loads for the living space. The sunspace was modeled for a one-story ranch house prototype with 1540 square feet of floor area (plus the sunspace).

As shown in Fig. 1, the sunspaces modeled were 8 feet wide, and either 12 or 24 feet long (96 and 192 ft^2, respectively). We simulated single-glazed sunspaces for all options and also ran some sensitivity analyses for double-glazed sunspaces. We assumed that side walls and the partition between the sunspace and the living space had the same level of insulation as the main building.

We modeled thermal mass in the sunspaces by assuming a 6-inch-thick concrete floor slab and a facing brick wall on the sunspace side of the partition. We assumed the sunspace roof extended at the same angle as the house roof (tilt: 18.4°) and modeled it in two configurations: glazed and opaque. We also assumed glazed roofs to have the same glazing as the rest of the sunspace and opaque roofs the same insulation levels as the roof of the main house.

We treated the sunspace as a semi-conditioned space representing a compromise between energy efficiency and livability—i.e., it could be occupied

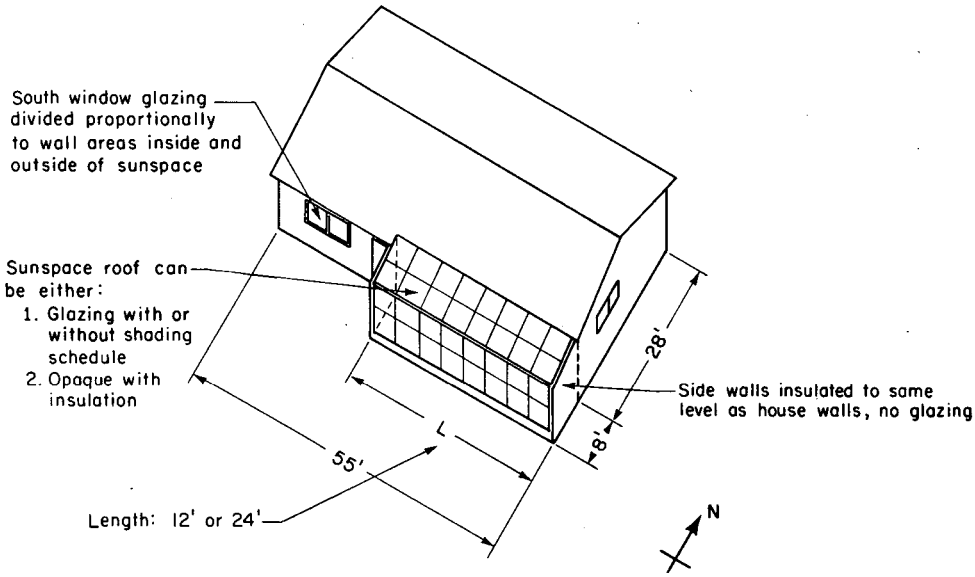

Figure 1. Sunspace model. (XBL 836-956)

during the day and was not allowed to freeze at night. Therefore, its thermostat settings differ from those of the living space. Temperatures were allowed to drop to 45°F, below which we assumed a baseboard heater would be used. When the sunspace temperature exceeded 80°F, natural venting would bring it down to that of the outdoors. In the heating season, night heat loss would be reduced by covering the sunspace's front glass wall (and the roof, if glass) with R-5 movable insulation from 10 p.m. to 8 a.m. In the cooling season, movable shading (shading coefficient of 30%) would be used during hours of sunlight exposure.

Heat was transferred from the sunspace to the living space by using a thermostatically controlled fan, thus reducing the living-space heat load. We assumed that the fan was activated hourly when the differential between the two areas was greater than 3°F during heating periods in the living space. Forced air was returned to the sunspace through another set of vents. We assumed convection did not occur between the two zones through either open doors or windows in the partition.

We made certain modifications to the DOE-2.1A code to account for the forced-convection heat transfer from the sunspace to the living space. We calculated a set of custom weighting factors and used them to estimate the impact of the thermal mass in the sunspace and to account for the difference in radiative heat losses between day (glass only) and night (glass plus movable insulation). In addition, we made code changes to approximate the impact of the solar gains through the windows in the partition wall between the sunspace and the living space.

Results

We performed sensitivity analyses for 11 cities representing different climatic conditions for four sunspace configurations (12 and 24 feet with glass roof, and 12 and 24 feet with opaque roof) and three thermal integrities (loose, medium, and tight). The cities and foundation types modeled are shown in Table 1, while Table 2 lists the various thermal integrities by foundation type.

Table 3 presents our sensitivity results for the sunspace configurations and for the various thermal integrities. The results are reported as net changes (in MBtu) in the total space conditioning loads of the house.

Table 1. Cities and foundation types modeled.

Slab	Basement
Albuquerque	Chicago
Atlanta	Denver
Lake Charles, LA	Minneapolis
Miami	New York
Phoenix	Seattle
San Francisco	

Table 2. Thermal integrities and foundation types.

Slab Foundation		
Loose	Medium	Tight
R-19 Ceiling	R-19 Ceiling	R-30 Ceiling
R-11 Wall	R-11 Wall	R-19 Wall
No Found. insul.	R-5 (2') Slab	R-5 (2')Slab
0.7 ach infltr.	0.7 ach infltr.	0.4 ach infltr.
Single glazing	Double glazing	Double glazing
Basement Foundation		
Loose	Medium	Tight
R-19 Ceiling	R-30 Ceiling	R-38 Ceiling
R-11 Wall	R-11 Wall	R-19 Wall
R-5 (4') Bsmt wall	R-5 (8') Bsmt wall	R-10 (8') Bsmt. wall
0.7 ach infltr.	0.7 ach infltr.	0.7 ach infltr.
Single glazing	Double glazing	Triple glazing

Conclusions

Table 3 indicates that in many climates a sunspace operated under the conditions assumed in this study can indeed reduce the space conditioning loads of a house. The reduction, however, is related to design factors like the size of the sunspace and the type of roof (glass or opaque) and to the particular space conditioning requirements of the location. The larger sunspace (24 feet long) with a glass roof usually performed better than the other configurations. For example, we estimate that such a sunspace could reduce the total space conditioning load of a house by more than 20% in Albuquerque and San Francisco, and by about 15% in Atlanta, Denver, and Phoenix. In other climates, the contribution was significantly smaller, and in some instances (e.g., Miami), an attached sunspace actually increased cooling loads so much that total space conditioning requirements were substantially increased.

For cold climates like Minneapolis, an attached sunspace, as operated in this analysis, will not contribute much to reducing space conditioning loads (only 1–2%); however, if the sunspace is double-glazed, the reduction in energy use improves significantly. The analysis suggests that in colder climates such as Chicago, Denver, Minneapolis, and New York, a double-glazed sunspace, although expensive, may be justified. Furthermore, in such climates one should consider the energy savings in Btu/ft^2 of usable area because the sunspace (96 ft^2 or 192 ft^2, depending on the design) substantially increases the inhabitable area of the base house.

We found that, at a minimum, sunspaces were able to heat themselves in all climates studied and, with proper design and operation, contributed to the heating requirements of the house to which they were attached. Since we did not let the sunspace temperature drop below 45°F, the sunspace becomes a usable addition only during the day. Doing this allows a modest decrease in total house energy use and provides a partially conditioned space even in cold climates. It becomes important to consider how usable that space is, i.e., the number of hours during the day (and which hours) the homeowner would be able to live in the space without paying any heating bill for it. In other words, an attached sunspace must have value to the homeowner as a living space beyond its value as an energy conservation measure.

PLANNED ACTIVITIES FOR FY 1984

We plan to continue this effort during FY 1984, when a new sunspace model (an addition to DOE-2.1) will become available at LBL. We will simulate the same sunspace options with the new code and compare the results with those given above. In addition, we will investigate the number of hours (and which hours) during the day that the sunspace can be used as a living space without requiring auxiliary heating.

Table 3. Net changes in total space conditioning load for six sunspace types with three insulation options in 11 climates.

Location/ Option	OP12 (ΔMBtu)	OP24 (ΔMBtu)	OP24(2) (ΔMBtu)	GL12 (ΔMBtu)	GL24 (ΔMBtu)	GL24(2) (ΔMBtu)
Albuquerque						
Loose	−3.76	−6.63		−5.70	−9.41	
Medium	−2.57	−4.56	−6.10	−3.97	−6.45	−8.41
Tight	−1.98	−3.38	−4.71	−2.81	−4.34	−6.01
Atlanta						
Loose	−1.81	−3.30		−3.00	−4.62	
Medium	−1.01	−1.93	−2.86	−1.65	−2.51	−3.91
Chicago						
Loose	−1.26	−2.68		−2.53	−4.44	
Medium	−0.56	−1.32	−2.86	−1.50	−2.51	−5.75
Tight	−0.07	−0.27	−1.62	−0.67	−0.97	−3.96
Denver						
Loose	−2.28	−4.51		−4.57	−7.90	
Medium	−1.52	−3.05	−4.90	−3.31	−5.67	−9.11
Tight	−0.99	−1.89	−3.66	−2.38	−3.87	−7.01
Lake Charles						
Loose	−1.40	−2.42		−2.16	−2.81	
Medium	−0.83	−1.47	−2.08	−0.91	−1.21	−2.13
Miami						
Loose	−0.10	−0.17		+0.27	+0.77	
Medium	−0.06	−0.09	−0.13	+0.31	+0.81	+0.81
Minneapolis						
Loose	−0.77	−2.02		−1.25	−2.29	
Medium	−0.03	−0.44	−2.97	−0.11	−0.05	−5.78
Tight	−0.58	+0.69	−1.59	−0.29	+1.68	−3.83
New York						
Loose	−1.47	−3.03		−3.04	−5.19	
Medium	−0.85	−1.83	−3.18	−2.04	−3.48	−6.04
Tight	−0.44	−0.93	−2.24	−1.16	−1.98	−4.46
Phoenix						
Loose	−1.55	−2.66		−2.27	−3.26	
Medium	−0.92	−1.62	−1.98	−1.14	−1.66	−2.14
San Francisco						
Loose	−2.67	−4.72		−5.62	−8.94	
Medium	−1.56	−2.86	−4.02	−3.54	−5.60	−7.85
Seattle						
Loose	−1.22	−2.55		−2.67	−4.78	
Medium	−0.57	−1.29	−2.46	−1.67	−3.01	−5.59
Tight	−0.11	−0.34	−1.44	−0.96	−1.60	−3.92

OP 12 = 12 ft. long sunspace with opaque roof.
OP 24 = 24 ft. long sunspace with opaque roof.
OP 24(2) = 24 ft. sunspace with opaque roof, double-glazed.
GL 12 = 12 ft. long sunspace with glass roof.
GL 24 = 24 ft. long sunspace with glass roof.
GL 24(2) = 24 ft. sunspace with glass roof, double-glazed.
Loose, medium, and tight options defined in Table 2.

Impact of Windows on House Heating and Cooling Loads: A Parametric Analysis*

I. Turiel, Y.J. Huang, G. Verzhbinsky, R. Ritschard, L. Chang, C. Hsui, and D. Wilson

To represent the energy-use characteristics of site-built single-family housing, the Energy Analysis Program defined five prototypical buildings that encompassed the majority of new residences built in the United States. These prototypes were one-story, two-story, split-level, and middle-unit and end-unit townhouses. A report on the methodology and assumptions employed in the energy analysis of these residential buildings has been written.[1] The report includes construction details of the buildings.

Here we discuss only the impact of movable window insulation on heating and cooling loads. A description of other studies in which the window area and the number of panes are varied is presented elsewhere.[2]

ACCOMPLISHMENTS DURING FY 1983

Methodology and Assumptions

For each building prototype, a full range of energy conservation options was identified and simulated in 45 U.S. locations. These options included various combinations of insulation (ceiling, floor, and walls), window glazings, and infiltration levels. Four types of building foundation (slab-on-grade, ventilated crawl space, heated and unheated basements) were also considered, depending on the location.

For these analyses, the DOE-2.1A computer program was used.[3] Test Reference Year (TRY) weather tapes were used for all locations except Juneau, Alaska, and Las Vegas, Nevada. For these two locations, Typical Meterological Year (TMY) weather tapes were used. The climate data included dry- and wet-bulb temperatures, wind speed and direction, barometric pressure, cloud cover, and an atmospheric clearness index.

Standard building operating conditions are those under the control of the homeowner, such as temperature settings, night thermostat setback, whole-house ventilation, day shading devices, load variations due to average house occupancy and use of appliances, and the type and operation of space conditioning equipment in the building. We kept these operating conditions constant to provide a basis for comparing different physical and climatic conditions. In addition, we tested many of these assumptions through sensitivity analyses in which a particular parameter was varied from the assumed value.

The whole building (living space) was assumed to consist of one zone; the basement, if there were one, constituted a second zone. The first zone was thermostatically controlled, while the second zone was allowed to have a floating temperature (no control). Thus, only one thermostat was required to control temperatures in the living space. The thermostat setting was assumed to be 70°F for heating and 78°F for cooling. A night setback to 60°F between the hours of 12 midnight and 6 a.m. was also assumed during the heating season.

Natural window venting was assumed when the outdoor temperature in the summer was lower than the indoor temperature, but not higher than 78°F. So that the indoor humidity would not be adversely affected by window venting, we also required that the enthalpy of the outdoor air must be less than that of the indoor air whenever venting was practiced. A single venting schedule was assumed for all climates (May 15 through September 30).

Two types of space-conditioning systems were modeled for all options in this analysis: (1) an oil or gas furnace for heating and (2) an electric air conditioner for cooling. The furnace was assumed to have a fixed efficiency of 0.70, which is achievable with an intermittent ignition device and a tight stack damper; its rated capacity was 50,000 Btu/hr. The rated capacity of the air conditioner was 33,000 Btu/hr. It had an EER of 9.2 at 95°F outdoor dry-bulb and 67°F indoor wet-bulb temperatures. A full-load efficiency curve (COP) versus outdoor dry-bulb and indoor wet-bulb temperatures was used to modify the COP as a function of weather. The curve for partial-load efficiency as a function of the partial-load ratio of the air conditioner was derived from measured data obtained by the National Bureau of Standards that assumed a one-cycle-per-hour frequency of operation.[4]

Variables for window sensitivity were window area, number of panes, window orientation, movable night insulation, reflective glazing, and absorptive glazing. The first two were studied in 45 cities, but the latter four in only 11. Climate studies had

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indicated that these 11 cities—listed in Table 1 of the preceding article—would adequately characterize heating and cooling load impacts of changes in these four variables for all U.S. locations.[1] Results were extrapolated to other cities by using correlations between heating and cooling load impacts and climate developed for the 11 cities.

Window area in new construction was found to equal 8% to 10% of the floor area in a 1979 National Association of Home Builders survey.[5] We assumed a 10% ratio for the one-story prototype. Windows were assumed in the base case to be equally distributed on all four sides to reflect the statistical randomness of building orientation.

Solar heat gain through the windows has both diffuse and direct components. For each component, the amount of solar radiation transmitted directly through the windows was added to the amount of solar radiation absorbed in the window and reradiated inwards. The transmittance and reflectance values for solar radiation at normal incidence are shown in Table 1 for single, double, and triple glazing. The DOE-2.1A program used precalculated transmission and absorption coefficients to determine solar gain as a function of the angle of incidence of the solar radiation.

Movable Window Insulation

Shades, drapes, and blinds drawn over windows in the evening to reduce wintertime heat losses are classified as movable insulation. We studied the impact of such movable insulation on the annual heating load, using the 11 cities mentioned earlier to represent the range of characteristic climates in the U.S.

Three types of products were modeled. Drapes or other typical window coverings, which are tightly fit and sealed around all edges of the window, are considered to have an R-value of approximately 1, corresponding to that of the air space between the drapes and the window. In the remaining categories, standard off-the-shelf products with material R-values of 2 and 4 were also modeled. Total component R-values for these products were assumed to be R-3 and R-5, respectively, the additional R-1 value being attributed to the air space between product and glazing. In all cases, the movable insulation was assumed to be in place between 10 p.m. and 8 a.m. during the heating season, but the length of the heating season was varied according to local climate. Thus, for cities in cool climates, the assumed heating season was from October 1 through April 30; for cities in temperate zones, from November 1 through March 31; and, for cities in hot climates, from December 1 through February 28.

The results of this study showed a good correlation between heating load reduction and nighttime heating degree-days (degree-days during the hours 10 p.m. to 8 a.m.). Figure 1 shows heating load reduction plotted as a function of nighttime heating degree-days (base 63°F) for ranch-style houses in 11 cities. For these houses, single-pane windows were evenly distributed (2.5% per side) among all four wall orientations with a 10% window-to-floor area ratio.

The straight line represents the least-squares best-fit for the 10 cities shown as triangles. To test the reliability of this regression analysis, three additional cities were simulated and plotted as X's. As can be seen, the test DOE-2.1A simulations were all within 10% of the original regression-line predictions. Miami was excluded from the original 11 cities in the analysis because of its extremely small (0.33 MBtu) heating load.

Similar fits were obtained for the 15% and 20% window area simulations. The lowest correlation coefficient (0.94) was for 10% window area, triple

Table 1. Transmittance and reflectance of glazing.

Glazing	Transmittance (%)	Reflectance (%)
Single pane	88	7
Double pane	75	16
Triple pane	68	18

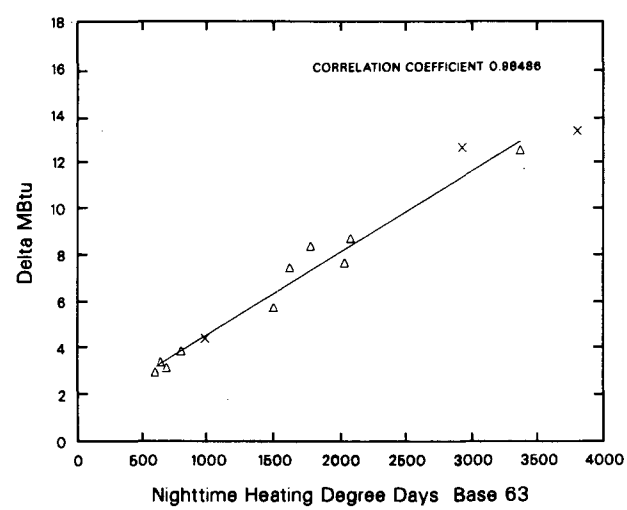

Figure 1. Reduction in annual heating load from use of movable insulation (single-glazed window, 10% window-to-floor area ratio). (XBL 836-10484)

glazing. The reduction in heating loads per square foot of window was not constant, but decreased as the window area increased. For example, for double-glazed windows, the heating load reduction for 15% window area was 1.42 times that for 10% window area (instead of being 1.5 times), while for 20% window area, the reduction was 1.78 times (instead of 2 times). For this reason, we used 15% window area simulation results in 10 cities to compute regression lines for prediction of heating load reductions in other locations. The following regression equations were used:

Single pane:

$$\frac{\Delta L}{A}\left(\frac{\text{MBtu}}{\text{ft}^2}\right) = 0.00677 + 2.247 \times 10^{-5}\,\text{NHDD}$$

Double pane:

$$\frac{\Delta L}{A}\left(\frac{\text{MBtu}}{\text{ft}^2}\right) = 0.00456 + 1.216 \times 10^{-5}\,\text{NHDD}$$

Triple pane:

$$\frac{\Delta L}{A}\left(\frac{\text{MBtu}}{\text{ft}^2}\right) = 0.00394 + 0.870 \times 10^{-5}\,\text{NHDD}$$

where:

NHDD = nighttime heating degree-days;
ΔL = change in heating load (MBtu);
A = window area (ft^2).

