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FY 1982 Annual Report

ENERGY ANALYSIS PROGRAM CHAPTER

March 1983

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ENERGY AND ENVIRONMENT DIVISION

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

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LBL-15299

ENERGY & ENVIRONMENT DIVISION ANNUAL REPORT

ENERGY ANALYSIS PROGRAM FY 1982

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

CONTENTS

ENERGY ANALYSIS PROGRAM STAFF 5-iv

INTRODUCTION 5-1

Building Energy Analysis

RESIDENTIAL ENERGY CONSERVATION: DEVELOPING A GUIDE FOR HOMEBUILDERS
R.L. Ritschard, Y.J. Huang, J.G. Ingersoll, M.D. Levine,
R.A. Boschen, L. Chang, C. Hsui, and D. Wilson 5-4

THE EFFECT OF WINDOW SIZE AND ORIENTATION ON HEATING AND COOLING LOADS IN RESIDENTIAL HOUSES
Y.J. Huang and R.L. Ritschard 5-7

CLIMATE ANALYSIS IN SUPPORT OF THE HOMEBUILDERS' GUIDE
Y.J. Huang 5-9

DETERMINATION OF THE SEASONAL COEFFICIENT OF PERFORMANCE OF CONVENTIONAL AIR SOURCE HEAT PUMPS IN RESIDENTIAL BUILDINGS
J.G. Ingersoll and D.K. Arasteh 5-15

ENERGY EFFICIENCY IN CHINESE BUILDINGS
Y.J. Huang, A. Canha de Piedade, A.H. Rosenfeld, and D. Tseng 5-18

OCCUPANT BEHAVIOR AND RESIDENTIAL ENERGY USE
P.P. Craig, J.C. Cramer, T.M. Dietz, B. Hackett, D.J. Kowalczyk,
M.D. Levine, and E.L. Vine 5-20

ENERGY CONSERVATION IN PUBLIC HOUSING
R.L. Ritschard and D.F. Dickey 5-25

SIMPLIFIED ENERGY ANALYSIS METHODOLOGY FOR COMMERCIAL BUILDINGS
I. Turiel, R.A. Boschen, M. Seedall, and M.D. Levine 5-29

Economic Studies

ESTIMATES OF RESIDENTIAL ENERGY SAVINGS FROM PROPOSED FEDERAL POLICIES FOR APPLIANCES
J.E. McMahon and M.D. Levine 5-34

COST/EFFICIENCY TRADEOFFS IN THE RESIDENTIAL APPLIANCE MARKETPLACE
J.E. McMahon and M.D. Levine 5-37

HEAT-PUMP ENERGY DEMAND ANALYSIS
H. Ruderman, J.A. Sathaye, and S. Ng 5-40

UTILITY CONSERVATION PROGRAMS: THEORY AND PRACTICE
E.J. Kahn 5-43

RESIDENTIAL HOURLY AND PEAK DEMAND MODEL
G. Verzhbinsky, E.L. Vine, and M.D. Levine 5-45

International Research

INTERNATIONAL PROGRESS IN RESIDENTIAL ENERGY EFFICIENCY
L.J. Schipper, A.N. Ketoff, S.P. Meyers, S. Rosse, and W. Chern 5-49

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ENERGY ANALYSIS PROGRAM

INTRODUCTION

The Energy Analysis Program is engaged in interdisciplinary activities in which analysts representing many different fields work together on issues of national significance. The program's emphasis on economics, public policy, and social issues and behavior 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 these issues. Virtually all of the research and analysis of the program is quantitative, and a large portion of the program research staff is engaged in developing and applying large-scale computer simulation models.

The primary emphasis of the Energy Analysis Program at present is 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 Energy and Environment Division on energy conservation in buildings (especially the Energy Efficient Buildings and the Solar Energy Programs). The Energy Analysis Program provides a rigorous and extensive analytical capability to complement the more specialized 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 will also extend and apply the analysis techniques to other important national and international energy policy issues.

The work of the program during fiscal year 1982 can best 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.

(2) Economic analyses, 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) Commercial building energy analysis, involving computer simulation studies and a preliminary effort to develop a simplified approach to understanding effects of conservation measures on commercial office buildings.

(4) International studies treating aspects of energy demand in member countries of the Organization for Economic Cooperation and Development (OECD) and in less developed countries.

The following describes some of the most interesting and important studies in these four research areas. The first two are in group (1), residential energy studies; the second two, in group (2), economic analysis; the fifth, in group (3), commercial building energy analysis; and the sixth, in group (4), international studies. They are meant to be illustrative of the research of the Energy Analysis Program in FY 1982; others could equally well have been chosen.

BUILDING ENERGY SIMULATION STUDIES

Simulations were performed for five house prototypes in 45 locations in the United States. The simulation, using the DOE-2 computer code developed at LBL, involved about 20 sets of measures to improve the thermal integrity of the prototype houses in each location. The results will be available during the next fiscal year as part of a guide to energy conservation for homebuilders and as the underpinnings of a simple slide rule for builders and others to estimate the effects of efficiency measures for all locations in the country. The research results will be useful for (1) providing a quantitative understanding of energy savings of the most important conservation measures, (2) improving considerably our understanding of the effects of weather on residential energy use, (3) providing the basis for a comprehensive economic analysis of residential energy conservation (to be conducted during FY 1983), (4) providing a comprehensive data base for energy demand forecasting

(currently used in the economic studies of the program), (5) evaluating the behavior of the market in the absence of policy interventions (used in the economic and policy studies of the program), and (6) providing information for the development of simplified analysis tools for residential energy audits, for example.

OCCUPANT BEHAVIOR STUDIES

This research was aimed at assessing the relationship between physical characteristics of houses (especially thermal integrity), occupant behavior, and cooling energy use. The approach involved gathering data on electricity use in about 300 residential buildings (from utility bills), occupant attitudes and behavior (from a one-hour survey developed by the project team), and, for a subsample of houses, measured data on air infiltration and temperature settings. The study produced a number of outputs: (1) a statistical model of cooling energy use for the houses in the sample, (2) a deterministic model of energy use against which the measured data were compared, and (3) a partial evaluation of a utility load management program that took place during the period in which the data were gathered. Three papers have recently been published on the findings of the study. Follow-up work now addresses (1) analysis of data collected for the heating season in Davis, California; (2) analysis of data collected in Lodi, California; and (3) a new study using submetered data, an analysis that will significantly refine our statistical models and help us better understand the effects of attitudes and behavior on energy use in houses.

MARKET PENETRATION OF HEAT PUMPS

This effort was aimed at improving an important element of the residential energy demand forecasting model used in the program. (The model was originally developed at the Oak Ridge National Laboratory; LBL has improved and extended it in several ways). The improvement in this work was in the projection of the market penetration of heat pumps. This is an important issue in energy forecasts, because heat pumps are considerably more efficient than alternative electric heating options.

The study noted that heat pumps do not at first sight enjoy an economic advantage over other systems in most parts of the nation. This was surprising because, in the past decade, heat pumps have increased their market share from very small percentages to about half of the residential electric heating market (about 25% of the total new heating market). The analysis of this problem (to understand and quantitatively characterize factors leading to market penetration of heat pumps) involved: (1) case studies of heat pump penetration in a number of regions of the United States; (2) use of the results of the case studies to formulate and apply a discrete-choice model to fully describe market penetration; and (3) use of results of the first two tasks to refine the energy demand forecasting model. During FY 1982, the first task was completed, with several interesting findings: if one defines the economics more broadly than as the first and operating cost of a system, heat pumps are economic in many regions. There are several reasons for this. Because of the natural-gas shortages of the 1970s, suburbs in some regions expanded without gas lines, and gas hookups are consequently expensive; because of the peak-power benefits of heat pumps, some utilities have offered preferential rates to heat-pump owners; and sometimes there is concern that natural gas will not be available in the future. A complex real-world situation revealed by these case studies provides an interesting challenge for the quantitative modeling of heat-pump market penetration (tasks 2 and 3, planned for FY 1984).

MARKET BEHAVIOR STUDIES

An important issue for energy conservation policy studies is the degree to which the market would achieve cost-effective conservation measures in the absence of policy intervention. This is a particularly relevant issue under the current Administration in Washington, D.C., which supports the belief that the market is likely to achieve many or most energy objectives without federal policies.

As a step toward resolving this issue, an empirical analysis has been performed of energy efficiency investments in the residential sector over the past decade. To our knowledge, this work is one of the few detailed empirical assessments of market behavior in residential energy conservation investments. Two papers are under preparation, one on investments in energy efficiency for residential appliances and heating and cooling equipment, the other on investments in thermal integrity in new houses.

The findings of both studies indicate that there is a

substantial underinvestment in energy efficiency improvements (relative to the behavior of a "free" or "optimal" market) for most residential energy conservation measures and that the market has *not* improved (relative to the cost-effective level of investment) during the past decade. Some of the reasons for this situation are discussed in the papers; however, much more empirical and theoretical work is needed to advance our understanding of market behavior and energy conservation investments. A continued effort in this area in FY 1983 is expected to make some progress in this direction.

COMMERCIAL BUILDING ENERGY ANALYSIS

The research in commercial building energy analysis was directed at performing a "proof of concept" test of a new idea for understanding the effects of conservation measures (including their interactions) on energy use in a commercial office building. The basic approach involved performing a set of DOE-2 computer simulations, fitting these results to equations, and using the equations to "predict" results of other DOE-2 simulations. The approach was modeled on the simulation work on residential buildings, with the difference that interactions among measures, which are very important for commercial buildings, were included. The long-term objective is to develop a new approach to energy analysis of commercial buildings that will greatly simplify the procedure for architects and engineers designing new buildings.

The work showed that the technique proposed is highly promising. Almost all predictions of DOE-2 energy simulations were within a few percent of the actual results. If work in this area continues, there is considerable potential for building a simplified microcomputer model that will permit building designers to perform energy analysis with little investment of time and money.

OECD RESIDENTIAL ENERGY STUDY

This work represents the first comprehensive assessment of residential energy use in nine OECD countries. It has produced (1) an extensive and consistent residential energy data base disaggregated to end uses, (2) an econometric study of residential energy use among the nine countries, and (3) as assessment of key factors that influence or determine the nature of residential energy demand in the OECD countries. One interesting observation is that heating energy use per square foot per degree-day in Sweden and Great Britain is roughly equal even though Swedish buildings are much more energy efficient than British buildings. The explanation is that the Swedes are able to maintain much higher (and presumably more comfortable) indoor temperatures than the British. One of several important findings is that econometric relations have considerable predictive power within the countries, in large part because the econometric studies were performed on data disaggregated to energy end uses.

Continuing research addresses energy use in commercial buildings in the OECD countries.

FUTURE DIRECTIONS ON THE ENERGY ANALYSIS PROGRAM

These projects (and others omitted for the sake of brevity) represent a good beginning to a systematic analysis of the issues studied. Most of these projects will continue and can be expected to deepen our understanding of the issues of energy use and energy conservation in buildings. In addition, the program is striving to expand its work to encompass other key energy 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 next few years for the program.

RESIDENTIAL ENERGY CONSERVATION: DEVELOPING A GUIDE FOR HOMEBUILDERS*

R.L. Ritschard, Y.J. Huang, J.G. Ingersoll, M.D. Levine, R.A. Boschen, L. Chang, C. Hsui, and D. Wilson

Rising fuel costs have focused attention on the need to improve energy efficiency in residential houses. In recent years, numerous energy strategies have been advocated, ranging from conventional measures such as improving the thermal integrity of the building shell or using more efficient heating and cooling systems to less conventional measures such as employing passive solar designs or experimental mechanical systems.

The Building Energy Analysis Project at LBL has included considerable work over the past several years in analyzing the energy benefits of conservation measures for numerous locations throughout the United States, using state-of-the-art computer simulation programs. Our research effort has resulted in a comprehensive data base that enables us to estimate the amount of energy use for typical houses located anywhere in the country. The ability to quantify energy budgets for various conservation measures is particularly vital to a housing market that traditionally has been sensitive to costs. The comprehensivenesss of our analytical effort is also important because of the strong relationship that exists between a building's energy use and its geographical location. Conservation strategies that are applicable to one location or building type may be ineffectual or even counterproductive when applied indiscriminately elsewhere.

ACCOMPLISHMENTS DURING FY 1982

The primary emphasis of the Building Energy Analysis Project in FY 1982 was on disseminating the valuable information gained from our previous and ongoing work to the general public. Part of this effort included ongoing research into technical issues such as building energy performance, energy analysis techniques, and evaluation of analysis results. However, FY 1982's work also involved a major effort to translate technical information into a format that will be understandable and relevant to homebuilders and others in the building industry.

To insure that this technical information reaches the homebuilder audience, we have been working closely with a consultant firm, Steven Winter Associates, to produce a guidebook on the energy use of new residential buildings. This book, referred to as the Homebuilders' Guide, will include information from our analysis effort on projected energy use, presented through simplified graphic techniques acceptable to the intended audience. In addition, corollary information will be presented on energy-efficient construction practices, design principles, and usable methods for doing economic analyses. The end product will be a document with solid technical background but that is attractive and understandable to those who will make a major impact on future residential energy use.

The primary objective is thus to provide, in simple format, information for homebuilders on the selection of conservation measures for new houses. The guide will permit homebuilders to calculate easily the energy savings and economics of numerous sets of conservation measures in various house designs.

Methodology

LBL has developed a comprehensive data base on the predicted energy consumption of typical residential homes in various U.S. weather locations. This data base was assembled from a series of simulations using the DOE-2.1A computer program for five building prototypes: one-story, two-story, split-level, mid-townhouse, and end-townhouse, in 45 weather locations. Significant research was also done on climate to develop a simple method for extrapolating results from the 45 base locations to more than 3000 intermediate locations. (See Y.J. Huang, "Climate Analysis in Support of the Homebuilders' Guide," this

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

annual report.) For each building prototype in any weather location, 16 to 19 effective combinations of energy conservation measures such as insulation (ceiling, floor, and walls), window glazings, and infiltration levels were simulated. Three types of building foundations (slab-on-grade, crawl space, or basement) were also simulated, depending on the weather location. Table 1 shows a matrix of base-case runs according to location, building prototype, and foundation type. This comprehensive data base of nearly 5000 DOE-2.1A runs is designed to cover the range in new residential construction in all U.S. climate regions and serves as the technical basis of the Homebuilders' Guide.

A sensitivity analysis of the effects on building energy use of variations in building design and operation was also done. This analysis was 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. Sensitivity studies were conducted in up to 11 locations for the following topics: building area, equipment efficiencies, window size and location, thermostat setback, internal loads, levels of air infiltration, and enhanced solar design (direct-gain and attached-sunspace configurations). More than 1500 computer simulations were done for these sensitivity studies.

Table 1. Matrix of base-case simulations by city, prototype, and foundation type.

	Ranch			Two-story			Split level			Mid townhouse			End townhouse		
City	Slab	Bsmt	Crawl	Slab	Bsmt	Crawl	Slab	Bsmt	Crawl	Slab	Bsmt	Crawl	Slab	Bsmt	Crawl
1. Albuquerque, NM	X			X			X			X			X		
2. Atlanta, GA	X	X	X	X	X	X	X	X	X		X	X	X	X	X
3. Birmingham, AL	X	X		X	X		X	X		X	X		X	X	
4. Bismarck, ND		X			X			X			X			X	
5. Boise, ID		X	X		X	X		X	X		X	X		X	X
6. Boston, MA		X			X			X			X			X	
7. Brownsville, TX	X			X			X			X			X		
8. Buffalo, NY		X			X			X			X			X	
9. Burlington, VT		X			X			X			X			X	
10. Charleston, SC	X		X	X		X	X		X	X		X	X		X
11. Cheyenne, WY		X			X			X			X			X	
12. Chicago, IL	X	X		X	X		X	X		X	X		X	X	
13. Cincinnati, OH	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
14. Denver, CO		X			X			X			X			X	
15. El Paso, TX	X			X			X			X			X		
16. Fort Worth, TX	X			X			X			X			X		
17. Fresno, CA	X		X	X		X	X		X	X		X	X		X
18. Great Falls, MO		X			X			X			X			X	
19. Honolulu, HI	X			X			X			X			X		
20. Jacksonville, FL	X			X			X			X			X		
21. Juneau, AK		X			X			X			X			X	
22. Kansas City, MO		X			X			X			X			X	
23. Lake Charles, LA	X			X			X			X			X		
24. Las Vegas, NV	X		X	X		X	X		X	X		X	X		X
25. Los Angeles, CA	X		X	X		X	X		X	X		X	X		X
26. Medford, OR		X	X		X	X		X	X		X	X	X	X	
27. Memphis, TN	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
28. Miami, FL	X			X			X			X			X		
29. Minneapolis, MN		X			X			X			X			X	
30. Nashville, TN	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
31. New York, NY	X	X		X	X		X	X		X	X		X	X	
32. Oklahoma City, OK	X			X			X			X			X		
33. Omaha, NB		X			X			X			X			X	
34. Philadelphia, PA		X			X			X			X			X	
35. Phoenix, AZ	X			X			X			X			X		
36. Pittsburg, PA		X			X			X			X			X	
37. Portland, ME		X			X			X			X			X	
38. Portland, OR		X	X		X	X		X	X		X	X		X	X
39. Reno, NV	X	X		X	X		X	X		X	X		X	X	
40. Salt Lake City, UT		X			X			X			X			X	
41. San Antonio, TX	X		X	X		X	X		X	X		X	X		X
42. San Diego, CA	X		X	X		X	X		X	X		X	X		X
43. San Francisco, CA	X		X	X		X	X		X	X		X	X		X
44. Seattle, WA		X	X		X	X		X	X		X	X		X	X
45. Washington, DC		X			X			X			X			X	

A more detailed discussion of the methodology and assumptions used in this research is presented elsewhere.[1] In addition, heat-pump and window sensitivities are described in separate articles in this annual report.

Results

The results of this project are being provided in both tablular and graphic formats to facilitate future analysis by internal users (LBL research staff) and outside researchers as well as those involved in the residential construction industry. Samples of such output are given in Tables 2 and 3, which summarize heating and cooling energy requirements for New York City and Phoenix, respectively. Figures 1 and 2 display some of this same information graphically.

Table 2. Energy requirements for a one-story ranch house (with basement) in New York City.

Option	RC RW Flr In Gls	Heating load (million Btu's)	Cooling load (million Btu's)	Heating energy (million Btu's)	Cooling energy (kWh)	No. of hours heated	No. of hours heated
A01	00-00-FMO-HI-1	106.453	16.092	152.078	2207.8	4589	1233
B01	11-00-FMO-HI-1	76.098	11.528	108.714	1702.1	4281	1240
C02	11-11-FMO-HI-1	60.722	10.539	86.747	1589.7	4018	1290
E01	19-11-FM1-HI-1	52.682	9.694	75.261	1490.6	3843	1271
F02	19-11-FM1-HI-2	43.766	9.337	62.525	1449.1	3611	1313
I05	19-19-FM3-HI-2	37.977	8.945	54.254	1403.2	3426	1315
I03	30-11-FM3-HI-2	38.765	8.838	55.380	1390.1	3452	1302
J03	30-19-FM3-HI-2	35.274	8.666	50.393	1369.9	3347	1318
K03	30-19-FM3-HI-3	32.800	8.419	46.858	1340.4	3273	1334
L04	38-19-FM3-HI-3	31.820	8.342	45.459	1331.2	3247	1339
M01	38-19-FM4-HI-3	29.077	7.999	41.540	1290.4	3113	1300
NO2	38-27-FM4-HI-3	27.194	7.939	38.849	1283.5	3053	1309
NO5	49-19-FM4-HI-3	28.242	7.954	40.346	1285.0	3091	1313
002	49-27-FM4-HI-3	26.361	7.911	37.659	1279.9	3032	1326
P01	60-27-FM4-HI-3	25.822	7.833	36.889	1270.5	3014	1327
P02	49-27-FM5-HI-3	25.377	8.408	36.253	1340.8	3017	1398
M51	38-19-FM4-LO-3	21.044	8.004	30.064	1291.7	2820	1403
052	49-27-FM4-LO-3	18.380	7.794	26.258	1266.4	2683	1402

RC = Ceiling R value; RW = Wall R value; Flr = Floor insulation; In = Insulation level; Gls = Number of glazings.

Table 3. Energy requirements for a one-story ranch house (slab foundation) in Phoenix, Arizona.

Option	RC RW Flr In Gls	Heating load (million Btu's)	Cooling load (million Btu's)	Heating energy (million Btu's)	Cooling energy (kWh)	No. of hours heated	No. of hours heated
A01	00-00-FM0-HI-1	30.375	81.977	43.394	10216.6	1981	3607
B01	11-00-FM0-HI-1	19.789	66.393	28.270	8499.1	1735	3557
C02	11-11-FM0-HI-1	15.443	59.759	22.062	7762.9	1589	3549
D01	19-11-FM0-HI-1	14.194	56.987	20.278	7449.3	1553	3539
E01	19-11-FM1-HI-1	11.026	48.515	15.752	6477.0	1312	3472
F02	19-11-FM1-HI-2	8.842	45.139	12.632	6083.1	1161	3479
G05	19-19-FM1-HI-2	7.851	43.228	11.216	5858.2	1098	3473
G01	30-11-FM1-HI-2	7.993	43.045	11.418	5835.1	1096	3480
H04	30-19-FM1-HI-2	7.017	41.128	10.024	5607.1	1032	3471
I07	30-19-FM1-HI-3	6.396	39.621	9.137	5425.1	982	3477
I06	38-19-FM1-HI-2	6.706	40.358	9.580	5514.2	1007	3480
J06	38-19-FM1-HI-3	6.092	38.826	8.704	5328.2	954	3481
K03	30-19-FM3-HI-3	5.945	38.347	8.494	5271.5	921	3469
K01	38-19-FM3-HI-2	6.255	39.088	8.935	5361.4	946	3471
L04	38-19-FM3-HI-3	5.646	37.545	8.065	5173.2	895	3473
M03	38-27-FM3-HI-3	5.178	36.626	7.398	5061.6	846	3475
H54	30-19-FM1-LO-2	4.180	37.951	5.971	5216.4	741	3556

RC = Ceiling R value; RW = Wall R value; Flr = Floor insulation; In = Insulation level; Gls = Number of glazings.

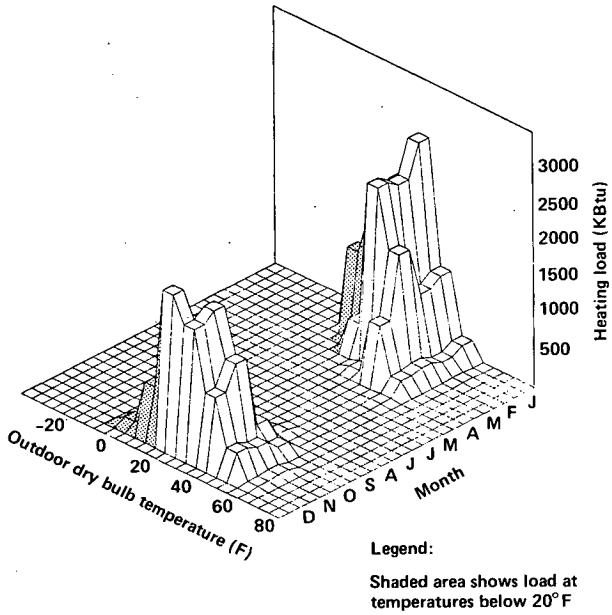

Figure 1. Calculated heating load: Three-dimensional graph shows relationship between monthly heating loads and outdoor temperatures for a one-story ranch house in New York City. Shaded area shows load at temperatures below 20°F. (XBL 824-8868)

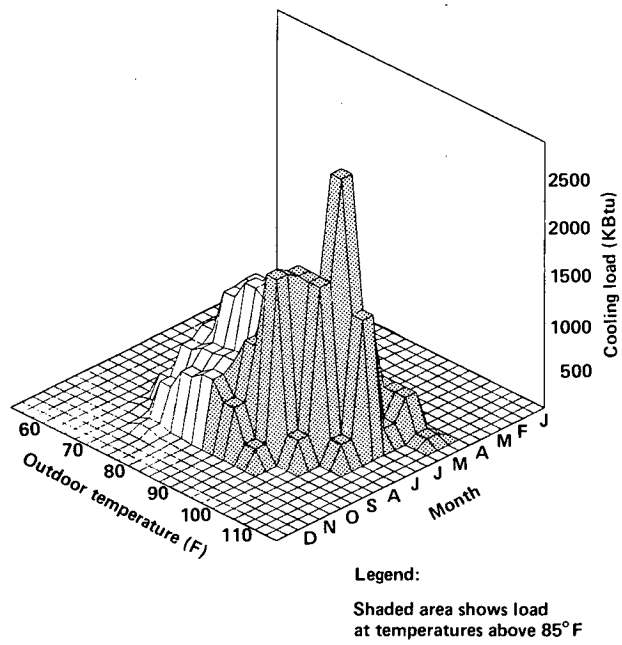

Figure 2. Calculated cooling load: three-dimensional graph shows relationship between monthly cooling loads and outdoor temperatures for a one-story ranch house in Phoenix, Arizona. Shaded area shows load at temperatures above 85°F. (XBL 824-8870)

PLANNED ACTIVITIES FOR FY 1983

This work will continue during FY 1983 with the major emphasis on the final completion of the Homebuilders' Guide and the preparation of various technical documents (LBL reports and journal articles) that support the research effort.

REFERENCE

1. J. Ingersoll, et al. (1982), *Methodology and Assumptions for the Evaluation of Heating and Cooling Energy Requirements in New Residential Buildings*. Lawrence Berkeley Laboratory Report LBL-13767.

THE EFFECT OF WINDOW SIZE AND ORIENTATION ON HEATING AND COOLING LOADS IN RESIDENTIAL HOUSES*

Y.J. Huang and R.L. Ritschard

A major objective for the Homebuilder's Guide (see preceding article) is to quantify the effects of various window configurations and control strategies on residential building energy use for various U.S. locations. To maintain consistency with the original data base, the DOE 2.1 computer program was used for the window sensitivity studies. Eleven representative cities were selected out of the original 45 after climate analysis and test runs. (How the cities performed is described in the next article.)

