VALIDATION OF THE LBL RESIDENTIAL ENERGY MODEL

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ABSTRACT

The U.S. Department of Energy (DOE) has used the LBL Residential Energy Model since 1979 to estimate the national impacts of federal minimum efficiency standards for residential appliances (including space conditioning equipment) on consumers' energy consumption and costs. The LBL model combines engineering (appliance costs and efficiencies) and economics (demand elasticities for fuel and efficiency choice, and usage) to simulate future energy consumption by end-use.

This paper examines the three forecasts using the model (published in 1980, 1982, and 1983) to quantify, in hindsight, their accuracy. The forecasted variables examined are: efficiency of new appliances and volume of shipments. In many areas, data and methodology changes improved the forecasts. Some problem areas remain.

The error of forecasts is composed of inaccuracy in exogenous variables (e.g., expected oil price, or economic growth) and the failure of the model methodology to capture the actual responses to those (or other) variables. After removing the error due to erroneous forecasts of driving variables, a backcast is performed from 1978-1984, using a new methodology for forecasting equipment efficiencies. We calculate the short-term model accuracy in replicating underlying components of residential energy consumption in the USA.

Abstract of refereed paper to be presented at ACEEE 1986 Summer Study.

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INTRODUCTION

Computer models can be very useful for analyzing complex systems. We have been concerned with modeling energy consumption in the U.S. residential sector. Residential energy consumption comprises 35% of electricity consumption in the U.S., and over 25% of the direct consumption of natural gas. The complexity in this system arises from the diverse services which each energy type provides, the variety of equipment designs capable of supplying these services, and the diversity of energy users (housing types, regions, income classes). In order to consider policies which affect the designs of energy-using equipment, an end-use model must keep track of each of the different equipment types (e.g., furnaces, air conditioners, refrigerators). The LBL[+] Residential Energy Model (REM) contains end-use detail, forecasting equipment efficiencies and purchases for each end-use and fuel.[1] This model has been used by the U.S. Department of Energy for policy analyses.

This paper attempts to quantify the accuracy of some of the model forecasts. First, published forecasts made in 1980,[2] 1982,[3] and 1983 [4] by this model are compared with reported values for 1985. The aggregate forecasts (e.g., total residential electricity or natural gas demand) show reasonable agreement with reported values in the short-term. However, there are no reliable measurements of national energy demand by end-use. In order to check the components of the forecast, we use data reported by the equipment manufacturing industries. The results demonstrate some areas in which the forecast accuracy improved with time, and other areas in which forecast accuracy is still poor. The intent is to develop a benchmark of forecast accuracy for several key components of energy demand, specifically, equipment efficiencies and volume of shipments. This will allow comparison with other models, and provide guidance for targeting future research to improve forecast accuracy.

Forecast inaccuracy is composed of two parts: forecasts of driving variables and model response to those variables. An inaccurate forecast may arise from a perfect model, if the driving variables are not forecasted correctly. We make no analysis of the error in forecasted values of driving variables. However, in order to test the model alone, the inaccuracy in driving variables must be eliminated. The method chosen here is called a "backcast." A backcast is simply a model simulation over a recent period,

+ LBL = Lawrence Berkeley Laboratory

* 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-AC03-76SF000098.

during which the values of the driving variables are known. A perfect model will produce an exact replication of observed residential energy demand, given accurate values for the driving variables.

We present the results of a backcast over the period 1978-1985, in which we test the constant discount rate algorithm for forecasting equipment efficiencies. This is an alternative to the published forecasts of equipment efficiencies. Limitations of this approach, with and without using lagged energy prices, are discussed.

Determining the accuracy of a long-term model is problematic. While the user would like a measure of the model's accuracy immediately, a short-term test is not conclusive. Reported values must be examined for their completeness and accuracy, before attributing all differences between model backcast and reports to model error. Even the ability to replicate a few years of recent history, while encouraging, provides no guarantee of the long-term accuracy of the model. For example, if the real price of a fuel moves outside the range previously experienced, the decisions about purchasing and using equipment requiring that fuel may change. In this regard, quantitative analysis should be viewed in perspective. A model which takes advantage of available data to provide a consistent framework for understanding recent history can serve as a long-term forecasting tool for a modeler who understands the limits of its abilities and who makes allowances for potential departures from observed behavior.