Nighttime heating degree-days are summed from 10 p.m. to 8 a.m., the hours during which the insulation covered all windows. These values can be inserted in the regression equation to obtain predictions of heating load reduction per square foot for single-, double- and triple-pane windows.

Movable window insulation can be placed over windows during nighttime hours to reduce heating loads. DOE-2.1A simulations show substantial reductions in load for cold climates. For example, the use of movable insulation in the base-case house with single-pane windows decreases heating loads by approximately 10 MBtu (15–20%) in 2000 nighttime heating degree (°F) day climates. We have not yet investigated the cost-effectiveness of the use of movable insulation.

PLANNED ACTIVITIES FOR FY 1984

We plan to assess several other conservation measures. These include: external window shading, movable interior shading under varying operator schedules, and reflective/absorptive glazing for selective orientations. We also expect to explore the interactive effect of carrying out two or more measures simultaneously. A more detailed analysis of the cost-effectiveness of these measures will also be conducted.

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Parametric Energy Analysis in Support of Singapore 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 surcharge of 20% tax 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.

ACCOMPLISHMENTS DURING FY 1983

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 a forthcoming 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]

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

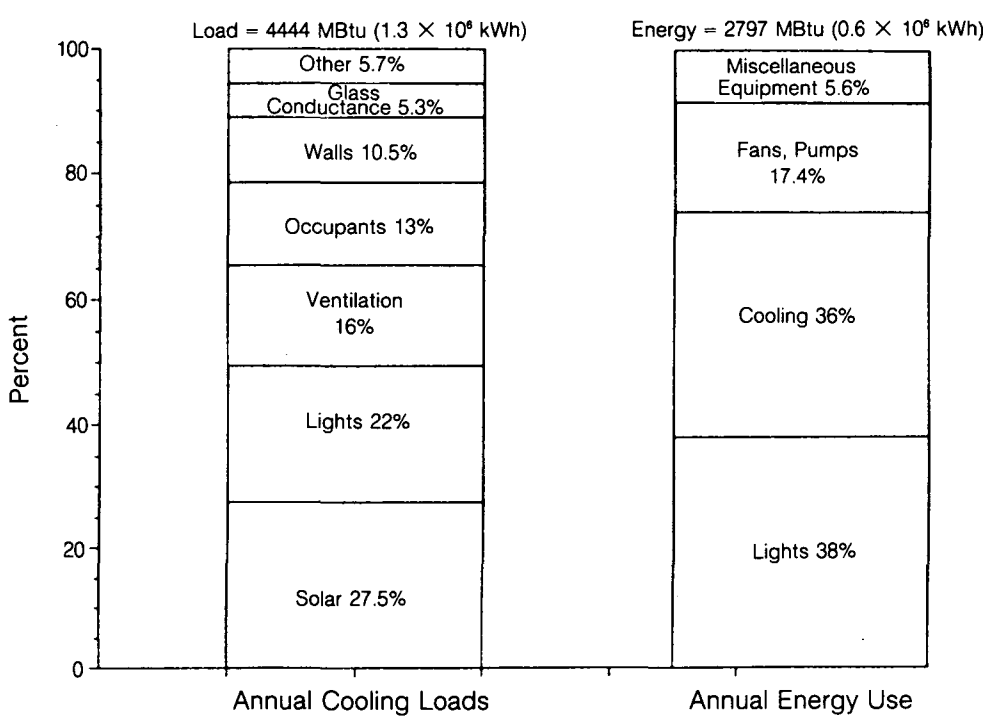

Figure 1. Base-case building cooling loads and energy use components shown as percentages of total. (XBL 841-67)

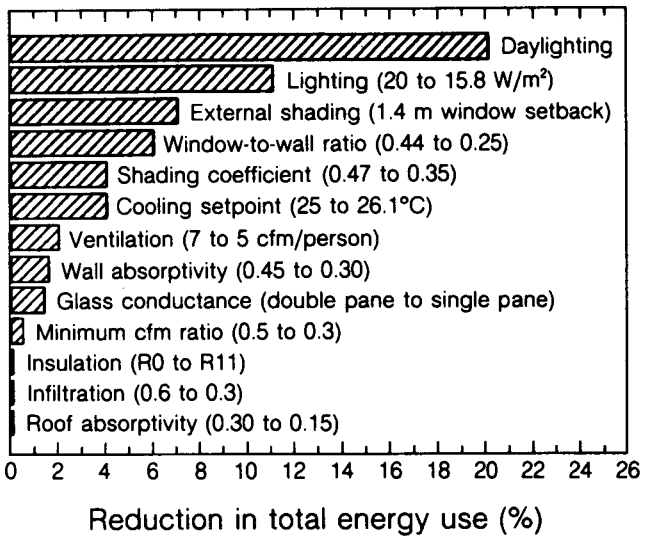

Figure 2. Conservation measures ranked by percentage reduction in total energy use. (XBL 841-68A)

ratio, but the rate of decrease is not constant. When 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

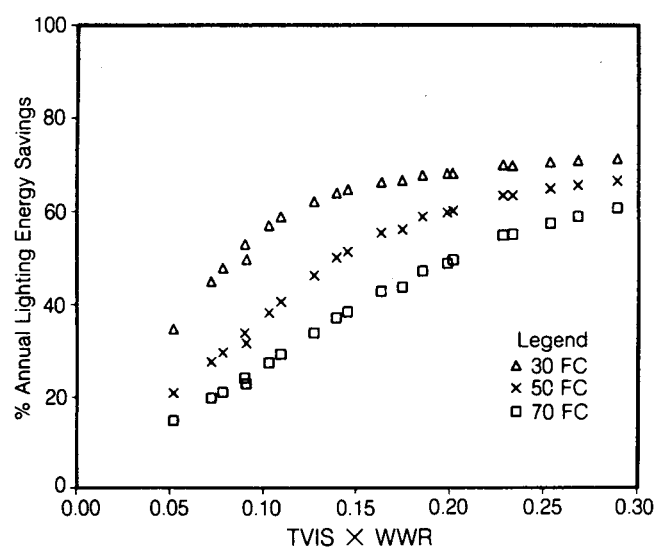

Figure 3. Percentage lighting energy savings from use of daylighting for three lighting intensities, shown as a function of TVIS × WWR. (XBL 841-69)

allows the user to choose his or her values for TVIS according to the glazing selected.

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.

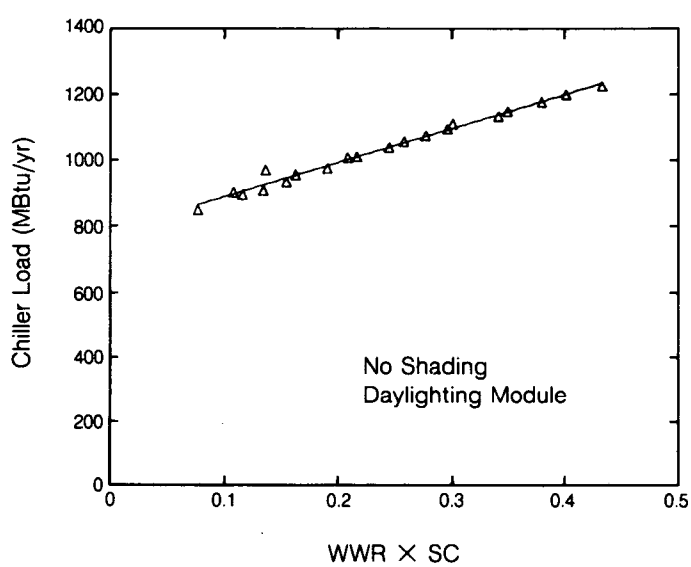

Figure 4. Chiller load plotted as a function of WWR × SC for a single-story module. (XBL 841-70)

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 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:

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

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

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:

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

PLANNED ACTIVITIES FOR FY 1984

We plan to work with the Singapore government in implementing some of the energy-conserving measures discussed here. In particular, we will estimate the cost-effectiveness of energy-efficient lighting and daylighting systems and develop a simplified approach for determining compliance with future daylighting regulations.

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Microeconomics of Residential Energy Conservation*

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

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.

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ACCOMPLISHMENTS DURING FY 1983

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..."). 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 appliance standards presented in an accompanying article by Levine *et al.*). (4) We construct a data base of energy prices for approximately fifty 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 only partially completed. The DOE-2 simulation data base has been put into a form suitable for the economic calculations. (Addi-

tional work, however, is needed to place the measures more easily in order of declining life-cycle costs.) The analysis of effects of appliance efficiency improvements on heating and cooling loads is under way. The data collection on costs and energy prices is largely completed and under review. The coding of the economic analysis computer program is just starting.

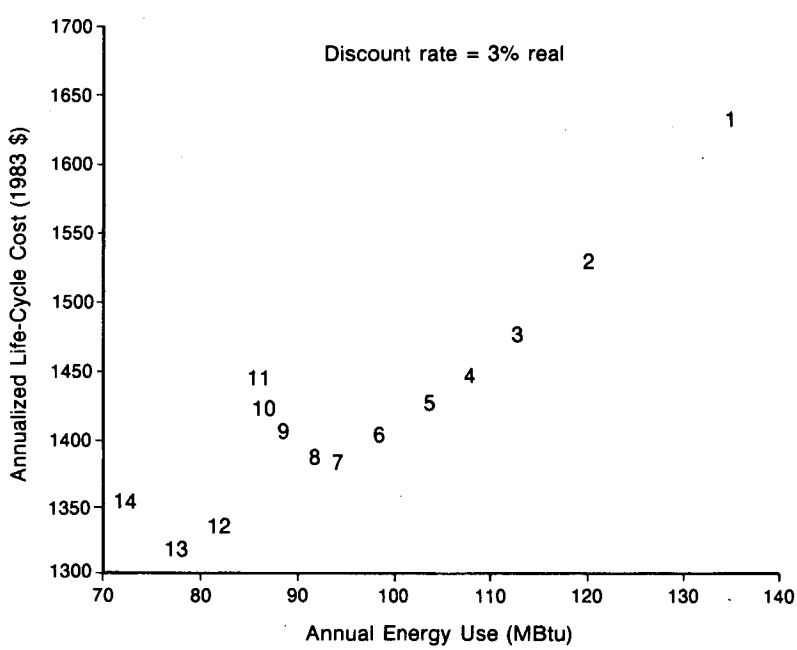
Here we summarize the results of two economic case studies: Chicago (a cold climate) and Phoenix (a hot climate). These case studies have not yet treated the effects of equipment downsizing or the interaction between appliance efficiency and heating and cooling loads. As such, these results will be interesting as a "base case" for determining the impact of these other factors on the economics of residential energy conservation investments.

Figure 1 shows the results of the life-cycle cost analysis of measures to improve thermal integrity for gas heating and central air conditioning in Chicago. The life-cycle costs are evaluated at a 3% real discount rate, comparable to the average cost of mortgage capital (over and above inflation) from the end of World War II until the late 1970s. (The real cost of mortgage capital has been higher during the past decade.) The life-cycle cost minimum assumes R-30 insulation in the ceiling, R-19 insulation in the wall, R-8 basement insulation extending 8 feet below the ground, and triple glazing. The resulting annual energy use (including electricity for air conditioning calculated at 3413 Btu per kilowatt-hour) is expected to be 40 kBtu/ft^2. Typical building practice in Chicago is R-11 ceiling insulation, R-19 wall insulation, R-4 basement insulation to a depth of 4 feet, and double glazing (generally with storm windows). The estimated energy use for these measures is 57.5 kBtu/ft^2. Thus, if new residences in Chicago were built at the life-cycle cost minimum, they would use 30% less energy. This would represent a life-cycle savings with a present value of $2700. (The increased first cost is about $1000. When the smaller cost of downsized equipment is accounted for, the first costs will also be reduced. The discounted fuel savings is about $4500.)

The decline in air infiltration (the air change rate in the building envelope is reduced from 0.7 to 0.2 per hour and a heat exchanger with mechanical ventilation is installed to maintain air quality) is cost-effective and could cut annual energy use by an additional 15%.

It is worth noting from Fig. 1 that at low levels of insulation and single glazing, the energy use of a typical house in Chicago increases dramatically.

Figure 2 shows the results for a new house in Phoenix with electric resistance heating and central air conditioning evaluated at a 3% real discount rate.



Order of Measures:
a - Ceiling Insulation
b - Wall Insulation
c - Foundation Insulation
d - Infiltration
e - Number of Glazings

	a	b	c	d	e
1	(11,	11,	0,	HI,	2)
2	(11,	19,	1,	HI,	2)
3	(19,	19,	1,	HI,	2)
4	(30,	19,	1,	HI,	2)
5	(30,	19,	3,	HI,	2)
6	(30,	19,	4,	HI,	2)
7	(30,	19,	4,	HI,	3)
8	(38,	19,	4,	HI,	3)
9	(38,	27,	4,	HI,	3)
10	(49,	27,	4,	HI,	3)
11	(60,	27,	4,	HI,	3)
12	(38,	19,	4,	LO,	2)
13	(38,	19,	4,	LO,	3)
14	(49,	27,	4,	LO,	3)

Figure 1. Life-cycle cost of measures to increase thermal integrity (no capacity credit), for a Chicago one-story ranch house with gas heating. (XBL 845-1968)

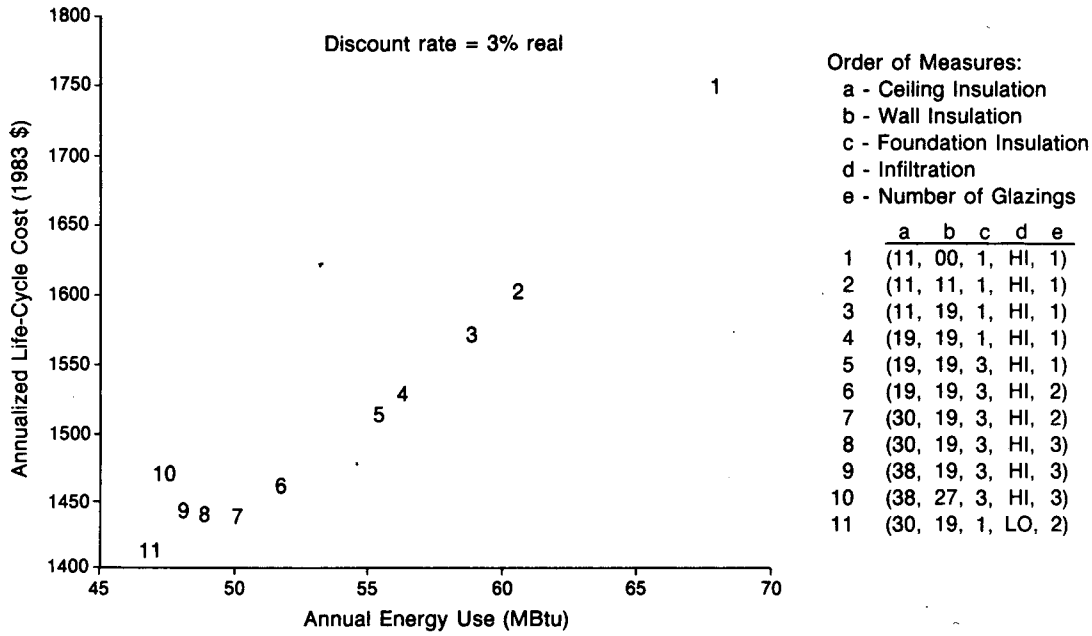


Figure 2. Life-cycle cost of measures to increase thermal integrity, for a Phoenix one-story ranch house on a slab foundation (no capacity credit). (XBL 845-1967)

The measures at the life-cycle cost minimum are R-30 ceiling insulation, R-19 wall insulation, R-8 perimeter insulation, and double glazing. These measures will reduce energy use by about 26% in Phoenix compared with current practice for new houses in the area. This represents a substantial life-cycle cost benefit of $5800 (increased first cost of $1800 and reduced discounted fuel savings of $7600) to the homeowner.

PLANNED ACTIVITIES FOR FY 1984

Continuing research will complete all tasks required to evaluate the economics of downsizing of space conditioning equipment and the effects of changes in internal loads on heating and cooling loads. The results will use local fuel prices and costs of conservation measures in 45 to 50 locations throughout the nation.

Occupant Behavior and Residential Energy Use*

E. Vine, J. Cramer, P. Craig, D. Kowalczyk, S. Gold, M.D. Levine, B. Hackett, and T. Dietz

Lawrence Berkeley Laboratory, in conjunction with a number of other organizations,† has been investigating the effects of occupant behavior on residential energy use since 1980. The principal objective is to improve our understanding of the determinants of energy use in occupied houses. During the past year, we undertook several activities to accomplish this objective. First, we extended our earlier work in modeling the immediate, physical determinants of summer electricity use in Davis, California, by developing statistical models of energy use. Second, we broadened our analysis of residential energy use by developing a causal model of summer electricity use in Lodi, California, that included both physical and social variables. Third, we surveyed studies of submetered space heating, space cooling, and water heating in the United States since 1970. Fourth, we initiated a study of energy use in households in the Pensacola, Florida, area that have had their heating and cooling energy use metered.

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†Kellogg Public Research Program, University of California, Davis; Pacific Gas and Electric Company, San Francisco, CA; Center for Environmental and Energy Policy Research, University of California, Davis; and the California Energy Commission, Sacramento, CA.

And fifth, we initiated a survey of energy-conserving behavior among households in the United States.

ACCOMPLISHMENTS DURING FY 1983

Statistical Models of Energy Use[1]

In this project, we investigated simple statistical models of summer electricity use and compared them to engineering models. The statistical models had four purposes: (1) to modify our earlier energy use models[2] by adding and redefining variables; (2) to compare the explanatory value of alternative models; (3) to perform sensitivity analyses and identify the variables most important to electricity use; and (4) to apply the models to other housing types besides detached single-family houses.

We collected the data for this research in 1980, from a random sample of 241 Davis households. The methodology is described in detail in Refs. 1 and 2 and summarized briefly below.

We measured social characteristics and self-reported, energy-related behaviors in lengthy interviews; immediately after the interviews, we performed energy audits, measuring building area and orientation, window area, shading, and insulation characteristics. We recorded the model numbers of major appliances and obtained efficiency ratings from the manufacturers; we also obtained billing data on electricity consumption from the local utility. We collected hourly weather data on solar radiation, dry-bulb temperature, air pressure, wind speed, and wind direction. After deleting cases that had incomplete summer electricity data or long vacancies, we analyzed 221 homes (74 single-family detached houses, 92 apartments, and 55 duplexes or townhouses).

We predicted summer electricity use (July 1 to September 30) with appliance and cooling-load models constructed previously. The appliance model (APPL) included an electric water heater, swimming pool or hot tub (with electric filter), refrigerator, freezer, electric stove, oven, dishwasher, and clothes washer and dryer. We obtained estimates of average electrical loads for each appliance from a variety of sources and referred to a specific manufacturer's model whenever possible. The cooling-load model (CE) included the major variables used in the U.S. Department of Energy's energy use model (DOE-2.1A) as well as residents' self-reported frequency of use of air conditioning.

Using ordinary least-squares regression, we were able to explain nearly 55% of the variation in summer electricity use in a sample of single-family detached homes with the following equation:

$$\text{Summer electricity use (kWh)} = -1160 + 0.715\ \text{CE} + 1.114\ \text{APPL}$$

An even simpler model explained nearly 60% of the variation between houses:

$$\text{Summer electricity use (kWh)} = -1700 + 1.054\ \text{APPL} + 0.458\ A + 0.186\ (A \times F_{ac})$$

where A is floor area and F_{ac} is frequency of air conditioning.