Results from these studies will appear in the Homebuilders' Guide as tables showing the estimated change in heating and cooling loads for various window configurations. The data base will also be studied more analytically in the future, and conclusions will be presented as technical reports.

ACCOMPLISHMENTS DURING FY 1982

Repetitive computer simulations were done using DOE-2.1 to determine the impact of window size, orientation, and control strategies on residential building energy use. More than 100 different glazing conditions were modeled, including both conventional construction practices and conservation strategies such as adding thermal mass and night insulation. ("Thermal mass") refers to the use of the concrete floor slab to store solar gains, "night insulation" to the use of R5 shutters at night.) These simulations were performed on a prototype 1540-ft^2 ranch house in all locations. In addition, attached sunspaces were modeled in two sizes (12-ft and 24-ft lengths) and in two configurations (opaque and glass roofs) for the same 11 cities.

Methodology

A DOE-2 master file was created, enabling parametric simulations for the following variations in window size, orientation, and control strategies:

(1) Window sizes and orientations:

(a) 154 ft^2 (10% of floor area)
- — equally distributed (2.5% each side)
- — 5% each on the north and south
- — 5% each on the east and west
- — 7.5% on the south and 2.5% on the north.

(b) 231 ft^2 (15% of floor area)
- — equally distributed (3.75% each side)
- — 7.5% each on the north and south
- — 7.5% each on the east and west
- — 5% on the east, 10% on the west
- — 10% on the north, 5% on the south
- — 10% on the east, 5% on the west
- — 10% on the south, 2.5% on the east and west
- — 10% on the south, 5% on the north
- — 12.5% on the south and 2.5% on the north.

(c) 308 ft^2 (20% of floor area)
- — equally distributed (5% on each side)
- — 15% on the south, 2.5% on the east and west
- — 15% on the south, 5% on the north.

(d) conditioned sunspace configuration, attached to the south wall
- — 96 ft^2 (12 ft by 8 ft), glass or opaque roof
- — 192 ft^2 (24 ft by 8 ft), glass or opaque roof.

(2) Glass types
- (a) single, double, and triple pane
- (b) single pane on the south, double pane elsewhere
- (c) double pane on the south, triple pane elsewhere

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

(d) reflective glass
(e) absorptive glass

(3) Conservation and control strategies
(a) night insulation
(b) light and heavy thermal mass
(c) night insulation plus light and heavy thermal mass.

Results

These window configurations and glass types, as well as appropriate combinations of the conservation and control strategies, were modeled for the following base cities: Albuquerque, Atlanta, Chicago, Denver, Lake Charles (Louisiana), Miami, Minneapolis, New York, Phoenix, San Francisco, and Seattle.

The results of these window simulations have been post-processed to produce a set of tables showing differences in annual heating and cooling loads or energies for different glazing conditions as compared to the base case of 10% glazing equally distributed. An example of the data is shown in Table 1.

PLANNED ACTIVITIES FOR FY 1983

More than 1000 simulations were performed on DOE-2 to analyze the impact of windows on residential energy use. The resulting data base represents a

Table 1. Results of parametric analysis of the impact of window configurations and control strategies on residential building energy use.[a]

		Equal Distribution				Different Window Orientations							South Window Orientation With Added Conservation Measures		
Standard		Ref.Gl	Abs.Gl	N.Ins	T.Mass	7.5N 7.5S	7.5E 7.5W	5.0E 10.0W	10.0N 5.0S	10.0E 5.0W	2.5E+W 10.0S	2.5N 12.5S	10.0S 5.0N	N.Ins	N.Ins+ T.Mass
Single-Glaze															
H	0.	5.41	5.05	-12.88	-.28	0.	-1.27	2.87	1.76	2.01	3.23	-6.69	-6.58	-4.46	-17.34
C	0.	-2.12	-1.96	0.	-1.81	-1.41	.44	1.12	-1.67	.09	.31	-.75	-.97	-.97	-2.76
												Double-Glaze, Single on South			
												.50 Inch Gap			
												H	2.90	-7.23	-7.85
												C	-.31	-.31	-2.08
												.25 Inch Gap			
												H	3.45	-6.78	-7.41
												C	-.25	-.25	-2.04
Double-Glaze															
.50 Inch Gap															
H	0.	4.64	5.25	-7.37	-.04	-1.23	2.57	1.61	1.64	2.90	-5.88	-5.87	-4.01	-11.38	-13.21
C	0.	-1.90	-2.12	0.	-1.68	-1.26	.41	1.04	-1.50	.09	.28	-.67	-.89	-.89	-2.53
.25 Inch Gap															
H	1.84	6.66	7.29	-5.80	1.81	.57	4.51	3.52	3.55	4.85	-4.25	-4.24	-2.31	-9.96	-11.85
C	.23	-1.74	-1.96	0.	-1.51	-1.08	.66	1.31	-1.32	.33	.52	-.46	-.69	-.69	-2.39
												Triple-Glaze, Double on South			
												.50 Inch Gap			
												H	-2.24	-8.68	-9.44
												C	-.51	-.51	-2.00
												.25 Inch Gap			
												H	-.90	-7.64	-8.43
												C	-.31	-.31	-1.87
Triple-Glaze															
.50 Inch Gap															
H	0.	3.99	4.94	-5.51	.05	-1.20	2.30	1.46	1.34	2.61	-5.15	-5.26	-3.62	-9.13	-10.61
C	0.	-1.73	-2.07	0.	-1.48	-1.16	.38	.99	-1.39	0.5	.24	-.64	-.80	-.80	-2.23
.25 Inch Gap															
H	1.42	5.59	6.59	-4.34	1.48	.17	3.83	2.95	2.83	4.15	-3.96	-4.07	-2.36	-8.12	-9.67
C	.22	-1.59	-1.94	0.	-1.32	-.99	.61	1.25	-1.23	.28	.47	-.45	-.62	-.62	-2.11

[a]Figures are MBtu differences in heating and cooling loads from a base-case house (Denver ranch house with basement), with standard windows (15% of floor area) equally distributed and (1) single-glazed, (2) double-glazed, and (3) triple-glazed. Ref.Gl=reflective glass, Abs.Fl=absorptive glass, N.Ins=R-3 night insulation, T.Mass=thermal mass (4-in. concrete slab).

valuable resource for further research and analysis. In addition to producing a technical paper documenting the methodology of this study, the Residential Energy Analysis Group intends to investigate further the energy relationships between windows and building types, and between windows and climate parameters.

CLIMATE ANALYSIS IN SUPPORT OF THE HOMEBUILDERS' GUIDE*

Y.J. Huang

The following climate analysis was done during FY 1982 as part of the technical support for the Homebuilder's Guide project. There were three major goals for this work: (1) to determine the number of cities for "base case" thermal integrity simulations, (2) to devise a simple technique for interpolating energy values from base city locations to other areas, and (3) to determine the number of cities for window sensitivity studies.

Major determinants in the analysis effort were the need to incorporate a large existing data base of DOE-2 simulations done in FY 1981 and the requirement that the techniques developed be comprehensible to the intended homebuilder audience.

ACCOMPLISHMENTS DURING FY 1982

Climate data and the existing DOE-2 data base for 52 cities showed that the relationship of building to climate in most of these locations was divergent enough to keep them as base cities. Nine cities were eliminated as redundant while two new ones were added, resulting in a final list of 45 base cities for thermal integrity studies (Table 1). Thirty-year average heating and cooling degree-day totals at various base temperatures were compiled for more than 3000 National Oceanic and Atmospheric Administration (NOAA) cooperative stations, as were average summer wet-bulb temperatures and insolation values for more than 300 locations. These climate parameters were used to define regions within which DOE-2 values for a base city could be used for extrapolation to other locations, using ratios of heating degree-days at 57°F base (for heating) and cooling degree-days at 65°F base (for cooling).

DOE-2 runs were done for all 45 base locations to determine geographical variations in the impact on building energy use of varying window sizes and orientations. Following analysis of results, 11 cities were selected as base cities for comprehensive window sensitivity studies (Table 1).

Table 1. Base cities for the Homebuilders' Guide.[a]

1.	Albuquerque, NM	(H*)	24.	Las Vegas, NV	(D)
2.	Atlanta, GA	(D*)	25.	Los Angeles, CA	(J)
3.	Birmingham, AL	(D)	26.	Medford, OR	(C)
4.	Bismarck, ND	(A)	27.	Memphis, TN	(D)
5.	Boise, ID	(B)	28.	Miami, FL	(F*)
6.	Boston, MA	(B)	29.	Minneapolis, MN	(A*)
7.	Brownsville, TX	(F)	30.	Nashville, TN	(D)
8.	Buffalo, NY	(A)	31.	New York, NY	(C*)
9.	Burlington, VT	(A)	32.	Oklahoma City, OK	(D)
10.	Cheyenne, WY	(G)	33.	Omaha, NB	(B)
11.	Chicago, IL	(B*)	34.	Philadelphia, PA	(C)
12.	Charleston, SC	(D)	35.	Phoenix, AZ	(K*)
13.	Cincinnati, OH	(C)	36.	Pittsburgh, PA	(B)
14.	Denver, CO	(G*)	37.	Portland, ME	(B)
15.	El Paso, TX	(H)	38.	Portland, OR	(I)
16.	Fort Worth, TX	(E)	39.	Reno, NV[b]	(C)
17.	Fresno, CA	(D)	40.	Salt Lake City, UT	(B)
18.	Great Falls, MO	(A)	41.	San Antonio, TX[b]	(E)
19.	Honolulu, HA	(F)	42.	San Diego, CA	(J)
20.	Jacksonville, FL	(E)	43.	San Francisco, CA	(J*)
21.	Juneau, AK	(A)	44.	Seattle, CA	(I*)
22.	Kansas City, MO	(C)	45.	Washington, DC	(C)
23.	Lake Charles, LA	(E)			

[a]Window zones are shown in parentheses (see Fig. 7); base cities selected for window sensitivity studies are indicated by asterisks.

[b]Reno, Nevada, and San Antonio, Texas, were added to complete national coverage. Cities for which DOE-2.1 runs were done but which had heating and cooling energy deltas within 5% of other cities were eliminated. They are: Raleigh, North Carolina; Tulsa, Oklahoma; Lake Charles, Louisiana; St. Louis, Missouri; and Richmond, Virginia.

Determination of Base Cities

A DOE-2 data base of over 3000 computer simulations was analyzed to determine the absolute as well as relative changes in heating and cooling energies for a prototype ranch house with varying thermal

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

integrity levels in 52 locations. (Figure 1 shows a typical plot of cooling energies for 16 levels of thermal integrity in 22 locations.) The original locations had been selected partly for climate differences and partly for population distribution. However, nine locations showed less than 5% difference in heating and cooling energies from that of other cities for the entire range of thermal integrity; these cities were therefore eliminated. Two new cities were added to differentiate between coastal and inland climates in the West and South, bringing the final number of base locations to 45.

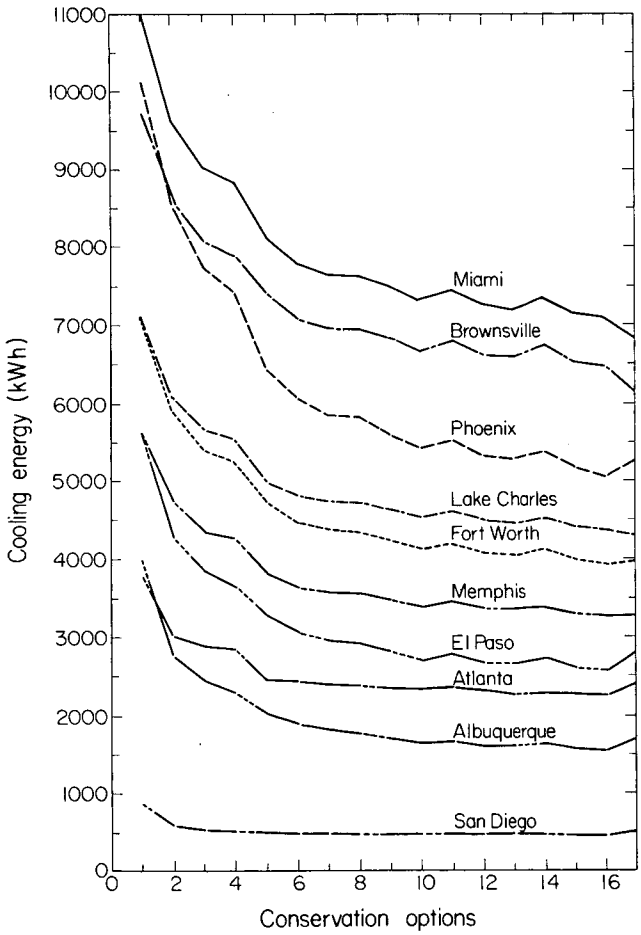

Figure 1. Cooling energies in 22 cities (slab foundations, up to 16 options). (XBL 831-1087)

Development of Interpolation Technique

To develop the interpolation technique, climate data were compared with energy values from the original DOE-2 data base to establish those climate parameters useful for interpolating heating and cooling energies. Four parameters were selected as first-order indicators for residential building energy values:

(1) 57°F base heating degree-days for absolute heating energies.

(2) The ratio of base 65°F heating degree-days to base 57°F heating degree days for the delta (relative) change in heating energies due to varying thermal integrities. (Since a tight house has a lower balance point temperature than a loose one, this ratio will reflect the relative change in heating energies).

(3) Base 65°F cooling degree-days for absolute cooling energies.

(4) Latent enthalpy hours for the delta change in cooling energies due to varying thermal integrities. (Since latent heat is unaffected by changes in thermal integrity, locations with high latent enthalpy hours will show little change in cooling energies due to improvements in thermal integrity).

To keep the interpolation method simple, regional boundaries are drawn around each base city in such a way that the only interpolation necessary will be for heating and cooling degree-day differences. These will appear in the Homebuilders' Guide as tables of "location multipliers" and are actually the ratio of heating and cooling degree-days between secondary locations and the base city.

Thirty-year averages of heating and cooling degree-days to various temperature bases for over 3000 NOAA cooperative stations and Test Reference Year (TRY) data on latent enthalpy hours for 300 stations were used for drawing boundaries around the base cities. Figure 2 shows a sample of the NOAA degree-day data compiled for this work. Figures 3 and 4 show sample computer maps of heating degree-days and the ratio of heating degree-days to different base temperatures.

Since the one-step interpolation will take care of degree-day differences, more weight has been placed on keeping the relative changes in energies as uniform as possible within each region. A three-tiered system was devised for drawing boundaries between base cities; if no significant variation between cities were found under the first-level criteria, the second-level criteria were used; if neither varied, then the third-level criteria were used. These criteria are as follows:

Heating Boundaries

(1) Equal differences in the ratio between heating degree-days base 65 to heating degree-days base 57 between base cities.

(2) Equal differences in heating degree-days.

(3) Equal geographical distance between base cities.

Cooling Boundaries

(1) Equal differences in latent enthalphy hours between base cities.

(2) Equal differences in cooling degree-days.

(3) Equal geographical distance between base cities.

Figure 5 shows the resulting boundaries for the 45 cities. These boundaries will not appear in the Homebuilders' Guide, although they can be inferred by the selection of base cities and the "location multipliers" given for secondary locations.

Determination of Window Sensitivities for Base Cities

The following set of sensitivity runs were done using DOE-2 for all 45 base cities to determine variations in relative heating and cooling energies due to changes in window size and orientation (the base case has 10% glazing equally distributed):

(a) 15% glazing equally distributed, loose thermal integrity

(b) 15% glazing equally distributed, tight thermal integrity

(c) 15% glazing, 12.5% on the south, loose thermal integrity

(d) 15% glazing, 12.5% on the south, tight thermal integrity

The equally distributed sensitivities indicate the combination of solar transmission gain and conduction losses as window size increases, while the

Station name	Station number	Zone no.	Lat-titude	Longi-tude	HDD 50	HDD 55	HDD 57	HDD 60	HDD 65	CDD 55	CDD 60	CDD 65	CDD 70
ANDALUSIA 1 NW	010252	12	31.19	86.30	573	975	1177	1535	2305	4498	3237	2181	1295
ANNISTON FAA AP	010272	2	33.35	85.51	812	1319	1567	1999	2872	3912	2771	1809	1043
AUBURN AGRONOMY FARM	010430	3	32.36	85.30	691	1153	1382	1783	2611	4109	2914	1921	1096
BAY MINETTE	010583	20	30.53	87.47	333	620	770	1061	1688	5028	3644	2447	1463
BELLE MINA 2 N	010655	3	34.42	86.53	1075	1630	1898	2371	3273	3684	2600	1680	971
BIRMINGHAM WSO CITY	010829	3	33.28	86.50	851	1368	1619	2066	2943	3965	2839	1891	1138
BIRMINGHAM WSO	010831	3	33.34	86.45	817	1318	1563	2002	2863	3987	2845	1881	1114
BREWTON 3 SSE	011084	12	31.04	87.03	430	770	945	1268	1970	4659	3332	2212	1283
CHATOM 3 N	011566	12	31.30	88.15	438	773	963	1287	2001	4624	3306	2193	1276
CLANTON	011694	3	32.51	86.38	823	1342	1592	2038	2896	3872	2746	1781	1025
DAYTON	012188	3	32.21	87.39	648	1069	1279	1646	2431	4462	3215	2177	1297
DEMOPOLIS LOCK AND D	012245	3	32.31	87.50	727	1190	1417	1813	2640	4230	3034	2033	1205
EUFAULA	012730	12	31.59	85.06	559	942	1144	1498	2266	4474	3202	2145	1274
EVERGREEN	012758	12	31.26	86.56	556	935	1136	1485	2241	4531	3253	2184	1292
FAIRHOPE 2 NE	012813	20	30.33	87.53	326	599	742	1017	1618	5155	3748	2524	1525
FAYETTE	012883	3	33.41	87.49	895	1435	1699	2149	3042	3830	2720	1786	1033
FRISCO CITY	013105	12	31.26	87.24	516	884	1082	1417	2144	4669	3373	2276	1352
GADSDEN STEAM PLANT	013154	3	34.02	86.00	956	1512	1782	2250	3160	3673	2587	1671	958
GREENSBORO	013511	3	32.42	87.36	597	1010	1223	1587	2361	4491	3240	2190	1319
HALEYVILLE	013620	3	34.14	87.37	1158	1750	2036	2527	3454	3470	2422	1528	845
HEADLAND	013761	12	31.21	85.20	506	852	1041	1367	2068	4699	3389	2269	1332
HIGHLAND HOME	013816	12	31.57	86.19	602	989	1193	1541	2302	4433	3155	2090	1216
HUNTSVILLE WSO	014064	3	34.39	86.46	1083	1636	1906	2379	3279	3716	2634	1708	995
LAFAYETTE	014502	3	32.54	85.24	707	1166	1395	1797	2637	3989	2798	1806	1010
MARION JUNCTION 2 NE	015121	3	32.28	87.13	678	1117	1335	1716	2518	4318	3095	2073	1229
MOBILE WSO	015478	20	30.41	88.15	347	633	787	1073	1695	5232	3848	2643	1647
MONTGOMERY WSO	015550	12	32.18	86.24	568	960	1167	1519	2277	4608	3338	2274	1387
MUSCLE SHOALS FAA AP	015749	27	34.45	87.37	1098	1663	1943	2414	3315	3783	2709	1788	1067
ONEONTA	016121	3	33.57	86.29	1105	1694	1984	2469	3406	3487	2437	1554	870
OZARK 6 NNW	016218	12	31.31	85.41	436	762	937	1249	1928	4778	3439	2293	1358
ROBERTSDALE 1 E	016988	20	30.32	87.40	362	655	809	1104	1738	4940	3563	2373	1398
ROCK MILLS	017025	3	33.09	85.18	880	1399	1655	2108	2996	3725	2609	1672	937
SAINT BERNARD	017157	12	34.12	86.47	1201	1817	2120	2612	3570	3402	2375	1508	836
SAND MT SUBSTA AU	017207	2	34.17	85.58	1114	1695	1985	2478	3411	3385	2338	1452	786
SCOTTSBORO	017304	2	34.41	86.03	1178	1783	2082	2587	3534	3431	2402	1531	854
SELMA	017366	3	32.25	87.00	469	819	1004	1334	2040	4858	3546	2433	1498
TALLADEGA	018024	3	33.27	86.06	816	1312	1556	2001	2878	3786	2649	1703	968
THOMASVILLE	018178	12	31.55	87.44	653	1064	1275	1636	2413	4438	3180	2132	1267
TROY	018323	12	31.49	85.59	466	811	1004	1333	2052	4633	3326	2219	1305
TUSCALOOSA FAA AP	018380	3	33.14	87.37	738	1208	1439	1842	2675	4289	3101	2102	1278
UNION SPRINGS	018438	12	32.08	85.43	642	1055	1268	1639	2433	4356	3113	2080	1225
VALLEY HEAD	018469	2	34.34	85.37	1413	2078	2403	2929	3958	3034	2058	1262	667

Figure 2. Sample page of heating (HDD) and cooling (CDD) degree-day data to different base temperatures (°F), from 3000 National Oceanic and Atmospheric Administration cooperative stations.

south-oriented sensitivities indicate the amount of solar transmission gain possible.

The results were then mapped to clarify the geographical differences. Figure 6 shows the change in heating energy for a tight house when window area is increased from 10% to 15% of floor area (gradient lines represent 1 MBtu difference in heating energy). Figure 7 shows the grouping of cities that resulted. There are six zones in the eastern half of the country running basically east-west (zones A,B,C,D,E,F). Zones G and H have been separated because of the large solar heat gains in the Rockies, as have Zones I and J because of the low solar heat gains along the Pacific coast. Finally, zone K in the southwest has been separated because of its extreme increase in cooling energies.

PLANNED ACTIVITIES FOR FY 1983

A large amount of climate data has been gathered and analyzed in the course of this work. This information is extremely useful for continued research into the relationship between climate and building energy use. More comprehensive analysis, particularly in correlating climate parameters to cooling energy use, will make it possible to reduce the DOE-2 data base to a set of mathematical equations.

The analysis so far has covered only single-family detached houses. Additional research will be necessary to extend the analysis to cover other residential buildings such as multi-family units and condominiums.

