The article by Rosenfeld, Bulleit, and Peddie shows how recent developments in microprocessor control technology make it technically and economically feasible to price electricity dynamically according to the theoretical ideal that the price of electricity be equal to its actual marginal cost, thereby overcoming one of the outstanding obstacles inhibiting consumer choices of the most cost-effective end-use technologies from the societal perspective — inappropriate market price signals.

The article by Williams and Larson shows that there is also a quiet revolution underway in more efficient electric power generating technology. Recent developments in gas turbine technology make it possible to generate electricity in relatively small-scale, short lead-time, low capital-cost, high-efficiency, central-station power plants at costs competitive with electricity production in conventional coal or nuclear power stations, even when the fuel is high-cost natural gas. With the availability of such gas turbines, utilities would not have to overbuild generating capacity based on long lead-time plants as a hedge against the uncertainties regarding future electricity demand growth. This is of fundamental importance to the development of effective utility energy conservation programs because if utilities overbuild, they have little incentive to conserve.

The articles in this issue show that technology has been changing rapidly to facilitate the more economical use of our electricity resources. The challenge for policy-makers is to find effective ways for our institutions to catch up with our technology and convert these technical opportunities into practical realities.

FEATURE ARTICLE

Energy-Efficient Residential Appliances: Performance Issues and Policy Options

HOWARD S. GELLER

I. INTRODUCTION

The residential sector now accounts for 21 percent of the energy consumed in the United States and 35 percent of the electricity consumed. Each year, some 34 million major appliances (refrigerators, air conditioners, water heaters, etc.) are sold. Furthermore, the electricity consumed by the new electrical appliances sold annually is equivalent to that produced by about 6000 MW of baseload generating capacity [1].

At the household level, operating appliances and lights can be costly. The typical household in the U.S. consumes about 8500 kWh/yr of electricity at an annual cost of about \$650 [2]. Furthermore, the average residential electricity price in the U.S. increased 41 percent above general inflation during 1973 – 84 [2].

Table I shows the estimated electricity consumption of the typical major appliances currently in use. At the current average electricity price (\$0.076/kWh), operating a refrigerator-freezer typically costs \$115/yr, an electric water heater typically costs \$300/yr, and a central air conditioner typically costs about \$275/yr. Clothes dryers, ranges, lights, and room air conditioners each typically costs \$60 – 75/yr. Consequently, the cost for operating residential appliances over their lifetime is a number of times greater than their first cost.

II. SAVINGS POTENTIAL

Rising electricity prices and some policy initiatives prompted manufacturers to improve the efficiency of appliances and lighting products during the past decade. The results are startling. A wide range of appliances and lighting products are now available that use 50 percent less electricity compared to conventional products manufactured in recent years[1] [3]. New models under

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[1] *A booklet listing the most efficient appliance models is available from the American Council for an Energy-Efficient Economy. For a copy, send \$2.00 to ACEEE, 1001 Connecticut Ave., NW, Suite 535, Washington, DC 20036.*

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TABLE I
ESTIMATED ELECTRICITY CONSUMPTION OF MAJOR APPLIANCES AND LIGHTS IN USE IN 1985

Product	kWh/yr
Refrigerator-freezer	1500
Freezer	1100
Water heater	4000
Cooking range	800
Clothes dryer	1000
Central air conditioner	3600
Room air conditioner	900
Lighting	1000

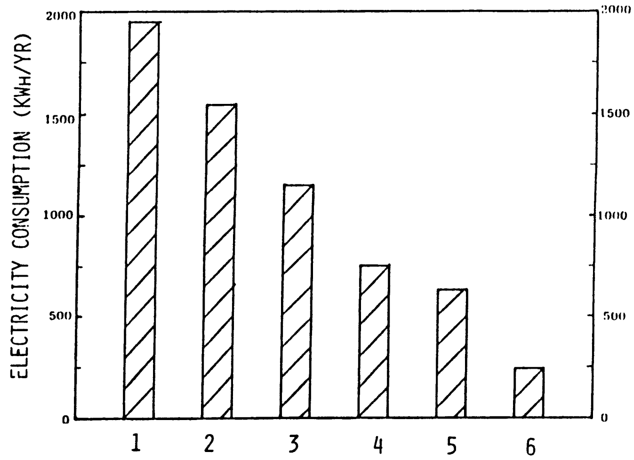

Fig. 1. Progress in the electricity consumption of top mount freezer, automatic defrosting refrigerator-freezers built in the U.S.
1-Typical model sold in 1972.
2-Typical model sold in 1978.
3-Typical model sold in 1983.
4-Best model made in 1985.
5-Prototype model made in 1984.
6-Custom-made model 1984.

development promise even greater savings. To a great extent, these advances are straightforward "technical fixes," providing much greater energy efficiency without affecting level of service or lifestyle.