The second model demonstrates that survey respondents reported their behavior well enough to provide valuable information. It is thus possible to predict electricity use from simple, easily obtainable survey data. Moreover, our results agreed reasonably well with calculations based on DOE-2.1A simulations, indicating that DOE-2.1A, built from engineering data for experimental houses, works also for occupied buildings. Relatively inexpensive survey research methods and statistical models can, therefore, be safely used to estimate energy consumption in individual households. This conclusion is important for residential energy conservation audits and labeling programs.

In summary, most structural research on residential summer electricity use has been done on single-family detached homes. However, by simplifying our models and incorporating self-reported behavior directly, we were able to predict summer electricity use in townhouses and apartments. Our findings thus suggest, at least tentatively, that it may not be difficult to extend such research to other housing types.

Causal Models of Energy Use[3]

This project integrates social and physical variables in a single causal model of household energy use. The social variables include household size, income, and a variety of measures of attitudes, values, and access to information. The physical variables represent the immediate, engineering determinants of energy use, and include an inventory of major appliances, the size of the home, and self-reported behaviors regarding frequency of use of appliances and air conditioning. We assumed that energy use was related to the two types of variables in a simple causal chain: consumption was explained entirely by the physical variables, and the

physical variables, in turn, were explained by the social variables.

The data came from a survey conducted in Lodi, California, during the summer of 1981. Using a questionnaire similar to one for the Davis project, we interviewed 291 households. These interviews provided information on appliance and air conditioning use, attitudes toward to energy and the environment, and demographic characteristics. We measured physical characteristics of the residence as part of an extensive energy audit. The municipal utility and Pacific Gas and Electric provided monthly energy use data for the survey respondents for 1980 and 1981. After deleting cases that had incomplete summer electricity data or long vacancies, we analyzed 192 single-family detached houses.

We first predicted summer electricity usage (June 1 to September 30) with appliance and cooling models (the physical variables) constructed previously.[1,2] The social variables examined were family income, education, minority status, employment of spouses, household size and composition, thermal comfort, conservation attitudes, environmentalism, and energy knowledge.

We were able to explain 51.3% of the variation in summer electricity use by including the appliance and air conditioning models by themselves (the engineering model) in a regression equation. In addition to successfully explaining electricity use in Lodi, these results compared favorably with the results reported for Davis in the previous section. With better measurement of appliance efficiencies and frequencies of use of appliances and air conditioning, these models doubtless would work even better.

When we included the social but not the physical variables in the equation, we were able to explain 33.5% of the variation in summer electricity use. Thus, there is clearly a social basis to energy use. The significant social variables were family income, household size, thermal comfort, minority status, and energy knowledge.

We then put all the variables in one equation. Adding the social variables to the physical variables increases R^2 from 0.513 to 0.584, a small increment. Most of the social variables have small and nonsignificant coefficients while the physical variables have large and significant coefficients. These results confirm our assumption that the social and physical variables are related to energy use as a simple causal chain.

We also examined how the social variables were directly related to the physical variables. Higher income was associated both with greater appliance load and greater cooling load, the latter due to larger house size and more use of air conditioning. Larger families had greater appliance loads; household size did not seem to be related to cooling load. Adults used more electricity than children, but there did not seem to be special consumption patterns by the very young or very old. Electricity demand, because of air conditioning, also was related to preferences regarding indoor temperature, as measured by our thermal comfort scale. The environmentalism scale was related to appliance saturation and house size, but was only weakly related to overall energy use. The conservation scale was not strongly related to energy use through any of the physical variables. Low energy use in Lodi, therefore, appears to by caused mainly be demographic and economic constraints rather than by concerns for environmental quality.

Submetering Survey[4]

In this project, we surveyed studies of metered space heating, space cooling, and water heating in the United States since 1970. We contacted as many of the major utilities involved in end-use metering as possible. While the survey did not include all utilities in the country, we believe that it covers much of the end-use metering conducted in the United States in the last 13 years.

After reviewing the energy literature, we personally contacted key people in the energy field and compiled a list of over 75 organizations involved in submetering energy use in the home. From each organization, we requested information on all projects (past, current, and proposed) that met the following criteria:

(1) Metered end uses must include space heating, space cooling, and/or water heating.
(2) Each project must have been conducted since 1970.
(3) There must be 20 or more households in each project.

We compiled lists of 100 submetered projects by utility company and by end use (cooling, heating, and water heating). We characterized each project according to the following types of data:

- Name and location of utility.
- Size of sample metered.
- Years in which project began and ended.
- Extent of data collected on house characteristics and occupants.
- Collection of whole-house energy use (in addition to the metering of specific end uses)

- Metering of other end uses in the same houses.
- Problems in analyzing metered data.
- Recording of indoor air temperature.
- Extent of published material on project.

One of the most surprising results of this survey was the discovery of many projects around the country that have collected end-use energy data from a large number of households. In addition, both the number of submetering projects and their sample sizes appear to be increasing. Most of these studies have not collected much data on house and occupant characteristics: the most common information collected was floor area and number of occupants. Only a few organizations collected data on socioeconomic characteristics of occupants, appliance saturation, thermal integrity (e.g., wall and ceiling insulation), indoor air temperatures, and air infiltration. We also found that many projects were concerned with peak energy demand (kW) rather than energy use (kWh) and that some were actually part of load control programs. In addition to end-use metering, whole-house energy use also was frequently metered. Finally, we obtained and reviewed 39 reports on these projects.

We are using a data base collected by one of these organizations to analyze the effects of occupant behavior on energy use; this project is described below.

Submetered Energy Use Study

From the list of projects reported above, we selected for further study one by a utility in which houses in the Pensacola, Florida, region were submetered. We chose this project because of its large sample size, an offer of cooperation from the local utility, and the area's high humidity and temperatures in the summer. During the summer of 1983, we surveyed 52 households that had their air conditioning and heating submetered. Through a questionnaire, we collected data on attitudes, behavior, socioeconomic background, and housing characteristics. We are in the process of obtaining energy and weather data from the local utility before analyzing electricity and heating use. We intend to develop engineering and statistical models of energy use similar to the ones constructed in the Davis and Lodi projects.

Survey of Energy-Conserving Behavior

During the summer of 1983, we contacted a number of utilities and state energy offices to see what kind of behavioral data they have collected in their energy programs. According to the responses, some households were audited, while others were interviewed in appliance saturation surveys. The types of information we collected were: insulation actions, heating and cooling behavior, water heater use, appliance behavior, lighting behavior, and audit information. We are in the process of analyzing these data and we hope to determine the kinds of energy-conserving behavior that are occurring in different parts of the country.

PLANNED ACTIVITIES IN FY 1984

We intend to analyze the heating season and total energy use in Davis and Lodi as was done for the cooling season in these communities. Some of the models will also include attitudinal and demographic data. We will analyze the submetered data from Florida, using models similar to the ones formulated in the Davis and Lodi projects. We will also analyze the data on energy-conserving behavior that we recently collected. Finally, we will work with the Energy Performance of Buildings Group in collecting and analyzing data on building retrofits.

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Energy Efficiency Choice in the Purchase of Residential Appliances*

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

Energy efficiency as a factor in the purchase of residential appliances and of heating and cooling equipment has been quantitatively analyzed in this study. Such quantitative assessments of market decisions about energy efficiency are necessary for accurate forecasts of residential energy use. The results of our investigation can lead to a better understanding of the barriers to investment in energy conservation. Such understanding of market behavior is also prerequisite to an evaluation of the need for, and importance of, policies to promote energy efficiency.

The importance of this 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. Our research will lead to improvements in the methodology and data in base-case residential energy forecasting, thereby improving estimates of the impacts of these proposed standards.

In this study, we examined 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 they account for a major part of residential energy consumption, data on their efficiency and costs are readily available, and they are under consideration by DOE for efficiency standards.

We characterized the behavior of the market for these eight products by a single quantity that 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 and 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. An LBL report on this work is being prepared for publication.[1]

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ACCOMPLISHMENTS DURING FY 1983

Method

The analysis assumes that consumer behavior in the appliance marketplace can be characterized as if the purchasers made some type of life-cycle cost decision. The observed average efficiency choice is characterized by an aggregate market discount rate. This measure is the discount rate at which the minimum of the life-cycle cost curve is at the observed average efficiency choice. Even if purchasers do not actually decide on the basis of life-cycle costs, the market discount rate is useful as a measure of market imperfections. This formulation looks at decision-making for products of different efficiencies but of the same fuel type. It does not account for other factors that might influence consumer choice.

The life-cycle cost for an appliance is the sum of the purchase cost, *PC*, and the discounted operating cost:

$$LCC = PC + (PWF \times FP \times TI \times E) \ , \quad (1)$$

where *PWF* is the present worth factor defined below, *FP* is the average fuel price (assumed constant over time, i.e., the consumer expects no price escalation), *TI* is the relative thermal integrity, and *E* is the average annual energy consumption by the appliance. The thermal integrity factor is included for temperature-sensitive appliances to account for the effects of the thermal characteristics of the building shell, such as insulation, on energy consumption. The present worth factor is defined in terms of a discount rate *r*:

$$PWF = \sum_{t=1}^{N} \frac{1}{(1+r)^t} = \frac{1}{r}\left[1 - \frac{1}{(1+r)^N}\right] \ . \quad (2)$$

Finding the minimum of Eq. (1) with respect to energy and solving for the present worth factor gives

$$PWF = \frac{-1}{FP \times TI} \left. \frac{dPC}{dE} \right|_{E_{\min}} . \quad (3)$$

Hence, given the analytic form of the cost versus energy use curve, we can evaluate the derivative dPC/dE at the annual energy use corresponding to average efficiency purchased during any year and determine the aggregate market discount rate.

For the relationship between purchase cost and energy use, we employed an exponential curve of the form

$$E = E_\infty + (E_0 - E_\infty) \exp[-A(C - 1)] . \quad (4)$$

where
- $C = PC/PC_0$
- E = annual unit energy consumption (UEC)
- E_0 = highest UEC
- E_∞ = minimum UEC attainable at infinite purchase cost
- PC = purchase cost corresponding to E
- PC_0 = purchase cost corresponding to E_0

and A is a parameter determined from the shape of the curve. With this expression, the present worth factor becomes

$$PWF = \frac{PC_0}{A \times FP \times TI} \frac{1}{(E - E_\infty)} . \quad (5)$$

Thus, to perform an analysis of aggregate market behavior, we must know: (1) purchase price and unit energy consumption of alternative design options for each product; (2) average efficiency purchased; (3) energy prices; (4) thermal characteristics of houses; and (5) average appliance lifetimes.

The major sources of data on the costs and energy use of appliances are the engineering cost analyses performed for the U.S. Department of Energy's analysis of the proposed Consumer Product Efficiency Standards.[2] These reports provided estimates of the purchase prices of individual appliances with different efficiencies. Supplemental data were obtained from Arthur D. Little, Inc. to extend the data back in time to 1972 and forward to 1980 from the original data sets, which were for 1978. The data were aggregated from the various appliance classes into a single set of data points representing the product type. Finally, a least-squares fit was performed to the functional form specified above to obtain the parameters of the curve. A typical cost versus energy use curve is shown in Fig. 1.

The Department of Energy's Survey of Manufacturers[3] provides historical data from appliance manufacturers on the average efficiencies of units shipped in 1972 and 1978 and projections for 1980. The efficiency factor (e.g., efficiency, energy efficiency ratio, etc.) for each model is multiplied by the number of units of the model shipped in the given year, then summed over all models and divided by the total shipments to give the shipment-weighted energy factor (SWEF). Table 1 shows the SWEFs used to calculate the market discount rates. Efficiency data from trade associations and individual manufacturers were used as a check on our results.

Average energy prices for 1972, 1978, and 1980 were obtained from the Energy Information

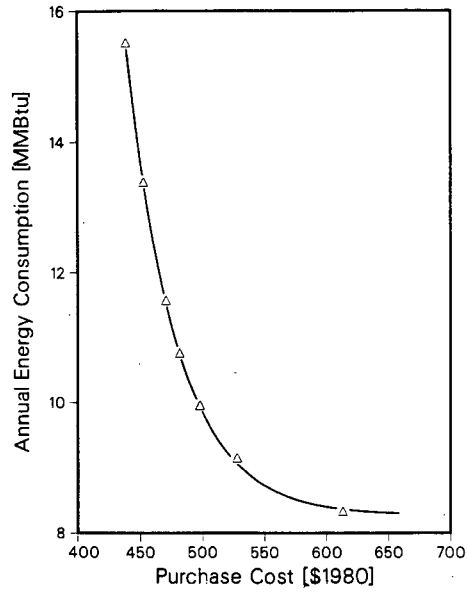

Figure 1. Cost vs. energy consumption for room air conditioners, according to design options. (XCG 8311-4908)

Table 1. Shipment-weighted energy factors (SWEF).

Appliance	1972	1978	1980
Gas central space heater	62.7	63.6	65.9
Oil central space heater	73.6	75.0	76.0
Room air conditioner	6.22	6.75	7.03
Central air conditioner	6.66	6.99	7.76
Electric water heater	79.8	80.7	81.3
Gas water heater	47.4	48.2	51.2
Refrigerator	4.22	5.09	5.72
Freezer	8.08	10.07	10.83

Source: Department of Energy Survey of Manufacturers.[3]

Administration.[4] Winter and summer marginal electricity rates are used for heating and cooling equipment, respectively. Marginal rates are calculated as the average rate for the 500 to 1000 kWh per month block. Thermal integrity factors were defined as the relative annual energy consumption for space conditioning end uses, reflecting changes from the stock house in existence in 1977 in terms of thermal characteristics (including insulation, window glazings, infiltration, etc.). The thermal integrity values for historical years were estimated from survey data.[5] The appliance lifetimes are the same values used in the Consumer Product Efficiency Standards analysis.[2]

Results

Aggregate market discount rates were calculated for years 1972, 1978, and 1980. The first step is to estimate the parameters of the annual energy use versus purchase cost curve for each appliance. Evaluating Eq. (5) at an E (annual unit consumption) corresponding to the shipment-weighted energy factor (SWEF) gives the present worth factor, which is then converted to a discount rate. The results presented in Table 2 are based on a single cost-efficiency curve for each appliance for the period 1972–1980. The tabulated discount rates are expressed in percent per year. Changes in discount rates over time for a single appliance are due to changes in SWEF, fuel prices, and, in the case of temperature-sensitive appliances, thermal integrity. The observed discount rates range from less than 20% to more than 200% per year. Those for central space heating and water heating appear to be increasing over this time, whereas the others either are decreasing or remain constant.

To understand these year-to-year differences, we performed an analysis of the sensitivity of the results to changes in SWEF and the cost-efficiency curve parameters. We found that the observed discount rate is extremely sensitive to the assumed SWEF; a change in SWEF of less than 5% could explain the year-to-year differences. Of the cost-efficiency parameters of Eq. (4), the greatest sensitivity is to the value of E_∞. Since the other three parameters all enter Eq. (4) in a similar way, they all have the same percentage effect.

Table 2. Aggregate market discount rates for appliances (in percent per year).

Appliance	1972	1978	1980
Gas central space heater	33.5	41.9	45.1
Oil central space heater	42.8	58.9	85.1
Room air conditioner	17.9	19.5	17.3
Central air conditioner	17.1	21.8	16.1
Electric water heater	209.1	244.4	243.2
Gas water heater	66.5	93.4	102.0
Refrigerator	74.0	69.0	59.2
Freezer	167.4	148.8	138.2

It is our judgment that the SWEFs are known to within 5%. They would thus lead to relatively little uncertainty in the discount rate. The parameters of the cost-efficiency curve are less well known, perhaps to within 10%. Because of the fitting procedure, E_∞ may be too low, leading to a high discount rate. Future work on the cost and efficiency of the most efficient products should lead to better estimates of these parameters. We do not, however, believe that the present uncertainty will affect the observed change in discount rate.

As a check on our results, market discount rates were calculated for refrigerators, freezers, gas furnaces, and room and central air conditioners using historical data on efficiencies from several sources. The discount rates show the same trends as the DOE Survey of Manufacturers data in Ref. 3.

The high discount rates observed for most appliances in this study make it difficult to interpret them as individual consumer discount rates. If a rational consumer's discount rate is higher than the current interest rate, he or she would borrow money to purchase a more efficient appliance. The data, however, indicate that this does not occur. We believe that the high discount rates show that imperfections in the market prevent consumers from making economically optimal decisions because:

- Consumers may not have adequate information about appliance efficiencies or access to capital markets.
- The person purchasing the appliance may not be the one who uses it.
- Price may be determined by factors other than efficiency.
- Or high-efficiency appliances may not be produced in quantities large enough to satisfy demand.

Thus all the participants in the marketplace could contribute to making the discount rate high.

Conclusions

Several generalizations can be made: (1) The values of the aggregate market discount rate for the appliances studied are higher than real interest rates

or the discount rates commonly used in life-cycle cost analyses of consumer choice. (2) The aggregate market discount rates appear to be relatively constant over time, with rates for some products (space and water heating) increasing somewhat over the past decade and rates for others (freezers and refrigerators) decreasing over the same period. (3) The sensitivity analyses show considerable changes in results as inputs are varied. This large variation, combined with other limitations of the analysis, suggests that considerable care must be used in discussing the numerical results; however, the first two observations are likely to be meaningful in a qualitative sense.

Overall, the high values of the aggregate market discount rates in Table 2 indicate that the average appliance or heating and cooling system purchased does not include energy efficiency measures that yield very high returns on investment. Several explanations for this underinvestment in energy efficiency in the residential sector have been proposed:

- Buyers lack information about costs and benefits of energy efficiency improvements or do not understand this information if it is available.
- Many purchases are made by a third party or under rushed or emergency conditions (e.g., landlord purchase of equipment for rental property or immediate replacement of malfunctioning equipment).
- The most efficient equipment may not be available in retail stores or may be available only with features (so-called "gold-plating") not desired by most purchasers.
- Manufacturer decisions to improve product efficiency are often secondary to other design changes and take several years to implement.
- Marketing strategies of manufacturers or retailers may intentionally promote sales of less efficient equipment.

Several studies have been initiated during this fiscal year to compare these explanations with empirical data.

A significant finding from Table 2 is that the aggregate discount rates have changed only modestly. We are aware of no previous work that has investigated the behavior of the market for energy efficiency in residential appliances over time. This work indicates that the behavior of the market from 1972 to 1980 has been relatively unchanged (in terms of return on investment for energy efficiency in consumer products). The market for appliances does not appear to be influenced by rapidly rising energy prices and consumer awareness of energy issues. This is similar to the results obtained by Levine and Scott[6] for investment in house thermal integrity.

PLANNED ACTIVITIES FOR FY 1984

An external review group has been empaneled by DOE to recommend future directions to improve the analysis of consumer product efficiency standards. We expect the review group to recommend additional research into market behavior. In the meantime, we are continuing to examine the possible effects of several programs aimed at making efficient appliances more attractive to purchasers. Studies begun in FY 1983 of utility incentive programs and the Federal Trade Commission's labeling program will be completed. Alternative methods for characterizing market behavior, such as internal rates of return and payback period, will be considered. The work on market behavior described in this article will be submitted for publication.

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Improvements in Residential Energy Modeling*

J.E. McMahon and P. Chan

Analysis of proposed federal policies affecting home energy use, especially appliances and residential heating and cooling equipment, requires modeling of residential energy demand. Since 1979, LBL has performed simulations of future energy demand and associated costs to provide estimates of the energy and economic effects of possible policy actions, incentives, and alternative scenarios.[1] New and more detailed data have become available through research and through public comments on proposed rules. In addition, our ability to analyze the effects of policies on consumers has been expanded to meet issues raised by rulemakers, equipment manufacturers, the public, and other interested parties.