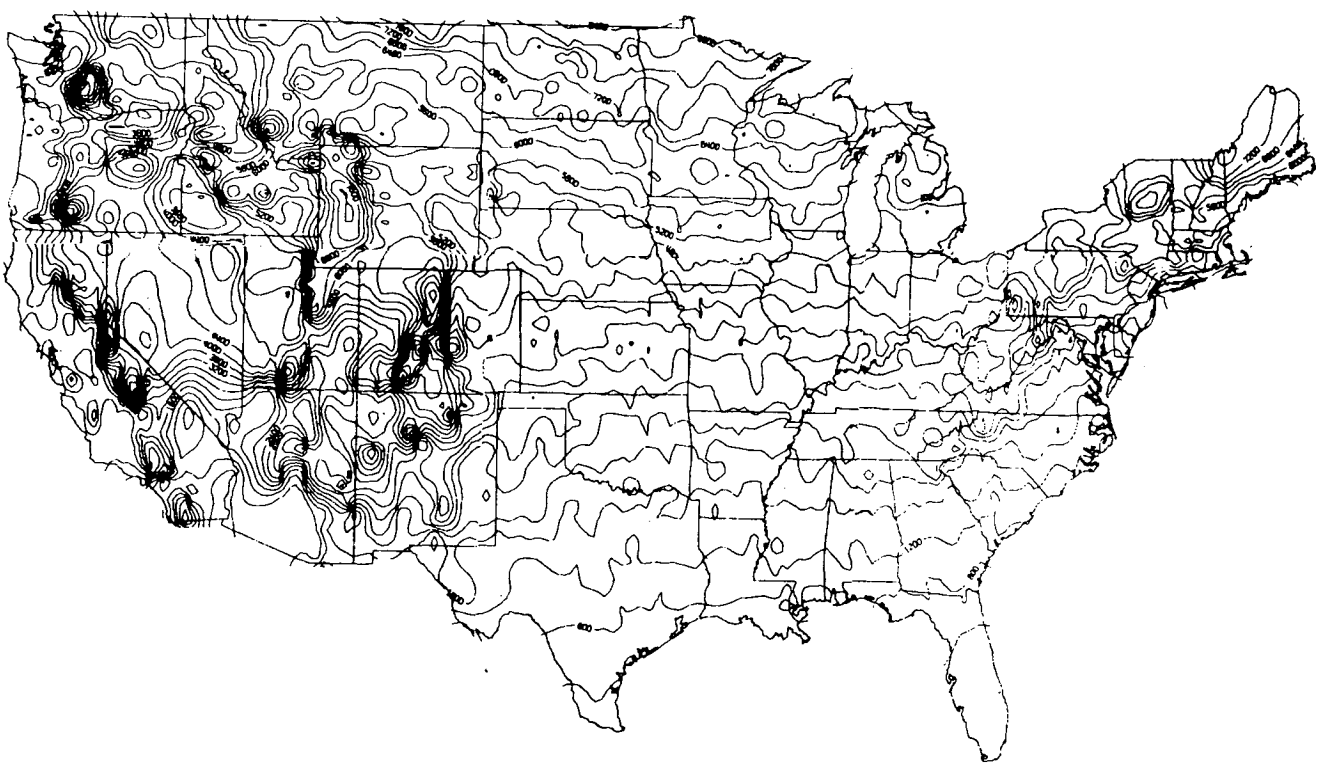

Figure 3. Heating degree-days (3118 Stations) at base 57°F. (XBL 831-1081)

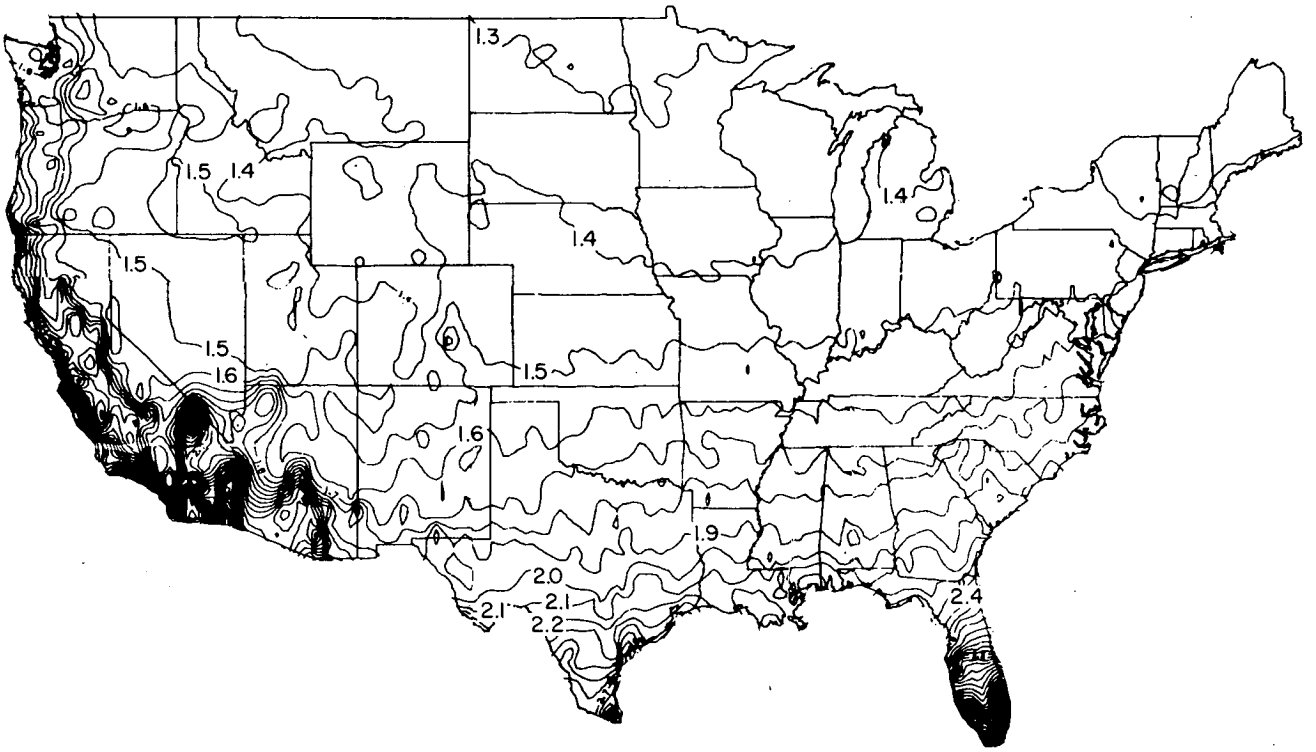

Figure 4. Heating degree-day ratios (HDD base 65/HDD base 57), in °F. (XBL 831-1082)

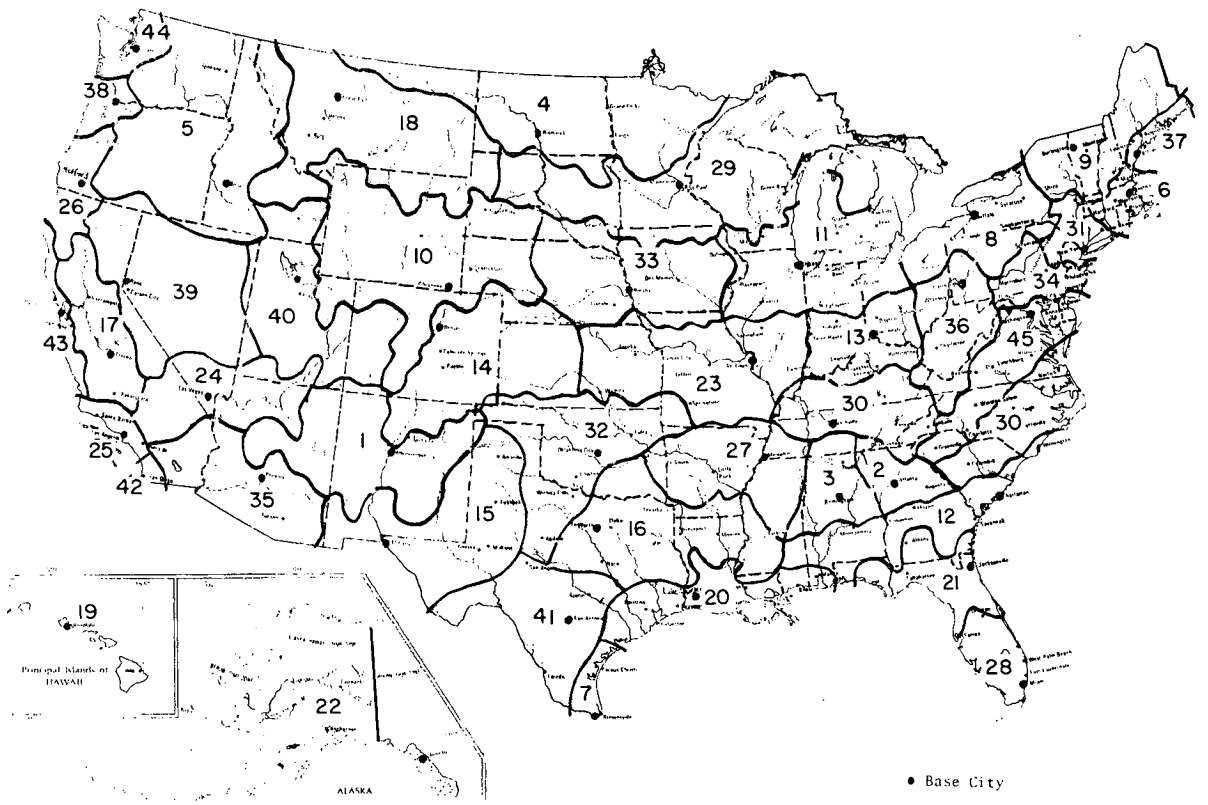

Figure 5. Base cities and boundaries for Homebuilders' Guide. (see Table 1 for numbered list of base cities.) (XBL 831-1083)

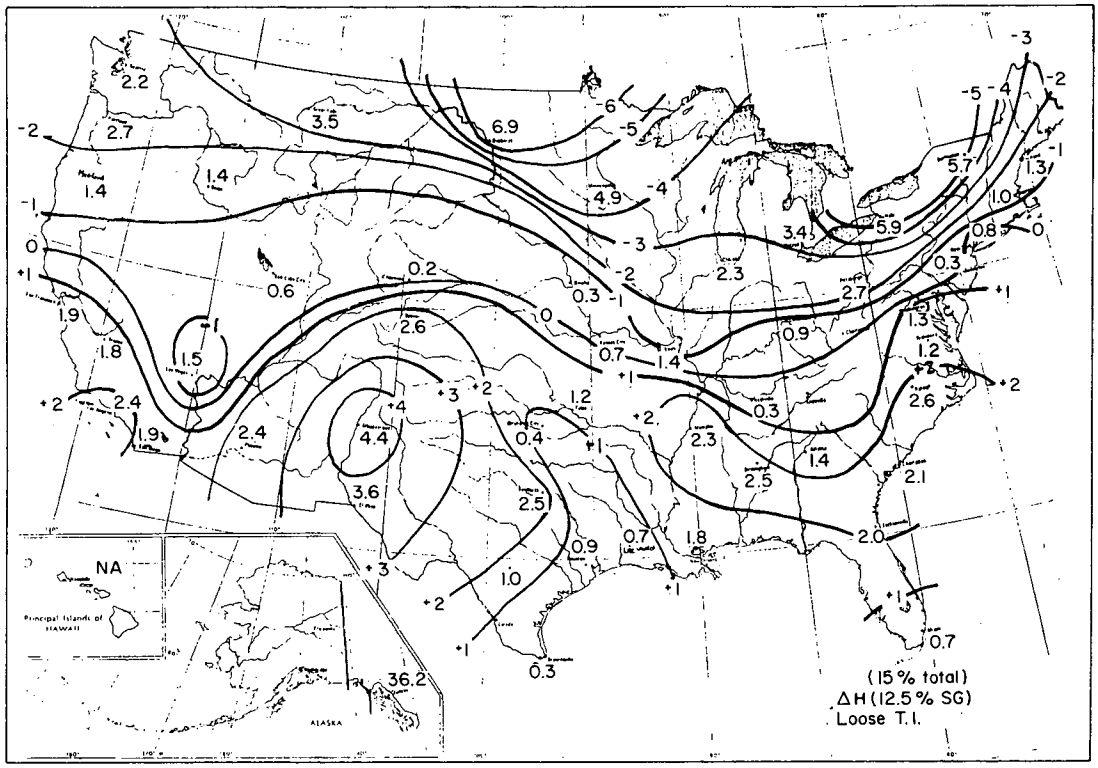

Figure 6. Relative heating energies for a loose house when window area is increased from 10% equally distributed to 15% (12.5% on the south, and 2.5% on the north). (XBL 831-1084)

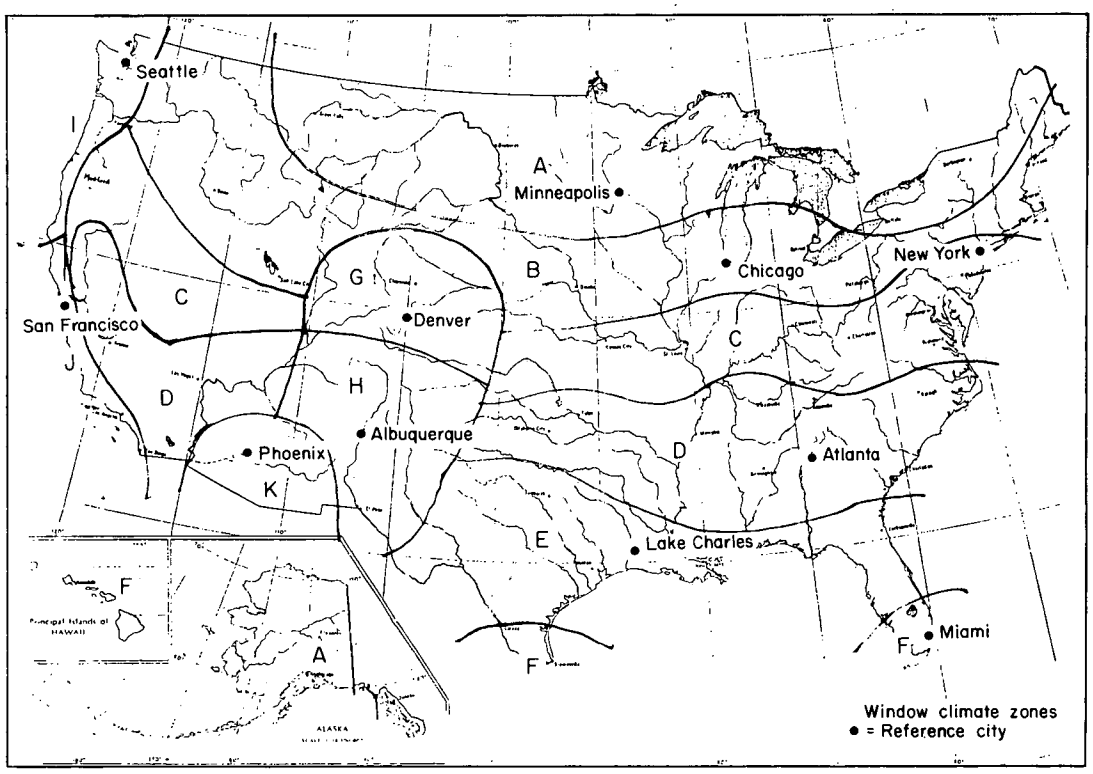

Figure 7. Base cities and zones for window sensitivity studies. (XBL 831-1080)

DETERMINATION OF THE SEASONAL COEFFICIENT OF PERFORMANCE OF CONVENTIONAL AIR SOURCE HEAT PUMPS IN RESIDENTIAL BUILDINGS*

J.G. Ingersoll and D.K. Arasteh

The steady-state coefficient of performance (COP) of a heat pump as given by the manufacturer does not provide adequate information to determine its seasonal (actual) coefficient (SCOP) as installed in a building. (The seasonal cooling COP is also the device's energy efficiency rating.) The diurnal and seasonal weather variability specific to any location coupled with the particular characteristics of the building and the heat pump will degrade any device's performance. Existing rules used to infer a seasonal COP from manufacturers' data and weather information are not detailed enough to provide accurate results.

The DOE-2 computer code has been applied, with proper adjustments, to the heat-pump parameters in order to match measured performance data. A SCOP has thus been determined for 44 locations in the United States for single-family one-story, two-story, and townhouse prototypical buildings. The results are universal in that they apply to any heat pump whose steady-state COP is known, that is, when the SCOP is expressed as directly proportional to the steady-state COP at the American Refrigeration Institute (ARI) established points for heating (47°F) and cooling (95°F). This constitutes a significant improvement over previous determinations of the SCOP, which appear limited to specific devices. Empirical equations have been derived expressing the SCOP for heating and for cooling as functions of the respective steady state heating and cooling COPs as well as heating and cooling degree-days.

ACCOMPLISHMENTS DURING FY 1982

Methodology

Four designs representative of current construction have been analyzed: a one-story, 1540 ft^2 house with 154 ft^2 of glass area; a two-story, 2240-ft^2 house with 224 ft^2 of glass area; a split-level 1905-ft^2 house with 210 ft^2 of glass area; and a two-story 1200-ft^2 attached townhouse with 144 ft^2 of glass area.[1] The window area is assumed to be equally distributed on all four sides so as to take into account the random orientation of buildings. Each prototype is assumed to be well-insulated with R30 to R38 (very cold climates) ceiling insulation; R19 wall insulation; R5 perimeter insulation up to 2 feet deep for a slab-on-grade foundation and 8 feet for a basement foundation, or R11 underfloor insulation for a vented crawl-space foundation; double or triple (very cold climates) glazings with 1/2-inch air gaps; and an average infiltration of 0.7 ach for the five winter months from November to March, including air changes due to building operation.

Each building is kept at 70°F during the heating season and at 78°F during the cooling season. The heat pump is assumed to have a 3-ton capacity, which is adequate for the heating and cooling of all prototypical buildings when they are well-insulated and have no temperature setbacks. A 3-kW electric resistance heater supplies any additional heating capacity that the heat pump may be unable to provide during very cold hours. It is also assumed that the electric resistance heater is thermostatically controlled and is automatically turned on when the ambient air temperature is below 30°F. Since the heat pump modeled here is a split system with the compressor located outdoors, it is assumed that a 50-W crankcase heater is activated whenever necessary.[2]

Taking into account the outdoor (climatic) and indoor (thermostat setting, internal load) conditions for each hour as well as those of the previous hours, DOE-2 calculates the building's heating/cooling load for that hour. The energy required to meet the load is then calculated from the capacity of the heat pump at the hour's outdoor dry-bulb temperature (full-load COP) and the ratio of the building load to the equipment capacity in that hour (partial-load COP). In our analysis, we had to determine the proper full-load and partial-load COP curves according to manufacturer's data and measured heat pump performance data in buildings.

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

The full-load COP curve, as supplied by the heat-pump manufacturer, has to be modified for the heating mode to include the effect of performance degradation caused by the accumulation of frost on the system's evaporator coils. The build-up of frost, which commences at about 50°F and becomes rather significant below 40°F, reduces the net heat transfer from the outside air to the refrigerant fluid, resulting in a lower system performance. Unpublished performance data for these conditions were obtained from a manufacturer of relatively efficient heat pumps.[3] These data agree with experiments, as yet unpublished, by the National Bureau of Standards (NBS), which show approximately a 15% decrease in performance at 35°F.[4] In the cooling mode, no such degradation takes place. However, the heat-pump performance in the cooling mode depends on the outdoor and indoor wet-bulb temperatures. The coil by-pass factor is furthermore assumed to be fixed at 0.1.

Heat-pump performance degradation due to cycling on and off has also been incorporated in the analysis. The resulting partial-load factor is defined as the ratio of the building's load (heating or cooling) at a given ambient temperature to the heat pump's capacity at the same temperature. Since DOE-2.1A performs only hourly calculations, a partial load is defined for every hour of the year. The partial-load curves are based on data taken at NBS and assume an average cycling rate of one cycle per hour (1.0 cph)—typical of new buildings with relatively long thermal constants due to high thermal integrities.

The curves for full load with defrost degrade and partial load were adjusted so as to be able to reproduce—using DOE-2.A—the measured seasonal COPs of specific heat pumps operated in buildings over a period of 2 years.[5] This adjustment provides a certain degree of confidence that our empirical heat-pump model is satisfactory for performance simulations and that the obtained seasonal COPs are therefore on the right track. Additional validation will be required, however, to further test both the model and the values of its parameters and to improve on either or both of them if necessary.

Results

The seasonal COPs for heating and cooling for each of the four prototypical buildings have been calculated for 44 locations representing all the major population centers and climatic regions of the country. Since an Oak Ridge National Laboratory (ORNL) study has indicated that the relative seasonal degradation of the COP is independent of the steady-state COP itself at the ARI points,[5] we have expressed all the seasonal COPs in a normalized form that makes them applicable to any heat-pump model, not just the one used here. This normalization has been achieved by dividing the heating and cooling seasonal COPs obtained through the DOE-2 simulations with the respective steady-state COPs supplied by the manufacturer for the ARI rating points.

The resulting COPS are presented in Table 1. Sensitivity studies have been performed to determine the effect on these COPs of a number of parameters. These parameters included: full-load curves from other manufacturers of heat pumps; buildings of

Table 1. Normalized seasonal heating and cooling COPs for four prototypical single-family houses in 44 locations in the U.S.[a]

	Heating (SHCOP/HCOP)				Cooling (SCCOP/CCOP)			
Location	1-S	2-S	S-L	T-H	1-S	2-S	S-L	T-H
Albuquerque, NM	0.62	0.63	0.62	0.59	0.71	0.72	0.72	0.69
Atlanta, GA	0.64	0.66	0.65	0.60	0.81	0.81	0.81	0.80
Birmingham, AL	0.64	0.65	0.65	0.60	0.83	0.82	0.82	0.81
Bismark, ND	0.51	0.49	0.50	0.52	0.66	0.69	0.69	0.63
Boise, ID	0.64	0.65	0.64	0.59	0.69	0.69	0.68	0.64
Boston, MA	0.65	0.66	0.65	0.60	0.64	0.67	0.67	0.61
Brownsville, TX	0.66	0.68	0.67	0.63	0.86	0.84	0.84	0.85
Buffalo, NY	0.63	0.62	0.62	0.60	0.52	0.58	0.58	0.51
Burlington, VT	0.57	0.55	0.56	0.57	0.55	0.59	0.60	0.52
Charleston, SC	0.66	0.67	0.66	0.61	0.85	0.83	0.83	0.83
Cheyenne, WY	0.60	0.59	0.59	0.57	0.44	0.49	0.51	0.44
Chicago, IL	0.62	0.61	0.61	0.59	0.68	0.70	0.70	0.64
Cincinnati, OH	0.64	0.64	0.63	0.60	0.77	0.78	0.77	0.74
Denver, CO	0.62	0.62	0.62	0.59	0.58	0.58	0.59	0.52
El Paso, TX	0.63	0.65	0.64	0.59	0.78	0.78	0.78	0.77
Fort Worth,TX	0.64	0.66	0.65	0.60	0.83	0.82	0.82	0.81
Fresno, CA	0.65	0.67	0.66	0.61	0.74	0.74	0.74	0.74
Great Falls, MT	0.57	0.56	0.56	0.55	0.44	0.49	0.51	0.44
Honolulu, HI	----	----	----	----	0.89	0.88	0.84	0.84
Jacksonville, FL	0.66	0.68	0.67	0.62	0.85	0.84	0.84	0.84
Juneau, AL	0.62	0.62	0.62	0.68	----	----	----	----
Kansas City, MO	0.61	0.60	0.60	0.59	0.80	0.80	0.79	0.77
Lake Charles, LA	0.65	0.67	0.66	0.62	0.85	0.84	0.83	0.84
Las Vegas, NV	0.66	0.68	0.67	0.62	0.77	0.75	0.75	0.75
Los Angeles, CA	0.71	0.72	0.71	0.67	0.24	0.28	0.30	0.27
Medford, OR	0.65	0.66	0.65	0.60	0.32	0.62	0.64	0.56
Memphis, TN	0.65	0.66	0.66	0.61	0.83	0.82	0.80	0.81
Miami, FL	0.66	0.68	0.67	0.62	0.88	0.86	0.86	0.87
Minneapolis, MN	0.53	0.51	0.52	0.53	0.75	0.76	0.76	0.72
Nashville, TN	0.64	0.64	0.64	0.60	0.81	0.80	0.80	0.79
New York, NY	0.65	0.66	0.65	0.61	0.73	0.74	0.74	0.70
Oklahoma City, OK	0.62	0.62	0.62	0.60	0.80	0.80	0.79	0.66
Omaha, NB	0.59	0.57	0.57	0.58	0.77	0.78	0.77	0.74
Philadelphia, PA	0.65	0.66	0.65	0.60	0.78	0.78	0.78	0.75
Phoenix, AZ	0.64	0.66	0.65	0.61	0.80	0.78	0.78	0.78
Pittsburgh, PA	0.63	0.63	0.63	0.60	0.70	0.72	0.72	0.68
Portland,ME	0.61	0.60	0.60	0.61	0.46	0.53	0.54	0.41
Portland, OR	0.66	0.67	0.66	0.66	0.47	0.47	0.47	0.47
Salt Lake City, UT	0.63	0.63	0.63	0.59	0.68	0.70	0.70	0.85
San Diego, CA	0.71	0.72	0.71	0.68	0.38	0.39	0.43	0.40
San Francisco, CA	0.68	0.69	0.68	0.65	0.09	0.10	0.12	0.11
San Antonio, TX	0.65	0.67	0.66	0.61	0.84	0.82	0.82	0.82
Seattle, WA	0.66	0.67	0.66	0.60	0.34	0.35	0.34	0.28
Washington, DC	0.65	0.66	0.65	0.61	0.79	0.79	0.78	0.76

[a]1-S = One-story; 2-S = Two-story; S-P = Split-level, T-H = Townhouse.

different thermal integrity than those used in this analysis; and different size (capacity) for the heat pump. The resulting sensitivities will only be summarized here. The effect of full-load or steady-state curves of other manufacturers is small, i.e., within a few percent. This is because heat-pump curves tend to be very similar in shape. The effect of different building thermal integrities is also within a few percentage points as long as the building has roughly R19 ceiling insulation, R11 wall insulation, double-glazed windows, no foundation insulation for a slab, R5 for a basement or R11 for a vented crawl space, and an infiltration rate of 0.7 ach or less.

These insulation levels are already typical of new construction in every part of the country[1] and are such that a typical building of every climate in the United States would not need a heating or cooling heat-pump system in excess of 3 tons capacity. For some climates and a higher level of thermal integrity, a smaller system—one as low as 1.5 tons capacity—could be acceptable, but this is true for cooling rather than heating. The hourly demand for heating is nearly as high in a heating climate as it is in a cooling climate, albeit for many fewer hours in the latter. The converse is true for cooling. The difference is that the hourly demand for heating is higher than that for cooling in all climates, although the duration of each changes with climate. Consequently, while a 3-ton heat pump will be needed for heating in both New York and Phoenix, a 1.5-ton heat pump will be adequate for cooling in both locations, at least in new construction or in buildings with better levels of thermal integrity. Heat pumps with a smaller capacity for cooling than for heating can be expected to perform a little better overall than heat pumps with equal heating and cooling capacities. This improvement of the seasonal COP in the cooling mode is nevertheless no more than 5%.

Conclusions

The results presented in Table 1 indicate clearly that in almost all climates the seasonal heating COP is degraded from the manufacturer's steady state COP anywhere between 35 and 45%; and the seasonal cooling COP is degraded between 20 and 30%. We can also discern a rather characteristic trend in both the heating and cooling seasonal COPs. In the heating seasonal COPs a broad maximum exists for climates with 2000 to 4000 heating degree-days, base 65°F. The seasonal heating COP is less for climates with fewer heating degree-days because of cycling or partial-load degradation and also for climates with more degree-days because of degradation from use of the auxiliary resistance heater. The seasonal cooling COP, on the other hand, appears to improve as the cooling degree-days increase. For any location with fewer than 1000 cooling degree-days, base 65°F, degradation due to cycling is substantial. Between 1000 and 3000 degree-days, the seasonal COP increases significantly, and, above 3000 degree-days, it remains virtually unchanged. Also, for all cooling degree-days, the seasonal COP rises with higher humidity, presumably because of a better utilization of the latent capacity of the device.

PLANNED ACTIVITIES FOR FY 1983

Although this task—determining the seasonal coefficient of performance of heat pumps—was concluded in FY 1982, the information gathered and the methods developed will be used to support other Building Energy Analysis Projects.

REFERENCES

1. National Association of Home Builders Research Foundation, Inc. (1980), *Single-Family Detached and Attached Construction Practices—1979,* Rockville, MD.
2. Dossat, R.J. (1978), *Principles of Refrigeration,* 2nd Ed., pp. 460-461, John Wiley and Sons, New York.
3. Hurle, G., The Coleman Company (1980), private communication.
4. Didion, D., National Bureau of Standards (1982), private communication.
5. Baxter, V.D., et al. (1982), "Comparison of Field Performance to Steady-State Performance for Two Dealer-Installed Air-to-Air Heat Pumps," Oak Ridge National Laboratory, Oak Ridge, TN (unpublished).