The design application of the LBL Residential Energy Model is *not* forecasting the future, but rather assessing the impacts of proposed policies. We are usually more interested in the sign and order of magnitude of the impacts of a policy (e.g., energy savings or consumer costs as the difference between two cases, one with no policy, and one with the policy in effect), than in the exact number of refrigerators that will be sold in future. On the other hand, the major application of the LBL REM to date has been to analyze proposed federal appliance efficiency standards. Consequently, the policy impacts depend strongly on the base case (no policy) forecast of equipment efficiency, and volume of shipments. Since there is no way to assess the model accuracy with regard to policy impacts, we turn to an assessment of the ability of the model to forecast parameters of interest to an impacts assessment.

Several perspectives could be presented as interpretation of the results. The model builder can point out the complexity of the system being modeled, the many levels of detail in the model, and the apparent capability of the model to at least consider the important interactions determining residential energy consumption. At the opposite extreme, a critic intent on refuting the model can point to the magnitude of the error in some variables for some end-uses, as an indication that the model is inadequate. The author maintains that both statements are true: the model may be the best representation developed so far, giving reasonable agreement in the aggregate, suitable for policy analysis, but still be measurably imperfect in some components. The intent of this paper is to begin quantifying the accuracy of the model and its components, as 1) further indication of the areas requiring new data and research; 2) a benchmark from which improvements or degradation in forecasting capability can be measured; and 3) a point of comparison with alternative models. From a research perspective, the most interesting parts of the model are the areas where the largest inaccuracies dwell.

DATA AND METHODS

The intent of this work is to quantify the forecast accuracy of the LBL REM. Two variables have been selected to represent the model outputs: equipment efficiency and volume of shipments.

Forecast accuracy is determined by the interaction between two components: accuracy of forecasts of driving (exogenous) variables, and model accuracy in replicating actual responses to those variables. First, we compare published forecasts with actual events, to get a measure of the overall accuracy of the forecasting method in practice, including both sources of inaccuracy. Three forecasts published by DOE are compared with the actual market response. By comparing several forecasts, we can show where accuracy increased or decreased. The changes from forecast to forecast include revising the input data (including forecasts of driving variables), and changing algorithms in the model. The three forecasts performed for the analysis of federal appliance efficiency standards were published in 1980, 1982, and 1983. All forecasts start in and are benchmarked to the same base year (1977).

Table I. Sources of data by end-use

Association of Home Appliance Manufacturers (AHAM)[5]	Refrigerators, Freezers, Room air conditioners
Air-conditioning and Refrigeration Institute (ARI)[6]	Unitary air conditioners, Heat pumps
Gas Appliance Manufacturers Association (GAMA)[7]	Furnaces (gas and oil), Water heaters (electric and gas)

The data against which the forecasts are measured are from industry sources. Units shipped and efficiencies are provided by trade associations as shown in Table I. Model forecasts of the shipment-weighted average efficiencies of new appliances shipped each year are compared with industry data. The number of units shipped by U.S. manufacturers are compared with model forecasts of purchases in the residential sector.

One complication arises from purchases of residential appliances by non-residential users. For example, residential-sized air conditioners may be purchased for small commercial establishments. The industry has not provided (and probably cannot provide) information about the ultimate users of equipment; shipments are usually tracked to dealers or direct purchasers, but no data is available about the buildings into which the equipment is installed. For some products, a significant portion of the error in forecasting shipments may arise from the lack of data on nonresidential purchases of these products.

A backcast is performed for the period 1978-1984. The driving variables are taken from reported values, and the model's expectations for equipment efficiencies are compared with actual. In this way, errors in forecasts of driving variables are removed, and the adequacy of the algorithms for simulating residential energy consumption is tested. Driving variables include energy prices,[8] income,[9] and housing starts.[10]

RESULTS

National residential energy consumption. Figure 1 shows the 1983 forecast for residential energy demand for electricity and natural gas in the period 1977-1984, compared with reported values. The residential energy consumption reported by utilities underestimates total residential demand; for example, electricity and gas utilities report some high-rise residential buildings as commercial customers. The forecast in 1977 is benchmarked above the reported values by about 4% to account for mass-metering. The forecast assumes normal weather in all years.