ACCOMPLISHMENTS DURING FY 1983

We have made advances both in the quality of the data base and in modeling methodology. We will first describe data improvements not requiring methodological changes and then our methodological improvements. A more complete account will be found in a forthcoming LBL publication.[2]

Data Base Improvements

Taking advantage of new data, we upgraded, in four steps, the data base upon which the modeling effort depends. First, we made significant improvements in the exogenous projections of housing starts and floor space per house. The number of houses constructed and their average size have been less than previously expected, because of the depressed economy of the last 5 years. We adjusted projections of future housing construction activity to account for these events.

Second, we incorporated into the model improvements in efficiency not previously made publicly available by manufacturers. This provides a better base from which to forecast future efficiency improvements. (The behavior of the market with regard to choices in efficiency[3] is described in the preceding article).

Third, we updated the set of appliance designs available for purchase to account for recent technological changes. This moves us closer to characterizing the full set of technologies expected to be available over the next 20 years.

Finally, we improved characterization of national average energy consumption by central air conditioners.

Methodological Changes

The existing model framework has proved its usefulness as an analytical tool. A number of changes this year improved the capabilities of this model to provide detailed simulations useful for policy analysis:

(1) We generalized the model to include all residential end uses. In the process, we reformatted the input stream to permit us to analyze either a subset of end uses or the full set. This change facilitates intensive analysis of particular end uses efficiently by foregoing calculations for other end uses. Further, this change provides a consistent forecast of total residential energy demand when all end uses are included, which eases the comparison of results from alternative models.

(2) We included heat pumps explicitly for the first time. These products are making a substantial penetration into the space conditioning market. They now comprise 15% to 20% of all central heating/cooling installations.[4] Further work is under way to improve the characterization of this technology in future years.

(3) We changed the formulation used to represent the relationship between equipment purchase cost and appliance efficiency to remove ambiguities in the old method. Also, we conducted preliminary work on specifying the technological limit. This limit is defined as the highest efficiency physically and economically achievable. These efforts, together with updates of the set of technologies currently available, should continue to reduce our uncertainty about the future energy consumption of appliances.

(4) We improved the analysis of policies restricting the choice set, such as mandatory appliance efficiency standards, by incorporating distributional data. That is, where we previously characterized appliance choices in a given year by the average efficiency, we now use a distribution of efficiencies.

(5) We installed a capability to allow for changes in the real price of appliances over time. Advances in manufacturing technique, as well as other factors, can lead to changes in the cost of producing

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appliances. The simulation model can now incorporate such changes, providing estimates of their effects on appliance selection and market penetration.

(6) We improved the analysis of the economic effects of government policies through a normalization process. Such policies as mandatory efficiency standards could have an impact on the market penetration of particular appliances. The old method mistakenly treated a policy-caused decrease in sales of a product as an economic benefit, since the decrease in purchases was treated as a drop in purchase and operating costs. The new approach normalizes economic benefits and costs on a per-unit basis, thus providing a better measure of policy effects.

(7) A previous improvement (FY 1982) involved incorporating the age distribution of appliances in use.[5] During FY 1983, we extended this to include an accounting of the differences in efficiency as a function of production year. This change captures the difference in energy consumption due to the replacement of an old (less efficient) product with a newer design.

(8) We added a number of auxiliary routines to the main simulation model. One of these performs comparisons between two simulations—usually a no-policy forecast and a policy scenario—to automatically provide difference tables of the significant variables. Other routines provide outputs integrated with graphics routines, so that the projections can be displayed pictorially as well as in tabular form.

Overall Impact of Changes

Updating the data base is an ongoing process, one that takes advantage of new data sources as they become available and corrects for changes in trends as they become apparent. The methodological changes are more fundamental, and in that sense more significant. Such changes affect the capabilities of the forecasting tool. Among the examples cited above are several in which the amount of detail delivered in a forecast is enhanced. Other changes involve incorporating factors affecting future residential energy consumption that were not previously considered. Consideration of these additional factors is important where they diminish uncertainty in the simulation and enhance insight into the determinants of energy consumption. The changes described here serve to refine our view of the future, while constraining the forecasts to treat all these factors in a consistent framework. The resulting methodology has new capabilities, greater detail, improved consistency, and better data than previous efforts. Of course, much remains to be done to reduce the uncertainty in the simulation results still further.

We now illustrate the effect of one methodological change, replacement of the retirement function of appliances. The old methodology used an exponential retirement scheme: a fixed percentage of the entire population of a product was retired each year, independently of the age distribution. Thus, 6% of all 1-year-old central air conditioners, as well as 6% of all 20-year-old central air conditioners, were assumed to retire each year. When data on historical purchases of products became available, we substituted an empirical retirement function for the exponential. Figure 1 illustrates the effect on installations in existing houses. Where the old method provided a smooth projection of annual installations, the new method shows waves of installations, such as the peak in 1987. These peaks correspond well with expectations based upon historical purchases. In particular, periods of high sales of equipment imply large numbers of replacement installations approximately one equipment lifetime later (about 12 to 15 years). The peak in shipments of residential central cooling equipment was in 1973. Note further that peaks in heating and cooling equipment sales tend to correlate with additions to the housing stock, such as the 1972 peak in housing construction.

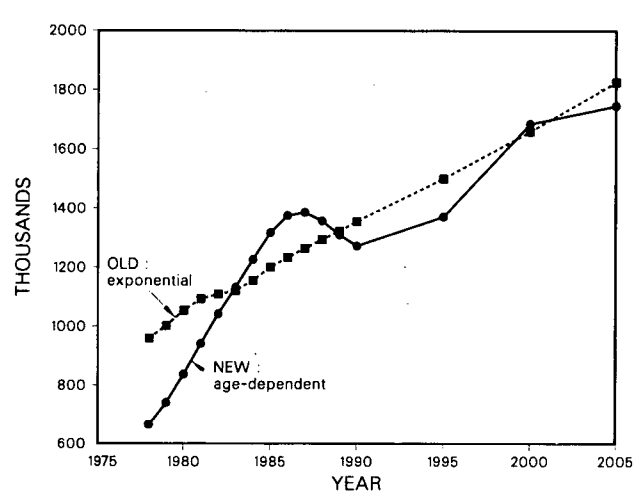

Figure 1. Predicted annual installations of central air conditioners, including heat pumps, in existing houses: a comparison of two forecasting methodologies. The older method is based on assumed appliance retirement rates; the newer method, using an age-dependent formula, takes actual retirement rates into account. (XCG 8312-4925)

The use of the empirical retirement function together with data on past purchases of equipment provides a much more detailed understanding of the driving forces behind future sales, and a more complex forecast. Furthermore, the interaction between changes in the housing construction industry and equipment installations is captured. This is one example of improvements to the model methodology in terms of increased detail and internal consistency.

All of the methodological changes together provide a lower estimate of future residential energy consumption than would have been obtained without this research effort (Fig. 2). The expected increase in primary energy consumption after 1977 is reduced by 35% in the year 2005, corresponding to a reduction of 0.86 quads in that year. Most of the reduction (0.40 Q) is in natural gas consumption, followed by electricity (0.23 Q), heating oil (0.16 Q), and other (0.07 Q). The end uses with the greatest percentage change in annual energy consumption are refrigerators, freezers, cooking appliances, air conditioners, and water heaters. Of these, only water heaters show an increase in energy consumption under the new method, compared with the old.

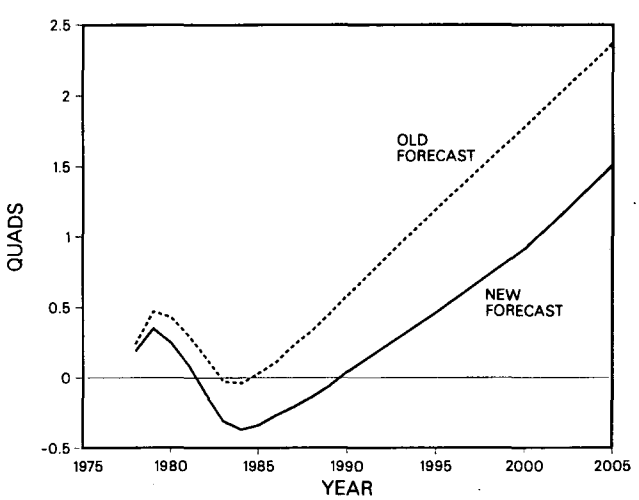

Figure 2. Predicted changes in total residential energy consumption after 1977; the new forecast incorporates changes in modeling methodology and improvements in the data base. (XCG 8312-4926)

PLANNED ACTIVITIES FOR FY 1984

We will obtain recommendations for further methodological improvements from a review group working for DOE. The review group is intended to provide an outside technical perspective on issues affecting the analysis of appliance efficiency standards, including the use of this model. It may address such issues as data requirements, availability, and quality; consumer and manufacturer behavior on energy efficiency and fuel choice; and engineering/economic issues affecting the availability and cost of more efficient equipment.

In addition, LBL research will address aggregation issues concerning variance in weather, energy prices, and classes of appliances. We wish to determine how great an error, if any, is introduced by using averages for input.

We will begin a preliminary investigation into methods for improving the treatment of heat pumps as a space conditioning alternative. As they become available, we will incorporate the results of other research activities such as an assessment of market behavior regarding energy efficiency choice and new analyses of elasticities in specific end uses.

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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 1983

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.

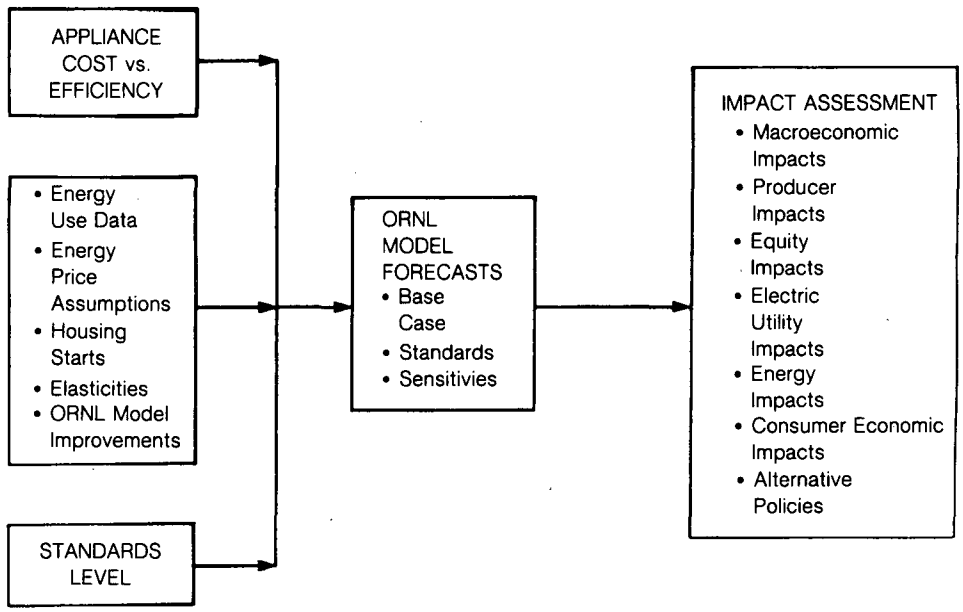

Figure 1. Overview of research methodology. (XBL 845-1963)

- 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.

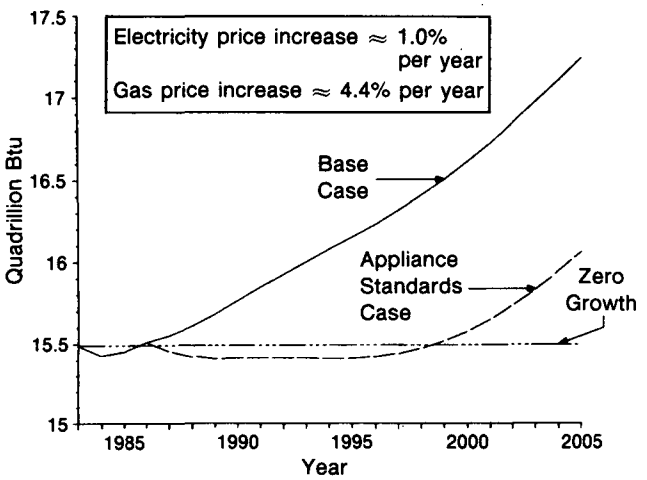

Figure 2. Residential energy demand forecasts. (XBL 845-1966)

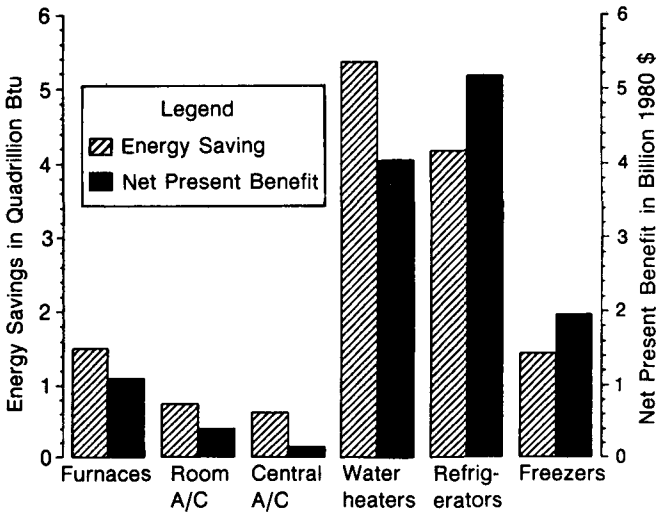

Figure 3. Energy savings and net present benefit of proposed federal standards, by product. (XBL 845-1965)

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

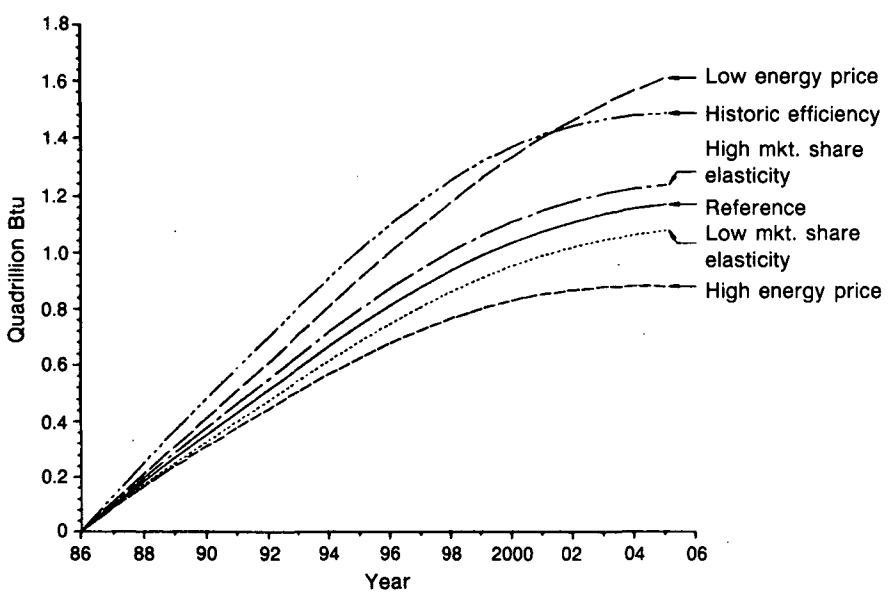

Figure 4. Projections of annual savings in residential energy use under proposed standards for appliance energy efficiency, using various base-case assumptions. (XBL 845-1964)

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 1984

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.

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Effects of Utility Incentive Programs on the Energy Efficiency of Newly Purchased Appliances*

D.F. Dickey and M.D. Levine

Rebates are a new form of financial carrot that utilities have developed to influence the appliance purchase decisions of residential customers. The novelty of utilities' provision of "up-front cash" to homeowners who select particular appliances has captured the interest of consumers, utilities, and regulatory bodies.

Appliance incentive programs have been offered only in the last several years and have spread widely since 1979. State public utility commissions have encouraged (and sometimes required) these efforts. Commissions and state legislatures have determined that utilities' direct subsidies of customers' appliance purchases are justified because they encourage use of efficient equipment, thus providing energy at a lower cost than investing in new generating capacity or purchasing expensive peak-load fuels.

The two primary forms of incentives offered are cash rebates and subsidized loan programs. Of the two, rebate programs have proved to be much more popular. A wide range of appliances have come under these rebates, and eligible recipients have included homeowners, renters, dealers, builders, and utility employees.

As part of an investigation into the impact of public policies (especially appliance standards) on the energy efficiency of residential equipment, we contacted 76 utilities to assess the effect 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, and if so, by how much. We also wanted know whether these utility programs would be likely to have a significant impact in the future.

*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 1983

Methodology

We surveyed the 76 utilities in two groups. Group 1 consisted of 41 utilities that had been identified before contact as offering incentives for residential appliance purchases. We surveyed these first to learn whether the programs were being continued in 1983, and to collect data on their results.

We then contacted a second group of 35 utilities that had *not* been identified as offering rebates or loans. To gain a broad perspective about utilities' interest in starting incentive programs, we included large investor-owned and municipal utilities from various states and climatic regions. Because many of the programs surveyed in group 1 had been identified through an air conditioner and heat pump manufacturers' industry association, we anticipated that group 2 would provide a more comprehensive indication of utilities' relative interest in appliance incentive programs.

Additionally, we included the Tennessee Valley Authority and the Bonneville Power Administration because of their unique capability to implement programs that include many utilities and power distributors.

We mailed written versions of the survey to respondents when an appropriate time to speak on the telephone could not be arranged. Some program managers sent pamphlets, promotional materials, and internal work plans to supplement the telephone or written survey.

Results

Extent of Incentive Programs

We found that 51 of the 76 utilities surveyed—67%—had incentive programs for appliances; these programs are thus much more widespread than we had anticipated and have the potential to affect a substantial proportion of appliance purchases.

The 51 utilities with incentive programs in 1983 represent 45.9% of investor-owned residential electric sales and 32.3% of municipal residential electric sales. Thus, at a minimum, appliance rebate programs can affect purchase decisions in regions of the country in which almost 50% of residential electricity is consumed. An upper limit on the magnitude of these programs was determined to be 60% [45% of total electric sales plus 0.4 (utilities not surveyed) × 0.4 (fraction of group 2 offering programs) = 60%].

Utilities operating programs appear likely to continue them. In the first group of utilities contacted, only one had discontinued its incentive efforts by 1983.† Additionally, one program was stopped during 1983 to allow the state regulatory commission to re-evaluate the cost-benefit assumptions under which the program was operating. Thus, at present it appears that the rebate programs will continue in the future.

Many utilities are presently in the process of implementing appliance incentive programs. More than 20% of the utilities in group 2 that we surveyed were considering or planning such programs, or awaiting regulatory commission decisions about them. Thus, 60% (by sales) of the utilities in group 2—the group not previously identified as offering appliance incentive programs—were either offering such programs (40%) or planning to do so (20%).

A summary of the results measuring utility interest in rebate programs is contained in Table 1.

Appliances Affected

Heat pumps and room air conditioners were the most popular appliances for subsidies. As noted in Table 2, 37 of the utilities surveyed offered incentives for central heat pumps in 1983, representing 36% of national investor-owned utility (IOU) residential electricity sales and 25.6% of national municipal utility sales.

Rebates for central air conditioners were the second most widely offered, chosen by 25 utilities that represent 31.1% of IOU residential electric sales (but only 6.3% of municipal sales).

Solar water heaters were favored next (20% of IOUs by sales) and were similarly the next choice among municipal utilities (16.8% by residential electric sales).

Room air conditioners were promoted by a slightly larger share of investor-owned utilities than solar water heaters (20.9% of sales versus 20.2%). No municipals offered incentives for room air conditioners.

Utility Objectives

The objective most frequently mentioned by utilities with rebate programs was peak-load growth reduction; 63% of the utilities offering programs cited this reason. Utilities' predominant selection of air conditioning and heat pump units for appliance subsidy programs appears directed toward this objective.