ENERGY EFFICIENCY IN CHINESE BUILDINGS*

Y.J. Huang, A. Canha de Piedade, A.H. Rosenfeld, and D. Tseng

Energy analysis of conservation measures for Chinese buildings is intriguing because there are large differences in construction, use patterns, and space conditioning demands in comparison with the United States. Since the construction industry in China is one of the largest in the world, its adoption of conservation measures could have a significant impact on world energy consumption. Furthermore, insights gained from this study may be applied to formulating conservation strategies for other developing nations.

ACCOMPLISHMENTS DURING FY 1982

A cost-benefit analysis of energy conservation measures for typical Chinese residential buildings was done using the DOE-2 energy analysis program and simple economic calculations. Through the help of a visiting Chinese architect as well as sources in China, fairly detailed information was gathered on building designs, construction practices, operating conditions, and building costs in the People's Republic of China. Weather tapes were also obtained for the two largest Chinese cities, Beijing and Shanghai.

Results from this preliminary study showed that simple conservation measures would conserve coal in Beijing at a cost below the international price, even without additional savings from infiltration reduction and possible downsizing of the central heating system. For Shanghai, similar conservation measures in unheated buildings would raise winter indoor temperatures to within the comfort zone.

Methodology

A DOE-2 input file was created for a "typical design" low-rise multi-family residential building representative of current Chinese construction. ("Typical design" is a term used in China to refer to standardized building designs that are mass-produced to meet urban housing needs.) For simplicity, only a middle floor unit with three apartment units and a stairwell was simulated (Fig. 1). The following input was used for internal loads: occupants at 1 person/12 m^2 of floor area, plus lights and cooling at 1 W/m^2. Since we were unable to find data on infiltration rates for Chinese houses, simulations were done using two rates—a "leaky" rate averaging 1 ach, and a "medium" rate averaging 0.5 ach. For Beijing, the building was modeled with a central heating system (coal-fired, circulating hot water); for Shanghai, the building was modeled both with and without a central heating system. No cooling system was simulated for either city.

Parametric analysis for Beijing and Shanghai included envelope conditions ranging from the current Chinese practice of using brick walls (37 cm thick on the north and 24 cm on the south) and single-glazed windows to options such as cavity brick walls, cavity walls with perlite, aerated concrete infill walls, insulated sandwich panels, and double-glazed windows.

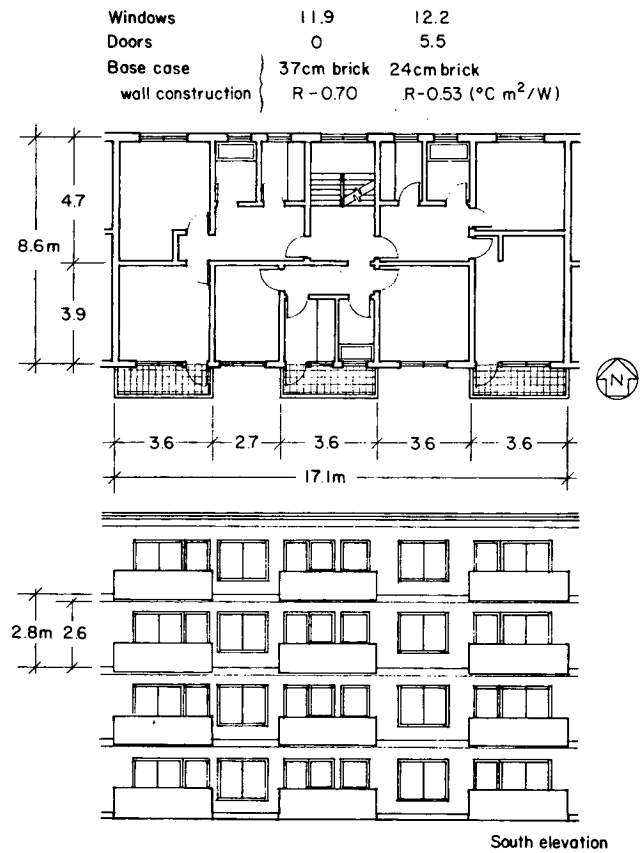

Figure 1. Typical design for three-apartment middle unit. For the base case, the north wall (37 cm brick) has a conductance k = 1.42 W/m^2K. When a 10-cm cavity filled with expanded perlite is introduced between the same 37 cm of bricks, k drops to 0.45 W/m^2K. (XBL 8210-4864)

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

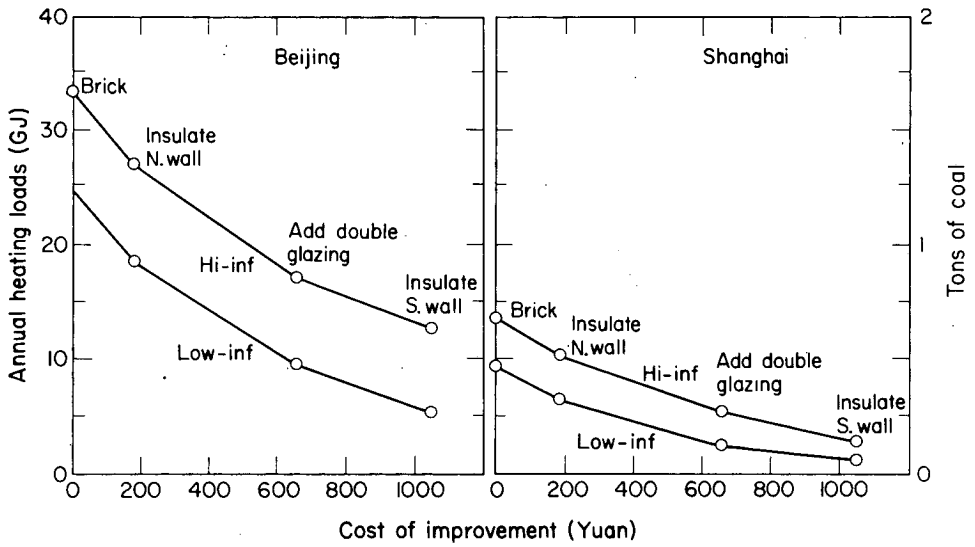

Figure 2. Annual heating load decreases as a series of conservation measures is applied to a three-apartment middle unit in Beijing and Shanghai. (XBL 8210-4865)

Economic analysis of the energy savings was based on Chinese domestic prices and used the two concepts of simple payback time and the cost of conserved coal. International coal prices were used because of uncertainties regarding the domestic pricing of coal in China. Since the heating system efficiency was assumed to be 70%, these economic estimates will be on the conservative side.

Results

Analysis of the DOE-2 results show that three simple conservation options have attractive payback periods in Beijing—insulating the north wall (7 years), adding double glazing (13 years), and insulating the south wall (22 years). The payback periods would be even shorter if we make the reasonable assumptions that infiltration is also reduced and the heating systems could be downsized. For heated Shanghai apartment buildings, the payback periods for the same options are nearly double because of the milder climate (Fig. 2). Figure 3 shows the heating loads for the same three options in Beijing separated into building components and clarifies the effects of each of the conservation measures.

The first option—adding insulation to the north wall—is particularly attractive since the only costs are for a slight modification of the wall construction to create a cavity, plus the cost of the perlite insulation.

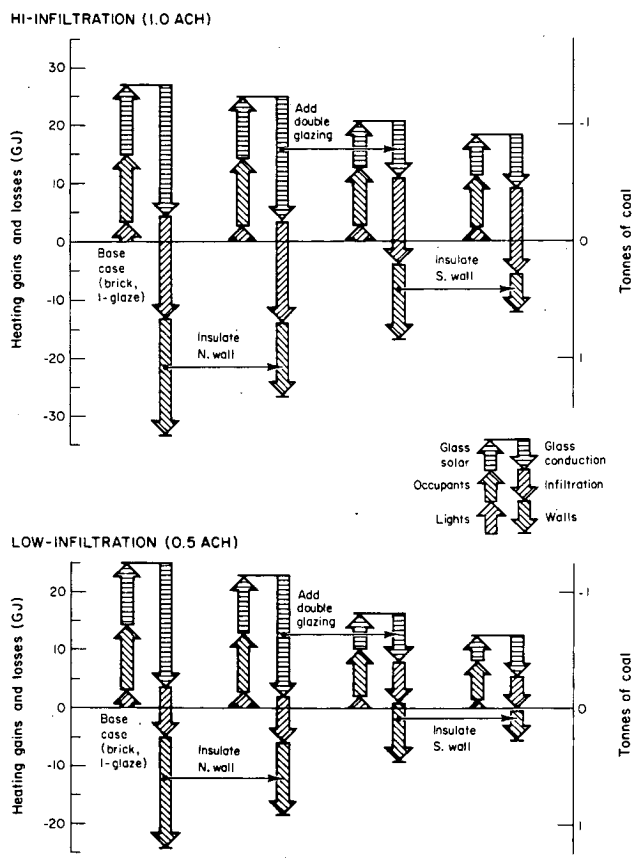

Figure 3. Heating gains and losses for a typical Beijing apartment building (base case) and seven energy conservation options. In each case, the effects are separated for various components of the building. (XBL 8210-4866)

For unheated residential buildings in Shanghai, the benefits from these same options are not in fuel savings, but in improving conditions within the living spaces. Figure 4 shows the differences in floating indoor temperatures between a typical brick building in Shanghai and buildings with insulation or both insulation and reduced infiltration. While the temperatures in the brick building never rise above 16°C (60°F), those for the insulated building with reduced infiltration are within the comfort zone during the daytime hours, reaching as high as 21°C (70°).

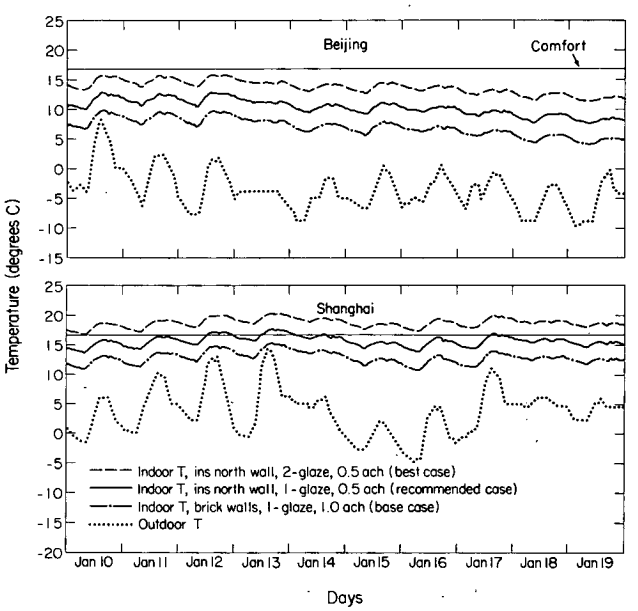

Figure 4. Floating indoor temperatures in winter for a typical building in Beijing and Shanghai with standard brick walls only, with insulation, and with both insulation and double glazing. (XBL 831-1085)

PLANNED ACTIVITES FOR FY 1983

More detailed information concerning this research effort will be available shortly as LBL report LBL-15183.

The results of this paper were presented by one of the co-authors, Professor A. Rosenfeld, at the First U.S.-China Conference on Energy Resources and Environment held in Beijing in November 1982. Further analysis is contemplated following review of comments from Chinese researchers, incorporation of more detailed data on Chinese buildings and climate conditions, and formulation of a research agenda.

OCCUPANT BEHAVIOR AND RESIDENTIAL ENERGY USE*

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

Lawrence Berkeley Laboratory, in conjunction with a number of cosponsoring organizations,† has been investigating the effects of occupant behavior on residential energy use for the last several years. Occupant behavior has been examined in three interrelated projects using household data collected in the California cities of Davis and Lodi: (1) comparison of estimated and actual summer electricity consumption using the U.S. Department of Energy's DOE-2.1A building energy analysis model; (2) the construction of a multiple regression model that combines structural-physical characteristics of a residence with appliance and behavioral data of occupants for explaining the variation in summer electricity use; and (3) the evaluation of utility-sponsored and locally run community electricity management programs in Davis and Lodi. The conclusions and issues resulting from this work have laid the foundation for continued work in the study of occupant behavior and energy use in other communities in the country for FY 1983.

ACCOMPLISHMENTS DURING FY 1982

Principal activities were the analysis of survey data previously collected in Davis and the collection of survey data in Lodi, California. The methods used in collecting the Davis data are described elsewhere[1] and are briefly summarized below.

During the summer of 1980, a random sample of 241 Davis households was surveyed. A questionnaire was developed and administered to the building occupants that contained over 200 questions covering a wide variety of energy use attitudes and behaviors and the background characteristics of the residents. The interviewers also obtained other data, such as building area and orientation, building shading, window area and orientation, appliance inventory, and

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insulation characteristics for the wall and ceiling, all of which affect energy loads. Additional information was collected on energy efficiencies of key appliances, and, for a selected subsample, air infiltration rates and internal building temperatures were recorded. Hourly weather data were collected on solar radiation, dry-bulb temperature, air pressure, wind speed, and wind direction. Monthly energy use data for the survey respondents for 1979 and 1980 were provided by the local utility, the Pacific Gas and Electric Company (PG&E).

During the summer of 1981, 291 households were surveyed in Lodi, using a questionnaire similar to that in Davis. The interviewers also obtained data on appliance and housing characteristics and internal building temperatures. Monthly energy-use data for the survey respondents for 1980 and 1981 were provided by the municipal utility and PG&E.

Comparison of Estimated and Measured Electricity Use

Total electricity use and cooling loads for a three-month cooling season (July-September, 1980) in 74 single-family detached houses in Davis were estimated and compared with measured data. Total electricity use for the summer was estimated by predicting cooling loads and appliance-related electricity demand. Appliance electricity use was derived from manufacturers' data, and patterns of appliance use were elicited from occupants through the household survey. Cooling loads were estimated by using an interpolation model to simplify application of the DOE-2.1A energy use computer model. The starting point for the interpolation model was the parametrization of a baseline house, representative of typical single-family detached residences in Davis. This baseline house was run on the DOE-2.1A program using Davis weather tapes for three summer months of 1980. The interpolation model was then developed, using a sensitivity analysis in which all the major house characteristics and occupant behavior patterns that affect cooling loads were varied singly, and sometimes jointly, in the DOE-2.1A model. The equations in the interpolation model (Table 1) represent the DOE-2.1A runs to within approximately 5%. The model was constructed in such a way that values from the questionnaire and building audit could be inserted into the model to predict cooling electricity use. The form was chosen to ensure that when base case values were inserted into the equations, total cooling use would equal the cooling load required by the base house.

Table 1. The interpolation model.

$$\text{Cooling electricity} = (7.1/\text{EER}) \times (\text{House area}/1975) \times (E1 + E2 + E3 + E4 + E5 + E6 + E7)$$

where

EER = Energy efficiency ratio of air conditioner

$$E1 = \{[55 \times (\text{Sch-3})] - 138\} \times (\text{Temp-79}) + [-505 \times (\text{Sch-3})] + 1745$$

$$E2 = [350 \times (11 - \text{Wall insulation})]/11$$

$$E3 = \{[-10 \times (\text{Sch-3})] + 9\} \times (19 - \text{Ceiling insulation}$$

$$E4 = [-1.3 \times (\text{Sch-3}) + 1.6] \times (\text{Area of south glazing} - 75)$$

$$E5 = [3.5 \times (\text{Sch-3}) - 7.4] \times (\text{Shaded glazing percentage} - 50)$$

$$E6 = [0.9 \times (\text{Sch-3})] \times (\text{Area of north glazing} - 225)$$

$$E7 = (-180 \times \text{Venting})$$

where

Temp refers to occupant-reported indoor room temperature
Venting refers to night venting (on = 1, off = 0)
Sch refers to occupant-reported air conditioning use with the following codes:

Almost always	Sch = 2
Often	Sch = 3
Sometimes or almost never	Sch = 4
Never	Cooling electricity = 0

Predicted total electricity use was calculated for each house by adding the cooling load from the interpolation model to the appliance load. After attempting several other forms of the model, the final interpolation model, using occupant-reported air conditioning schedules and indoor temperatures, was run on the 74 single-family detached houses. Analysis of the means of measured and predicted total electricity use showed that this procedure overestimated the electricity use of single-family detached homes during the cooling season by 499 kWh, or 18% of average use.

We next examined the accuracy of our estimates of total electricity use for each house (instead of the entire sample), by using multiple regression analysis. This analysis showed that our procedure explained 31% of the variation in measured energy use (Fig. 1). When cooling loads were examined by subtracting the appliance load from total electricity use for both measured and predicted values, regression analysis indicated that only 12% of the variation in measured cooling electricity use could be explained by our method (Fig. 2).

Thus, while the procedure used in this project is helpful in predicting the mean total electricity use for a large sample of single-family detached houses, it is

very unlikely that precise forecasting of individual house electricity use is possible, even when there are no changes in occupancy, unless expensive monitoring techniques are utilized. (In FY 1983, we plan to examine households that have been submetered to see if we can increase the predictive capability of our models for individual homes.) Accordingly, conservation planners should be extremely careful to limit their promises for cooling-season electricity reduction and should emphasize average as opposed to individual benefits.

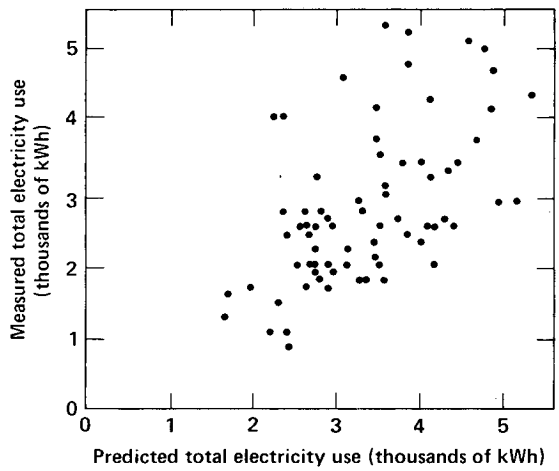

Figure 1. Predicted vs. measured total electricity use, using LBL's appliance saturation index as an indicator of appliance energy use and the DOE-2.1A model for cooling energy use. (XBL 824-8887)

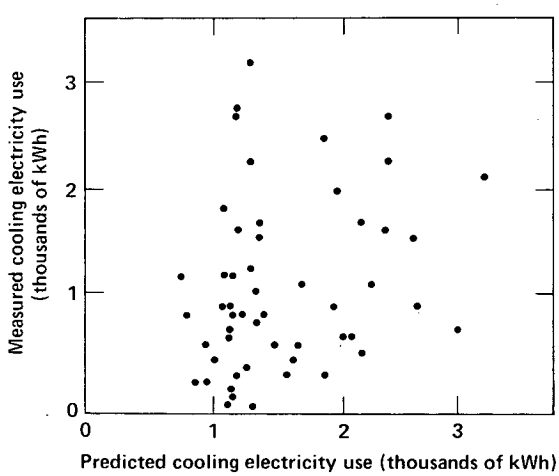

Figure 2. Predicted vs. measured cooling electricity use, using LBL's appliance saturation index as an indicator of appliance energy use and the DOE-2.1A model for cooling energy use. (XBL 824-8886)

Multiple Regression Models of Residential Energy Use[2]

The purpose of this project is to discover and understand the structural-physical, behavioral, attitudinal, and demographic determinants of residential energy consumption in order to identify where programs to promote energy efficiency should be directed. Using multiple regression analysis, we construct models that attempt to explain the variation in energy use among Davis and Lodi households.

Several regression models are being developed in this project. A model incorporating structural-physical and behavioral determinants has been constructed and run on all the building types in the Davis sample during the cooling season and is discussed in this report. Similar models will be constructed for analyzing the heating season and total energy use in Davis. In addition, other models will include demographic and attitudinal determinants and will be used for analyzing the cooling and heating seasons, as well as for the entire year. All these models will be run with the Lodi data in order to determine the generalizability of our results.

In this project, several structural-physical and behavioral variables important in influencing electricity use were selected from the survey and energy audit for statistical analysis. These variables included wall and ceiling insulation levels, floor and glazing areas, number of rooms, orientation of house, frequency of air conditioner use, venting, shaded glazing areas, air conditioner settings and schedules, and a constructed conductivity measure. Multiple regression analysis (using the least squares method) was conducted with total electricity use as the dependent variable and with the above variables as the selected independent variables. Hierarchical regression was used, and many combinations of variables were tested to find the best equation. The models were run separately on single-family detached homes, on all other types of residence (e.g., apartments, duplexes, single-family attached houses, condominiums, duplexes, triplexes, and fourplexes), and on all residences to discover which independent variables were statistically significant and which models explained the most variation in household electricity use (i.e., high R^2).

After testing for interaction effects and nonlinearity and examining the problem of multicollinearity, where independent variables are highly correlated with one

another, a final structural-behavioral regression model was constructed for all households as follows:

Total electricity use (kWh) =

-701.11 + 87.90 (Frequency of air conditioner use)

+ 0.36 (Appliance saturation index) + 0.52 (Floor area)

+ 0.06 [(Appliance use) × (Number of people home)]

+ 0.11 [(Floor area) × (Air conditioning use)]

+ 408.37 (Building type)

where

- Frequency of air conditioner use was coded from 0 (never) to 4 (always)
- Appliance saturation index was composed of the following electrical appliances: water heater, clothes dryer, clothes washer, oven, refrigerator, freezer, dishwasher, and swimming pool filter/pump
- Building type was coded (1) single family-detached and (0) for all other building types.

This model explained 75% of the variation (R^2 = 0.75) in electricity use in the cooling season for all the households in the Davis sample (Fig. 3); for single-family detached households and for all other households, R^2 was 0.51 and 0.60, respectively.

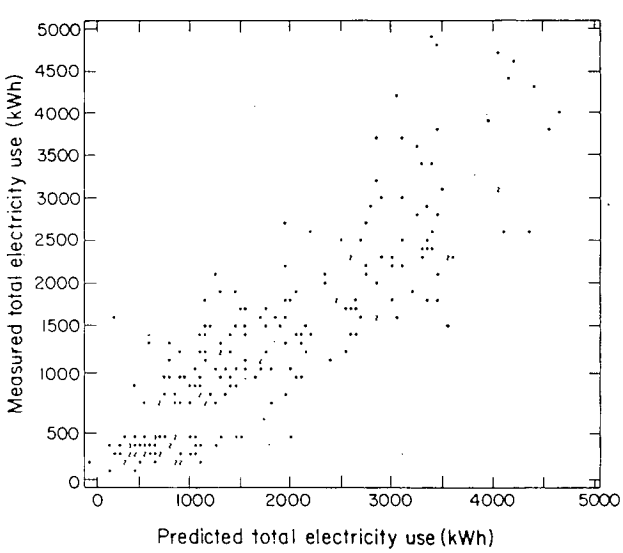

Figure 3. Predicted vs. measured total electricity use, using multiple regression analysis. (XBL 8211-7358)

Thus, it appears that information on selected key variables is sufficient for explaining more than three-quarters of the variation in total electricity use for all households, although our ability to explain energy use was diminished for specific housing types. This research therefore strongly supports the theory that occupant behavior is a significant determinant of residential electricity use after controlling for structural-physical characteristics of dwellings. Accordingly, the education of the residential energy consumer should be an important focus of public policy in reducing energy use, as exemplified in the project described below.

Despite our success in predicting household electricity use, there is still a large amount of variance unexplained by both the structural-behavioral regression model and the procedure used in the first project. Some of the likely reasons for the differences in values between predicted and measured electricity use are:

1. Self-reported behavior (e.g., occupants' reports of air conditioning use) was sometimes wrong.
2. Some major building characteristics (e.g., percentage of window shading) were very difficult to measure.
3. Appliance loads were not accurately estimated for individual homes (e.g., we sometimes relied on national appliance energy efficiencies when household-specific data were missing).
4. Cooling electricity use was calculated from weather data for one local site instead of site-specific weather information, thereby neglecting important microclimatic conditions.
5. Some household behaviors affecting cooling energy use are only partially captured in regression models (e.g., night venting).
6. Some household behaviors affecting cooling energy use are not represented at all in regression models (e.g., microclimatic effects of exterior vegetation).
7. Responses to the survey were elicited from one household member while energy use is a composite of all household members.

Evaluation of Peak Load[3]

During the summer of 1980, the City of Davis and PG&E implemented the first year of a two-year experi-

mental peak-electricity load-management program named Prime Time. The program was based on the principle of inducing peak electricity use reduction via goal-setting, community and individual financial incentives, and feedback. A similar program was implemented in Lodi during the summer of 1981.

In these programs, residents were asked to reduce their weekday use of electricity during a specified afternoon time period (in Davis, from noon to 6 p.m.). Throughout the program, literature drops, newspaper, radio, and television reports, and a wide variety of special community events organized by citizen activists and civic leaders brought the message of peak-load management to the public. The Prime Time program made reductions voluntary and offered as a reward a portion of the utility's cost savings resulting from the program: $10,000 would be awarded the city for every 1% reduction in peak electricity use compared to the use of the previous summer. The maximum amount PG&E would pay was $100,000. The target of the program in Davis was primarily the residential sector, especially persons who lived in single-family detached houses.

The index used by PG&E and the City of Davis for estimating changes in peak electricity use was 100 $K(C-D)/C$, where C was the peak electricity use for 1979 measured on summer weekdays from noon to 6 p.m., D was the peak electricity use measured over the same time period in 1980, and K was an adjustment for the difference in the number of summer weekdays and number of customers in 1979 and 1980. According to this index, the Prime Time program resulted in a total peak load reduction of 22%. Davis earned the maximum reward of $100,000, which was spent on capital improvement projects oriented toward conservation, such as planting more trees along streets.

Because the index did not take into account changes in weather, fuel prices, and conservation behavior, we conducted an evaluation of the Prime Time program using data collected from our survey of Davis residents and other data sources. We found that although 80% of our sample had heard of the Prime Time program, very few respondents stated that they had recently shifted appliance use from the afternoon to some other time period. In addition, respondents also indicated that there was very little opportunity to shift appliance use away from peak hours. This was particularly true for air conditioning, a major target of the program. Moreover, program participants reported significantly less air conditioning use than nonparticipants by setting their air conditioner at higher temperatures and by greater reliance on night venting, which was promoted by the Prime Time program. In sum, many people responded to the program by reducing their total consumption of electricity, rather than by shifting the timing of electricity consumption.