Water heaters

Conventional electric water heaters employ resistance coils to convert "high quality" electrical energy into "low quality" hot water — a thermodynamically inefficient process. In addition, storage tanks typically include only 5.0 cm of fiberglass insulation [3].

Heat pump water heaters (HPWHs) first became available in the U.S. around 1980. A HPWH uses a vapor compression cycle to "pump" heat from the air surrounding a water heater into the tank in the same manner as an air conditioner removes heat from a building.

Field tests show that today's generation of HPWHs typically consume about half as much power as electric resistance water heaters [4]. This leads to a savings of 2000 kWh/yr for an average household with electric water heating.

The top-rated HPWH now mass-produced in the U.S. is significantly more efficient than other commercial HPWH models [5]. It features a plate condenser built into the storage tank and thicker-than-average foam insulation. Electricity savings are about two-thirds compared to a conventional electric resistance water heater [1].

HPWHs are generally placed in the basement or garage where heat is extracted from the surrounding air. It is also possible to extract heat from ventilation air in a tight house where mechanical ventilation is needed to maintain good indoor air quality. A HPWH coupled to a home ventilation system can efficiently recover heat from exhaust air during the space heating season and remove heat from the incoming air stream during the cooling season. HPWH-ventilation systems are now commonly used in new homes in Scandinavia [6], and they are beginning to appear in North America.

Refrigerators and freezers

Fig. 1 shows the progress that has been made in improving the energy performance of top-mount refrigerator-freezers (R/Fs) during the past decade. This is the most common refrigerator style with a total volume of 16 – 18 cf. Through a variety of simple design changes including shifting to polyurethane foam insulation, use of more efficient motor-compressors, and reducing internal thermal loads, the typical model sold in 1983 consumes approximately 40 percent less electricity than the typical model sold during the early 1970s [7]. The energy efficiency of stand-alone freezers has improved to a similar extent.

The best mass-produced R/F in the U.S. in 1985, rated at 750 kWh/yr, uses 50 – 65 percent less electricity than older models of equivalent size and style [8]. Once again, no radical modifications are required to achieve this level of performance.

Some prototype and foreign refrigerators and freezers do even better than those now on the market in the U.S. For example, a prototype R/F featuring an efficient compressor and separate evaporator coils in the refrigerator and freezer compartments is rated at 600 – 650 kWh/yr [9]. Some Japanese refrigerators and freezers are also relatively energy-efficient [10].

Well-designed, extremely efficient R/Fs are being custom-built by a small company in California for use with photovoltaic power systems. These units feature high levels of insulation, separate cooling systems for the refrigerator and freezer boxes, and better overall design (e.g., the motor-compressor is above rather than below the food storage space). A 16 cf. model consumes only 240 kWh/yr based on the standard test [3]. Although this custom-made R/F costs $2500, using it rather than a conventional R/F saves about $10,000 in photovoltaic system costs.

A recent study found that it would be very cost-effective to reduce the energy consumption of mass-produced refrigerators and freezers to 200 kWh/yr or less [11]. Such large savings can be achieved through a combination of measures, including greater insulation, better motor-compressors, and better refrigeration system design. Use of evacuated panel insulation is one especially promising advanced design option [11].

Air conditioners and heat pumps

Fig. 2 shows the progress in improving air conditioner (AC) efficiency since 1972. The average central AC system sold in 1984 was 30 percent more efficient than that sold in 1972 [12]. Furthermore, the top-rated AC models now produced are nearly twice as efficient as typical models sold in recent years. Large improvements in overall efficiency have been achieved through the use of larger condenser and evaporator coils, more efficient motors and compressors, and improved controls [3]. Some highly efficient models use two-speed compressors or dual compressors. This provides a much better matching of output to load, thereby reducing cycling losses.