The forecast for total gas consumption tracks reported values well, with differences ranging from 1 to 6%. If mass-metering consumption remains proportional, actual consumption is about 4% above EIA reports, and the corrected difference between model and actual ranges from +1 to -3% annually.

The electricity forecast shows a trend toward underestimation of reported values. As discussed below, the difference is due to underestimation of shipments and small overestimates in efficiencies. Overestimates of changes in usage behavior in the model (not analyzed here) may also contribute.

Equipment Efficiency Forecasts. Figure 2 shows the new equipment efficiencies from 3 forecasts for 1985, compared to reported shipment-weighted average efficiencies of new units shipped in 1985. Gas furnaces and water heaters show the same pattern of changes over the 3 efficiency forecasts. For both end-uses, the lowest efficiency forecast is made in 1980, the highest in 1982, and a slightly lower forecast (compared to 1982) was made in 1983. The changes reflect changing assumptions in the exogenous variable, gas prices. The efficiency forecasting algorithm responds directly to energy prices each year.

Gas furnaces have shown consistent improvements in equipment efficiency, particularly after the introduction of condensing units in 1981. On the other hand, gas water heaters showed improved efficiency initially, then decline after 1980. The model algorithm gives relative success in forecasting furnace efficiencies (within 4% in the 1983 forecast), but fails to foresee the decline in water heater efficiencies (10% overestimate in 1983 forecast). Similarly, based on increasing price of distillate oil, the model expected significant improvements in oil furnace efficiencies. However, little technology change occurred for oil-burning equipment, and in 1983 the model overestimated the 1985 efficiency for this product by 7%. Efficiency improvements for oil furnaces appear nearly linear, and nearly independent of short-term changes in oil price. (This could imply that oil price effects on efficiency are substantially lagged; alternatively, the sharp decline in unit sales in response to higher operating costs may have adversely impacted investment and innovation by the manufacturers, limiting efficiency improvements.)

For electric appliances, the results are much more varied, and cannot simply be traced to changing the forecast of electricity price. The set of designs considered and their costs changed from one forecast to the next, and new data on trends in efficiency improvements were introduced. The model consistently provided good estimates of efficiencies of electric water heaters (within 3%).