A comparison of average electricity consumption per customer in the residential sector between Davis and a group of 50 cities (all being served by the same utility, receiving the same electricity rates, and having similar weather) showed that electricity consumption in Davis declined by about 6.9% over that in the control group. If, as we believe, the 50 cities are comparable to Davis, then the 6.9% reduction can be attributed to the Prime Time program. The survey data, combined with PG&E's figures on household electricity consumption, also provide support for the aggregate results. Using multiple regression analysis, we constructed a model that contained as variables pre-program electricity consumption, floor area, percentage of shaded glazing, type of dwelling unit, health need for air conditioning, and participation in the Prime Time program. By comparing participants and nonparticipants, we found that the average household savings of electricity due to the Prime Time program was about 8.4%. Since 54% of our sample said they participated in the program, overall conservation in the residential sector would have been about 4.5%. Given that 4.5% is an underestimate because of increased participation after the interview and spillover effects not consciously attributed to the program, this estimate is consistent with the aggregate estimate of 6.9% residential conservation. This estimate represents about 34% of the reduction in total residential electricity consumption (a reduction of 20%). If we assume that this share applies to peak load as well as to total consumption, then of the observed 22% reduction in peak load, approximately 7.5% would have been due to Prime Time (after controlling for weather, prices, etc.).

We intend to examine the electricity load management program in Lodi in the near future. Preliminary evidence indicates that participants in this program have saved energy compared to nonparticipants.

PLANNED ACTIVITIES IN FY 1983

We intend to analyze the heating season and total energy use in Davis as was done for the cooling season in the first two projects. The models will also

include attitudinal and demographic data. We also expect to analyze the Lodi data (including the electricity load management program) in the same fashion as the Davis data. We also plan to continue our evaluation of the effects of occupant behavior on residential energy use by analyzing households that have had key appliances submetered.

REFERENCES

1. Vine, E., et al. (1982), "The Applicability of Energy Models to Occupied Houses: Summer Electric Use in Davis," *Energy*, in press.
2. Vine, E., et al. (unpublished, 1982), "Structural-Physical and Behavioral Determinants of Residential Energy Use: Summer Electric Use in Davis."
3. Kowalczyk, D., et al. (1982), "Evaluation of a Community-Based Electricity Load Management Program," *Energy*, in press.

ENERGY CONSERVATION IN PUBLIC HOUSING*

R.L. Ritschard and D.F. Dickey

Building energy efficiency will demand increasing attention by public housing officials in this decade. Rising energy costs during the past several years have created an ever-widening gap between the allowable expenses of a local public housing authority and the income that it obtains from rents. The difference between these is made up by federal public-housing operating subsidies, which increased from $12.6 million in 1968 to $685 million in 1978.[1]

A large and growing proportion of a local public authority's expenditures consists of utility costs, which have risen primarily as a result of increasing prices rather than increased consumption. Preliminary surveys indicate that energy consumption for a sample of large public housing authorities actually decreased slightly during the last three years.[2] The energy costs for public housing nationwide have climbed from $185 million in 1970 to an estimated $740 million in 1980 (an increase of over 400%).[1] This cost varies widely between building types, climates, and user characteristics. Most of this increase has occurred during the last few years and will probably continue: fuel costs are expected to rise over general inflation for many years to come. Public housing not only has many of the financial problems that face private market rental housing, but, as in multi-family rentals, tenants have few incentives to conserve energy. In addition, there is a proposal by the federal government to shift financial and management responsibilities to state and local agencies.

The federal agency charged with overseeing the energy characteristics of public housing is the Department of Housing and Urban Development.[3] In the bygone days of cheap energy, HUD's involvement in energy efficiency was limited.

Before 1973, consideration of thermal integrity was "suggested" by HUD to local housing authorities at the time of construction, but no mandatory standards existed.[4] As a result, perhaps 75% of the existing public housing stock was constructed without regard to effective thermal insulation.[4] Compliance with HUD's early guidelines resulted in very little thermal integrity. Application of the 1963 standard to San Francisco's climate, for example, meant that no insulation of *any* type was recommended in any component of either a low-rise or high-rise building.[4]

Mandatory insulation standards were finally promulgated in 1973.[4] HUD's new conservation requirements had little impact on the public housing stock, however, because a moratorium on new public housing construction was imposed during that same year and lasted until 1977. HUD has required cost-benefit analyses of energy conservation improvements in public housing projects. These conservation decisions are targeted for completion by 1983 and must favor measures with the shortest payback periods (rather than the lowest life-cycle costs).[9] Local public housing authorities have also begun to make energy efficiency improvements in existing stock in an attempt to reduce rising energy expenditures. A significant source of funds for energy conservation retrofit has been modernization money provided by HUD.

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

ACCOMPLISHMENTS DURING FY 1982

National Perspective on Public Housing Characteristics

Physical Condition

Public housing provides about one-fifth of the low-income rental housing in the nation. A recent report commissioned by HUD evaluated the physical condition of the public housing stock and estimated that there are approximately 1.2 million dwelling units (9900 projects managed by 2700 local housing authorities) with more than 3.4 million occupants.[1] The average single project was built before 1965 and contains 119 units. More than half of the units are classified as family low-rise apartments, which means the buildings are predominately four stories or less (Table 1). A surprising finding is that many of the projects conform to key points in the minimum property standards and are well-built.

Table 1. National public housing characteristics.

	Total units (percent)	Avg. age (years)	Number of dwelling units
Family low-rise[a]	30.8	23	Greater than 200
Family low-rise	26.2	18	Less than 200
Elderly	23.8	12	
Family high-rise[b]	17.1	20	Greater than 200
Family high-rise	2.1	14	Less than 200

[a]Low-rise buildings predominately four stories high or less.
[b]High-rise buildings predominately five or more stories (also those with combinations of high and low-rise buildings).
Source: Reference 1, p.11.

Energy Use

Public housing annually uses an estimated 146 million Btu per dwelling unit, or 175 trillion Btu for the entire stock.[1] Of this annual total amount, 65% is used for space heating, 22% for domestic hot water heating, and the remainder for lighting and appliances. The average annual energy use by fuel type (Btu) is as follows: natural gas—64%, oil—25%, and electricity—11%. Since the per-unit cost is greater for electricity than for the other sources, electrical costs account for nearly one-third of the average annual energy bill. The average cost per dwelling unit is estimated at $673 (in 1980 dollars).[1]

Potential for Energy Conservation Investment

Energy efficiency retrofit of the nation's public housing inventory was the subject of a study recently completed for HUD. Four hundred public housing projects were surveyed, and the cost of bringing each project up to three separate energy efficiency standards was calculated. The results were then weighted so that estimates for all projects could be computed.

An average investment of $1347 per dwelling unit is estimated by the study to yield average annual savings of $324 per unit (for an average payback of 4.2 years).[3] Nationwide costs for this level of investment would be $1.5 billion. A wide range of levels of investments would be necessary to accommodate different types of projects. High-rise housing projects with over 200 units and vacancy rates above 10% were found to require an average of $2680 to meet the standard. Low-rise projects designed exclusively for elderly tenants were estimated to require only $600.[6] Regardless of how the estimates are disaggregated, however, the total investment needed (some $1.5 billion) is certainly substantial. On the other hand, this investment would reduce the average per-unit energy consumption from 146 million Btu to 68 million Btu, which is comparable to typical, private-sector housing adapted for energy conservation.[1] Since HUD currently provides the bulk of the public housing subsidies to local housing authorities, the federal government will be the major benefactor of any investments it makes today. In addition, the comfort level and well-being of the low income tenants can also be enhanced if the physical condition of the public housing stock is improved to some minimum level.

Examples of Energy Conservation

To gain an understanding of how energy conservation has been addressed in the public housing sector, we review three examples of local energy-saving strategies. These examples are not an exhaustive listing, but instead cover some of the major activities that public housing authorities are pursuing. Data on specific energy measures, their costs and savings, and implementation processes are not readily available because most local housing authorities have not yet reached this stage in the energy retrofit process.

Window Retrofits

The New York City Housing Authority, which ini-

tiated an energy conservation program in 1974, is deeply committed to energy conservation. One particularly successful strategy has been the replacement of over 22,000 steel casement windows with energy-efficient, double-hung, double-glazed aluminum windows (including thermal breaks) at the Cypress Hills and Brownsville Houses. The costs of the windows, which were funded by a Department of Energy (DOE) weatherization grant, amounted to approximately $3.3 million.[7] The prior steel casement windows were subject to excessive air infiltration and frequent glass breakage during windy weather and sharp fluctuations in outside temperature. As shown in Table 2, the energy savings, as measured by fuel oil consumption per degree-day before and after installation of the energy-efficient windows, were significant. If domestic hot water usage is excluded by subtracting a constant hot water factor per year for each project (calculated from summer-season fuel consumption), estimated savings for space heating are only 21.1 gallons/degree-day (16.1%) for Cypress Hills Houses and 18.1 gallons/degree-day (14.5%) for the Brownsville Houses. This method presents a more accurate picture of the effects of window replacement on fuel consumption because neither the number of degree days nor the type of windows affects hot water consumption.

Table 2. Window retrofit data for two New York City housing projects.

	Cypress Hills	Brownsville
No. of apartments	1,444	1,338
Windows replaced	10,980	11,548
Total cost (including insulation)	$1,524,447	$1,774,447
Gallons fuel oil/degree-day (1978-1979)	182.6	167.7
Gallons fuel oil/degree-day (1980-1981)	159.7	148.5
Savings (gal/degree day)	22.9	19.2
Percent energy savings (including domestic hot water)	12.5	11.4
Gallons fuel oil (space heating)/ degree day (1973-74)	131.1	124.8
Gallons fuel oil-(space heating)/ degree day (1980-81)	110.0	106.7
Savings (gal/degree-day)	21.1	18.1
Percent energy savings (space heating)	16.1	14.5

Source: New York City Housing Authority memorandum from John Kelleher, February 22, 1982.

Another significant benefit of the double-glazed windows is a reduction in glass breakage and in routine maintenance (cycle painting of frames). It is estimated that, for an average 1000-unit project, this saves about $20,000 per year in maintenance costs.[8] With an additional grant, another 2266 apartments are being retrofitted at Highbridge Houses and St. Nicholas Houses; however, energy-use data are not yet available.

Even though the initial cost for window replacements is significant and the payback period involved is relatively long (probably 10 years), the potential energy savings from such an option are appreciable. These are especially significant if we consider that as much as 65% of a public housing unit's average energy consumption is attributed to space heating.

Computerized Energy Management System

An innovative approach to energy conservation was taken by the Trenton Public Housing Authority in New Jersey. At the Page Homes complex—six 3-story brick buildings totaling 159 units and constructed in 1954—a computerized energy management system was installed with federal funds.[9]

The heating system consists of a central plant, located in a separate building, that circulates hot water through underground pipes to the six project buildings. The operation of the energy management system is straightforward. A number of indoor temperature sensors are placed in selected apartments (72 throughout the complex). The main program reads apartment temperatures, outside temperatures, and time of day on a 15-minute cycle and operates pumps and boilers to regulate the amount of heat delivered to the apartments. The system was activated on January 27, 1981, when outdoor temperatures were between 20° and 30°F. At that time, inside temperatures were generally in excess of 82°F. By mid-February, average building temperatures were being maintained at approximately 74°F daytime and 72°F at night.

Significant reductions in fuel-oil consumption were achieved with this system (Table 3). For the seven months of 1981 in which the computer system operated and for which heat was supplied (excluding the months of June through September), oil consumption was reduced by about 53% from the previous year. If weather adjustments are considered, the savings were approximately 48%. After the first full year of operation, consumption was roughly cut in half

from the previous year, making Page Homes one of the most fuel-efficient old apartment complexes in New Jersey, even though apartment temperatures were held at a relatively balmy 72° to 75°. It is estimated that fuel oil savings in the past winter exceeded $60,000.[10]

Meter Conversions

A major emphasis of HUD's energy conservation efforts in public housing has been the active promotion of conversion from master metering of tenants' utilities to either submetering or individual metering. In rules first promulgated in May 1976, HUD required public housing authorities (PHA's) to perform benefit/cost analyses regarding metering conservation.[11] Empirical evidence indicates that when a single master meter is used to record energy consumption for an entire multi-family building and utility bills are included as part of the monthly rent, tenants have little incentive to save energy and will therefore consume more than when individually metered. A report on this topic estimates an average savings in electricity use of 15 to 20% and in natural gas of 5 to 7% after converting from master to individual meters.[12] These results, however, are for multi-family dwellings where tenants are made financially responsible for the energy they use, but not specifically for public housing occupants. HUD's regulations established a presumption that conversion to either individual metering or submetering would automatically conserve 25 to 35% of PHA heating energy, regardless of significant variables such as the condition of the project, amount of insulation, or types of tenants.[13]

Table 3. Page Homes fuel-oil consumption (gallons of #4 oil).

Month	1978	1979	1980	1981
Jan.	31,000	30,300	26,100	24,100
Feb.	27,200	26,700	24,900	10,800[a]
Mar.	22,200	19,000	20,800	9,600
Apr.	15,900	17,600	10,200	5,600
May	12,000	4,000	4,200	3,500
June-Sept.	(No heat supplied to apartments)			
Oct.	12,000	10,600	8,400	4,500
Nov.	18,600	14,400	17,500	6,400
Dec.	19,600	22,600	18,600	8,650

[a]First full month of operation of the computer system.

Source: Page Homes Demonstration Project for the Application of Computers to Energy Conservation in Public Housing Projects, Trenton Housing Authority, Trenton, New Jersey, February 1982.

As a result of litigation brought by tenant groups, HUD has been required to temper somewhat its preference for meter conversion over other conservation retrofit measures.[14] New regulations promulgated in May 1980 require that meter conversion must be considered against 20 other conservation and solar measures as part of energy audits of public housing.[15] Additionally, until HUD can substantiate its presumption of 24-35% savings from meter conversion, a nationwide injunction prohibits further conversion.[16]

Conclusions

Our assessment of energy conservation efforts in public housing leads to the conclusion that there is substantial potential for saving energy in public housing projects. Because HUD plays a substantial portion of the costs of tenant energy consumption under any billing option, it is in HUD's long-term economic interest to invest in cost-effective weatherization and retrofit measures.

Since data on energy-saving strategies that have been successful for public housing are virtually nonexistent, local authorities are forced to make decisions about conservation investment strategies in a void of technical information. The federal government, which has been a major funding source in other energy conservation research, has not fully addressed this sector. With assistance from the Department of Energy and/or the Department of Housing and Urban Development, the technical research community can provide high quality documentation of effective energy conservation measures in public housing.

PLANNED ACTIVITIES IN FY 1983

This work will continue in 1983 if funding is available. In particular, an analysis of the San Francisco public housing stock will be concluded to determine the effect of utility-financed retrofit on energy-use patterns.

REFERENCES

1. Perkins & Will Inc. and Ehrenkrantz Group (1980), *An Evaluation of the Physical Condition of Public Housing Stock: Final Report, Volume I*, HUD Report H2850.

2. Patten, C. (1981). *National Trends in Fuel Prices and Their Relationship to Public Housing Operating Subsidies,* CLPHA Research Report #82-1, Council of Large Public Housing Authorities, Boston.
3. 42 USC § 1437 (d), 3535 (d).
4. Ferrey, S. (1977), "The Ghosts of Cold November: An Examination of HUD's Energy Conservaton Policy for the Poor," *Clearinghouse Review,* May, p. 5.
5 24 CFR 865.301 et seq.
6. Strunk, R.J. (1980), "Public Housing Modernization Program: An Analysis of Problems and Prospects," *Journal of Housing,* October, pp. 492-496.
7. Research and Policy Development Department, New York Housing Authority (1981), *Status of Fuel Oil-Related Experiments and Initiatives, 1977–Present.*
8. Taleisnik, B, Director, Energy Control and Conservation, New York City Housing Authority (May 28, 1982), personal communication.
9. Trenton Housing Authority (1982), *Page Homes Demonstration Project for the Application of Computers to Energy Conservation in Public Housing Projects*, Trenton, N.J.
10. 24 CFR 865.5400 *et seq.*
11. Booz, Allen Hamilton (1979), *Alternative Metering Practices: Implication of Conservation in Multi-Family Residences*, prepared for the U.S. Department of Energy (HCP/M 1693-03).
12. 24 CFR § 865.404.
13. *Massachusetts Union of Public Housing Tenants et al. v. Landrieu et al.* (April 7, 1981), in U.S. Court of Appeals for the District of Columbia, Docket No. 78-1895, 80-1332.
14. *Fed. Reg.* 30347 *et seq.* (May 7, 1980).
15. *Mass. Union, op. cit.* (March 31, 1982). Injunction issued prohibiting further meter conversion pending remand to HUD for substantiation of meter conversion presumptions by August 1, 1982. HUD did not supply further substantiation by that deadline. Injunction remains in effect, pending district court review. It should be noted that HUD did not issue instructions to its regional offices prohibiting conversion until early June 1982, after a motion for contempt had been filed against HUD for continuing to convert meters in violation of the injunction.

SIMPLIFIED ENERGY ANALYSIS METHODOLOGY FOR COMMERCIAL BUILDINGS*

I. Turiel, R.A. Boschen, M. Seedall, and M.D. Levine

Energy analyses of commercial buildings may be used for new building design, energy end-use forecasting, and energy audit calculations. Most methods of energy analysis are expensive and require long training to be used properly. There are two ways to reduce this time and expense. One is to write a faster-running computer program with simplified algorithms having fewer options and less accuracy than a complex building simulation program such as DOE-2.1[1] or BLAST, for example. Kusuda and Sud used this approach in developing a modified bin method for commercial building energy analysis.[2] A second method is to create a data base by performing a large number of DOE-2.1 runs for the building parameters relevant to energy-use impact and then use this data base to predict the outcome of other energy-conservation measures. This paper discusses our approach to the latter method.

ACCOMPLISHMENTS DURING FY 1982

We have performed a parametric energy analysis using the DOE-2.1A version of the DOE computer program for an office building in one climatic region, Denver, Colorado. An equation based on this analysis was developed that predicts heating, cooling, and total building energy use as a function of 11 building-envelope and systems-control parameters. These parameters are the key ones for determining energy use-impact in the Denver climate. The equation takes into account both single-parameter changes and the interactions that occur when two parameters are changed simultaneously.

With this methodology, a microcomputer can be used to predict energy consumption in commercial buildings in various climates very cheaply and with high accuracy, as the results will be based on previously performed DOE-2.1 runs. Our initial work indicates, that, at least for the climate studied, this technique indeed predicts energy use very accurately.

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Base-Case Building Characteristics and Operating Conditions

Many assumptions must be made concerning the operating conditions and characteristics of the base-case building before its interaction with the appropriate climate and its operation can be simulated with DOE-2.1A. The office building we modeled was selected as typical and studied during Phase II of the Department of Energy (DOE) Building Energy Performance Standards (BEPS) project.[3] The building has been altered slightly to make its construction characteristics internally more uniform throughout.

The base-case building is a 100,000 ft^2 (72 ft × 232 ft), six-story office building in Denver, Colorado. Denver has a climate with 6000 heating degree-days (base 65°F) and with 667 hours when the outdoor dry-bulb temperature is greater than or equal to 80°F. Weather information was obtained from a Test Reference Year (TRY) tape for 1976.

The composition of walls, roof, and floors is described under the materials heading in Table 1. The total R-value of the external walls and roof varies with the R-value of the insulation in each assembly. We have not studied the effect of varying the R-value of the underground floors, since heat transfer to the ground is not well enough understood to be properly modeled. All interior floors have a fixed R-value of 9.

Each of the four exposures has the same window-to-wall ratio (22%), and the windows have the same solar transmission (40%) and glass conductance (0.574 Btu/hr·ft^2°F). We have studied the effect of fixed shading by varying the window setback. Lighting is provided by fluorescent lamps recessed in a suspended ceiling. The average lighting power density is 2.5 W/ft.^{2}, and 50% of the heat of lights is assumed to enter each space according to its installed wattage. The remaining 50% is exhausted to the outside through the ventilation system.

Three types of HVAC systems have been studied. The first is composed of a number of water-to-air unitary heat pumps for both heating and cooling, with a circulating water loop. A 300-kW electric boiler provides back-up heat generation if the water temperature of the loop falls below 60°F. The other two are double-duct constant-volume and double-duct variable-volume systems. Both have a gas-fired hot water boiler and centrifugal chiller.

Table 1. Base-case values for large office building.

LOCATION AND ORIENTATION

City: Denver
Size: 72 ft × 232 ft (6 stories)
Orientation: Long axis points 60° east of north
Ground reflectance: 0.20

MATERIALS

Average Mass Density: 62 lb/ft^2

External Walls:	4″ heavyweight concrete, R9 polystyrene insulation, 5/8″ gypsum board. Total R=9.5.
Internal Walls:	5/8″ gypsum board, 4″ air layer, 5/8″ gypsum board. Total R=2.7.
Roof:	0.5″ roof gravel, 3/8″ built-up roofing, R15 polystyrene insulation, 6″ heavyweight concrete, 4″ air layer, 0.5″ acoustic title. Total R=19.
Ground floor:	R24 fiberglass batt insulation, 6″ heavyweight concrete, 3-1/4″ lightweight concrete, carpet with fibrous pad. Total R=30.

Solar Absorptivity:

Walls: 0.65
Roof: 0.30

WINDOWS AND LIGHTING

Glass solar transmission: 0.40
Glass conductance: 0.574 Btu/hr · ft^2 °F (double glazing)
Window-to-wall ratio: 22
Window shading setback/window height: 0.125 (1-foot setback)
Heat of lights to space: 0.50
Lighting power: 2.5 W/ft^2
Infiltration: 0.6 air changes/hour

SYSTEMS

Outside air/person: 7 cfm/person
Thermostat setpoints:

Heating: 72°F
Cooling: 78°F

Night Setback:

Heating: 60°F
Cooling: 99°F

Economizer: None

Base-Case Building Results

We have performed parametric energy analyses for 16 building parameters and the three HVAC system types. Here, we report only the results for the heat-pump system. Five variables—orientation, ground reflectance, window setback ratio, roof absorptance, and wall absorptance—have very small effects (<2% change) on total energy use in Denver's climate. For the other 11 parameters, curves were fit to the DOE-2.1 simulation results.

Of these 11 parameters, only six cause a 10% or greater change in total energy use. These parameters are wall insulation, glass conductance, window-to-wall ratio, lighting power, amount of outside ventilation air, and nighttime heating setback temperature. A 10% change in total energy use is quite large when we realize that, except for lighting power, the variations in each parameter do not affect lighting, hot water, and elevator energy use, which total 60% of the total base-case energy use. A 25% change in space conditioning energy use is required to obtain a 10% change in total energy use.

It is important to note that a change in the HVAC system can have a greater impact on energy use than a change in the value of a building-envelope or system-control parameter. For example, at a 50% window-to-wall ratio, a heat-pump system may use 33% less energy than a dual-duct constant-volume system, whereas a change in the window-to-wall ratio from 75% to 25% reduces energy use by only 15% (Fig. 1). Table 2 lists the functional relationship between heating and cooling energy use and each of the 11 parameters studied.

When the interaction matrix element is small, multiple measures may be treated by adding the results of single measures taken one at a time. The parametric equations developed for changes in a single parameter can be used for these cases. For large interactions, a different methodology must be used to estimate energy use accurately. When heating and cooling energy use are separately estimated, the errors resulting from not considering interactions between multiple simultaneous conservation measures are, in general, larger than the errors for the total energy use estimation.

Energy-Use Prediction Methodology

Our single-parameter energy analysis indicated that total energy use (in Denver's climate) can be accurately expressed as an analytic function of each of 11 building parameters, while all others were held constant. When the interaction between two parameters is small, simple addition of energy savings from multiple measures will provide reliable estimates of the combined total energy savings. To determine heating, cooling, or total energy use as a function of two simultaneously varying parameters, where the interaction between parameters is large, we performed a Taylor series expansion of energy use as a function of two variables, P_i and P_j. P_i and P_j represent any two building parameters. Equation (1) is the second-order expression used.

$$E\,(P_{i1},P_{j1}) = E_o + \frac{\partial E}{\partial P_i}\,\Delta P_i + \frac{\partial E}{\partial P_j}\,\Delta P_j + \partial^2\frac{E}{\partial P_i^2}\,\frac{\Delta P_i^2}{2} + \partial^2\frac{E}{\partial P_j^2}\,\frac{\Delta P_j^2}{2} + \frac{\partial^2 E}{\partial P_i \partial P_j}\,\Delta P_i \cdot \Delta P_j \qquad (1)$$

In Eq. (1), E_o is the base-case energy use and $E(P_i,P_j)$ is the energy use when the parameters P_i and P_j have values P_{i1} and P_{j1} respectively. All derivatives are evaluated at (P_{io}, P_{jo}), the base-case values of parameters P_i and P_j. ΔP_i equals $(P_{i1} - P_{io})$, and ΔP_j is defined similarly.

All five partial derivatives were evaluated by using actual DOE-2.1 runs.