In Japan, AC manufacturers are starting to include solid-state inverters in their AC and heat pump systems. This provides capacity modulation through continuous speed variation. The Japanese are also producing AC and HP systems in which the refrigerant is circulated to independently-controlled indoor heat exchange coils, providing zonal space conditioning within the house [11].

Evaporative coolers have long been used for cooling in hot, dry climates. Evaporative coolers are relatively efficient, consuming 80-90 percent less electricity than conventional vapor compression AC systems [11]. But conventional, direct evaporative coolers add considerable moisture to indoor air and this has limited their popularity in the U.S. Indirect, two-stage evaporative coolers overcome the moisture problem. Indirect evaporative coolers are now marketed for commercial buildings; systems for residences are expected on the market in the near future [11].

Air conditioners present very substantial peak loads for utilities [13]. Daily storage of "coolth" can shift air conditioning load to off-peak periods. Thermal coolth storage systems using ice, eutectic salts or water-clathrate mixtures are starting to be used in commercial buildings. Prototype systems have been tested in residences [11].

Clothes dryers

Electric clothes dryers (ECDs) are found in about 40 percent of households nationwide. Some new ECDs sense the temperature or moisture level of the exhaust air and automatically shut off the dryer. Automatic termination controls can reduce electricity consumption by up to 15 percent [14].

Some very innovative ECDs are now at the prototype stage. Heat pump dehumidification dryers are now used for drying lumber and food products, and heat pump clothes dryers are close to becoming commercially available]11]. They use up to 60 percent less electricity than conventional dryers, and do not require an exhaust vent [3]. Microwave clothes dryers are also under development. It is estimated that they could provide 40-60 percent electricity savings and substantial time savings at a very attractive first cost [11].

Electric ranges

Electric ranges are used in about 50 percent of households in the U.S. Simple improvements, including better oven insulation, improved door seals, reduced thermal mass, and better contact resistance for the stovetop elements can reduce electricity use by about 20 percent [11].

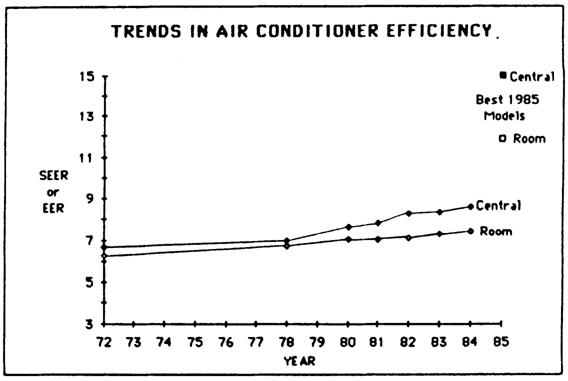

Fig. 2. Trends in air conditioner efficiency. The efficiency values for 1972 through 1984 are shipment-weighted averages for all new systems. The efficiency of the top-rated models on the market in 1985 are also shown.

Room air conditioner values are given in terms of EER, the BTUs/hr of cooling output divided by watts of electrical power input. Central air conditioner values are given in terms of SEER, the seasonal energy efficiency ratio.

Microwave ovens are three to four times more efficient than conventional ovens in standardized tests involving heating a pan of water [15]. Studies involving the cooking of actual food items show that the use of a microwave oven can reduce overall electricity consumption for cooking by 20 – 50 percent [16].

The induction cooktop is another advanced cooking technology now commercially available. An induction cooktop features magnetic coils that induce currents in iron or steel pans, eliminating losses from the heating elements. Induction cooking should lead to about a 15 – 25 percent electricity savings for stovetop cooking only [11].

Lights

Of course, incandescent lights provide virtually all lighting in households at the present time. Incandescent bulbs typically provide only 15 lumens per watt, with about 90 percent of the power drawn by the bulb given off as heat. Considerable attention has been devoted to increasing the efficiency of residential lighting.

Compact fluorescent lamps are now produced by major lighting manufacturers in Europe, the U.S., and Japan [11]. They are available either as a complete unit containing tube and ballast or as a separate conversion base and plug-in tube. One advanced model manufactured in the U.S. by Philips includes a high frequency electronic ballast. The electronic ballast reduces size, weight, and ballast power consumption.