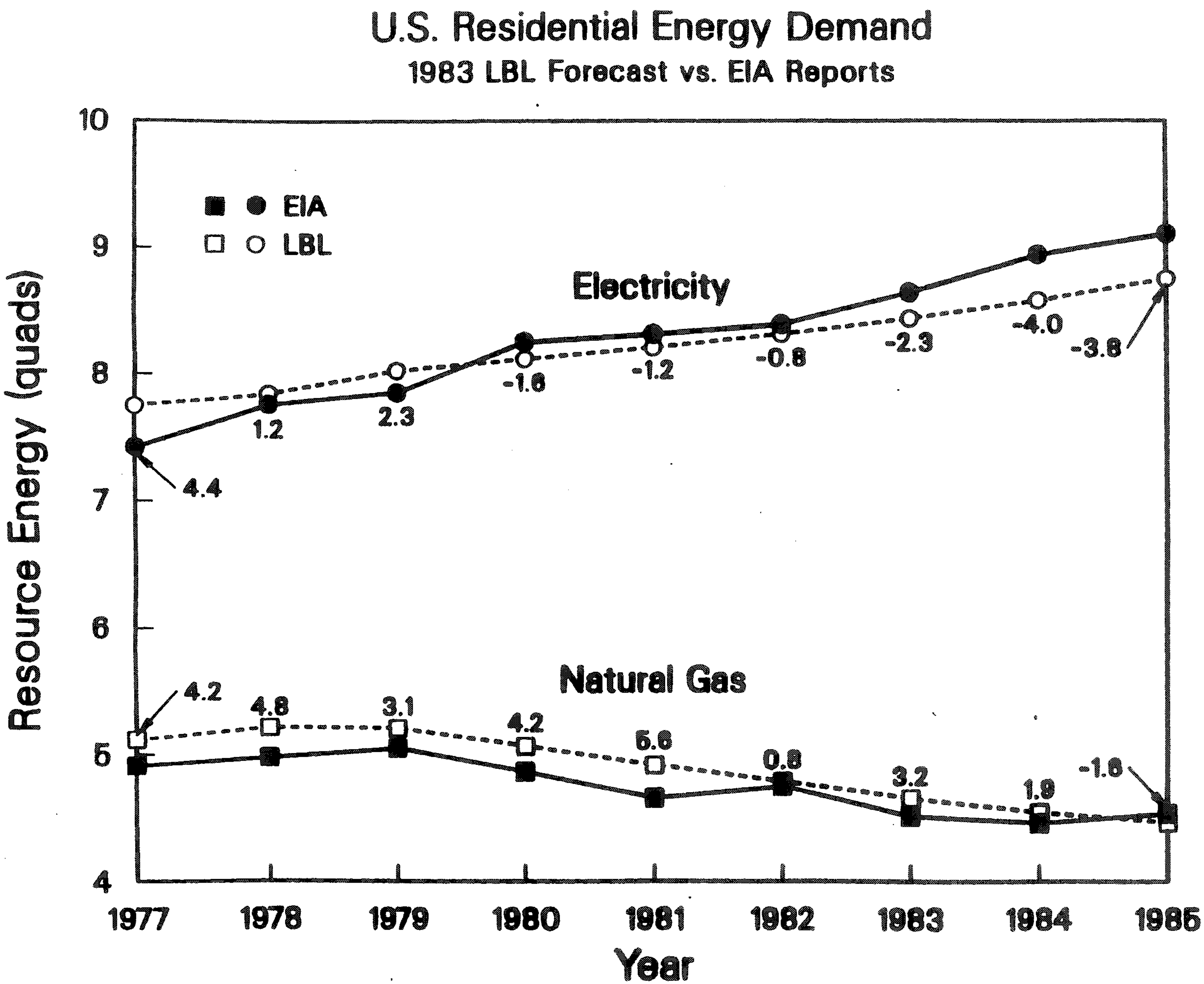

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Figure 1. Comparison of reported and modeled total U.S. annual residential energy consumption, 1977-1984.