†The reason given for discontinuation was that higher fuel costs were providing sufficient incentives for energy conservation. Thus the incentive program was seen as no longer needed.

Table 1. Status of utilities' incentive programs and percent of national residential electric sales represented by utilities surveyed.

	Total				Group 1[a]				Group 2[b]			
		% of	% Natl. resid. electric sales			% of	% Natl. resid. electric sales			% of	% Natl. resid. electric sales	
	Number	Sample	IOU	Muni	Number	Group	IOU	Muni	Number	Group	IOU	Muni
Utilities surveyed	76	100	61.7	45.3	41	100	38	21.6	35	100	23.6	23.7
Utilities offering programs in 1983	51	67	45.9	32.3	38	92.6	36.4	16.0	13	37	9.6	16.2
Utilities planning/ considering or awaiting regulatory approval	9	11.8	5.2	7.9	1	2.4	0	5.5	8	22.5	5.2	2.3
Utilities not considering or offering programs	16	21	10.6	5.1	2	4.9	1.6	0	14	40	8.8	5.1

Note: IOU = investor-owned utilities; Muni = municipal utilities.

[a]Utilities identified before survey as having incentive programs.

[b]Utilities not known before survey to have incentive programs.

Reduction of base load was cited in 22% (11/51) of the responses, followed by balancing of seasonal loads through increased off-peak sales (20% or 10/51).

Table 2. Appliances for which incentives are offered.

Appliances	Utilities offering incentive	% Natl. resid. electric sales	
		IOU	Muni
Central heat pump	37	36.0	25.6
Window/room heat pump	14	16.4	0
Central air conditioner	25	31.1	6.3
Room air conditioner	15	20.9	0
Solar water heater	20	20.2	16.8
Heat pump water heater	14	17.1	10.3
Heat recovery water heater	8	9.9	0.8
Gas water heater	5	0.8	0
Electric water heater	4	3.8	1.0
Gas heat	4	1.5	0.3
Electric heat	3	2.1	1.0
Solar heat	2	0	1.3
Gas dryer	4	3.7	0
Refrigerator/freezer/r/f	5	13.1	0
Gas ranges/ovens	3	0	0

Impact on Energy Efficiency

Utility incentive programs were found to have little impact on the energy efficiency of household appliances, despite their rapid and extensive penetration throughout the nation. This conclusion can be inferred from the data in Table 3. Some calculations for the most important appliances are given in the discussion below.

We concluded that the effect of utility incentive programs on the average energy efficiency of heat pump shipments is negligible. The average minimum SEER (seasonal energy efficiency ratio) for a utility heat pump program is 7.5, while the sales-weighted SEER for the nation is 8.0, the more efficient level. In addition, 38% of the incentive programs require an average of 8.0 and above, so we infer that 8.5 is about average for the efficient units.

Adjustment for the impact of program requirements above the survey average yielded a maximum increase of 0.01 SEER. This estimate is derived as follows: the fraction of utility programs requiring efficient heat pumps is 38% (0.38); the fraction of heat pump sales affected by the programs is 10% (0.1); and the increase in SEER for heat pumps owing to the efficiency requirements of the programs is 20% (0.2). The product of these three factors (0.38 $\times$ 0.1 $\times$ 0.2) is approximately 0.01—as stated, a negligible increase. (The estimate assumes that per-

Table 3. Estimated annual incentives and average program efficiencies for utilities providing data.

Appliance	% Utilities reporting data	Total annualized incentives	% Annual U.S. shipments	Annual U.S. shipments	National sales-weighted energy efficiency	Utility program avg. effic.
Central heat pump	62	32,089	8.7[a]	372,615	7.97 (1982)	7.5
Room heat pump	50	321	n/a	n/a	n/a	8.1
Central air conditioner	52	121,651	11.9	1,018,938	8.31 (1982)	8.5
Room air conditioner	60	43,241	1.2	3,692,500	7.06 (1981)	8.39
Solar water heater	55	18,287	n/a	n/a	n/a	n/a
Heat pump heater	64	1,114	n/a	n/a	n/a	n/a
Heat recovery water heater	63	3,247	n/a	n/a	n/a	n/a
Gas water heater	60	6,402	0.2	2,921,052	48.17 (1978)	n/a
Elec. water heater	50	1,511	0.5	2,684,104	80.67 (1978)	n/a
Gas range	0	n/a	0	1,794,200	17.66 (1978)	n/a
Gas dryer	25	3,915	0.6	682,400	2.41 (1980)	n/a
Gas furnace	25	3,300	0.2	1,764,000	63.58 (1978)	n/a
Elec. space heater	33	0.84	n/a	n/a	n/a	n/a
Solar space heater	50	0	n/a	n/a	n/a	n/a
Refrigerator, freezer r/f (new)	100	84,552	1.5	5,704,000	6.12(r&r/f) (1982) 11.28(f) (1982)	n/a
Refrigerator, r/f (old)	100	12,500	n/a	n/a	n/a	n/a

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

Sources: *Appliance Manufacturers' Magazine*
Air Conditioning, Heating, and Refrigeration Institute (1983), *Comparative Study of Energy Efficiency Ratios.*
Association of Home Appliance Manufacturers.
U.S. Department of Energy, CS-179 Survey of Manufacturers.

sons purchasing the more efficient heat pump under an incentive program would not otherwise do so.)

Incentives for central air conditioners identified in the survey total 12% of national sales. Correcting for utilities not included in the survey (by assuming the same percentage of these as those in group 2 also had incentives) yields a best estimate of 14% of total sales.

The impact of current incentive programs on the efficiency of central air conditioners is larger than for heat pumps but nonetheless small. The average SEER of the air conditioner incentive programs is 8.5. The sales-weighted SEER for central air conditioners is 8.43. However, 40% of all incentive programs require an SEER of 9.0 or above (to a maximum of 9.5). Assuming that the high-efficiency programs promote an average SEER of 9.1, and that consumers in these programs would have purchased at the national average of 8.31, the effect of the utility programs on the SEER can be calculated as follows: 0.8 (increase in SEER) $\times$ 0.12 (fraction of central air conditioner sales impacted by utility programs) $\times$ 0.4 (fraction of utility programs requiring high efficiency central air conditioners) = 0.04. This is a negligible increase in SEER.

It might be argued that to the extent that utility incentive programs are speeding up the replacement of older, less efficient central air conditioners, they will improve the average SEER more rapidly than the estimate presented here. However, available data (to 1972) indicate that older central air conditioners are only slightly less efficient than current models. It is unlikely that efficiencies of central air conditioners improved significantly before 1982. Thus, the replacement effect is not expected to be large.

Interestingly, the minimum EERs for room air conditioners were substantially above the national sales-weighted EER: 8.4 versus 7.1. However, the number of incentives offered was too small to raise

the efficiencies of room air conditioners for the nation as a whole.

For all other products, the incentives identified in the survey covered only a small fraction of total sales nationwide. Incentives for refrigerators among utilities surveyed were 1.5% of total sales, and for room air conditioners, they were about 1%.

PLANNED ACTIVITIES FOR FY 1984

A final report is being prepared that will detail the results of the survey. Otherwise, no further work is planned.

Residential Hourly and Peak Demand Model*

G. Verzhbinsky, E.L. Vine, H. Ruderman, and M.D. Levine

For the past few years, we have been developing a residential hourly and peak demand model under the sponsorship of the Department of Energy. This peak load model has enabled 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. Knowledge of 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.

The model operates by disaggregating projections of annual residential electricity consumption for 12 end uses to each hour of the year. 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 peak load and the ORNL/LBL models, utility and government policies targeted at specific appliances and building characteristics can be evaluated. Details of the construction, operation, and validation of the peak load model will be appear in a forthcoming LBL report.[3]

ACCOMPLISHMENTS DURING FY 1983

Several types of analysis have been performed using the LBL residential and peak demand model. Data from the Detroit Edison Company (DECO) have been used for model validation and for sensitivity runs (this utility provided us with the most complete set of data), and several scenarios were chosen to study the effect of various conservation policies on this service area. The validation and sensitivity studies required some improvements in the model and changes in its operation.

One of the main reasons for developing the hourly and peak demand model was to create a tool that would help electric utilities to evaluate the results of different conservation policies on peak demand, load factor, and load-duration curve. To illustrate the broad spectrum of options that can be simulated with the model, the following scenarios for newly built houses were examined:

(1) Base case
(2) Passive solar case
(3) Low infiltration case
(4) Base case with Consumer Product Efficiency Standards (CPES)
(5) Tight houses
(6) Case 5 combined with Case 2
(7) Case 5 combined with CPES.

Each case was run for a summer- and a winter-peaking utility. The summer-peaking utility was based on data obtained from Detroit Edison; the winter-peaking utility was derived from the DECO data by increasing the saturation and market penetration of electric heating systems. (At present, heating in the DECO service area is primarily by gas.) Cases 4 and 7 assume that the level 4 Consumer Product Efficiency Standards proposed by DOE[4] were implemented in 1982. The standards affect gas and oil central space heaters, room and central air conditioners, electric and gas water heaters, refrigerators, and freezers, but not electric space heaters. Table 1 shows the house characteristics used in the simulations.

Each case required adjustments to the fraction-in-use (appliance-use) matrices[5] because of the differences in house thermal characteristics and energy performance. A fraction-in-use matrix shows the fraction of appliances of a given type that are in

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Table 1. Summary of house characteristics in LBL peak and hourly demand model simulations.

Case no.[a]	Ceiling insulation (R-value)	Wall insulation (R-value)	Foundation insulation (R-value)	Type of glazing	Infiltration (ach)	Window orientation
1	23.7	11.3	0.0	1.5	0.7	equal
2	23.7	11.3	0.0	1.5	0.7	75% south 25% north
3	23.7	11.3	0.0	1.5	0.4	equal
4	23.7	11.3	0.0	1.5	0.7	equal
5	38.0	19.0	10.0 (8 ft deep)	3.0	0.7	equal
6	38.0	19.0	10.0 (8 ft deep)	3.0	0.7	75% south 25% north
7	38.0	19.0	10.0 (8 ft deep)	3.0	0.7	equal

[a]See text for descriptions of these scenarios.

operation in a service area during each hour of the day under different temperature conditions. To adjust these matrices, we used the DOE-2.1A program to simulate the heating and cooling loads in the building for all cases considered. The output routines of the DOE-2.1A program were modified to reformat the hourly loads into electricity demand matrices by hour and temperature (or temperature-humidity index). Each element of the matrix gives the electricity load for specified time and temperature conditions. Then the original fraction-in-use matrices were adjusted by multiplying each element of the matrix by the ratio of the corresponding elements in the electricity demand matrices for the policy and base cases.

We were particularly interested in how different conservation policies would change the peak demand and the load factor. The load factor is the ratio of average hourly load to peak load; it quantifies how much the load varies over time. Utilities like to keep their load factor high—i.e., to have a minimal difference between average and peak loads—because it makes more efficient use of their generating capacity. Reducing the growth in peak load is important to a utility facing capital constraints, since it reduces the need to invest in new generating capacity.

Some of our simulation results are illustrated in Table 2 and in Figs. 1 and 2. In the base case, peak demand is expected to increase from 2800 MW in 1980 to 4000 MW in 2005. This will be accompanied by a continuing decline in load factor as air conditioning saturation increases. Large peak savings occur in Case 4 (appliance standards), in Case 5 (highly insulated houses), and in Case 7 (Cases 4 and 5 combined). The difference in the peak savings for cooling and heating in Case 4 (7.81% versus 0.82% in 2005) occurs because of the absence of efficiency standards for electric heating appliances. The small savings for electric heating are caused by switching from electric heaters to gas heaters having improved efficiencies.

The biggest improvement in load factor for summer-peaking utilities occurs in Cases 4 and 7, due mainly to the increase in air conditioner efficiency. For winter-peaking utilities, however, peak load decreases relatively less than average load, degrading the load factor. Again, the lack of standards for electric heaters, which contribute to the peak load, is responsible, whereas standards for other appliances, which contribute to the average load, exist. Lowering the air infiltration rate in residential buildings is an important consideration for this type of utility. It should be noted that load factor is a nonlinear characteristic; two policies that by themselves improve load factor may lead to smaller load factors when implemented simultaneously.

For these studies, it was necessary to construct a simplified version of the peak demand model. The

Table 2. Summary of sensitivity analysis runs.

Case no.	Peaking season	Year	Peak load (MW)	Percent saving	Load factor	Percent change
1	Summer	1990	3105		0.4323	
		2005	3994		0.4173	
	Winter	1990	10098		0.2659	
		2005	13864		0.2548	
2	Summer	1990	3091	0.45	0.4342	0.44
		2005	3954	1.00	0.4212	0.93
	Winter	1990	10113	−0.15	0.2651	−0.30
		2005	13935	−0.51	0.2526	−0.86
3	Summer	1990	3072	1.06	0.4366	0.99
		2005	3895	2.48	0.4272	2.37
	Winter	1990	9982	1.15	0.2672	0.49
		2005	13558	2.20	0.2570	0.86
4	Summer	1990	2862	7.82	0.4536	4.93
		2005	3682	7.81	0.4376	4.86
	Winter	1990	9988	1.09	0.2631	−1.05
		2005	13750	0.82	0.2520	−1.10
5	Summer	1990	3002	3.32	0.4437	2.64
		2005	3817	4.43	0.4321	3.55
	Winter	1990	9836	2.59	0.2671	0.45
		2005	13229	4.58	0.2564	0.63
6	Summer	1990	3027	2.51	0.4407	1.94
		2005	3881	2.83	0.4263	2.16
	Winter	1990	9830	2.65	0.2672	0.49
		2005	13223	4.62	0.2563	0.59
7	Summer	1990	2803	9.73	0.4610	6.64
		2005	3525	11.74	0.4524	8.41
	Winter	1990	9749	3.46	0.2645	−0.53
		2005	13133	5.27	0.2535	−0.51

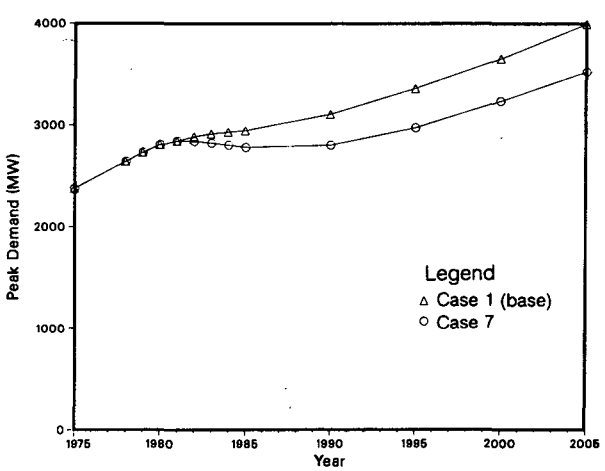

Figure 1. Two scenarios of annual residential peak demand, 1975–2005, based on Detroit Edison Company data for its service area. Case 7 assumes appliance standards and tight insulation of housing are in effect. (XCG 8311-4912)

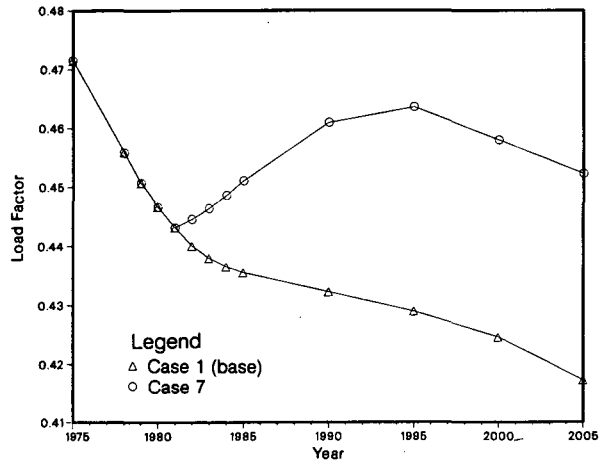

Figure 2. Two scenarios (same as Fig. 1) of annual residential load factor; projections based on Detroit Edison data. (XCG 8311-4913)

model was originally designed to compare the base case with a single conservation case in one run. Validation and sensitivity studies, however, require comparisons of the base case with several other cases. For these comparisons, the same weather file must be used for all years. These considerations were taken into account in constructing the simplified version. The changes in the model also reduce the running time from 30 to 4 minutes.

We also began incorporating heat pumps into the model. The key part of this study was the analysis of the difference in performance of heat pumps and electric resistance heaters. The results were used to construct fraction-in-use matrices for heat pumps. The DOE-2.1A program was used to simulate residential buildings employing heat pumps or resistance heaters. We developed matrices and vectors that provide quantitative information about temperature- (and load-) dependent coefficients of performance for heat pumps. Elements of these matrices are calculated as ratios between corresponding elements of the demand matrices from the DOE-2 simulations of heat pumps and heaters. Vectors were produced by averaging the matrix elements over 24 hours, a procedure very similar to one used in the sensitivity runs.

PLANNED ACTIVITIES FOR FY 1984

The results obtained during FY 1983 show that the hourly and peak demand model is a useful tool in understanding the effects that energy conservation programs can have on an electric utility service area. Further insight is provided by running this model in conjunction with the DOE-2 building energy simula-

tion model and the ORNL/LBL residential energy use model. During FY 1984, we intend to expand the capabilities of the model, make it easier to use, and apply it to other utility service areas.

Other main activities planned for FY 1984 include:

- Completing the addition of heat pumps to the model, as well as other selected model improvements.
- Continuation of validation and sensitivity studies based on various weather files and diversity procedures.
- Development of a module for calculating the effects of load shape changes due to the implementation of conservation policies on utility finances.

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Price Elasticity of Residential Electricity Demand*

E. Kahn, J. Sathaye, and D. Robbins

As the cost of electricity increases substantially, it is important to be able to assess the consumption changes that will occur in response. Such an analysis must begin with the economist's notion of price elasticity. The basic definition of price elasticity is the percentage change in consumption due to a 1% change in price (i.e., the ratio of percent change in consumption to the percent change in price; a price increase that causes a decline in consumption thus yields a negative elasticity). This can be measured both for short-run periods when the stock of devices is fixed and for the long run when the stock varies. In this project, we examined the various factors that affect elasticity estimates, reviewed the literature on price elasticities, and provided a critical evaluation of some of the more interesting and controversial studies.[1] As a case study, estimates for both short- and long-run price elasticities were developed from data for the Gulf States Utilities Company.[2] In addition to these data, the DOE-2 and ORNL models were used to improve the engineering specificity of the consumption model.

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ACCOMPLISHMENTS DURING FY 1983

Literature Evaluation

Our review of the literature and critical evaluation of some of the studies led to the following general conclusions:

(1) Elasticity estimates show great variation. This has been reported by Bohi for studies published before to 1978,[3] and our review of studies made since 1978 yields the same result. In extreme cases, short-run estimates are higher than long-run estimates.

(2) The published studies show great variation—a factor of two—in elasticity estimates within a state. State-level analysis therefore averages over broad estimates without adequate justification for doing so. The results of such analysis are not representative of utility area elasticities and should be used with caution.

(3) Studies using monthly models rely on independent variables that are not observed monthly but are interpolations from annual data, e.g., income. In some cases, the dependent variable is observed monthly, but the data are suspect. Annual models

have none of these problems. On the other hand, they result in very few data points over a long time period, so that changes in the underlying structural and economic relationships may be obscured; e.g., prices declined until the early 1970s, were stable for a short while, and then increased rapidly. Elasticity estimates are sensitive to the period chosen for study.