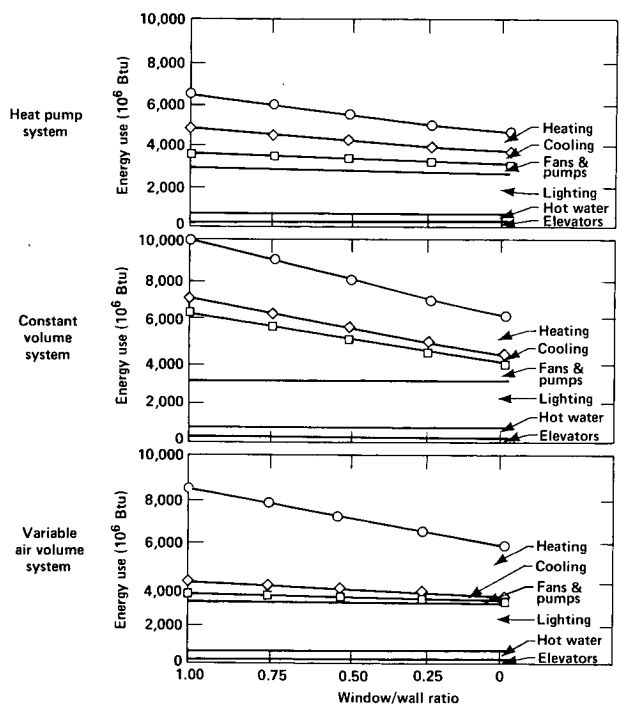

Figure 1. Annual total energy use with varying window-to-wall ratios in a large office building, Denver, Colorado. (XBL 824-8924)

Table 2. Parametric equations for heating and cooling.

Parameter	Functional Form	Fitted equation
Roof Insulation Heating	Asymptotic	$E_H = 1507.65(3.22 + R)^{-1} + 800.63$
Roof Insulation Cooling	Linear	$E_C = 6(RR + 3.22)/5 + 621.14$
Wall Insulation[a] Heating	Asymptotic	$E_H = 2682/(1.52 + RW) + 609.3$
Wall Insulation Cooling	Linear	$E_C = 618 + 4.26(RW)$
Window to Wall Ratio—Heating	Linear	$E_H = 755.16 + 671.65(WWR)$
Window to Wall Ratio—Cooling	Linear	$E_C = 536.16 + 611.65(WWR)$
Glass Solar Transmission—Heating	Linear	$E_H = 1110.8 - 468.1(GST)$
Glass Solar Transmission—Cooling	Linear	$E_C = 448.8 + 607.7(GST)$
Glass Conductance Heating	Quadratic	$E_H = 487.6 + 791.2(GC) - 132(GC)^2$
Glass Conductance Cooling	Quadratic	$E_C = 789.4 - 280.3(GC) + 98.9(GC)^2$
Lighting—Heating	Linear	$E_H = 1732 - 347.1(LIT)$
Lighting	Linear	$E_{Light} = +979.4(LIT)$
Lighting—Cooling	Linear	$E_C = 217.35 + 169.8(LIT)$
Outside Air—Heating	Quadratic	$E_H + 374.4 + 58.4(OA) + 2.4(OA)^2$
Outside Air—Cooling	Quadratic	$E_C = 1042.5 - 76.2(OA) + 3.1(OA)^2$
Heat of Lights to Space—Heating	3rd order polynomial	$E_H = 1764 - 2874.2(LS) + 2731.3(LS)^2 - 892.5(LS)^3$
Heat of Lights to Space—Cooling	3rd degree polynomial	$E_C = 234.66 + 816.40(LS) + 313.6(LS)^2 - 516.9(LS)^3$
Heating Setpoint Heating	Linear	$E_H = -997.0 + 26.4(TH)$
Heating Setpoint Cooling	Linear	$E_C = 138.2 + 7.3(TH)$
Cooling Setpoint Heating	Linear	$E_H = 743.6 + 2.05(TC)$
Cooling Setpoint Cooling	Quadratic	$E_C = 10{,}941 - 219.55(TC) + 1.12(TC)^2$
Night Thermostat Setback—Heating	3rd degree polynomial	$E_H = -3853.6 + 275.3(THS) - 5.95(THS)^2 + 0.0447(THS)^3$
Night Thermostat Setback—Cooling	2nd degree polynomial	$E_C = 1440.8 - 29.1(THS) + 0.268(THS)^2$

[a]R3 to R19 only.

Model Testing

After all coefficients needed for the Taylor series expansion were determined for all combinations of parameter pairs, a FORTRAN program was written to facilitate energy analysis with a microcomputer. We tested our simplified energy analysis methodology by using the computer program to predict energy use for combinations of parameters (two at a time) not previously studied. Table 3 shows the results of this comparison between the DOE-2.1 simulations and the simplified-model predictions.

The predictive capability of the simplified model is very good for both heating and cooling energy use, except where the parametric deviation from the base-case values is both large and in a direction opposite from that originally taken when the derivatives used in the Taylor series expansion were calculated. As can be seen from Table 3, as we move closer to the base-case values for glass solar transmission (GST) and window-to-wall ratio (WWR), there is a dramatic improvement in the accuracy with which heating and cooling energy use is predicted. For most test runs, the model prediction and the DOE-2 model simulations differ by less than ±5% for both heating and cooling energy use.

Aside from the test results shown in Table 3, we also compared DOE-2 runs to model predictions for the 55 two-at-a-time simulations that were used to obtain the mixed partial derivatives in Eq. (1). The DOE-2 simulations and the model predictions differed by less than 15% in all cases for both heating and cooling energy use. In 51 out of 55 cases, the heating energy use differed from the DOE-2 runs by less than 10%, and in only one case did the cooling energy use differ from the DOE-2 runs by more than 10%. The accuracy of our model can be improved by reducing the region of application of each pair of conservation measures. This requires applying the Taylor series expansions to several regions rather than only one and thus entails additional DOE-2 runs.

To perform our analyses, 200 DOE-2 were required. This includes both the single-parameter and two-parameter simulations that were necessary to complete the interaction matrix and calculate the Taylor series expansion coefficients.

PLANNED ACTIVITIES FOR FY 1983

The simplified methodology described in this paper worked well in the case tested, a mid-sized office building in Denver. A FORTRAN program that is easy to use and fast running can be used to accurately predict (if one takes DOE-2.1 results as a measure of accuracy) heating, cooling, and total energy use as a function of 11 major building parameters. We plan to test the sensitivity of our results to changes in building base case assumptions and in HVAC system type.

Table 3. Summary of predictive capability of simplified energy use model.

Parametric Values (two at a time)			Total energy use			Heating energy use			Cooling energy use		
			DOE-2.1A results (MBtu)	Model prediction	% diff.	DOE-2.1A results (MBtu)	Model prediction	% diff.	DOE-2.1A results (MBtu)	Model prediction	% diff.
LIT = 0.25	LS = 0.75		3124	3172	1.5	1632	1687	3.4	275	267	3
WWR = 0.16	GC = 0.43		4809	4819	<1	787	784	<1	639	647	1
GST = 0.25	GC = 0.23		4741	4761	<1	734	713	3	632	655	5
RW = 3	WWR = 0.24		5281	5094	3.5	1203	1020	15	639	666	4
WWR = 0.16	LIT = 2.1		4417	4460	1	993	1018	2.5	518	531	2.5
GST = 0.75	RW = 11		5054	5024	1	684	679	<1	919	868	5.5
LIT = 0.5	GC = 0.23		3032	3157	4.1	1265	1307	3.3	327	403	23
WWR = 0.10	GST = 0.25		4804	4833	<1	859	863	<1	557	564	1
WWR = 0.60	GST = 0.45		5673	5665	<1	1110	1135	2.2	996	987	1
WWR = 0.50	GST = 0.50		5552	5469	1.5	1011	1001	1.0	993	963	3
WWR = 0.75	GST = 0.75		6516	6194	5	947	761	20	1754	1676	4.5
RW = 11	OA = 9		5047	5053	1	1021	1040	2.0	624	608	2.5
THS = 57	TH = 70		4752	4784	2	724	749	3.5	641	645	<1
RW = 19	TC = 80		4734	4772	<1	737	808	9.6	608	593	2.5
LIT = 2.0	TC = 80		4433	4469	<1	1038	1060	2.0	478	499	4.4

Notes: LIT = lighting, WWR = window-to-wall ratio, GST = glass solar transmission, RW = wall insulation rating, THS = night thermostat setback, LS = heat of lights to space, GC = glass conductance, OA = outside air, TH = heating setpoint, TC = cooling setpoint.

In addition, we expect to determine the validity of this approach for other climate regions and building types. Finally, we need to compare the results obtained from our model, which uses a prototypical base-case building, to the results of a DOE-2 simulation for a specific building.

REFERENCES

1. Lokmanhekim, M., et al. (1979), *DOE-2: A New State of the Art Computer Program for the Energy Utilization Analysis of Buildings,* Lawrence Berkeley Laboratory Report LBL-8974.
2. Kusuda, T., and Sud, I., (1982), "Update: ASHRAE TC4.7 Simplified Energy Analysis Procedures," *ASHRAE Journal*, July.
3. American Institute of Architects (AIA) (1979), *Life-Cycle Cost Study of Commercial Buildings,* Final Report by AIR Research Corporation, for Department of Energy, Office of Conservation and Solar Energy, Office of Buildings and Community Systems, Washington, D.C.
4. W.S. Fleming and Associates, Inc. (1981), *Draft Recommendations for the Standard Evaluation Techniques (SET) of the Building Energy Performance Standards (BEPS),* Landover, Maryland.

ECONOMIC STUDIES

ESTIMATES OF RESIDENTIAL ENERGY SAVINGS FROM PROPOSED FEDERAL POLICIES FOR APPLIANCES*

J.E. McMahon and M.D. Levine

Energy conservation was the goal of legislation passed by Congress in the 1970s. The U.S. Department of Energy has subsequently considered several alternative policies that could save energy. This study focuses on the residential sector of the United States and uses the ORNL/LBL Residential Energy Model to assess the consequences of these potential policies. The objectives of this study were:

(1) to estimate the energy savings from specific policies;
(2) to estimate the monetary savings or costs to the nation's consumers from specific policies;
(3) to define the range of values of energy and economic savings using different assumptions about the future; and
(4) to compare the expected effects of several alternative federal policies.

Two measures of the policies' effects were selected as useful indicators: energy savings and economic savings. All policies considered that save energy have also shown overall economic savings. Some policies have negative economic effects for specific products. The major policies considered were:

(1) proposed mandatory efficiency standards for eight products;
(2) four alternative levels of mandatory efficiency standards;
(3) four alternative labeling programs, differing in the assumed fraction of consumers that would respond;
(4) a 5-year delay in the proposed mandatory efficiency standards;
(5) a 25% tax credit to consumers for the incremental cost of more efficient appliances.

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ACCOMPLISHMENTS DURING FY 1982

Method

The ORNL/LBL Residential Energy Model simulates energy consumption over the period 1977-2005. Among the results from the model, four elements were considered:

(1) annual energy consumed (by end use);
(2) annual cost of energy (using average, not marginal cost);
(3) annual cost of equipment; and
(4) the number of each appliance type sold annually.

Energy was expressed in source units, including losses in generating and transmitting electricity (1 kWh = 11,500 Btu). All costs were expressed in 1980 dollars.

A 19-year period was considered, from 1987 to 2005. Policy effects were determined by comparing the results of two runs of the model, one for the base (no policy) case, and one for each policy. Input assumptions used in the LBL/ORNL model are fully described elsewhere.[1] The same base case was used for comparing all policies.

Sensitivity analyses were performed only for the proposed mandatory efficiency standards policy. Each sensitivity analysis involved two runs, a base case and a policy case. The key variables altered in the sensitivity analyses were energy costs, equipment costs, and efficiency trends.

Energy savings were defined as the difference between the energy consumed in the base case by a particular end use and the energy consumed in the policy case. Thus any changes caused by the policy—whether in investments in the thermal integrity of buildings, appliance purchases (e.g., to those using a different fuel), efficiency choice, or usage behavior—are included. The eight end uses analyzed were: central space heaters, room air conditioners, central air conditioners, water heaters, refrigerator/freezers, freezers, ranges/ovens, and clothes dryers. Only the results for the three major end uses (central space heating, central air conditioning, and water heaters) and the total for all eight products are presented here.

Sensitivity Analysis

The energy savings calculated for proposed mandatory efficiency standards are presented in Fig. 1, under a variety of assumptions. The first row is the reference policy, using energy costs from the National Energy Policy Plan ("mid" scenario), equipment costs from DOE's engineering analysis,[2] and base-case efficiencies as calculated by the ORNL/LBL model. The efficiency standards proposed for furnaces achieve no energy savings under these assumptions. Significant energy savings are expected for central air conditioners and water heaters, together accounting for 85% of the total energy savings of the policy.

The reliability of these results was tested by altering the key assumptions. First, future energy-cost assumptions were varied to the upper and lower bounds in the National Energy Policy Plan. The high and low NEPP energy-cost scenarios produce energy savings similar to those obtained with the original assumptions. The total energy savings were 1% lower when high fuel prices were assumed, and 11% higher when low fuel prices were used. Less investment in efficient equipment occurs in the no-policy case when fuel prices are lower.

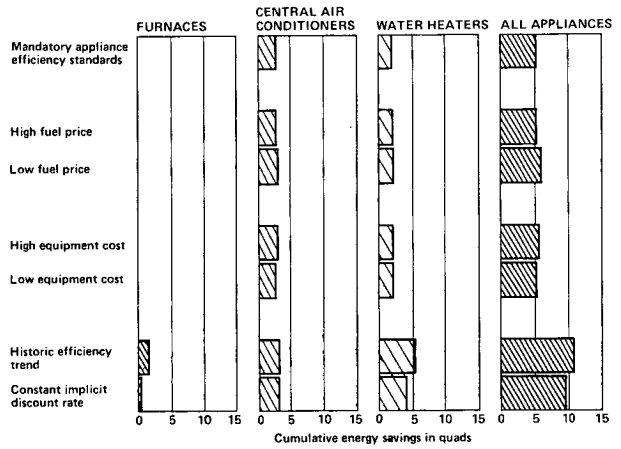

Figure 1. National energy savings, 1987-2005, from proposed DOE consumer product efficiency standards.
(XBL 824-8932)

Next, the purchase cost of equipment was varied. In the high equipment cost case, the purchase costs of all equipment were increased 10%. With higher equipment costs, less efficient appliances are purchased in the no-policy case. Thus the policy mandating a minimum efficiency saves more energy. In this sensitivity case, 10% higher equipment costs would mean 4% additional energy savings. Conversely, 10% lower equipment costs would mean 4% less energy savings attributable to the policy.

The original scenario included projections of significant improvements in equipment efficiencies in the no-policy case. The "historic efficiency trend" case assumes instead that the trend in efficiencies seen from 1972 to 1978 is carried on indefinitely into the future. This produces a more gradual transition to higher efficiency products in the no-policy case and an energy savings estimate due to mandatory efficiency standards nearly twice that obtained from the original assumptions. Water heaters and furnaces both show substantially increased energy savings.

Another alternative assumption about efficiency trends is that purchasers of appliances will continue to apply the same relative weight to operating costs, compared to purchase costs, when buying appliances in the future as they applied in 1978. That is, the

implicit discount rate will be constant in the future at the value observed in 1978. Consumers in this case would buy less efficient appliances than in the original no-policy case. The energy savings are nearly 82% higher than in the original estimate, with noticeable increases for water heaters and for refrigerators (not shown).

The implication of these last two sensitivities is that the ORNL/LBL model assumes a more rapid move toward more efficient products in the future than has been observed historically, or than would be expected if purchasers continued to discount operating costs as much as they have until the present.

The net present benefit of the proposed standards for the eight products is $5.5 billion, with more than 72% of that amount due to water heaters and central air conditioners. All future costs are discounted to 1980, assuming a real discount rate of 10%. The different energy cost assumptions have little effect on the net present benefit, since the differences occur in future years, where the values will be greatly discounted. High equipment costs, since they apply in all years, have a greater but still moderate effect. The efficiency-trend assumptions cause the greatest variation in the energy-savings results with both the historic efficiency case and the constant discount rate case showing substantially higher net present benefit than the original assumptions ($10.9 billion and $10.7 billion, respectively).

Alternative Federal Policies

National energy savings were calculated for a variety of Federal policies, including: (1) mandatory appliance efficiency standards; (2) four levels of alternative mandatory standards; (3) four alternative labeling programs; (4) mandatory standards, delayed 5 years before implementation; and (5) a 25% tax credit toward the incremental cost of more efficient products.

The proposed mandatory standards would save 5.2 quads (source energy), most of which can be attributed to central air conditioners and water heaters. This set of standards is composed of different levels for different products. Four efficiency levels were analyzed for each product, with energy savings ranging from 2.74 Q (level 1) to 7.80 Q (level 4). The higher efficiency levels provide greater energy savings, as expected.

Each product is affected somewhat differently by the standards. Furnaces show no energy savings for any level considered. Central air conditioners and water heaters show increasing energy savings at higher efficiency levels. (The efficiency assumed for levels 3 and 4 was the same for water heaters.)

The labeling programs were assumed to reduce the implicit discount rate of the average consumer by 50% for most products, but only 20% for furnaces, central air conditioners, and water heaters. (This is consistent with the strong influence that third-party purchasers, such as builders and landlords, have on efficiency choices for the latter three products.) The four alternative labeling programs differ only in the fraction of appliance purchases expected to be affected. The four levels correspond to 10, 25, 50, and 75% of appliance purchases having the desired decrease in the implicit discount rate. None of the labeling programs achieve the energy savings accomplished by the mandatory standards.

The mandatory standards under consideration would save $5.5 billion (1980 dollars), almost half attributable to water heaters. The four standard levels show increasing savings from level 1 to level 3, but decreased savings for level 4. This result is due to the high purchase cost when very efficient air conditioners are mandated. While the economic savings still amount to over $4 billion, this is only slighter higher than the $3.86 billion saved at level 2.

The economic savings of all other programs considered are less than the level 2 savings. Increasing fractions of consumers influenced by labeling show increasing economic savings, up to $3.6 billion when 75% of the appliance purchasers are affected. The 5-year delay in mandatory standards would reduce the savings by almost half, from $5.5 billion to $2.8 billion. Finally, the tax credit program would save $2.3 billion.

PLANNED ACTIVITIES FOR FY 1983

The greatest uncertainty in simulating future energy consumption seems to lie in the rate of penetration of efficient appliances into the marketplace in the absence of governmental intervention. Therefore, research effort should be directed at characterizing the elements upon which such penetration depends. Particular attention should be paid to separating the effects of various components of the marketplace such as manufacturers, wholesalers/retailers, homebuilders, landlords, and consumers.

Second, the range of uncertainty in all the input parameters and formulations should be ascertained,

so that the absolute range of variation in the results can be quantified.

REFERENCES

1. U.S. Department of Energy (1982), *Consumer Products Efficiency Standards Economic Analysis Document,* Office of Conservation and Renewable Energy, DOE/CE-0029, Washington, D.C.
2. U.S. Department of Energy (1982), *Consumer Products Efficiency Standards Engineering Analysis Document,* Office of Conservation and Renewable Energy, DOE/CE-0030, Washington, D.C.

COST/EFFICIENCY TRADEOFFS IN THE RESIDENTIAL APPLIANCE MARKETPLACE*

J.E. McMahon and M.D. Levine

Manufacturers' decisions to manufacture and market certain products from the universe of technically possible designs interact with purchasers' decisions to purchase a particular set of products from the range of alternatives perceived to be available. The marketplace which results does not offer perfect freedom of choice. Manufacturers' decisions determine the set of products available, and purchasers have imperfect knowledge of these products, at least with regard to energy efficiency. Policy analysis must rely on some estimate of how the marketplace will behave both with and without a given policy.

We need to understand the historical performance of the marketplace to make reliable estimates of its future behavior. In fact, multiple marketplaces exist, at least one for each type of product—refrigerators, furnaces, water heaters, air conditioners, etc.—and for each type of consumer, such as homeowners, landlords, rich and poor. The marketplace is shaped not only by consumers, but by manufacturers, who limit the choice of designs by their decisions on which products to manufacture and the efficiencies of those products. While there is a considerable body of literature on the theory of consumer decision-making,[1] this theory does not encompass all the problems of market analysis. There has been no analysis of the quantitative relationship of all the determinants of decision-making in the marketplace, including the role of appliance manufacturers. In particular, data on the efficiency of particular products may be available, but it is not known to whom they are sold.

Data on the average efficiency of products purchased in the United States have recently become available.[2] This article describes the use of such aggregate data as a starting point from which aggregate measures of market behavior can be inferred. Results are expressed as "aggregate implicit discount rates" for each product and fuel type. These discount rates, as defined here, serve as a single parameter that describes market behavior with respect to energy efficiency investments. Their value depends on the set of design options available; equipment purchase cost as a function of energy efficiency; energy consumption per unit; energy prices and assumed fuel escalation rates; appliance lifetimes; and, for space conditioning end uses, the thermal integrity of the building.

ACCOMPLISHMENTS DURING FY 1982

Method

The analysis, by using implicit discount rates, assumes that behavior in the marketplace can be characterized as if individuals made some type of life-cycle cost decision. (Whether or not this is actually the case, the implicit discount rates may nonetheless be revealing.[3]) No competition among alternative fuels is considered here. The formulation looks at decision-making for products of different efficiencies but same fuel type. For a given product type and fuel, the life-cycle cost formulation quantifies the marketplace decision process for selecting the efficiency purchased. The method, as presently applied, does not account for other factors, such as special features, which might influence efficiency choice. (Extensions of the method, using hedonic approaches,[4] could be applied if sufficient data were available.) The observed average efficiency choice is characterized by an aggregate implicit discount rate. This measure is the discount rate

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which, if used to achieve a minimum life-cycle cost, would produce the observed efficiency choice of the marketplace.

Shipment-weighted energy factors for each product and fuel type were obtained from the U.S. Department of Energy Survey of Manufacturers.[2] Table 1 shows the numerical values for the products purchased in 1972 and 1978, and manufacturers' estimates for 1980 and 1985.

Table 1. Efficiency improvements since 1972 in residential appliances.

Product/Fuel	Shipment-weighted energy factors[a] 1972	1978	1980 (est.)	1985 (est.)
Room Air Conditioner	6.22	6.75	6.97	7.24
Central Air Conditioner	6.66	6.99	7.41	8.44
Water Heater - Electric	79.80	80.67	81.33	N.A.[b]
Water Heater - Gas	47.35	48.17	51.18	N.A.[b]
Refrigerator/Freezer	4.22	5.09	5.67	6.26
Freezer	8.08	10.07	10.73	11.68
Range/Oven - Electric	35.79	41.41	42.98	43.81
Range/Oven - Gas	13.81	17.66	20.55	25.13
Dryer - Electric	2.61	2.59	2.70	2.70
Dryer - Gas	2.10	2.38	2.41	2.42
Furnaces - Gas	62.68[c]	63.58	65.86	72.06
Furnaces - Oil	73.64[c]	75.20	76.0	77.66

[a]The shipment-weighted energy factor is the product of the energy factor (e.g., efficiency, energy efficiency ratio, etc.) of a particular model times the number of units of that model shipped in the year indicated summed over all models reported to DOE, divided by the total shipments.

[b]N.A. - Not available.

[c]For 1975.

The cost-versus-efficiency data were obtained from the engineering analysis performed for the March 1982 DOE Consumer Product Efficiency Standards Analysis.[5] The cost-versus-energy consumption data were aggregated and a curve-fitting approach was applied to obtain a continuous relationship between purchase cost and energy consumption. The specific formulation adopted was taken from the Oak Ridge National Laboratory Engineering-Economic Model of Residential Energy Use.[6]

Results

Table 2 presents the results of the analysis of the aggregate implicit discount rates in the purchase of residential equipment using the life-cycle-cost methodology described above. The results are for 1978, the last year for which complete data are available. (Data on shipments, equipment usage, purchase price versus energy efficiency, and average fuel price are compiled in Ref. 2.) The aggregate implicit rates are for returns in real dollars (i.e., they should be increased by the annual inflation rate if the analysis is done in current dollars). An annual real fuel escalation rate of zero percent is assumed for all fuels. (If higher fuel escalation rates are assumed, then the results in Table 2 would increase.)

Table 2. Aggregate implicit discount rates in 1978 for existing single-family homes.[a]

Appliance/Fuel		Assumed lifetime (years)	%[b]
Central space heat	- Electric	23	50
	- Gas	23	40
	- Oil	23	40
	- Other	23	60
Room heaters	- Electric	23	270
	- Gas	23	170
	- Oil	23	530
	- Other	23	280
Air conditioners	- Room	15	50
	- Central	12	10
Water heater	- Electric	13	160
	- Gas	13	450
	- Oil	13	60
	- Other	13	670
Refrigerator	- Electric	19	80
Freezer	- Electric	21	100
Range/oven	- Electric	18	80
	- Gas	18	60
	- Other	18	10
Clothes dryer	- Electric	18.5	10
	- Gas	18.5	30

[a]*Source*: DOE Consumer Product Efficiency Standards base-case data (September 1981).

[b]Values rounded to nearest 10%.

Overall, the high values of the aggregate implicit 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. For example, an investment of $21 in a refrigerator to include increased door insulation, a higher compressor efficiency, a double door gasket, and an anti-sweat heater switch in a refrigerator would save $22/year at 1978 fuel prices, an annual return of 100% on the investment. Yet the average refrigerator purchased in 1978 did not have these features. For those appliances with aggregate implicit discount rates higher than the 80% calculated for refrigerators (freezers, electric and gas water heaters, room heaters), efficiency measures with even greater returns were not included in the average product purchased in 1978.

It is widely believed that products purchased by parties other than the homeowner will be less energy efficient than those purchased directly. This seems reasonable because the homeowner pays the bill and thus has an incentive for investing in equipment of higher efficiency. However, the results in Table 2 do not support the perception that second-party purchasers are less willing to invest in products of higher energy efficiency. Central air conditioners are usually purchased by the homebuilder; room air conditioners, by the homeowner. The aggregate implicit discount rate for the purchase of room air conditioners is much greater than for central air conditioners. (Efficiency improvements with payback periods of 2 years are excluded from the average new room air conditioner purchased in 1978, while improvements with payoffs in about 10 years are included in the average central air conditioner.) Similar central space heating systems (generally purchased by the builder) have much lower aggregate implicit discount rates than room heaters (purchased by homeowners in most cases). The only products with unusually high discount rates that are mostly purchased by second parties are electric and gas water heaters.