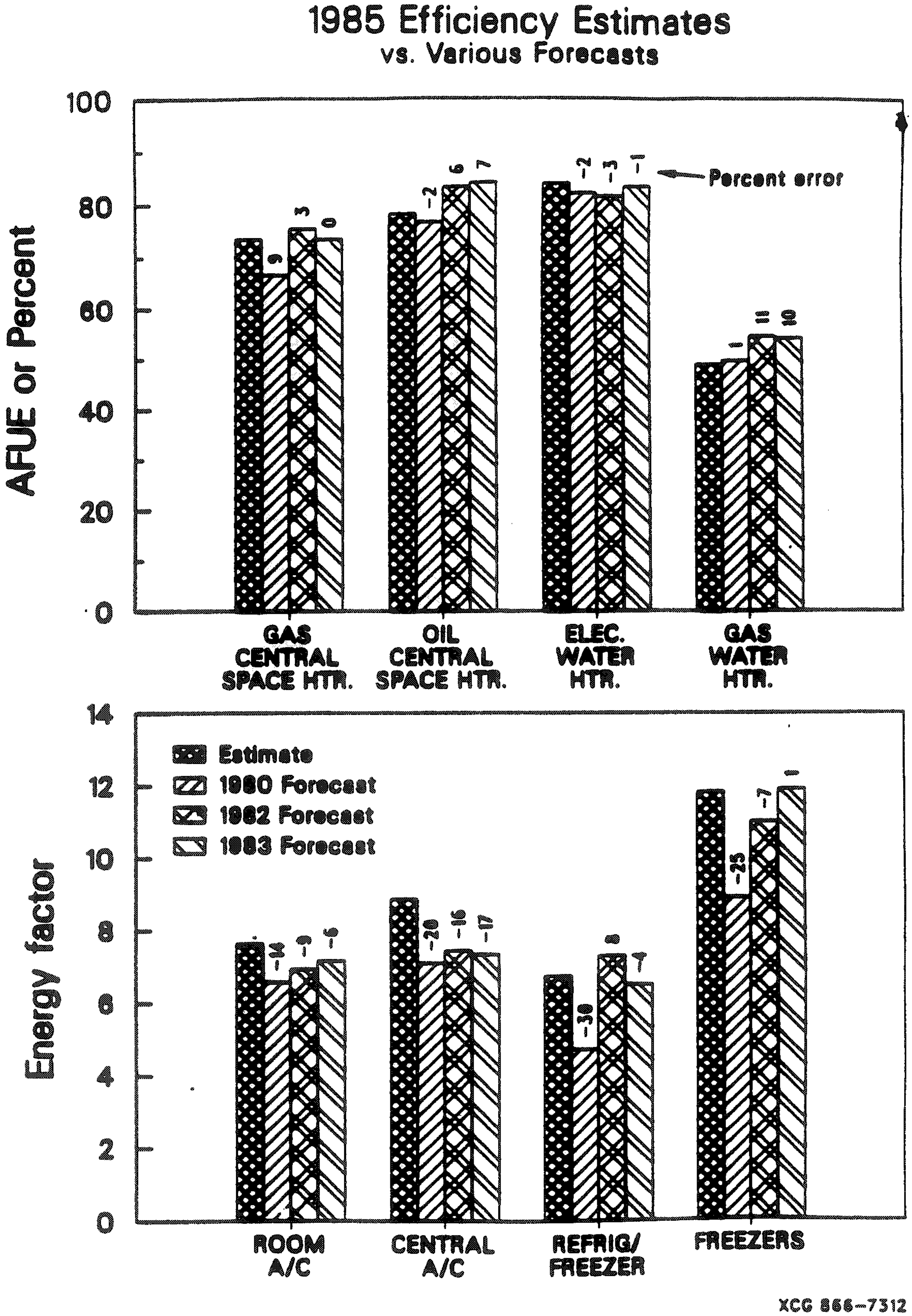

Figure 2. Comparison of 3 forecasts (made in 1980, 1982, 1983) of efficiencies of new equipment with reported average efficiencies in 1985. Percent error is indicated at the top of each bar.

For all other products, except central air conditioners, the absolute magnitude of the error declined from each forecast to the next; the 1983 forecast gave estimates within 6% of actual efficiencies for electric water heaters, room air conditioners, refrigerators, and freezers. The mean absolute percent error for the five products was 18% (1980 forecast), declining to 9% (1982), and to 6% (1983). For four electric products (excluding central air conditioners), the mean absolute percent error declined from 18% to 7% to 3%.

The error for central air conditioners is between 16 and 20% in all 3 forecasts. The data for historical efficiencies of central air conditioners contains a change in measurement units in 1981, and definition of a conversion factor from one measurement unit to the other is controversial. A reasonable conversion could account for a consistent error of about 6-7%. The remaining 10% error should probably be considered the model's error. Some unique factors may have contributed to the recent improvements in unitary air conditioner efficiencies, particularly incentives offered by electric utilities to purchasers of more efficient units. The model did not consider the effective reduction in purchase cost to the homeowner that resulted from the utility programs. In this regard, we observe that the model accuracy with regard to unitary air conditioner efficiency declined significantly beginning in 1982. Incentive programs affected about 10% of total shipments of unitary air conditioners in 1982,[11] in the high efficiency end of the distribution, and more incentives were offered thereafter.

Shipments Forecasts. The capability of the model to forecast 1980 shipments was tested by comparing the 3 published forecasts with industry data. While the ability to forecast shipments in a single year is an overly rigorous test, given the normal fluctuations in demand for appliances in the marketplace, such a test is easy to administer. Table II shows striking improvements from the 1980 forecast, with a mean absolute percentage error of 83%, to the 1982 forecast, with 33%. From 1982 to 1983, there was some additional improvement, to a mean absolute percentage error of 26%. Excluding oil central space heaters, the mean errors decline from 43 to 25 to 15%.

The major modeling change from the 1980 to the 1982 forecast affecting shipments estimates involved replacing the form of the retirement function.[12] The abandonment of the exponential retirement scheme and adoption of an empirically-based polynomial and an initial age distribution resulted in much better characterization of the replacement market. This change did not affect the estimate of equipment purchases in new homes.