(4) Elasticity estimates are sensitive to cooling loads. However, depending on the study, the elasticity may either increase or decrease. Lawrence reports very high cooling elasticities,[4] whereas Betancourt and Chern have shown lower elasticities.[5,6]

(5) The interaction of weather sensitivity and price trends on elasticity estimates has not been thoroughly examined. It appears that prices, appliance saturation, and weather sensitivity are linked in more a complex fashion than previously realized.

(6) Elasticities appear to increase with increasing fraction of income devoted to electricity consumption, i.e., a higher budget share. The precise trend is not clear, however, because the two studies that reviewed this question indicate diverse trends.

(7) Generally, studies in the academic literature are methodologically sophisticated and advanced but are not usable without highly detailed data that match survey information to customer bills. Utility companies wish to rely on simpler techniques that would yield reliable and consistent results.

(8) Analysis of simple models used by three utilities—Long Island Lighting Company (LILCO), Public Service of Indiana (PSI), and Philadelphia Electric Company (PECO)—confirms that the elasticity of customers with electric space heating is around -1 and is much higher than for customers without space heating. The short-run elasticity in most cases is around -0.3 to -0.4.

Further generalizations regarding elasticity changes with respect to data period and model specification are difficult. For LILCO and PECO, model specification strongly influences elasticity estimates; for PSI, time period has a stronger effect.

(9) Empirical studies show elasticities declining from 1956 to 1975. Since these were done for periods of declining prices and suffer from aggregation bias, the implication for forecasting elasticities in a period of increasing prices is unclear.

Gulf States Utilities Case Study

We conducted a study of the Gulf States Utilities (GSU) service area that linked engineering methods with econometric techniques to estimate short- and long-run price elasticity. Data on appliance saturation and efficiency, thermal integrity of houses, and prices and incomes are available for this utility service area. These are used to separate various end-use components of electricity consumption. Such end-use analysis can reveal the potential for change in residential electricity use.

Price Elasticity in the Short Run

We adapt a standard model of electricity consumption to include an explicit representation of the capital stock. The basic equation is:

$$E = CP^{a_1}Y^{a_2}Z^{a_3}S \quad , \tag{1}$$

where E = electricity consumption,
P = electricity price,
Y = real income,
Z = other explanatory variables,
S = appliance stock,
C, a_i = constants.

The coefficient a_i is the price elasticity, which we limit here to changes in the use of existing appliances.

To estimate the coefficients statistically, we transform this basic model in a number of ways. First, we divide both sides by S to produce a measure of capacity utilization, E/S. Second, we distinguish the variable part of consumption from the fixed part by the relation

$$E_v = E - E^* \quad , \tag{2}$$

where E^* is that part of electricity use which is fixed in the short run.

To make Eq. (2) consistent with the capacity utilization notion, we re-write Eq. (1) in logarithmic form as follows:

$$\ln CU = \ln C + a_1 \ln P + a_2 \ln Y + a_3 \ln Z \quad , \tag{3}$$

where $CU = E_v/(S - E^*)$.

To specify a version of Eq. (3) that can be estimated, we identify E_v with the weather-sensitive demands of air conditioning and space heating. This represents about half of the residential energy consumption of GSU. Additional empirical problems involve the separation of heating and cooling demands and the proper treatment of the price variable. For statistical reasons, it is not appropriate to use average prices in Eq. (3). Since average price is determined simultaneously with consumption (because there is a nonlinear rate structure), we tried two alternatives. The first version used a representation of the rate structure based on prices at two fixed

consumption levels. To do this, we changed Eq. (3) to the form

$$\ln CU = \ln C + b_1 \ln P_1 + b_2 \ln P_2 + a_2 \ln Y + a_3 \ln Z \quad . \tag{4}$$

The two price coefficients of Eq. (4) must be weighted to produce a short-run elasticity, i.e.

$$N = w_1 b_1 + w_2 b_2 \quad , \tag{5}$$

where $w_1 + w_2 = 1$.

The second an alternative to Eqs. (4) and (5) that we tried is an instrumental variable approach to finding an "average" price that does not involve the simultaneity problem.

A final version of the short-run model involves a further transformation of the dependent variable. It takes advantage of the bounded nature of the capacity utilization variable CU. By definition, CU must be between 0 and 1. To incorporate this into the estimation procedure, we use the logit transformation

$$\text{Logit } CU = \frac{CU}{1 - CU} \quad . \tag{6}$$

We then put the logarithm of Logit CU into Eq. (4). To interpret the coefficients estimated in this manner, we scale down the parameter values to get elasticities. This compensates for the transformation of Eq. (6). The procedure typically recommended is

$$N_i = a_i \; CU_j(1 - CU_j) \quad , \tag{7}$$

where N_i = elasticity with respect to variable i, and
a_i = estimated coefficient of variable i.

To use Eq. (7), we must specify a capacity utilization level CU_j. Although Eq. (7) is hard to use in practice, we do not need the scale factor if we are only interested in the relative value of the coefficients.

Table 1 shows the results of estimating with various models. For our purposes, version A2 is the most useful. The coefficients of A1 are similar, but instead of two price variables at fixed usage levels, this model has only one and a variable representing the slope of the rate structure. The instrumental variable for average price (AVI) has the wrong sign. Both logit versions show the same ratios of coefficients as A2. Of particular interest are the ratios of CDD to HDD (cooling degree-days to heating degree-days), of price to income, and of price at 500 kWh to price at 1000 kWh. These results substantiate the estimated coefficients in model A2.

Now we must find a weighting scheme in the form of Eq. (5) to use the coefficients of A2. We rely on a basic property of residential utility billing and consumption data. The sales frequency distributions characterizing consumption are typically so skewed that, at the mean level of consumption, 75% of the total quantity has been consumed. Since the mean for the GSU data occurs at 1000 kWh/month, we get a natural weighting of the price coefficients for A2 in Table 1 as follows:

$$N = 0.75(-0.44) + 0.25(+0.03) = -0.32 \quad . \tag{8}$$

The Eq. (8) elasticity only accounts for the weather-sensitive part of consumption. It is common to use a consumption-weighted elasticity that refers to all end users. If we modify Eq. (8) by accounting for the utilization elasticity of water heating (−0.25), weighting this by its share of average use (13%), the resulting elasticity is given by

$$N = 0.5(-0.32) + 0.13(-0.25) \tag{9}$$

$$= -0.19 \quad .$$

Long-Run Stock Adjustment—Engineering Economic Projections

The long-run response to price is a change in the stock of appliances. We estimate this by projecting changes in average use, using the following identity:

$$\text{AVU} = \sum_{i=1}^{n} \text{SAT}_i \times \text{UEC}_i \quad , \tag{10}$$

where AVU = average monthly use per customer;
SAT_i = saturation of end use i;
UEC_i = average unit energy consumption of end use i.

The stock adjustment part of price elasticity is the percentage change in average use corresponding to the percentage change in price. Formally,

$$N_{LR} = (\Delta\text{AVU}/\text{AVU})/\Delta P/P_j \tag{11}$$

where Δ is the difference operator.

We estimate Eq. (11) by disaggregating 1982 average use into nine end uses that comprise more than 90% of use. We then project saturations and UEC's for each according to the general logic illus-

Table 1. Estimates of capacity utilization (CU) by weather-sensitive demand models for Gulf States Utilities.

	Model				
	A1	A2	A3	B1	B2
Dependent variable	CU	CU	CU	Logit CU	Logit CU
Price variables					
500 kWh	−0.451	−0.443		−0.589	−0.582
750 kWh					
1000 kWh		0.031			0.041
AVI[a]			1.689		
Slope	−0.181		0.001[b]	−0.205	
Income	0.008	0.008	0.001[c]	0.010	0.010
HDD	0.104	0.102	0.090	0.134	0.131
CDD	0.490	0.489	0.359	0.662	0.660
Dummy HDD	1.946	1.947	1.477	2.641	2.644
Dummy LA	0.136	0.122	−0.096	0.194	0.177
R^2	0.476	0.476	0.555	0.493	0.493

[a]Instrumental variable for average price.

[b]Insignificant, i.e., t statistic = 0.04.

[c]Significant at 5% level only.

trated in Fig. 1. We chose the year 1992 to estimate the long-run stock adjustment. Projections of new customer growth and appliance saturations are based on GSU estimates. The only exception involves space heating, for which a special economic evaluation procedure must be introduced because the competition between gas and electricity is intense.

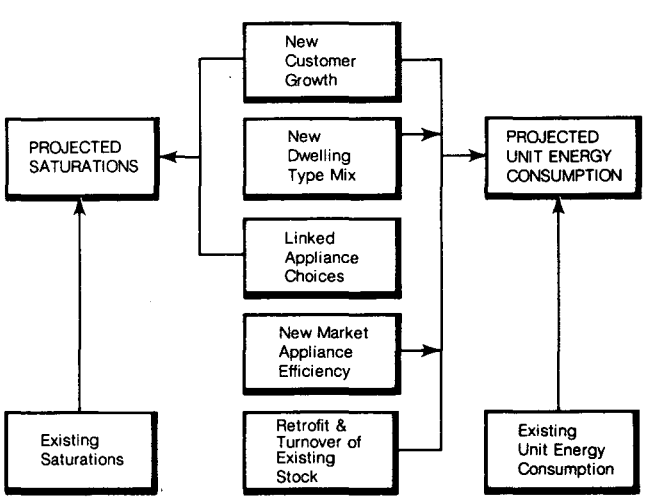

Figure 1. Methodology for projecting unit energy consumption and appliance saturation. (XBL 8310-611)

The 1982 UEC's for most appliances are estimated from other utilities. Simulations for single-family homes, apartments, and mobile homes provide detailed knowledge of current consumption and potential future changes. Surveys of current building practices by the National Association of Home Builders provide specifications of thermal properties that allow reasonable matching to DOE-2 simulations. It is then possible to see the improvement in performance of new buildings relative to the average building in GSU's service territory. Estimates of heating and cooling loads for further plausible improvements are also easily obtained. This information is necessary for the economic model of heating fuel choice.

To project the UEC's for the 1992 appliance stock, we make use of the ORNL model adapted to the GSU situations. Relying upon a GSU price fore-

cast and DOE-2 estimates of cooling hours, we calculated the year-by-year average efficiency of new appliances. Figures 2 and 3 give two examples. These are graphs of efficiency improvements induced by price increases relative to new units of base year 1982 vintage. For refrigerators, a 50% efficiency increase occurs. For central air conditioning, the ORNL model projects a trajectory that looks much like the GSU price forecast, on which it is based. There is a steep increase in the middle 1980s followed by a more gradual decline. According to the logic of the ORNL model, the difference in Figs. 2 and 3 follows from air conditioning being closer to its economically optimal efficiency, compared with the substantial distance of refrigerators from the optimal.

Table 2 shows the results for 1982 and 1992, for the same nine end uses. Broadly speaking, the change between 1982 and 1992 is increasing appliance saturation and decreasing UEC. Space heating grows from 24% to 30% of the market, and central air conditioning from 53% to 65%. Room air conditioning declines from 28% to 21%. Large decreases occur in the UEC's of some uses due to the substantial price increases anticipated by GSU. The net effect of these two trends is a decline in average use. For the period estimated, the resulting numerical values required for Eq. (11) yield the following stock adjustment elasticity:

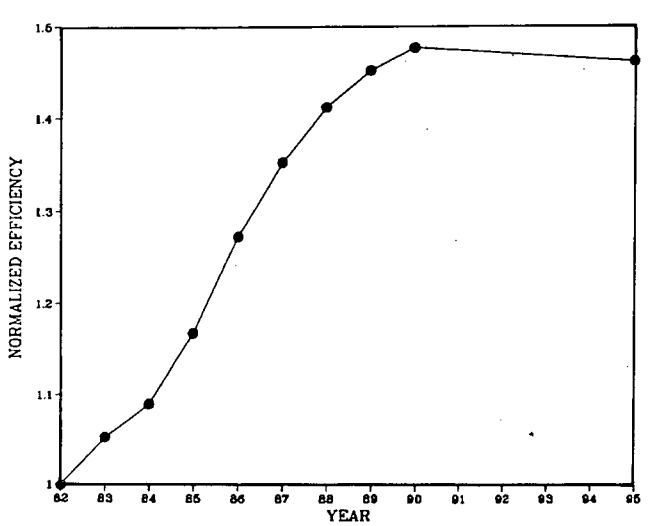

Figure 2. Year-by-year average efficiency of new refrigerators, showing efficiency improvements induced by price increases relative to units of base year 1982 vintage.
(XBL 845-1961)

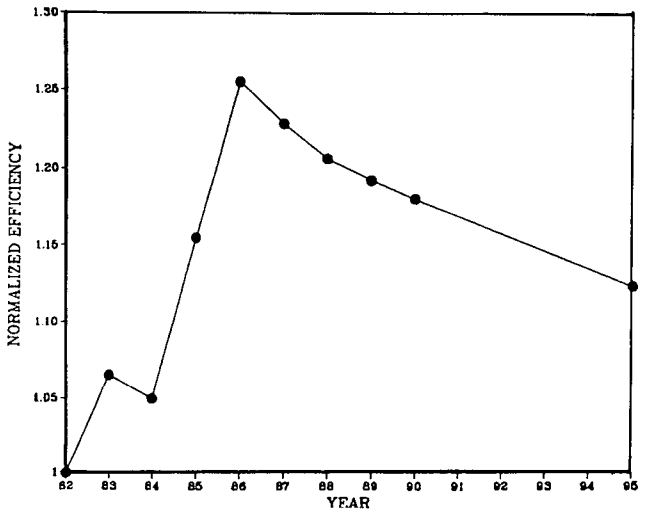

Figure 3. Year-by-year average efficiency for new air conditioners, showing efficiency improvements induced by price increases relative to units of base year 1982 vintage.
(XBL 845-1962)

$$N_{LR} = (-17\%)/(+48\%) \quad , \tag{12}$$

$$= -0.34 \quad .$$

What is usually referred to as the long-run price elasticity is the sum of the two effects we have studied, the short-run utilization elasticity and the long-run stock adjustment. For our data and procedures, this results in an estimated elasticity of -0.53.

As we noted at the beginning, elasticity figures vary widely in the empirical literature, and it would be useful to understand the sources of this variation. One cause, certainly, is that elasticities are typically estimated from data over which it is impossible to have perfect control, so that there is always a question about the comparability of various results. It is clear, however, that the share of the consumer's budget that electricity takes is positively related to elasticity. Figure 4 illustrates this relationship, as given by two recent reports,[4,7] as well as the variability of results among studies.

Our research indicates that short-run utilization elasticity is much easier to estimate in a controlled manner than the long-run stock adjustment. The slow turnover of the appliance stock and the influence of exogenous factors makes empirical estimation of Eq. (11) quite difficult. It is not uncommon, therefore, to find widely ranging differences.

Table 2. GSU average use per customer-month of nine appliances and services, 1982 and 1992 (projected).

	SAT_i		UEC_i		Avg. kWh/Mo.	
End use	1982	1992	1982	1992	1982	1992
Non-weather sensitive						
Refrigerators	1.10	1.10	100	70	110	77
Water heating	0.32	0.36	443	331	142	119
Electric range	0.51	0.50	60	60	30	30
Freezer	0.48	0.48	100	70	48	34
Clothes dryer	0.55	0.55	100	100	55	55
Lighting	1.00	1.00	90	80	90	80
					476	395
Weather sensitive						
Central air conditioning	0.53	0.65	548	387	290	252
Room air conditioning	0.28	0.21	180×1.78[a]	142×1.78[a]	90	53
Space heating	0.24	0.30	494	375	119	113
					499	418

[a]Average number of room air conditioners per household.

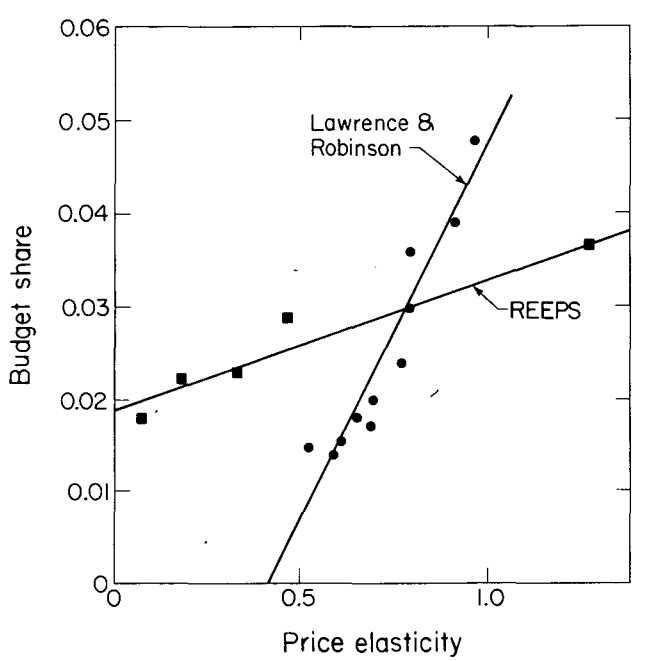

Figure 4. Price elasticity vs. share of budget for electricity, as estimated by two recent studies.[4,7]

(XBL 835-9868)

PLANNED ACTIVITIES FOR FY 1984

The approach outlined here could be extended to other utilities or to other consumption sectors. In particular, commercial buildings represent a possible extension. However, no work is currently planned.

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Residential Energy Use and Conservation in OECD Countries*

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In 1979, the Lawrence Berkeley Laboratory (LBL) was asked by the U.S. Department of Energy to gather demographic, economic, and energy data for the residential sectors of a variety of countries in the Organization for Economic Cooperation and Development (OECD); the study was to cover energy use from 1960 through the present,[1,2] and to analyze consumption patterns and their evolution.[3] The purpose of the study is to permit valid comparisons between countries over time so that trends and national cultural and policy differences can be interpreted. The project is continuing through FY 1984.

ACCOMPLISHMENTS DURING FY 1983

Our efforts concentrated this year on interim analysis of data covering the years 1960 through 1980, and on written description of our work.[4] Special studies of Denmark[5] and Sweden[6] were performed. We also prepared a series of research memoranda on Italy, France, and West Germany that will be expanded into full reports. Finally, we developed a large amount of data on U.S. residential consumption and conservation, covering numbers of dwellings, new dwellings, fuels and heating systems, degree-days, and so forth.[7,8] Econometric analysis of energy consumption data was also undertaken.[9] The following review highlights our data findings and analytical results, and discusses changes in energy use that have taken place over the past decade.

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Method

For each country and year, we developed a matrix of residential energy end uses and fuels using measurements or surveys and engineering or economic estimates. In most cases, our estimates are validated by more than one independent study. After determining the structure of space heating energy use, we calculated energy uses for hot water, cooking, and appliances. We interpreted reductions in intensity as signs of energy *conservation*; if appropriate, further normalization accounted for changes in intensity caused by other factors. As an example of our findings for a particular country and year, 1980 data from Sweden are displayed in matrix form in Table 1. The table shows consumption in petajoules (PJ, 10^{15} J), equipment stocks, and energy intensity (in GJ/unit), for each fuel and use. Space heating data are given separately for single-family and multi-family dwellings.

Comparisons of Residential Energy Use

We have assembled data into matrices similar to Table 1 and have reconstructed residential energy use by fuel and end use[2] for ten OECD countries. Table 2 gives aggregate energy intensities and indicators, corrected for climate, over a variety of years for six countries. It gives energy use per dwelling reckoned as actual consumption, consumption including primary energy losses in the production and distribution of electricity and district heating, and "net" or delivered energy. Liquid and gaseous fuels are counted at 66% efficiency, solids at 55%, and all cooking at 75%. Electricity and district heating are counted at their delivered values.

Although residential energy uses vary widely, certain trends and characteristics are clearly shared by all countries. All energy uses except cooking increased considerably through the mid-1970s, when heating's dominating share of consumption began to fall. Growth rates for fuel and electricity use were generally higher before 1972, slowing thereafter; the share for electricity grew most rapidly, though this

Table 1. Sweden: Residential energy use data for 1980.