That most of the products purchased by second parties (generally builders) appear to have *lower* discount rates associated with the investment in energy efficiency is a suprising finding. Most studies have assumed that the greatest incentive to invest in energy efficiency would occur when the purchaser and the person paying fuel costs were the same. However, the results presented in Table 2 are not unreasonable. The builder or contractor who purchases a central air conditioner is likely to be much more sophisticated than a homeowner who, often on a very hot or humid day, decides to buy a room air conditioner. Furthermore, the manufacturers of room and central air conditioners, knowing their respective markets, are more likely to design more efficient products for purchasers who can discriminate among different models on the basis of energy efficiency.

PLANNED ACTIVITIES FOR FY 1983

Further analysis of these phenomena is needed to confirm or reject these hypotheses. In particular, we intend to compare more carefully the efficiencies of products sold primarily to builders with those of products sold to homeowners, to better understand the range of choices in the marketplace. Further, manufacturers might be willing to discuss some of the considerations relating to the market that strongly influence their decisions about energy efficiency of product lines. Finally, considerable information about decisions in the marketplace (including manufacturers' decisions) could be gained by applying our analysis techniques to derive aggregate implicit discount rates for room and central air conditioners and heating systems on a regional basis. The difficulty in extending the analysis in this way is that a breakdown of regional sales data by product efficiency is not available, to the best of our knowledge.

An important general conclusion of this work is that the aggregate implicit discount rate obtained by our approach is much higher than the cost of capital or the average return on investments available to homeowners (personal or business investments) for most products. (Central air conditioners appear to be a major exception to this rule in many parts of the nation.) For example, improvements in gas furnaces can yield a return of 40% per year, in real dollars. Furthermore, since the returns are in the form of a reduced fuel bill rather than higher earnings, the return is not taxed. More efficient refrigerators can yield, on average, an 80% after-tax return on investment. However, our results indicate that, in 1978, these efficiency investments were not made in most purchases.

Additional research will focus on understanding better some of the reasons for this apparent market failure. We hope to do time series studies to understand how discount rates have changed over the past decade. We are also conducting research to improve and make more sophisticated the methodology by

which the implicit discount rates are calculated. (For example, a forthcoming paper by R. Scott, M. Levine, and P. Back[3] considers such factors as demand and usage elasticities in deriving implicit discount rates.) Because we are still developing methodology and scrutinizing data, the numbers in Table 2 may change somewhat; however, we believe the general conclusions of this article are unlikely to be altered.

REFERENCES

1. Amemiya, T. (1981), "Qualitative Response Models; A Survey," *Journal of Economic Literature, 19*, pp. 1483-1536.
2. U.S. Department of Energy, Office of Conservation and Renewable Energy (1982), *Consumer Products Efficiency Standards Economic Analysis Document,* DOE/CE-0029.
3. Scott, R.E., Levine, M.D., and Back, P. (1982), *Estimates for an Economic Model Incorporating Price and Usage Elasticity Adjustments for Consumer Decision-Making Over Energy Efficiency Options in the Purchase of New Single-Family Housing,* Lawrence Berkeley Laboratory report (in preparation).
4. Rosen, S. (1974), "Hedonic Prices and Implicit Markets: Product Differentiation in Pure Competition," *Journal of Political Economy 82* (1), pp. 34-55, January/February.
5. U.S. Department of Energy, Office of Conservation and Renewable Ennergy (1982). *Consumer Products Efficiency Standards, Economic Analysis Document*, DOE/CE-0030.
6. Hirst, E., and Carney, J. (1978). *The ORNL Engineering-Economic Model of Residential Energy Use,* Oak Ridge National Laboratory Report ORNL/CON-24.

HEAT-PUMP ENERGY DEMAND ANALYSIS*

J.A. Sathaye, H. Ruderman, and S. Ng

Sales of heat pumps for heating and cooling homes have increased dramatically in the past 7 years, replacing gas, oil, and electric heaters. Growing future use of heat pumps could significantly increase the demand for electricity relative to gas and oil. Electric and gas utilities are concerned about the impact that heat pumps could have on their peak loads during summer and winter. Heat pumps can add to winter electricity loads if they replace oil or gas furnaces. They can increase summer load if the demand for air conditioning is higher. Electric utilities that have little capital may face difficulties in financing new generating plants to meet the increased demand. Some utilities, however, are encouraging the purchase of heat pumps to replace electric resistance heaters because they use less electricity. Heat pumps can also change load characteristics, thus having an impact on utility system planning.

This study will help determine changes in energy demand due to heat pumps and will provide a tool for analysis for a region or a utility-service area. In forecasting heat-pump sales and energy demand, we have adopted a unique mixed estimation approach in which traditional econometric analysis is performed along with case studies to determine the reasons for heat-pump penetration. The two approaches are then combined to arrive at demand elasticities for our residential model of energy demand. The approach can be adapted to other end-use studies in specific utility-service areas. Preliminary results were presented at the 1982 Santa Cruz conference of the American Council for an Energy Efficient Economy.[1]

ACCOMPLISHMENTS DURING FY 1982

Our investigation of heat pumps started by examining the historical and geographical variation in market penetration. The history of heat-pump penetration (Fig. 1),[2,4] may be divided into two periods, before and after 1975. Prior to 1975, heat pumps comprised

*This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Building Energy Research and Development, Building Equipment Division of the U.S. Department of Energy under Contract Number DE-AC03-76SF00098.

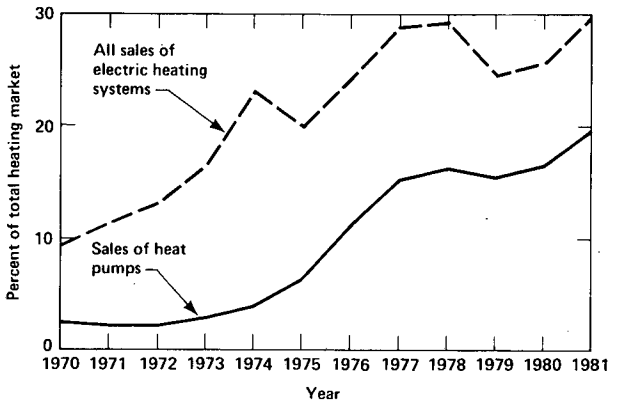

Figure 1. Sales of electric heating systems as percent of space heating market. Sources: Data for 1970-1978 are from Ref. 2; data for 1979 are from Ref. 3; and data for 1980-1981 are from Ref. 4. (XBL 824-8903)

3-5% of the total sales of central heating equipment. Sales of heat pumps increased rapidly after 1975; by 1981, they accounted for 20% of total sales. An important reason for this increase was the restriction on new natural-gas hookups that prevailed from 1976 to 1979 and still continues in some areas.

Figure 2 maps heat-pump penetration in 1979, the last year for which data are available.[5] The variation from state to state is large, ranging from little or no penetration in the Northeast and Northern Rocky Mountain states to nearly complete penetration in Arizona and South Carolina. Sales of heat pumps have been high in states with relatively high electricity prices as well as those with low prices. In most states, gas restrictions were an important factor in determining sales. However, there were some exceptions, such as Colorado. Even in Nevada and Iowa, states where natural gas has been widely used, heat-pump saturation was high. Our examination of the heat-pump sales data indicates that their penetration is not easily explainable on the basis of a few simple variables such as price or gas restrictions.

The second phase of the study was to make an economic comparison of space conditioning alternatives. During the 1970s, heat pumps were more expensive than natural gas systems on both first and life-cycle cost bases in most parts of the country. There are three important components to consider in comparing the costs of alternative systems: first costs, fuel costs, and maintenance costs. Estimates of these costs from three studies (including ours) are shown in Table 1.[6,7] The Oak Ridge National Laboratory (ORNL) study[6] concluded that in some areas of the country, such as Knoxville, the first cost and life-cycle cost of heat pumps are lower than those of natural-gas systems. Our analysis of these costs suggests that, although the equipment costs may be very different from those assumed in the other studies, the life-cycle costs of most systems fall within the uncer-

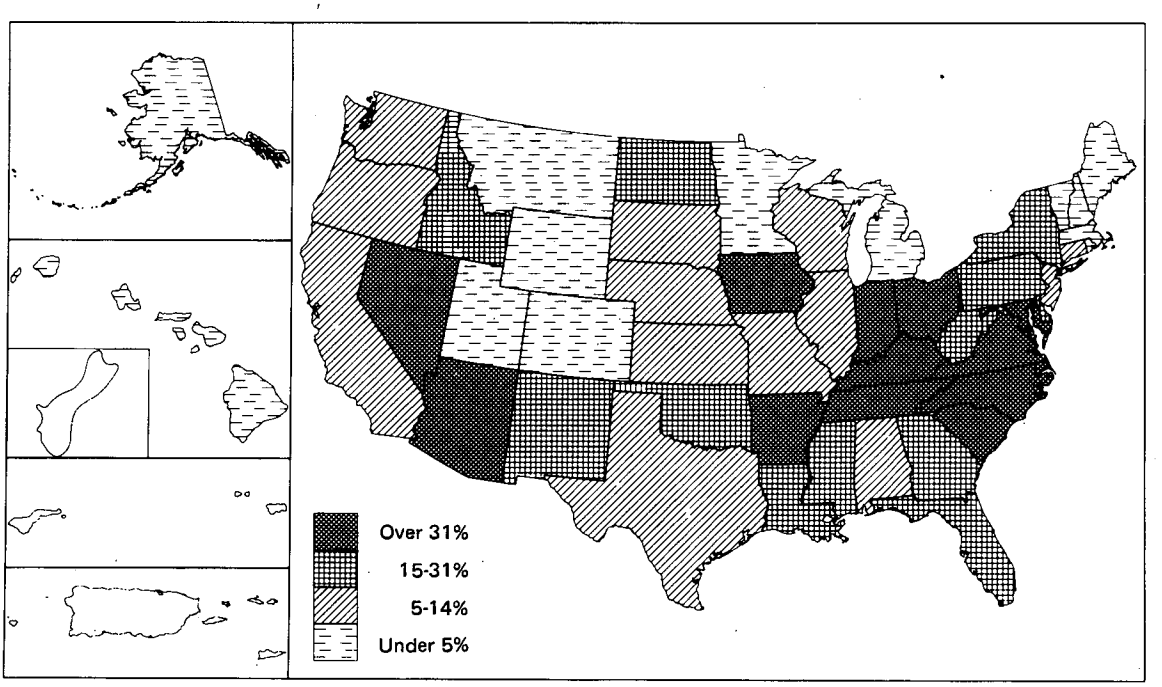

Figure 2. Heat-pump saturation in new single-family units, 1979. Source: Ref. 5. (XBL 823-8678)

tainties associated in making such comparisons. Oil systems are definitely more expensive in all three studies.

Table 1. Cost comparison of central heating and cooling equipment.

Study		Heat pump	Gas furnace, central A/C	Electric furnace, central A/C	Oil furnace, central A/C	central A/C
LBL[a]	Equipment cost	1,640	1,435	1,179	1,479	749
	Life-cycle cost	15,302	14,887	15,583	21,609	
ORNL[b]	Equipment cost	1,199	2,024	1,559	1,969	1,279
	Life-cycle cost	14,861	15,476	15,963	22,099	
AGA[c]	Equipment cost	1,869	1,808	--	1,919	1,019
	Life-cycle cost	15,531	15,260	--	22,049	

Note: Life-cycle cost includes other equipment costs, installation cost, maintenance cost, and energy cost. These costs are from an ORNL report[3] and were added to the equipment cost to estimate comparable life-cycle costs for the three studies. Energy costs are based on prices in the Knoxville, Tennesee area and the following present-worth factors: electricity, 18.59; fuel oil, 25.25; natural gas, 31.17.

[a] Ref. 1.

[b] Ref. 6.

[c] American Gas Association, Ref. 7.

Our analysis of historical penetration data and the present cost of space-conditioning systems suggested that heat-pump penetration should decline after 1979, the last year with widespread restrictions on new gas hookups. However, the data indicate otherwise. By 1981, heat pump penetration had increased to 20% of all sales of central heating equipment. To understand this increase, we conducted an informal survey in several places that had high penetration in 1979. The results, summarized in Table 2, indicate that local factors are important considerations.

Another part of our approach is to construct a discrete-choice model of market penetration of space-conditioning equipment. This is an econometric model that simulates consumer decision-making when faced with mutually exclusive choices. In this study, the choice is the initial investment in the type of residential space heating and cooling system, e.g., gas furnace with central air conditioning vs. electric resistance heating with room air conditioning vs. a heat pump. The decision is assumed to depend on the initial capital and long-term operating costs of the equipment, as well as on income, family size, dwelling size, and location. The capital and operating costs depend the climate, energy prices, and thermal integrity of the structure, and on the type, efficiency, and size of the appliance.

Parameters of the model were estimated from data on newly constructed residential units between 1975 and 1979 in the Census Bureau's *Annual Housing Survey.*[8] Additional data on climate, energy prices, and natural-gas restrictions were from other sources. Numerous statistical and consistency tests were conducted to confirm the goodness of fit and the significance of the key parameters. Preliminary results on the parameters were obtained during FY 1982.

Table 2. Regional factors affecting heat-pump market penetration.

Region	Gas permit moratorium	Cost of gas distribution	Other factors
Phoenix, AZ	Recent	High	Hook-up charges
Philadelphia, PA	Current	Low	Utility incentives for installation
Tennessee Valley	Recent	High	Utility incentives for installation
Iowa	Recent	High	Displacing propane heaters
Kentucky (except Owensboro)	Recent	High	Consumer preference, lower operating cost
Maryland	Recent	High	Operating cost expected to be competitive with gas
Southern and Central Indiana	Recent	High	Non-availability of gas
Cincinnati, Ohio	Recent	Low	Consumer preference, lower operating cost
Northeast Ohio	Recent	Low	Used as a back-up system for gas

PLANNED ACTIVITIES FOR FY 1983

Besides investigating the reasons for the large market penetration of heat-pump in additional regions of the country, the main emphasis during FY 1983 will be to improve and apply the discrete choice model. Results from simulations with the model will be used to calculate market share and usage elasticities for

heat-pump and other heating and cooling appliances. These elasticities will be used directly in the ORNL/LBL Residential Energy Demand Model. We are investigating the possibility of incorporating technical efficiency elasticities in the simulation. The discrete choice model will also provide estimates of implicit discount rates and project market saturation for these appliances.

To date, the ORNL/LBL Residential Energy Demand Model has treated space heating and cooling as independent end uses, linked only through common characteristics of the housing shell. The model will be substantially improved by combining these two end uses into one—space conditioning. Heat pumps will be allowed as an explicit option, where previously heat-pump saturation was buried in electric central space heating systems along with electric warm-air furnaces.

The results of the discrete-choice-model estimation will be used directly in the ORNL/LBL model. Specifically, the market share and usage elasticities will be input into the new space conditioning methodology. The result will be a more realistic and complete treatment of space conditioning system choice.

When completed, this change will provide an improved methodology for simulating future energy consumption in the residential sector, with explicit treatment of heat pumps. The treatment will better reflect the interrelationship between heating and cooling systems.

REFERENCES

1. Sathaye, J.A., Ruderman, H., and McMahon, J. (1982), "Heat Pump Energy Demand Analysis," presented at the ACEEE Santa Cruz Conference, August 1982, Lawrence Berkeley Laboratory Report LBL-14422.
2. Fiechtel, R.B., Novicky, E.R., and Wusterbarth, A.R. (1980), *Energy Capital in the U.S. Economy,* MTSC, Inc., Bethesda, Maryland.
3. U.S. Department of Commerce, Bureau of the Census (1980), *Current Industrial Reports,* MA-35-M.
4. *Air Conditioning, Heating, and Refrigeration News* (1981), December.
5. National Association of Home Builders (1980), Survey Data, Washington, D.C.
6. Abbatiello, L.A., Nephew, E.A., and Ballou, M.L. (1981), *Performance and Economics of the ACES and Alternative Residential Heating and Air Conditioning Systems in 115 U.S. Cities,* Oak Ridge National Laboratory Report ORNL/CON-52.
7. American Gas Association (1982), *An Economic, Efficiency and Environmental Comparison of Current Home Heating and Cooling Systems,* Washington, D.C.
8. U.S. Department of Commerce, Bureau of the Census (1974-1979), *Annual Housing Survey.*

UTILITY CONSERVATION PROGRAMS: THEORY AND PRACTICE*

E.P. Kahn

In this project, large-scale conservation programs sponsored by regulated utilities are examined on both a theoretical and case-study basis. Utilities have increased the scope and scale of their conservation activities substantially over the last several years. Experimental or demonstration programs have been upgraded and, in many cases, currently involve substantial expenditures. To understand long-range incentives for utilities to continue and expand these efforts, a theoretical model is employed. The model is complemented by a case study.

This research continues previous work devoted to analysis of utility programs to promote solar water-heating,[1] and consideration of the role played by current utility construction projects on the evaluation of conservation programs.[2]

ACCOMPLISHMENTS DURING FY 1982

The principal problem facing utility planners is the pervasive uncertainty surrounding estimates of the supply and demand functions in their markets. However, conventional engineering economics of alternative projects assumes that all relevant information is known. Choices in such a framework are reduced to relatively straightforward optimization; thus risk and uncertainty play no major role in analysis. This traditional framework is not well-suited to current conditions. To address the essential problem of uncer-

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tainty, economic models developed to understand commodity price stabilization[3] are adapted to the context of regulated utilities.

Theory

Energy prices in unregulated markets turn out to exhibit as much instability as the prices of widely traded agricultural commodities. Stabilization theory addresses the benefit to consumers and producers of reducing this instability by regulatory or investment policy. Stabilization benefits are of two kinds: (1) changes in average producer income (positive or negative), called transfer benefits; and (2) changes in producer income variations, called risk benefits. The sign and magnitude of each benefit depends upon a small number of parameters.

Because regulation has stabilized consumer prices substantially more than unregulated energy prices, any transfer benefits from further stabilization come at the expense of producers. Conservation programs tend to reduce these producer losses to some degree by increasing price elasticity. This effect is less beneficial to producers than a partial price destabilization.

Stabilization produces different risk benefits for different utility projects. Three generic projects are compared: (1) traditional regulated production, (2) utility conservation programs, and (3) unregulated supply projects. The latter promises the greatest producer benefits, although the non-traditional nature of this alternative raises questions of regulatory policy. Conservation programs compete favorably with traditional regulated production provided that their output and scale can be controlled sufficiently. If conservation programs do not have less output variability than supply projects, they are less attractive to utility shareholders.

The theoretical model is formulated at such a great level of generality that many details of practical utility conservation programs are suppressed. The case study explores such neglected dimensions.

Case Study

The proposed conservation and load management programs of Southern California Edison Company (SCE) are analyzed in detail. Cost/benefit analysis of the SCE program indicates substantial differences between the high productivity of conservation programs and the lower value of load management. In spite of these differences, however, SCE allocates a large share of its budget to the less valuable load management activities. Table 1 characterizes the SCE program. A variety of factors explains the allocation decision.

Table 1. Total 1983 SCE proposed program—utility perspective (millions of 1983 dollars).

Program Segment	Cost	Benefit
1. Commercial & Industrial		
(a) Conservation (Audit + Incentives)	28	696
(b) Load Management	18	32
Total	46	728
2. Residential		
(a) Conservation		
(1) ZIP/CIP	18	54
(2) Rate Case	17	58 (?)
(b) Load Management	28	68
Total	63	180

Total Budget Commitment	Cost	Benefit	Benefit/Cost Ratio
Complete Program	109	908	8.3
without 1a	81	212	2.7
without 1a, +2a2 fails	81	154	1.9
Total Load Management	46	100	2.2
ZIP/CIP Refrigerators	1.5	23	15.3
C & I Audits (=1a)	28	696	24.9

The value of load management is in reduced future kilowatt capacity requirements. SCE uses gas turbine and oil-fired station refurbishment costs as a proxy for this value. These costs are considerably more stable than the oil costs avoided by conservation programs, the savings from which are primarily in kilowatt-hours.

Regulatory policy also favors load management. Fuel-adjustment clauses—whereby fuel price increases are automatically passed through to utility customers—reduce the incentive to save kilowatt-hours, since no earnings risk is attached to energy. Only the fixed capacity cost component of rates is related to shareholder earnings.

Other factors distinguishing the SCE program are the magnitude of incentives offered to participating customers, and the decision to expense rather than capitalize program costs.

Utility conservation programs involve potential conflicts of interest between participants and non-participants. Such conflicts are most clear when large financial incentives are offered for participation. Figure 1 shows the relationship between participant incentives (horizontal axis) and indirect benefits to non-participants for various elements of SCE's ZIP/CIP programs (standing for zero-interest and cash-incentive programs, respectively). In general, greater participant incentives mean smaller non-participant benefits. Mandatory programs such as air-conditioner cycling are necessary to keep the whole program from injuring nonparticipant interests.

Finally, the costs identified in Table 1 are revenues SCE proposed to collect without any effect on shareholder earnings. This treatment concentrates costs at the onset of the program and typically does not match the benefit stream. If SCE had a long-range interest in conservation and load management, one would expect a capitalization treatment that spread costs out over time and contributed to earnings.

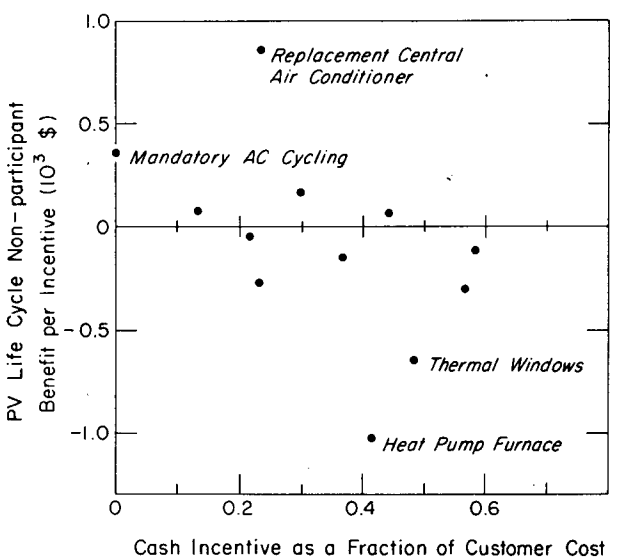

Figure 1. Participant incentives (horizontal axis) and benefits to nonparticipants (vertical axis) in Southern California Edison's ZIP/CIP (zero interest/cash-incentive) programs. (XBL 827-913)

PLANNED ACTIVITIES FOR FY 1983

The theoretical model of utility behavior will be expanded to account for the capitalization-versus-expensing-question, and to treat the conflict of interest among various groups of consumers. Practical programs will be examined to develop evidence on the critical issue of controllability. Factors contributing to conservation output flexibility will be identified.

REFERENCES

1. Kahn, E., Benensen, P., and Brown, B. (1981), "Commercialization of Solar Energy by Regulated Utilities," *Energy and Environment Division Annual Report 1980,* Lawrence Berkeley Laboratory Report LBL-11990.
2. Kahn, E., (1983), "Electric Utility Conservation Programs and the Decision to Abandon Partially Completed Supply Projects," *Energy: The International Journal* (in press).
3. Newbery, D., and Stiglitz, J. (1981), *The Theory of Commodity Price Stabilization.* Oxford University Press, Oxford.

RESIDENTIAL HOURLY AND PEAK DEMAND MODEL*†

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

We have continued to develop a computer model that simulates the hourly electricity demand for electric utility service areas. This model is integrated with the Oak Ridge National Laboratory (ORNL)/ Lawrence Berkeley Laboratory (LBL) Residential Energy Demand Model. The most important new feature of the hourly demand model is that it is disaggregated to 12 end uses. This disaggregation, in addition to its extensive time-of-use and engineering/econometric data base, makes possible the evaluation of specific electric utility conservation programs and various energy conservation policies.

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†A more detailed description of this work is found in the report "LBL Residential Hourly and Peak Demand: Description and Preliminary Validation" by G. Verzhbinsky, E.L. Vine, and M.D. Levine (unpublished, 1982).

ACCOMPLISHMENTS IN FY 1982

Key Issues

Electric utility systems design, capacity projections, financial impacts of alternative supply and demand management strategies, rate setting, and energy conservation and load management programs are all important facets of the electric utility industry. Each raises key issues confronting electric utilities today. Many issues relating to energy conservation and load management are assuming increasing importance to utilities in the current economic climate because of the difficulty in raising capital for new power plants.

In an effort to understand these issues and to provide a quantitative evaluation of some of them, we have developed a computer model that forecasts hourly electricity demands for the residential sector. A key feature of this model is its disaggregation into each of 12 major end uses. The model is based on both econometric and engineering/economic data, as well as measured data on time of use of energy demand by end use. The high degree of detail about hourly demand by end use, combined with economic information and a specification of the average efficiency of each appliance type in the thermal integrity of the house, make possible the evaluation of the potential impact of specific energy conservation and load management activities within an electric utility service area. The model has been applied to the evaluation of the likely impacts of the proposed Building Energy Performance Standards and the Consumer Products Efficiency programs of the U.S. Department of Energy.

The residential hourly demand model is currently integrated with the ORNL/LBL Residential Energy Demand Model.[1,2] To achieve this integration, selected changes were made in the ORNL/LBL model, especially in the characterization of the thermal integrity of new houses and the addition of a utility-specific data base.[2,3] This approach of incorporating the hourly and average energy demand forecasting models takes advantage of the key features of the ORNL/LBL model: its treatment of socio-economic determinants of energy demand growth, its engineering/economic data, and its analysis of residential end-use efficiency choices. At the same time, including hourly demand data and appropriate algorithms substantially increases the analytical capabilities of the ORNL/LBL model.