The most significant error in all 3 forecasts is in the number of central oil-fired heating systems installed. The error was 605% in the 1980 forecast, and 143% in the 1983 forecast. A new forecast using recently derived market share elasticities[13] for space conditioning equipment reduces this error to 67%. Further research is expected to reveal the extent to which the remaining error can be attributed to two factors: 1) overestimation of purchases in new houses, based upon an inaccurate initialization of the market share; and 2) mischaracterization of the rate of retirement, particularly failure to account for early replacement of functioning equipment with non-oil equipment due to fuel cost and availability considerations.

Table II. 1980 Appliance Shipments and Forecast Errors				
	Shipments	Forecast error (%)		
	(000)	1980	1982	1983
Water heaters, electric	2451	73	44	18
Water heaters, gas	2818	76	13	2
Refrigerators	5124	44	9	-13
Freezers	1681	26	-11	-23
Room air conditioners	3203	-33	-26	-39
Unitary air conditioners	1655	37	26	-8
Heat pumps	412	na	na	-15
Central space heat, electric	642	78	66	10
Central space heat, gas	1739	47	-27	-24
Central space heat, oil	115	605	121	143
Room space heat, gas	434	68	-35	-33
Ranges, electric	2532	61	49	3
Ranges, gas	1539	73	-6	-9
Clothesdryers, electric	2497	11	9	-17
Clothesdryers, gas	682	-3	-24	-33
Mean absolute percent error		83	33	26
MAPE excluding oil central heat		43	25	15

Error in excess of 20% still exists for oil central space heating equipment (143%), room air conditioners (-39%), gas clothesdryers (-33%), gas room heaters (-33%), gas central space heaters (-24%), and freezers (-23%). The data on U.S. shipments include non-residential sales. If such purchases are significant, then the model estimates will be low. In the 1983 forecast, the model estimates are low for 10 of the 15 products (Table II).

Backcast: efficiencies of new appliances. As a consequence of analyses of market behavior in the purchase of efficient equipment, we decided to test a constant market discount rate algorithm for forecasting efficiencies of new appliances. The observed average (shipment-weighted) efficiency of new appliances in a particular year is used together with engineering estimates of the costs of designs of varying efficiency, to derive a discount rate (or payback period) implicit in the market decision of that year. "Market discount rates" derived in this manner are relatively high, and for most products do not decline dramatically from year to year, even during periods of substantial increases in energy prices.[14]

A proposed version of the LBL REM uses reported shipment-weighted efficiencies for historical years, and a constant market discount rate for forecasting efficiencies in future years. In this paper, we report a backcast of efficiencies in the period 1978-84, to test whether the proposed efficiency forecasting algorithm replicates reported efficiency changes.

The market discount rates consistent with observed market behavior in 1978 were calculated. Assuming these discount rates remained constant, equipment efficiencies were forecast through 1984. The percent efficiency improvement forecasted was compared with that reported for each product. If efficiency improvements kept pace with energy prices so as to retain an existing tradeoff between equipment cost and operating cost, then a single parameter (e.g., our "market discount rate") would serve as a good basis for forecasting efficiency improvements. Figure 3 shows that the forecasted efficiency improvements for gas furnaces were slightly low, while the forecasted efficiency improvement for oil furnaces agreed with observation.

For all the electrical appliances, the forecasted efficiency improvement fell short of the actual improvements reported. The slow growth in electricity prices alone is not sufficient to account for the observed efficiency improvements. We hypothesize that manufacturers' decisions to make more efficient models available to the public are based upon more complex factors than simply current electricity prices. For example, the largest efficiency improvements occurred for refrigerators, where manufacturers automated their production lines and adopted a different type of insulation. This conversion achieved both lower production costs and higher equipment efficiencies.

Lagging energy prices up to 4 years gave no better consistency for market discount rates, except for gas and oil furnaces. For gas-fired space heating equipment, assuming a 1-year lag in energy prices when calculating the market discount rates reduces the standard deviation of the discount rates by over 40%. (The standard deviation is calculated from the time series of discount rates, one for each year where the shipment-weighted efficiency of new units is known.) A similar improvement was observed for oil-fired space heating equipment when a 4-year lag in energy price was assumed.