Population: 8,317,000 Central heating (%)[a]: 98.5/99.8				Number of dwellings: 3,655,000 Climate: 4474 DD_{18c}		
Fuel	Space heating[a]	Water heating[a]	Cooking[a]	Electric appliances	Total actual	Total normalized[e]
Oil, PJ	133.1	48.6	-	-	181.7	167.9
Stock, 10^3	860/1040	860/1040	-	-		
Intensity, GJ	92.7/50.6	29.9/22.0	-	-		
Kero, Coke, Gas, PJ[b]	1.87	0.48	0.58	-	2.93	2.68
Stock, 10^3	16.3/17.5	10.3/12.5	-	-		
Intensity, GJ	70/40	-	-	-		
Wood, PJ	26.7[c]	2.3	0.2	-	29.17	26.4
Stock, 10^3	122/3.5	90/2.5	100	-		
Intensity, GJ	72/36	25/18	2	-		
District heating, PJ	41.8	17.2	-	-	59.0	54.6
Stock, 10^3	62.9/921.3	62.9/921.3	-	-		
Intensity, GJ	79.0/40.0	20/17.3		-	-	
Electricity, PJ	25.4[d]/1.5	11.25	7.6	37.51	83.25	80.46
Stock, 10^3	550/65	575/75	3300	3655		
Intensity, GJ	44.6/25.4	18/12	2.7/2.0	10.26		
Total, PJ	230.3(206.4)	79.8	8.4	37.5	356.3	342.2
Total, GJ/dwelling	63.0(56.5)	21.8	2.3	10.3	97.5	93.6
Share	60%	23%	2%	15%	104%	100%

[a]Slashes separate houses (SFD, single-family dwellings) from apartments (MFD, multi-family dwellings).

[b]Kerosene, gas, and coke were combined; kerosene (0.2 PJ) is used only in noncentral systems, coke (0.4 PJ) only in central systems, gas in both. Cooking is gas only; water heating, both coke and gas.

[c]Includes 17.4 PJ used as second fuel in 400,000 SFD; about one-fourth of the SFD and one-half of the MFD have noncentral wood systems.

[d]Includes 0.75 PJ used in 200,000 SFD.

[e]Heating is normalized by multiplying the ratio of normal degree-days (base 18°C) to actual. End-use shares are given relative to the normalized total.

growth has slowed as many appliances approached saturation.

Our analysis of these trends showed that:

(1) Increases in dwelling area and equipment ownership (central heat, running hot water, and major appliances) due to higher incomes account for the increases (4–8%/annum) in residential energy use through 1973 and the remaining growth in the late 1970s.

(2) Great variations in ownership, lifestyle, and energy intensity occur even at roughly similar income levels. Differences in prices, climate, housing stocks, heating, bathing and cooking habits, and engineering efficiency contribute to these variations. After these principal factors are accounted for, however, there are still significant differences in efficiency of heating and appliance systems among countries.

(3) Increased energy prices since 1972 have induced reductions in energy intensities and, more recently, caused shifts away from oil heating systems where alternatives existed.

(4) Energy conservation programs have encouraged investments in energy-saving equipment that might not otherwise have been undertaken. Still, the effects of these programs on total energy saved appear to be less than the short-term actions taken by consumers alone. Information programs have probably played an important role advising consumers of options

Table 2. Average residential energy use per dwelling in six OECD countries (GJ per dwelling; series are climate-corrected).

	1970/71	1972/73	1975/76	1977/78	1980	1981	1982	AAGR[a]
				Delivered Energy per Dwelling				
Canada	187	-	175	-	-	143	-	−2.6%
Denmark	124	124	-	118	92	85	82	−4.1%
France	-	80	73	77	72	70	-	−1.7%
Germany	-	84	83	87	81	75.5[d]	76[d]	−1.0%
Sweden	110	111	105	96.5	91	91	89	−2.2%
U.S.	162	-	147	-	133	-	122	−2.4%
				Primary Energy Use per Dwelling[b]				
Canada	246	-	249	-	-	222	-	−1.0%
Denmark	147	150	-	150	123	115.5	111	−3.0%
France	-	92	87	95	93	91.5	-	±0%
Germany	-	102	104	110	106	99.6[d]	100[d]	−0.2%
Sweden	137	143	142	140	138.5	140[d]	143[d]	±0%
U.S.	212	-	203	-	193	-	179	−1.4%
				Useful Energy per Dwelling[c]				
Canada	134	-	129	-	-	109	-	−2.0%
Denmark	91	92	-	89	71	63	62.5	−3.8%
France	-	55	-	58.5	51.5	49	-	−1.4%
Germany	-	58	59	62	59	52[d]	54[d]	−0.7%
Sweden	80	82	80	75	73	72.5	72	−1.3%
U.S.	116	-	107	-	98	-	90	−2.1%

[a]AAGR = average annual growth rates; these are calculated for the years between 1972 (1971 Canada, 1970 U.S., 1973 France) and the last year for which data are shown for each country.

[b]With district heating counted at 75% total efficiency and electricity counted at 34.6%. (Actual consumed DH multiplied by 1.33; consumed electricity multiplied by 2.89.)

[c]Oil and gas consumption for heating and hot water multiplied by 0.66, solid fuels by 0.55. For cooking, all consumption was multiplied by 0.75.

[d]Preliminary value.

for conserving energy, but no measure of their actual effect has been attempted.

The explanation of these differences depends upon several factors. *Energy prices* and *disposable income* influence the choice of systems and fuels, the marginal cost of using systems, and the economic attractiveness of conservation investments; *outdoor climate* affects heat required to maintain a given indoor temperature, which also depends on *habits* and on the *cost of maintaining* that temperature; also important are *dwelling and appliance* type, size, vintage, and construction materials; and *demographic characteristics*, including household size, age distribution, and number of people at home during heating hours.

We used a multinomial logit model to analyze aggregate residential consumption, space heating consumption, and fuel shares over the 1960–1978 period, using many of the factors outlined above. Energy price, central heating saturation, income per dwelling, and dwelling size are all important in explaining energy use. Climate shows important explanatory power only for heating, which increases with the square root of the number degree-days.

Our results gave lower aggregate price elasticity (−0.35 to −0.60) and income elasticity (+0.7 to +0.9) than most other studies we reviewed. They may be interpreted either as long term, because of the cross-sectional nature of the study, or short/mid-term, because of its time-series nature. Long-term effects cause changes in fuel, equipment, and weatherization; short-term effects mean reductions in heating, hot-water, and appliance use. Our elasticities are so low because we used an aggregate price and included more explanatory structural variables than other studies.

Dummy variables suggest that Europe uses less energy per dwelling, relative to the United States, than can be explained by the logit model. Stock vintage, building codes, and government housing policies may play a role here. In the Japanese space-heating data, there is a large unexplained residual that we believe is accounted for by lifestyle and culture.

To learn more about the nature of residential energy use, we studied Denmark, Sweden, and the U.S. in great detail. Before 1972, U.S. residential energy use was the highest, followed by that in Denmark, then Sweden. The drop in Denmark after 1973 was so great, though, that it fell below the level of Sweden in 1982. Denmark and Sweden have many common features, such as the highest shares of oil heating and district heating in the OECD. But after 1973, Sweden, like the U.S., found many alternatives to oil use, while Denmark found few. Through conservation efforts, however, the drop in oil use per home in Denmark was the largest in the OECD. We examine this and other conservation trends in the following section.

Our comparison of energy use is made easier with indicators that relate energy use per dwelling to key structural features of the dwelling stock or the economy. Table 3 shows (net) energy use for heating, per degree-day, per square meter of home floor area, for six countries. It shows clearly both Sweden's dominance in efficiency and the drop in energy use in the U.S. and Denmark after 1973.

Energy Conservation Since 1972

Energy "savings" depend both on conservation—the decrease in intensity—and on structural changes, reflected in the increase in penetration of devices over time as incomes rise. Measured over energy form, dwelling type, and end use, the total savings per dwelling can be multiplied by the total number of existing dwellings, and end-use energy can be converted to primary energy, to show the grand total savings.

Our estimates of energy savings, on a per-dwelling basis, are shown in Table 4. We separated fuel, electricity, and district heating, found the savings, then compared the 1980 total energy use of the stock of central heated homes at actual and at 1972 intensities. In this analysis, we lump all "conservation" into the heating indicator, and assume that more efficient use of hot water and appliances has just balanced increased use of hot water or larger appliance sizes.

Actual energy use per dwelling was lower in 1980 than in 1970–72 in Denmark (by 20%), Sweden (15%), the U.S. (about 20%), and Canada (5% in 1978)—all countries that had already reached saturation of energy services and appliances by the early seventies. Further decreases were recorded in 1981, but 1982 appears to have been stable. In Germany, France, Japan, and Italy, structural growth appeared to offset much conservation. But in these countries,

Table 3. Normalized residential energy consumption.

	Heat per dwelling per degree-day per m^2 area, kJ							
	1970/71	1972/73	1975/76	1977/78	1980	1981	1982	AAGR[a]
Canada	211	-	194	-	-	148	-	−3.6
Denmark	284	-	-	242	179	164[b]	149[b]	−5.4
France	-	232	-	204	176	161[b]	-	−4.6
W. Germany	-	199	192	199	177	160[b]	-	−2.4
Sweden	160	159	-	134	122	124[b]	119[b]	−2.5
U.S.	216	-	189	-	157	-	-	−3.2

[a]Average annual growth rate calculated from year closest to 1973 to latest year.

[b]Preliminary value.

Table 4. Estimated total energy conservation in centrally heated dwellings, by percent reduction per dwelling, 1972–1980.

	Fuel (%)	District heat (%)	Electricity (%)	Total (%)	GJ/ Dwelling
Denmark	45	20	5	35	32
France	19	21	15	18	27
Germany	25	~20	10	18	20
Sweden[a]	22	15	10	13	17
U.S.[a]	22	-	?	20	18

Source: Energy Analysis Program data base.

[a]The Swedish and U.S. figures are reduced to reflect the use of wood as a secondary fuel. Data on the use of wood are not available for other countries.

energy use per dwelling would have been significantly higher—as much as 20%—had not heating energy use been reduced. In Sweden and elsewhere, back-up fuels (electricity and wood) have become important as sources of extra heat, particularly in individual rooms or sitting areas.

We judge that most of these savings came about through reversible short-term actions arising primarily from higher prices, except in the notable case of Sweden. Energy use in Sweden was reduced significantly because of conservation in the long term. In addition, the structural increases were considerably slower than in the 1960s, as can be seen by comparing rates of increases in penetration of central heat, appliances, and hot water before and after 1972. This means that future growth in total energy use will slow even more because of conservation investments, stock turnover, and the eventual saturation of the largest energy services. In the future, vigorous conservation programs and rising energy prices could reduce markedly the residential energy demand of the U.S., Canada, Denmark, Sweden, Germany, and the United Kingdom.

Implications for Developing Countries

Aggregate data are also useful for making comparisons with OECD-like portions of populations in developing countries, particularly those in cities. Our studies may therefore help those trying to improve our understanding of energy use in those countries.

In other work,[10] we have found that energy use in urban middle- and upper-income households in a variety of countries—Kenya, the Republic of Korea, Tunisia, Taiwan, Thailand, Venezuela—closely resembles household energy use in the OECD countries once allowance is made for differences in income, eating habits, and climate. This suggests that the "OECD style" of household energy use is popular. Careful study of the evolution of energy use in OECD households with changes in incomes and with changes in technologies might provide clues important to forecasting and funding attractive energy-conservation strategies in developing countries.

Conclusions

When all the countries studies are considered together, the relevance of income level in determining energy use appears obvious. Within this group, however, the most efficient countries are those with higher energy prices. The colder countries heat more efficiently than the moderate or warm countries. Higher energy prices in 1974 and 1979 had a marked impact on consumption and growth.

One implication of the cross-sectional analysis is that heating in most countries is still far from the efficiency levels found in Sweden. Not all of this difference can be captured in existing homes through retrofit, but retrofit and stock turnover can reduce heating needs markedly. Similarly, we expect that new electrical appliances, water heating systems, and even cooking appliances will be far more efficient in the long term. Thus, in each country there may be a constant decline in energy use per dwelling towards the end of this century, depending on the costs and benefits of additional energy-saving measures.

PLANNED ACTIVITIES FOR FY 1984

We are updating our data base to focus on changes in energy use through 1982, a year in which energy prices stopped rising in real terms. We expect to be able to test our econometric model with more recent data as well, and to estimate the impact of conservation programs in some countries. We will improve estimates of the permanence of the decline in oil consumption.[11] Analysis will be extended to the Netherlands and Norway. We are also building a data base on energy uses in commercial buildings in our study countries. Finally, we will be investigating many developing countries to see how energy use is developing in the residential and commercial building sectors.

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Energy Efficient Housing in Sweden*

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LBL studies have shown that energy use for space heating in Swedish homes are among the lowest for countries in the Organization for Economic Cooperation and Development (OECD).[1,2] We therefore decided to examine Swedish practices more closely, and associated policies as well, to look for techniques and policies that might be of interest in the United States.

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ACCOMPLISHMENTS DURING FY 1983

We began by comparing Swedish and U.S. residential energy use (and living patterns)[3] and confirmed that Swedish heating practices are the most efficient in the world. We then produced a short history of energy conservation in new homes in Sweden and examined technical progress (including actual R-values in walls and ceilings of new homes); analyzed the role of home loans, building codes, and other factors that stimulated improved technologies; estimated the costs and savings produced by these technologies; and speculated on the role these techniques might play in the United States.

The major findings of our study can be summarized as follows:

- Homes in Sweden use less energy for heating, adjusted for climate, than homes in any other OECD country, yet maintain the highest standard of indoor thermal comfort (Fig. 1).
- Since 1973, older homes in Sweden have reduced heating needs by about 15%, primarily by adding insulation, as well as through other techniques. Figure 2 shows heating, in MJ/degree-day, for three classes of single-family dwellings representing about 75% of the stock. In contrast, most of the savings observed in homes in the United States and

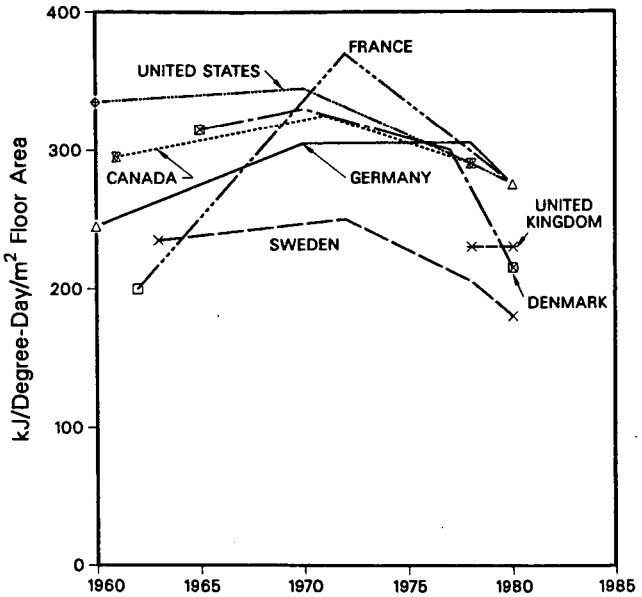

Figure 1. Comparison of average annual energy consumed for space heating, adjusted for climate and area, among seven developed countries, including Sweden and the United States. (XCG 8310-7246)

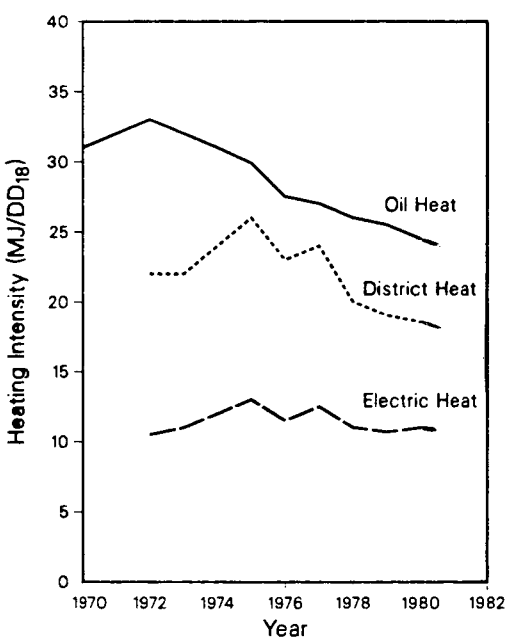

Figure 2. Heating energy use, by fuel, in single-family dwellings in Sweden; heating intensity given in megajoules per degree-day (base 18°C). District heating burns natural or coal gas. (XCG 834-7031)

elsewhere have been achieved by reducing temperatures and other short-term measures.

- Homes built in Sweden since 1973, and particularly those built since 1978, are considerably more efficient than those built before 1973, and are still world leaders in heating efficiency. Figure 3 shows energy consumption per square meter for heating and hot water in 1981 in all-electric single-family dwellings built in the years indicated. The low values for the oldest homes reflect retrofit actions.

The technical reasons for these achievements include high insulation levels (even in homes built long before 1973), multiple glazing, efficient heating systems, good installation and upkeep of components, and, more recently, use of heat pumps and other new heating technologies. Lifestyle plays only a minor (if not offsetting) role in achieving energy savings in Sweden. The Swedish building industry and homeowners/occupants have achieved these savings at lower costs than the cost of obtaining energy. Indeed, the primary motivation for the achievements we have seen has been to *reduce the cost of staying comfortable.* This suggests that the achievements in Sweden are achievable and economic elsewhere, and that Swedish housing technologies could save a great deal of energy in the United States, particularly in new housing.

When we examined the policies that encouraged energy efficiency in Sweden, we found that the Swed-

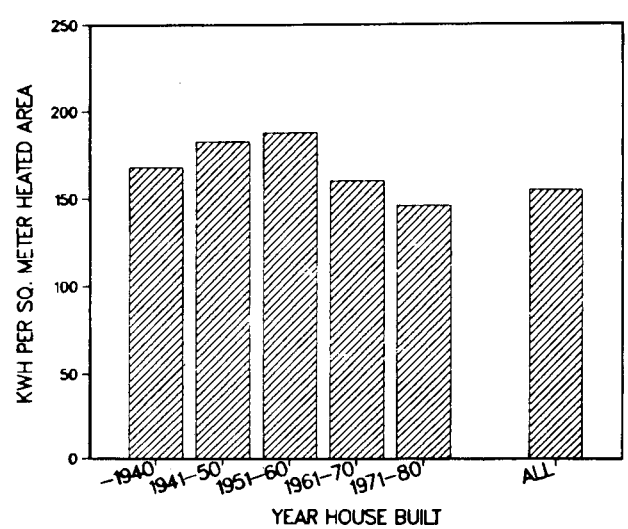

Figure 3. Average electricity consumption for heat and hot water in Swedish single-family houses using electric-only heating. (XBL 845-1969)

ish achievements in energy efficiency did not arise out of a system of forcing regulations, but rather out of a need, recognized by all members of society, to achieve a high level of indoor comfort and hygiene at a reasonable cost. While building codes have played an important informational role in showing consumers and builders the approximate economic levels of insulation and in stimulating the building community to reduce the heating needs of new homes, they have not yet forced energy conservation upon the great majority of builders or occupants.

Actual energy-saving practices in Sweden have always exceeded code requirements. Shown in Fig. 4 are actual values of k [($k = 1/(5.6 \times R)$], installed in the walls and attics of all single-family dwellings built in the 1970s in Sweden when the builder initiated the project (50% of starts) and the state provided financing (typically 90% of starts). The state-financed system of home loans has actively encouraged increasingly greater thermal performance by effectively removing the first-cost barrier for a wide variety of heat-saving investments. Specifically, home loans expanded to cover the increased first cost for extra insulation and other measures. Thus, the *carrot*, not the *stick*, has been the primary policy instrument in Sweden.