Overview of Residential Hourly Demand Model

The disaggregated residential hourly demand model was developed by LBL with the assistance of Hittman Associates, Inc. (HAI).[4] The model:

- Projects the hourly and peak electricity demand for the residential sector of an electric utility service area.
- Estimates the impact of different energy conservation policies on the hourly demand curve (load shape, including peak demand in the residential sector).
- Estimates reductions in the fuels and capacity for electric generation, by fuel type, resulting from residential energy conservation programs.

The model considers 12 end uses, divided into two groups: temperature sensitive (central space heating, room space heating, heat pumps, room air conditioning and central air conditioning) and temperature insensitive (water heating, refrigerating, freezing, cooking, clothes drying, lighting, miscellaneous). The model deals with three housing types: single-family, multi-family, and mobile homes. Also, it disaggregates the total housing stock into three groups by age of the house (and hence, by average, its thermal integrity): houses built before 1974, those built from 1974 to the present, and homes built after the start of the U.S. Department of Energy Building Energy Performance Standards program, assumed to have its initial impact in 1982. The model can handle as many as five climate zones within a utility service area. It simulates hourly electricity demand for each year from 1977 to 2005 (8760 hours each year). The total hourly demand curve is transformed into the load duration curve, which presents the number of hours where load exceeds any fixed value.

The model is part of a larger modeling effort to assess conservation impacts on utilities. This effort has the following objectives:

- Computing hourly electricity demand profiles under a wide range of economic conditions
- Evaluating and projecting hourly load profiles by climate region within a service area, by building type (single-family detached house, single-family attached house, mobile home), and by building thermal integrity
- Evaluating the likely impacts of energy conservation programs on the hourly and peak demands of an electric utility

- Quantifying the costs and benefits of energy conservation programs to the consumer
- Evaluating the effect of utility conservation programs on the cost of delivered electricity and on the financial performance of electric utilities
- Estimating the degree to which energy conservation will reduce demands for oil and gas to generate peak and intermediate electricity
- Evaluating a range of potential load management strategies to reduce peak demand in the residential sector
- Providing a quantitative basis for comparing costs and effects of investments in energy conservation programs and in increased generating capacity (including expansion of transmission and distribution systems, if required) in specific electric utility service areas.

Input Data

The model is extremely data intensive. Estimates of time of use of each end use are the most important and most difficult data to obtain. For the five weather-dependent end uses (central space heating, room space heating, heat pump, room air conditioning, and central air conditioning), time of use is a function of temperature and humidity, as well as time of day.

To keep track of the data, we have followed the NEPOOL model[5] procedure of defining time-of-use matrices. Initial matrices of relative fraction of capacity of individual appliances in use, as a function of temperature and hour of day, are input into the model. Adjustments are applied for service area, climate zone, house type, house vintage, and day type (weekday or weekend). Specification of the hourly temperature profile permits selection of relative use values from the adjusted matrices. The final set of values is normalized to the annual demand obtained from the ORNL/LBL residential energy use demand model.

All calculations of hourly electricity demand for temperature-sensitive end uses are based on appliance-use matrices.[5] Each element of these matrices gives the fraction of the connected appliance that is operating at any specified temperature and time-of-day conditions. In other words, these matrices show the shape of hourly demand for any given hourly temperature curve.

For temperature-insensitive appliances, the corresponding appliance-use matrices do not depend on temperature conditions and house vintage but instead depend on housing type (single-family, multi-family, and mobile homes), day type (weekday/weekend), season (winter/summer), and hour of day. The load shapes for these appliances are considered to be the same for all service areas. These matrices are provided by a California Energy Commission study (1979).[6,7]

Results

Three types of analyses have been performed using the LBL residential hourly and peak demand model: (1) comparison between diversified demand predicted by the model and aggregation of computer simulation results of undiversified hourly energy use of individual houses using the DOE-2 energy analysis model, (2) analysis of data for a test utility (Detroit Edison) to partially validate and refine the model inputs, and (3) parametric studies to evaluate impacts of energy conservation programs on the hourly load profiles of electric utilities. The first two analyses have been completed during the past year and the third is presently under way.

Figure 1 presents the comparison between the hourly model results and the energy simulations on a typical residential building in the New England area. The simulations are compared for different temperatures, ranging between 9°F and 60°F at 8 a.m. Below 27°F, the simulations on an individual house (using the DOE-2 computer code) were generally 15 to 20% higher than the diversified demand predicted by the LBL model. Above 27°F, the estimated total demands from the hourly model and from the simulation of individual houses approach each other until they are essentially identical above 40°F.

The significance of these results derives from two major differences between models: (1) DOE-2 estimates the hourly heating (and cooling) energy of a building from weather data and building characteristics. As such, it can provide estimates of undiversified residential heating energy demand. (2) The heating load inputs to the hourly model are based on interpolations and extrapolations from measured diversified demand. Thus, if both models were completely accurate, one could conclude from Fig. 1 that (1) undiversified demand appears to be about 20% higher than diversified demand at temperatures below 27°F, leading to an estimated diversity

factor of about 0.8 during cold weather in New England; and (2) at higher temperatures, where space heating is required a smaller fraction of the time, the diversity factor appears to approach 1.0. These results are probably less meaningful as a measure of the diversity factor of residential heating demand than they are as a measure of the reasonableness of the model results. Since the diversity factors and the comparison of diversified demand (from the hourly load model based on measured data) with undiversified demand (from DOE-2) are both reasonable, we conclude that the hourly model is operating in a generally acceptable manner. This is a necessary but not sufficient condition for gaining full confidence in the model results.

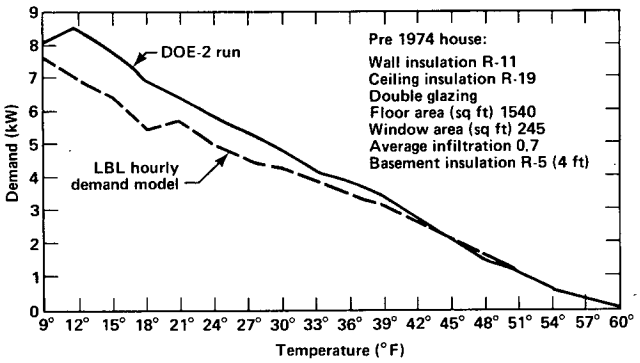

Figure 1. Hourly consumption for heating (New England, 8 a.m.) by temperature in pre-1974 single-family houses. (XBL 824-8955)

The second application of the model provides additional information on the accuracy and meaningfulness of the model results. Figure 2 shows a comparison between utility data and model estimates of residential peak demand for the period 1978 to 1982; the estimates reflect three different approaches to peak demand. In the TEMP approach, dry-bulb temperature was used to construct the room air conditioning fraction-in-use matrix. In the THI approach, the matrix was based on the temperature-humidity index. And in the diversified THI approach, these matrices were additionally adjusted by a "flattening" procedure; demand was apportioned to other hours of the day by multiplying the elements of the THI matrices that are less than 0.3 by 3, an arbitrary number. This flattening procedure is intented to simulate the diversity in hourly demands due to differences in customer behaviors.

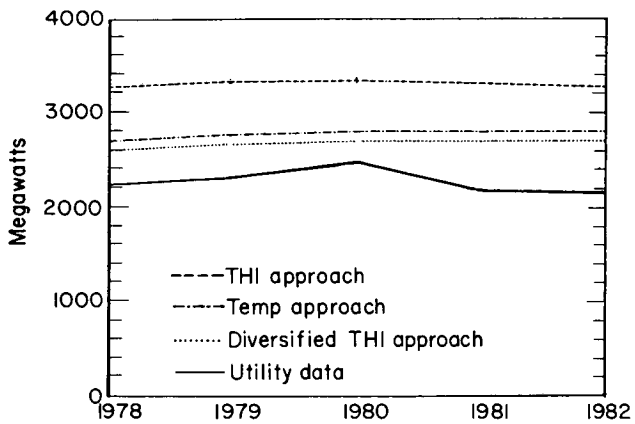

Figure 2. Residential electricity peak demand comparisons, 1978-1982. (Sources: Detroit Edison, Load Research Department, 1982; and residential hourly and peak demand model, LBL.) (XBL 831-1092)

We expect the diversified THI approach to yield the best results, as it contains the most complete and realistic data set. This is borne out by the results in Fig. 2. However, agreement between measured and predicted residential peak demand is only within about 20% for this case. At the present stage of model development, this degree of difference is not surprising. It can be accounted for by any one or more of the following:

- The utility data are low because of the methods employed by Detroit Edison to calculate residential peak load.
- The hourly weather data run on the peak load model are not suitable for detailed comparisons, since only a "typical" year was run and adjustments for the real weather conditions were not made.
- Additional improvements in the model and the data in the model are needed.

Future work will attempt to identify the sources of discrepancies between model results and utility data for Detroit Edison and other utilities, in order to refine the model.

The third area of analysis involves parametric studies to estimate the hourly and peak load impacts of residential energy conservation measures. This work is just beginning and will be pursued after additional research has been completed to improve the model.

PLANNED ACTIVITIES FOR FY 1983

The main activities projected for FY 1983 involve:

- Completing the comparisons between utility data and model estimates
- Performing sensitivity studies on major residential energy conservation measures and programs

- Carrying out selected model improvements
- Working with utilities to begin the process of adoption of the model in the electric utility planning process
- If resources permit, initiation of research on a model of hourly demand in commercial buildings.

REFERENCES

1. Hirst, E., and Garvey, J. (1978), *The ORNL Engineering-Economic Model of Residential Energy Use,* Oak Ridge National Laboratory Report ORNL/CON-24.
2. McMahon J.E. (1981), *Residential End Use Demand Modeling: Improvements to the ORNL Model.* Lawrence Berkeley Laboratory Report LBL-12860.
3. Herring, H., and McMahon, J.E. (1981), *Applications of the ORNL/LBL Residential Energy Demand Model to Utility Service Areas.*
4. Hittman Associates, Inc. (1980), *An Analysis of Energy Efficiency Standards on Electric Utility Peak Loads, Task 5 Final Report.*
5. NEPOOL Load Forecasting Task Force and Battelle Columbus Laboratories (1977), *Report on Model for Long-Range Forecasting of Electric Energy and Demand to the New England Power Pool,* Columbus, Ohio.
6. California Energy Commission (1979), *Technical Alterations of the Residential Sales Forecasting Model: Electricity and Natural Gas,* Sacramento, CA.
7. California Energy Commission (1979), *Technical Documentation of the Peak Load Forecasting Model,* Sacramento, CA.

INTERNATIONAL RESEARCH

INTERNATIONAL PROGRESS IN RESIDENTIAL ENERGY EFFICIENCY*

L.J. Schipper, A.N. Ketoff, S.P. Meyers, S. Rosse, and W. Chern

In 1979, the Lawrence Berkeley Laboratory (LBL) was asked by the Energy Information Administration of the Department of Energy (DOE) 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). It was discovered that neither the OECD nor most of its member countries kept such statistics for the residential sector in one place. For the first two years, therefore, this work was primarily directed toward data collection.

The research focused on nine OECD countries: the United States, Canada, Denmark, France, West Germany, Italy, Japan, Sweden, and the United Kingdom. The data collected included information about incomes and expenditures, size of households and dwelling characteristics, household equipment, and actual consumption of fuels, often by purpose and dwelling type. The output of the study includes a data base covering energy use from 1960 through 1980 and several analyses of consumption patterns and their evolution, including comparisons of consumption patterns among countries and within a country over time. Finally, an econometric analysis of the energy consumption data is under way.

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ACCOMPLISHMENTS IN FY 1982

Major Factors Affecting Consumption

We examined many factors to study the determinants of energy demand, including dwelling and family size, climate, income and prices, central heating penetration, appliance size and use frequency, efficiency, habits, and "culture." Many of these are highly intertwined, so a statistical and econometric investigation was performed to estimate their importance and their correlation.

Factors such as climate and number of people per dwelling vary widely across the sample and over time. To explain some of the important differences, we stu-

died a range of *structural* indicators of energy use:

- *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. In this study, we have examined real energy prices for each fuel, as well as for heating and non-heating, where possible. Currencies were compared using purchasing-power parities.
- *Outdoor climate,* measured in degree-days (adjusted throughout the study to the same base, 18°C) affects the amount of heat required to keep a given structure at a given indoor temperature. For each day of the heating season, the difference between the outdoor temperature and an indoor reference temperature is noted, and the sum of these over the season indicates the severity of the climate.
- *Indoor temperature* strongly affects energy demand for space heating and cooling. Differences among countries are influenced by the cost and physics of heating.
- *Dwelling characteristics* include type (detached, semi-detached, farmhouse, attached, etc.), size, vintage, and construction materials. Homes have become larger in nearly every country studied. It is worth noting that large houses have less outside surface per unit of floor area than smaller homes, which reduces heat losses per unit of floor area. This fact has certainly contributed to reductions in heating per unit area in some countries over long periods of time.
- *Demographic characteristics* such as household size, age distribution, and number of people at home during heating hours all influence energy use. Households have become smaller in every country. Smaller households mean more wall area per person, which increases heating needs per capita. On the other hand, lower density decreases per-dwelling use of cooking, hot water, and appliances, though not in proportion to the number of people. Therefore, energy intensities should be examined on both per-dwelling and per-capita bases.

Econometric Findings

Because so many factors influence consumption, it is clear that no simple, linear form would describe residential energy use. Therefore, in our econometric study we used a multinomial logit model (a specialized statistical model for econometric analysis) to analyze aggregate residential consumption and space heating consumption as well as their fuel shares, over the 1960-1978 period. Heat was converted to "useful energy" by assuming conversion efficiencies of 45-65% for different fuels. Prices and incomes were converted to U.S. dollars, using 1970 purchasing power parities, and then deflated, using respective consumer price indices. Explanatory factors tested include climate, people per dwelling, size and type of dwellings, central heat penetration, energy prices, and incomes. Obviously, there may be multicollinearity—for example, between income and central heating penetration, between climate and central heating penetration, or between energy prices and the persistence of noncentral heat.

Currently, we are validating our model and updating calculations to 1980. Highlights of the analysis to date include the following:

1. Energy price, central heat saturation, income per dwelling, and dwelling size are all important in explaining energy use.
2. Climate, measured in heating degree-days (base 18°C) shows only weak explanatory power for total energy, but was far more important for heating.
3. The economic and structural variables explain most of the variations in energy use per dwelling, but the European countries still exhibit consumption that is lower than is explained by the model.
4. Fuel shares for heating depend on price, but at the same time, increased incomes led to the use of less solid fuels, an increase in the use of oil, and a growth in electricity relative to oil use.
5. Our results gave lower aggregate price elasticity (-0.2 for total demand, -0.3 for space heating) and income elasticity (+0.3 for total demand, +0.4 for space heating) than most other studies we reviewed. These results may be interpreted as both long-term, because of the cross-sectional nature of our

study, or as short- to 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.

Conclusions of OECD Study

- Increases in equipment ownership (central heat, running hot water, and major appliances), driven by higher incomes, were responsible for the great increases (4-8%/annum) in residential energy use through 1973 and for the sustained growth rates that continued through the late 1970s, although after 1973 these growth rates slowed considerably relative to income growth. Increased equipment penetration absorbed some of the gains from conservation between 1973 and 1978.
- Great variations in equipment 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 account for these variations, but in differing proportions.
- Increased energy prices since 1973 have induced reductions in energy-use intensities and have more recently caused shifts away from oil heating systems where alternatives existed. Heating energy use has been reduced considerably in centrally-heated homes since 1972.

When all factors are counted, there are still significant differences in efficiency of heating and appliance systems among countries. The best techniques used in one country may allow significant energy savings through their introduction elsewhere. Information programs have probably played an important role in informing consumers of options for conserving energy. Energy conservation programs have promoted investments in energy-saving equipment that otherwise might not 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 in response to higher prices or other motivating factors.

Cross-Country Differences

A major portion of the variability in energy use can be explained by prices, incomes, climate, etc., but a residual fraction that is not accounted for by the model still remains. Other countries use less energy per dwelling, adjusted for climates, than the United States as shown in Fig. 1. When the heating component of energy use is examined separately, and each country's consumption is divided by the number of degree-days (Fig. 2), the United States still consumes more energy than the other countries, though the difference is due in part to the larger size of U.S. housing. Stock vintage, building codes, and government housing policies may play a role here. The Japanese space-heating data contain a large residual fraction that we believe is accounted for by lifestyle and culture. Finally, the growth in the structural component continued after the oil embargo, largely obscuring the real conservation achievements.

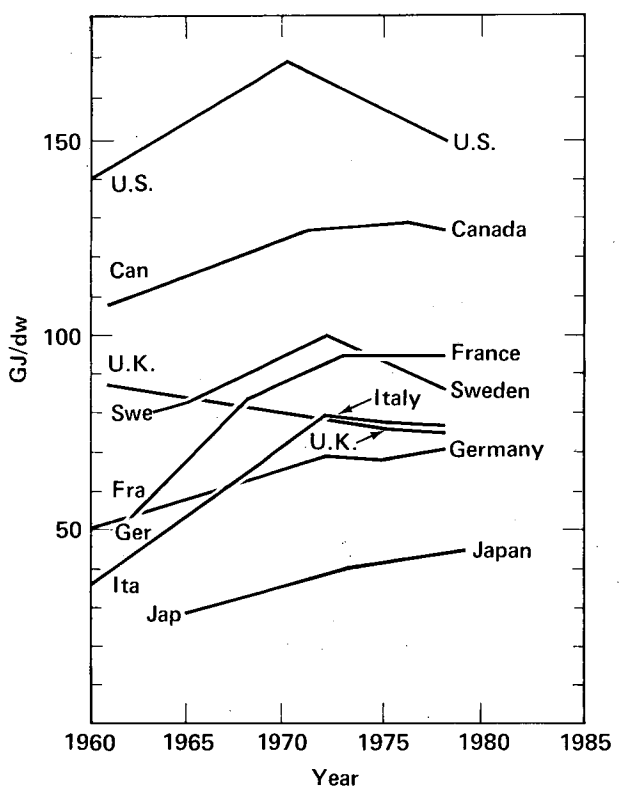

Figure 1. Energy consumed per dwelling (heat adjusted at U.S. climate). (XBL 824-8882)

Conservation

All countries showed a decrease in the growth rate of energy use after the 1973–74 oil shock, but some of the decrease was only temporary. Most showed

more permanent decreases in heating energy use during the period between 1978 and 1980. Higher prices have primarily brought on low-cost conservation measures such as additional insulation or lower indoor temperatures, and incremental improvements in new systems.

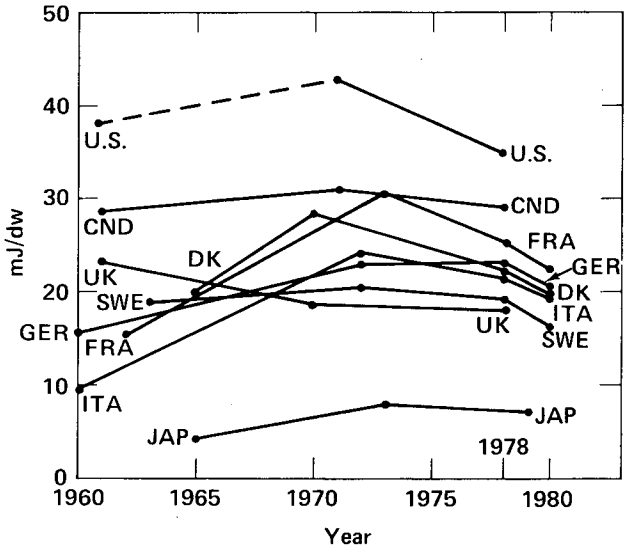

Figure 2. Space heating energy use per degree-day. (XBL 824-8893)

District Heating

District heating—heat piped to many buildings from a central system—is rapidly approaching saturation in Sweden and Denmark in multi-family dwellings; its cost savings, however, are questionable, particularly in single-family dwellings. In new multi-family dwellings in the densest areas, and in older, leaky multi-family dwellings, there is still a small advantage. Much lower penetration occurred in Germany and France. Although district heating often recycles "waste heat," it should not be seen as "free"; only a fraction of the heat delivered is really "waste heat" that would otherwise have been lost. For most of the United States, it appears that weatherization and tightening will save far more energy at less cost than district heat.

Electric Heating

Electric heating received a boost from the 1973–74 oil-supply disruption, as its share in new homes (principally single-family dwellings) and in conversions from non-central heating increased. However, it fell back somewhat as gas advanced. In 1979, gas gained most from oil price increases. Therefore, electric heating's competition with gas is crucial. In Sweden, where gas is non-existent and electricity is as cheap as oil, electricity has made significant gains.

Comparisons with gas- and oil-fueled homes for purposes of estimating relative economics are difficult. The best data we have (from Sweden) show that for homes of the same kind (SFD), of the same vintage, and in similar climate regions, the consumption of oil per unit area is 1.6–2.1 times greater than that of electricity, measured at the building boundary, for central or baseboard heat and hot water. This difference is smaller than others have claimed.

Increasing penetration of electric heating is occurring primarily in Sweden and Canada, where prices are lowest and are close to parity with oil. Homes in Sweden, however, are so tight that the cost difference between electricity and oil would be minimal, and either fuel is less costly than district heat for single-family dwellings. Heat pumps have had some success in Sweden and Germany, but their greatest penetration has been in the U.S.

Policy

Market forces are necessary for improved energy efficiency, but not sufficient for complete adjustment to higher costs. In virtually every country, consumers are willing to make simple investments but need help to make larger long-term investments. Renters always fare worse than owners. Government research, demonstration, and direct support are important for the development and testing of new ideas and major products. Demonstration and testing of components in whole houses are important research areas.

Governments have an important role in sponsoring research and development in long-term conservation investments as well as in encouraging construction practices that would result in far better building shells. Codes affecting building practices in Sweden, Denmark, and France appear to have been effective in stimulating technological advances resulting in improved building shells. Standards appear to have been most significant in Denmark; in Sweden, they are tighter, but building practices at the time of implementation were closer to what the codes called for. Ultimately, however, the Swedish standard will result in significantly tighter homes, and will demand more of homes heated with electric-resistance heating. In addition, the southern areas of Sweden, which

had the least demanding codes, are now following the stricter requirements of the north.

U.S. Residential Energy Use and Conservation

The National Interim Energy Consumption Survey (NIECS) conducted by the Energy Information Administration provided the opportunity to estimate residential energy use in the United States by energy source and end use from comprehensive household and utility survey data. By carefully comparing groups of households for equipment ownership and factors affecting energy consumption for particular uses, it was possible to estimate average household energy consumption for the main end uses (Table 1). Using these averages and data from the Annual Housing Survey on equipment ownership, a portrait of residential energy use was assembled (Fig. 3).

Table 1. Average household energy consumption by end-use and fuel, April 1978 – March 1979 (in gigajoules).

	Gas	Oil	Electricity	LPG
Space heating	95	127	35	65
Water heating	26	38	14	17
Cooking	10	–	[a]	9
Air-conditioning	–	–	9	–
Other appliances	–	–	16	–

[a]Average electricity consumption for cooking could not be accurately derived by the method used in this study.

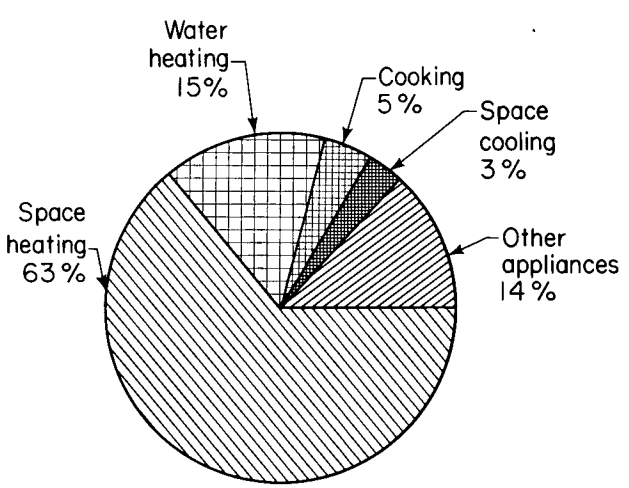

Figure 3. U.S. residential energy use, 1978-1979 (site energy). (XBL 831-1078)

Space heating is by far the most important residential energy end-use. Statistics indicating the average intensity of oil, gas, and electricity use were developed both for all households and for households in single-family structures (which constitute two-thirds of the U.S. housing stock). As can be seen in Table 2, after accounting for climate and dwelling size (estimated from NIECS data), oil and gas in single-family structures have roughly the same energy intensity, and it is about twice that of electricity (measured as site energy). This difference is attributable to furnace losses with oil and gas, the higher level of insulation in electrically heated homes, climatic factors other than temperature (i.e., solar gains), and, perhaps, differences in heating habits.

Table 2. Average energy consumption for space heating in single-family[a] structures.

	Oil	Gas	Electricity
Single-family (GJ)	124	109	46
per C-degree-day (MJ)	43.0	39.1	20.6
per C-degree-day and per square meter (KJ)	270	268	129

[a]Single refers to households in detached and attached structures.

The decline in average energy residential use from 142 million Btu per household in 1973 to 117 million Btu in 1980 (site energy, excluding wood) indicates that decreases in the energy intensity of various end uses have occurred. Part of this decline is due to the increasing penetration of electricity in space heating (from 10% of all households in 1973 to 18% in 1980), since electricity is roughly twice as efficient in terms of site energy as oil or gas. Part is due to the increased use of wood, particularly since 1979. Such factors make interpretation of changes in aggregate energy use difficult. Reliable data on changes in energy intensity for particular energy sources and end uses are unfortunately scarce. The best indicator of energy conservation is gas space heating: average consumption per degree-day fell 16% from 1970 to 1978, and has fallen further since then. An even greater drop, probably in the range of 25-30%, has occurred in oil space heating. With respect to other end uses, assessment of changes in energy intensity is difficult, though it seems clear that the stock of appliances is more efficient in 1980 than in 1973.

PLANNED ACTIVITIES FOR FY 1983

Activities planned for FY 1983 include completing the econometric analysis of residential energy use, using 1980 data, and beginning an investigation of commercial-sector energy use in the OECD countries.

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