If the manufacturer decisions are related to energy prices, then different derivations of implicit market discount rates may provide better models for forecasting equipment efficiencies. For example, our simple model assumed no expectations of energy price increases, and considered only current energy prices. If the market decisions to offer and purchase higher efficiency appliances are based on experienced energy prices and expected future energy price increases, then lagged energy prices and perceived price escalation rates should be used. Alternative models of the driving forces behind efficiency improvements will be tested for forecasting accuracy over recent history. If these models also fail, we believe a need exists for research into manufacturer decisions, to identify (forecastable) factors other than energy price and engineering costs which determine the introduction of more efficient appliances into the marketplace.

CONCLUSIONS

Residential energy consumption comprises 35% of electricity consumption in the U.S., and over 25% of the direct consumption of natural gas. The LBL Residential Energy Model is a detailed computer model of residential energy demand, which has been used by the U.S. Department of Energy for policy analysis. In this paper, we report some of our attempts to quantify the accuracy of the LBL Residential Energy Model and some of its component parts.

The model, as used in 1983, gave reasonable results in the short-term for total U.S. residential demand for electricity and natural gas. Correcting for mass-metered apartments but not for weather, the mean absolute percentage error (MAPE) for annual consumption during the period 1978-1984 is 1.4% for natural gas, and 5.4% for electricity.