It is important to note, however, that energy conservation has always been embedded in housing policy, which was important for decades, if not centuries, in the Swedish political tradition. When the 1973 oil embargo increased concerns over energy,

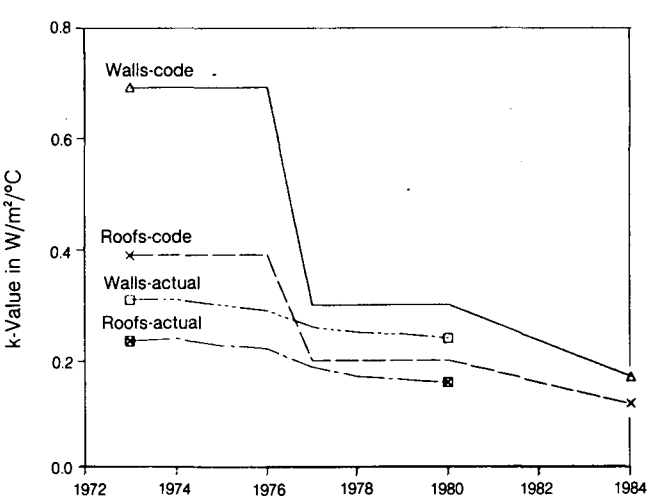

Figure 4. Values of k [($k = 1/(5.6 \times R)$; k-values, in watts/m^2/°C, correspond to English U-values], both as installed in the walls and attics of all single-family dwellings built in the 1970s in Sweden, and as prescribed by Swedish building codes. Note how installed values are always well within code. (XBL 845-1970)

few new agencies, actors, or arrangements were needed for the government, the private sector, and individuals to respond.

This is not to say that the policies put in place after 1973 were unnecessary, rather that they were well matched to existing policies and organizations. After 1973, the Swedes presumably increased the flow of information relating to home energy conservation, and research was increased measurably to accompany the increased use of state financing programs (the carrot).

In short, energy conservation programs and incentives for new and existing homes were widespread and pervasive before 1973, but the primary stimulus for savings in existing homes since then has still been the significant increases in oil prices. Without the pervasive information existing in Sweden before and after 1973 and a stepped up R&D program, however, it is doubtful that the post-1973 achievements in both existing and new dwellings would have occurred. Furthermore, the well-established R&D program contributed over many decades to the ease with which Swedish scientists and companies developed even more energy-efficient heating practices after 1973.

A separate program of loans and grants for retrofit also succeeded in stimulating substantial investment in conservation in existing homes. In all, the program provided nearly $850 million (at 1983 exchange rates) in low-interest loans and grants, and a smaller but important sum in interest subsidies that affected over one-half of the building stock. However, as many owners of single-family dwellings made conservation investments *without* state aid as with it, suggesting that while the program was sufficient to cause savings, it would not have been entirely *necessary*. For multi-family dwellings (for which heat is by tradition almost never metered), the program had a stronger role in spurring savings that otherwise might not have been made.

The loans/grants program and the information campaigns of the 1970s were primarily *passive* efforts. Little outreach was attempted, except through media advertising. Other programs of information instituted during the later 1970s or early 1980s have taken on a more activist nature, but it is too early to judge their success. However, many regions of the United States have utility or community programs that are more aggressive than those in Sweden.

Swedish homes use 30% to 50% less heat, adjusted for climate and house size, than do homes in the U.S. In addition, insulation levels have increased roughly with oil prices, thus stabilizing the

cost of home heating. In the U.S., though, overall achievements in home energy conservation still lag considerably behind heating costs, particularly in technologies for walls, windows, air-tightness, heat recovery, and indoor air quality.

These differences suggested that it would be worthwhile, both from a purely technical/economic standpoint and from a policy standpoint, to examine the prospects for adapting the Swedish techniques in this country. We found that these technical achievements are both transferable and economically attractive here. In fact, Swedish technology appears to save energy at lower cost, per unit of energy saved, than do U.S. techniques in the same areas of construction (windows, roofing, etc.).

Unfortunately, we also concluded that the marketplace alone—the pressure of higher energy prices—will probably not support the duplication of the Swedish achievements in the United States, for several reasons: the lack of knowledge in the U.S. building industry about the technology and techniques used in Sweden; financial barriers in the building industry and in financial and real estate institutions and practices (basically, the added first costs that must be figured into the price of a home); and the perceptions of the homebuyers themselves, who move more often than homebuyers in Sweden do and thus realize they might not recover their first costs. For these reasons, it would be impossible to simply "legislate" the Swedish improvements overnight in the U.S.

The primary difference between Swedish and American housing can be interpreted as a difference in time horizons. Swedes build homes with investments that take decades to pay back at low rates of return, reflecting low discount rates, while Americans appear to require very quick paybacks, i.e., times less than 7 years, at high rates of return. In Sweden, the carrot, not the stick, is the most important policy instrument that overcomes this potential problem by assuring that loan funds are available for any reasonable conservation strategies in new homes. This, in turn, encourages builders to experiment and develop, since good ideas are taken up rapidly in the marketplace. In the U.S., by contrast, deeply entrenched traditions in home building and financing make it difficult to increase the first cost of a home unless the payback is so large that all parties see immediate benefits.

Housing policy, not energy policy, created the environment that encouraged energy-efficient building practices in Sweden. This lesson may prove applicable in the United States. There is great incentive to find ways to express energy policy goals through the actors and institutions already established in the housing area, such as builders, utilities, and local banks.

We believe that the most important single policy measure the U.S. could undertake to stimulate energy-efficient construction practices is to remove the bias against investments in energy efficiency inherent in the American housing process. This could be done by including energy-related investments in mortgages without applying them against the loan applicant's affordability criteria. This would be justified because these investments would lower the applicant's future space-conditioning costs considerably.

Because Swedish technologies are so well proven in Sweden, the U.S. may be able to adopt many of them without the long tradition of housing development that supported progress in Sweden. This adoption could be accelerated if the U.S. would:

- Encourage buyers, builders, and occupants to invest in efficient homes through changes in national and local lending practices;
- Increase its R&D in the area of housing and energy, working primarily with builders and suppliers;
- Support a massive builder and owner/occupant education effort;
- Support a widespread information and testing program to demonstrate the savings that good building practices in the U.S. have achieved in some areas;
- Support a widespread program of retrofit research, demonstration, and education;
- Support a massive builder and owner/occupant education effort; and
- Price energy at its replacement cost.

At present, the most attractive option for U.S. builders and homebuyers seeking to reduce their comfort costs may be to purchase Swedish technologies or manufactured houses, whose energy-saving properties have been validated from years of experience in Sweden. These technologies and houses could convince U.S. builders, financers, and homebuyers that energy efficiency in homes is both affordable (in its first costs) and economically attractive over the long run.

PLANNED ACTIVITIES FOR FY 1984

We will complete a book-length manuscript and several shorter articles, and we will conduct seminars in the U.S. and Sweden. We expect to follow up this study by examining consumption in the newest

homes in Sweden, and then comparing recent achievements there with better practices and results in regions of the U.S. where there is interest in energy-efficient housing practices.

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Energy Demand and Energy Efficiency in the Developing Countries*

J. Sathaye and L. Schipper†

During the 1970s, energy use in developing countries increased at an average annual rate of 6.6%, more than four times the rate in the developed market economies. This pattern suggests that most of the future growth in world energy use will occur in developing countries. In addition, their financial stability and overall socioeconomic progress are closely related to their imports of oil and other fuels. The tenfold increase in oil prices over the past decade has thus given urgency to energy-demand analysis as a key to understanding the future development of these countries.

To improve our understanding of both energy demand and economic development in developing countries, we have undertaken a study of their energy use patterns. For our initial study, we chose 15 countries on the basis of their energy use. These countries account for over 75% of the energy demand in all developing countries. Most of them also compile official statistics on energy supply and demand, which greatly simplifies the gathering of information for analysis. The countries are Argentina, Bangladesh, Brazil, Columbia, India, Indonesia, Korea, Malaysia, Mexico, Pakistan, Peru, the Philippines, Taiwan, Thailand, and Venezuela.

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†Assisted by S. Meyers and A. Ghirardi.

ACCOMPLISHMENTS DURING FY 1983

Approach

Studies of energy demand are often limited to examining energy balances. While energy balances are useful, they are only the starting point in understanding energy use. Therefore, besides compiling energy balances for the countries under consideration, we sought to establish or validate the proportion of energy use for which the various subsectors of the economy were responsible, and to relate energy use to the production of goods and services.

Our analysis of energy demand is based on the use of indicators, an approach developed for the study of energy demand in OECD countries.[1] To relate energy consumption to economic and structural variables, we developed a systematic approach that uses suitable *indicators* of energy demand. We define these indicators according to the individual characteristics of each sector. Table 1 gives examples of some of the indicators used so far. Indicators can be constructed at more detailed and finer levels than shown in the table. For specific countries, where detailed data are available, we will define additional indicators.[2]

Our study is based on three factors that influence fuel consumption in each sector. These are: (1) composition of sector, (2) fuel substitution and switching, and (3) conservation (reduced energy intensity).

Composition is defined according to the structure of each sector. In the industrial sector, composition is defined by the contribution of each type of industry to value added. In the transportation sector, it is defined by the number of vehicles of each type—cars, trucks, and two- and three-wheelers. In the residential sector, it is defined by the number of households of each type—single versus multi-family. Additionally, in this sector, composition can be defined by income class.

Changes in composition occur for many reasons, of which energy is only one. Other, perhaps more

Table 1. Examples of indicators for energy-demand analysis.

Economic sector	Indicator
Overall economy	Energy/gross domestic product (GDP)
Industrial	Oil/value added Electricity/value added Energy[a]/value added
Transportation	Fuel use/vehicle Cars/GDP Fuel use/passenger-km
Residential	Electricity use/customer Fuel use/m^2–degree-day[b] Total fuel use/national population
Power	Electricity generated/ electricity sales

[a]Total of oil and electricity.

[b]This indicator was used only to analyze heating use in OECD countries; it was not used in our analysis of developing countries.

important reasons include production factors (land, labor, and capital) and government policies such as taxes, subsidies, price controls, and licensing.

Fuel substitution or switching is determined by the price of fuels, their availability, costs of switching from one fuel to another, and government policies.

Conservation can result from installation of new plant and equipment, as well as from improved management. Conservation in the form of new plant and equipment can be prompted by any of the reasons that affect composition. Conservation in the form of improved plant management is primarily a response to higher prices and, sometimes, to government policies.

Data Base

To facilitate the comparison of energy information and indicators for each country, we developed a computerized data base containing the following types of data for each study country:

- fuel supply and end use by sector (primary and secondary fuels);
- fuel prices;
- economic data—Gross Domestic Product (GDP) by sector, population, trade, households, composition of sectoral output, price indices, etc.;
- sectoral structure, e.g., for the transportation sector, number of cars, trucks, and buses, and length of highways and paved roads.

The primary sources of data have been official publications issued by the individual countries and by international institutions such as the International Monetary Fund (IMF), International Energy Agency (IEA), United Nations (UN), Latin American Organization of Energy (LAOE), Interamerican Development Bank (IDB), Asian Development Bank (ADB), and the World Bank.

At present, the data base contains most of the information available on energy use in Latin America, some energy data for the Asian countries in the study, and economic information on population, GDP, and structural variables. The energy data for Latin America were obtained primarily from a single source, LAOE. The information on energy use in Asia comes from several sources.

Results

Industrial Energy Use

In the Asian oil-importing countries—Korea, Taiwan, Thailand, the Philippines, India, and Malaysia—the energy use per unit of value added declined from 1970 to 1980. In the Latin American oil-importing countries—Brazil and Colombia—a decline is also noticeable. In Venezuela, the trend was upward (i.e., toward less efficient consumption) until 1979. In Argentina and Peru, the trends are less clear.

Oil use per unit of value added declined more rapidly than energy use per unit of value added in Argentina, Brazil, and Colombia. In three countries—Korea, Taiwan, and India—the ratio increased faster than did the ratio of energy use to value added. This suggests a move, in these countries, toward petroleum products and away from other fuels during the 1970s. Four countries—the Philippines, Malaysia, Thailand, and Peru—showed the same rate of decline (which is not surprising, since oil accounts for over 90% of the energy used in these countries).

Electricity use per unit of value added increased about 10% above its base value during the 1970s in Mexico, Peru, Korea, Taiwan, Thailand, and India. In Peru, the ratio jumped 22% from 1970 to 1972 but has changed little since then. The increase was about 20% above its base value in Brazil and Colombia. In the Philippines and Malaysia, the ratio

declined by about 10%. In Bangladesh, the 1973 value should be ignored because the country had a turbulent birth in 1971 and the economy had not yet settled down; however, the ratio increased by 20% from 1975 to 1980. In Venezuela and Argentina, the ratio varies abruptly without any clear trend. These electricity ratios show that more intense use of electricity is generally not occurring in the industrial sector.

There are three basic reasons for these changes in intensity: composition of industrial output, fuel substitution, and conservation. The extent to which each factor was responsible for these changes varies by country.

South Korea provides a good example of composition change and conservation at work. The Philippines present a contrast to the Korean example, since there was no change in composition. Conservation through management played the most important role in improving energy efficiency in the Philippines.

The changing composition of the industrial sector is having an important effect on energy demand. We find in most, but not all, Asian countries in our study that: (1) the rate of growth in the manufacturing sector has been higher than the rate of overall economic growth; (2) the growth rate of the manufacturing sector's share of total GDP is not proportional to the rate of overall economic growth; and (3) the composition of the industrial sector does not change in proportion to the rate of overall economic growth.

These observations have consequences for energy demand. First, a high overall growth rate often implies a rapid manufacturing growth rate, further implying that there will be room for conservation though the installation of more efficient new plants and equipment. The improvement in energy efficiency is likely to be permanent if it occurs for this reason rather than because of improved management.

Second, the manufacturing sector's share of economic activity may not increase very rapidly even in growing economies. Most of the East Asian countries are at or beyond the shares that manufacturing constitutes in the developed world. On the other hand, the economies of these countries rely on exports of manufactured goods. This may account for the manufacturing sector's relatively high share, a share that may continue to increase as exports expand. If the manufacturing sector does grow rapidly, then future gains in energy efficiency will be more rapid.

Third, in most countries the composition of the manufacturing sector is slow to change; Korea, however, appears to be an exception.

Transportation

In Latin America, transportation accounts for 24 to 30% of the commercial energy use in each country. In Asian countries, consumption for transportation varies from 11% in Taiwan and Korea to 37% in Thailand.

Gasoline use per *vehicle* declined in all the study countries. Gasoline use per *car* declined in Argentina, Brazil, Colombia, Mexico, Korea, the Philippines, and Thailand. The decline was especially sharp from 1975 to 1980 in Brazil and Korea—33% and 53%, respectively. In Thailand, the decline was smaller, 18%. The number of cars per capita increased with per-capita GDP, again at different rates. We have looked at a few countries in detail to show how the three factors—composition, fuel substitution, and conservation—have changed in the last decade. Gasoline use per vehicle declined by 43% in India during this period. Gasoline consumption can decline because of the introduction of more efficient vehicles, reduced driving, and an increasing share of two- and three-wheel vehicles. In India, the cars are mostly of 1960s design, and there have been no substantial improvements in engine efficiency. Reduced driving did occur during the oil price increases. However, the major reason for reduced gasoline use per vehicle appears to have been the large increase in two- and three-wheel vehicles (carts, scooters, and motorcycles). From 1970 to 1980, the number of these vehicles increased by 274% while the number of cars increased by 48%.

In the Philippines, fuel substitution—that is, a switch to diesel fuel—has played a major role in reducing the consumption of regular gasoline. Premium gasoline use responded to price changes, but did not exhibit a long-run decline because all cars use premium in the Philippines.

The story for diesel fuel is similar to that for premium gasoline. The price of diesel fuel doubled from 1972 to 1974; it increased slowly from 1974 to 1978, then rose sharply from 1978 to 1981, the last year for which we have figures. In the same period, diesel consumption increased continuously. The increase may be explained by the increased stock of diesel vehicles caused by lower prices for diesel than for gasoline, and by the conversion of engines in commercial vehicles from regular gasoline to diesel.

Residential

The share of primary energy used in the residential/commercial sector varies, depending on the amount of heating needed for both space and water. Developing countries that are further from the equator or have populated mountainous regions use more energy in this sector. In 1980, Korea required 26% of its total commercial energy for this sector as compared to only 10% in Taiwan, which is relatively close in per capita income but not in climate. In lower-income countries like India, traditional energy sources such as wood and kerosene still predominate in this sector. Thus in India, only 6% of modern fuels go to residential and commercial uses.

The role of traditional fuels has declined with urbanization and income growth. In our study countries, the level of traditional energy use ends to be inversely related to the level of urbanization. The notable exceptions are Thailand and Malaysia. Given their income levels, both have low urbanization levels—14% and 29%, respectively.

Migration to the cities brings people into the modern sector with respect to fuel consumption. This increases the per capita consumption of commercial fuels. Rising incomes bring more energy consumption, since more appliances are purchased, raising energy use per capita.

Rising incomes also bring about a change in the fuel usage pattern to gas and electricity. Cooking fuel switching occurs from wood and kerosene to electricity and liquified petroleum gas or town gas. For lighting, the fuel switch is from kerosene to electricity.

Perhaps the most striking growth has been in the use of electricity. In Korea, Taiwan, the Philippines, Malaysia, and Thailand, residential electricity use has been growing faster than total electricity use. In Thailand and the Philippines, the growth rates are several times the overall rates.

Two major factors are behind this increase in residential electricity. First, with rising incomes, the number of appliances has increased rapidly. Second, the number of customers is also growing rapidly, due partly to rural electrification programs as well as population growth and migration to the cities. Electricity use in appliances can therefore be expected to continue to increase as the growing population of urban dwellers purchases more electricity-intensive appliances.

Improved energy management is unlikely to have any sizable impact in the short run among users of commercial fuels, except among those with the highest incomes. (In the noncommercial sector, use of improved wood- and charcoal-burning stoves can double the efficiency of fuel use, but their development and penetration is uncertain.) Among high-income users, appliances are large, use depends on lifestyle factors, and there are many water-heating, cooking, and cooling devices whose energy use could be reduced quickly.

In the long term, there is potential for more efficient energy use. As newer, more efficient appliances enter the stock, they will increase residential energy-use efficiency far above what it would have been if only appliances from the early 1970s—and before—were available. Our study of OECD residential energy demand from 1960 to the present confirms the trend to more efficient electric and gas appliances. Of course, there will be more appliances per household, and these will be larger as incomes grow, but they may be more efficient than those now in use.

PLANNED ACTIVITIES FOR FY 1984

During the coming year, our data base will be computerized and expanded to include economic information provided by the IMF and energy data from the IEA and the UN. Additionally, we will document the data sources, validate the data, and issue energy balances for our study countries.

Our major goal for 1984 is to complete our analysis of the 15 countries. This will include a detailed description of sectoral energy use over time, and a review of important trends in structural change or composition, conservation, and fuel switching. Indicators will be developed to measure changes in energy intensity in each country. Trends will be compared among countries to draw parallels between the more developed and the less developed countries. We plan to prepare country reports for Taiwan or Korea, the Philippines, and Brazil in March/April; Taiwan or Korea, Thailand, Peru, and Colombia in June/July; Malaysia, Indonesia, Bangladesh, and Venezuela in September/October; and India, Pakistan, Argentina, and Mexico in December.

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