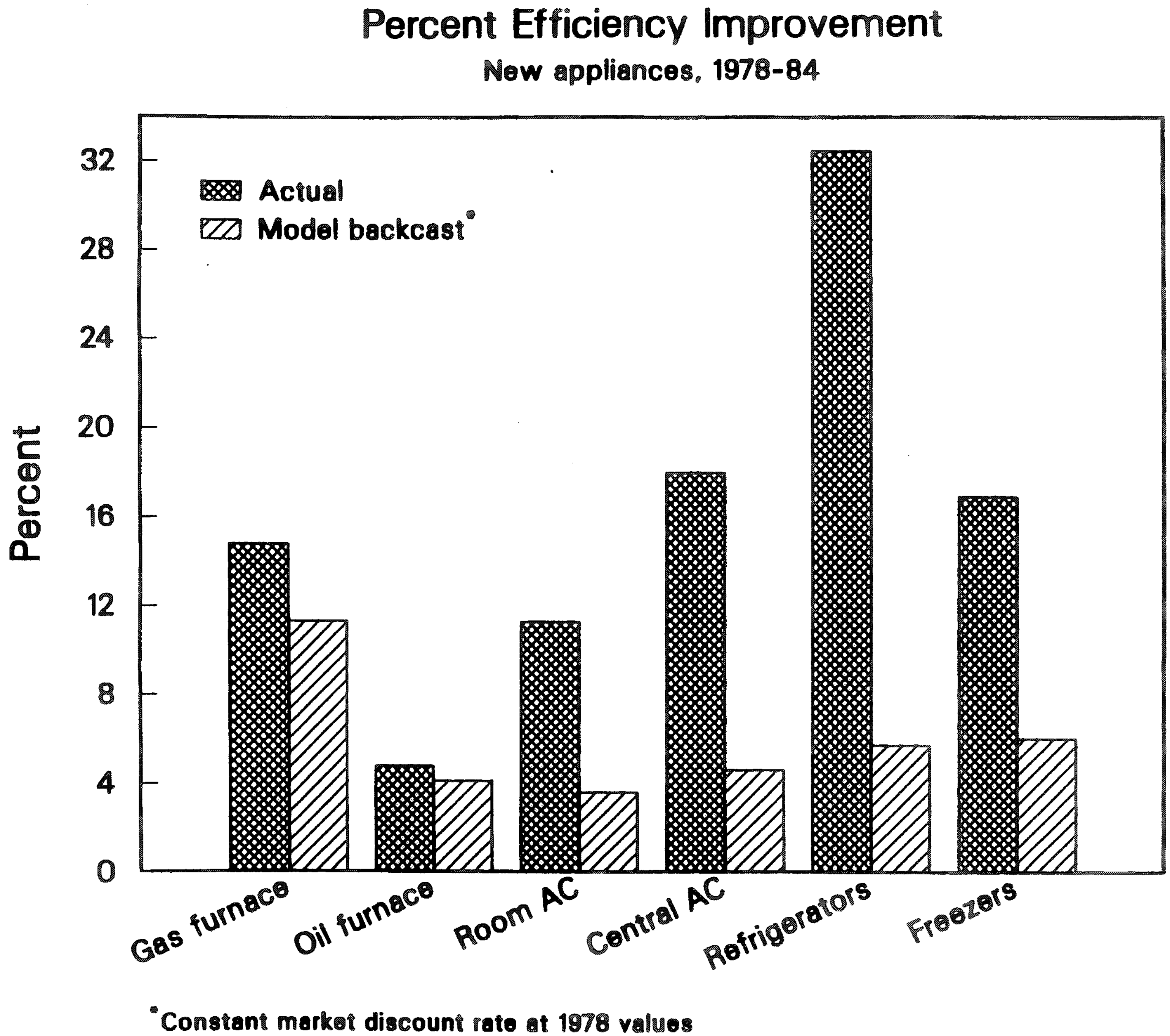

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Figure 3. Comparison of backcast and actual percent efficiency improvement in equipment efficiency from 1978 to 1984.

There is no apparent trend in the difference between the forecast and reported values for natural gas, but the electricity forecast tended toward underestimation over time (Figure 1).

Next, we examine a series of forecasts made at different times for their accuracy with regard to specific outputs, namely, product-specific equipment efficiencies and shipments. In forecasts made between 1980 and 1983, the accuracy of forecasted 1985 equipment efficiencies improved for most electric products, except central air conditioners. Accuracy also improved for gas furnace efficiencies, but not for gas water heaters or oil furnaces. The error in the 1983 forecast was less than 8% for all products except central air conditioners (-17%) and gas water heaters (+10%). The MAPE in equipment efficiencies for 1985 was 18% in the 1980 forecast, and 6% in the 1983 forecast. Half of the remaining error in 1983 is due to central air conditioners. The differences between products may imply that complex factors, beyond engineering possibilities and energy costs, influence the decision to put more efficient designs on the market.

The shipments forecasts show larger inaccuracies, with a MAPE for 1980 shipments of 83% in the 1980 forecast. The forecast accuracy improved from 1980 to 1983 for most products, yielding a MAPE of 26%. The largest single contribution to the error is from oil central space heaters. Excluding those, the MAPE declines from 43% in 1980 to 25% in 1982, and 15% in 1983. We hypothesize that a major portion of the remaining error is due to uncertainty about the replacement decision. We have insufficient knowledge about both physical lifetimes of residential appliances and about economics-motivated turnover. Another source of error is the lack of data on non-residential purchases of appliances (e.g., refrigerators installed in offices).

Finally, the model is examined more closely by removing the uncertainty in forecasting driving variables (such as oil prices), and testing a new algorithm, assuming constant market discount rates, for its ability to replicate observed improvements in equipment efficiency, given the actual values of the driving variables, namely energy prices. The percent improvement in appliance efficiencies from 1978 to 1984 is forecast well for oil furnaces, less well for gas furnaces, and poorly for electric appliances (room and central air conditioners, refrigerators, and freezers). Apparently some factors other than current electricity price are needed to account for efficiency improvements. Lagged energy prices (up to 4 years) generally provide no better forecasts, except for gas and oil furnaces, where a 1- and 4-year lag, respectively, reduces the standard deviation in the market discount rate significantly. We propose to test future price expectations for providing better estimates of efficiency improvements.

The general conclusion is that absolute equipment efficiencies for most products can be forecast over the short term with average errors around 3-6%. The recent rate of improvement of efficiencies for electrical appliances, however, is not explained well by a constant market discount rate formulation based on 1978 market behavior and current energy prices. While the 1983 model slightly overestimated equipment efficiencies in general, the constant market discount rate algorithm gives a larger error and tends toward underestimation.

Shipments are more difficult to forecast than efficiencies, with short-term errors averaging 15-26%. Recent work, not reported here, has involved derivation of market share elasticities for space conditioning equipment from household-specific data.[13] Implementation of these estimated elasticities includes a formulation in which the elasticities are not constant, but depend upon the size of the perturbation of the independent variables. We expect this formulation to improve the forecast of equipment purchases in new homes. In addition, research is needed on replacement decisions, including both the physical lifetimes of residential equipment and the decision process leading to early retirement of functioning appliances. Data is also needed to characterize the extent to which new appliances are installed elsewhere than in homes.

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