Compact fluorescent lamps typically consume 60 – 75 percent less power than incandescents for the same light output [11]. Unlike conventional fluorescent lights, compact fluorescents provide "warm" light similar to incandescents. In addition, they last five to ten times longer than incandescent bulbs.

The drawbacks to today's generation of compact fluorescents are, first, that most models are somewhat larger than incandescent bulbs. However, the West German-based company Osram has developed a compact fluorescent bulb of equivalent size that should become the industry standard. Second, the first cost for a compact fluoresent lamp is \$10 – 20. But, as shown in Section III, the bulbs are economical on the basis of life-cycle cost.

Incandescent bulbs are also being improved. A spherical bulb with a heat reflecting inner coating has been developed. It uses half as much electricity as ordinary incandescents for the same light output [17]. This bulb is expected to be marketed in the U.S. in 1986 [11].

Overall savings potential

The aggregate energy and cost savings potential with today's top-rated appliances is enormous. Consider a few examples: If all households had the most efficient refrigerator now on the market, electricity use would drop by the equivalent of the output from twelve 1000 MW baseload power plants and consumers would save about four billion dollars per yar in electricity bills. Use of heat pump water heaters could "knock out" another fifteen 1000 MW baseload plants.

Air conditioners contribute a disproportionately large percentage of peak electrical demand during hot summer months. If all residential air conditioners were as efficient as the best units on the market today, peak power demand would be reduced by approximately 60,000 MW, about 12 percent of national peak electric power demand in all sectors.

III. ECONOMIC FEASIBILITY

Highly efficient appliances generally cost more than models of average efficiency. Table II shows the estimated extra first cost for the top-rated models on the market in 1985 relative to models of average efficiency. The extra first cost does not necessarily reflect the increased production cost, but rather what a more efficient (and sometimes "deluxe" style) model can command in the marketplace.

In the case of the heat pump water heater, the first cost for the top-rated model is about four times greater than that for an ordinary electric resistance water heater. For highly efficient air conditioners, the first cost premium is about 50 – 100 percent over comparable average models. On the other hand, highly efficient refrigerators and freezers are only about 10 percent more expensive than their counterparts of average efficiency.

When viewed in terms of *life-cycle costs,* highly efficient appliances turn out to be big money savers for consumers since the reduced operating cost more than offsets the increased first cost. Table II shows the simple payback period and "internal rate of return" on the extra first cost assuming national average energy prices and demand conditions. The payback period ranges from 2.4 to 8.1 years and the internal rate of return ranges from 12 to 45 percent. These returns are greater than what a consumer could earn by investing in a bank account, money market fund, or the stock market. In addition, the returns are above inflation and are tax-free. Considered as an investment opportunity, efficient appliances and light bulbs are hard to beat.

IV. MARKET FAILURE

For a few products, there have been substantial improvements in the average efficiency of new models in the marketplace during the past decade. The refrigerator-freezer is a case in point (see Fig. 1). There have been less spectacular gains in the average efficiency of new air conditioners (10 – 30 percent in ten years). For water heaters, available national sales data reveal no evidence of efficiency improvement in the marketplace [3].

These trends are a consequence of a complicated set of factors including the availability, promotion, and acceptance of more efficient models, state regulations, and incentive programs for the purchase of efficient appliances. In any event, it is clear that the typical appliances manufactured and sold in this country are nowhere near to minimizing life-cycle cost.

Several factors lead to the production and purchase of rather inefficient appliances. First, a substantial proportion of appliances, particularly the largest energy-consuming products (furnaces, central air conditioners, and water heaters) are selected by builders, landlords, and contractors [1]. Since these so-called "third party purchasers" usually do not pay operating costs, they have little incentive to minimize the life-cycle cost of the appliances they buy.

A second problem is the absence of simple, trustworthy information to enable consumers to make wise decisions about appliances. The yellow energy guide labels displayed on models in stores are helpful, but are not enough; they do not indicate life-cycle costs and they are not available for all product types. The labels are of limited value unless consumers engage in comparative shopping and consider the trade-offs between higher first cost and lower operating cost. In addition, it may not be easy to identify highly efficient models or find one in a particular geographic area, and dealers may not be helpful when it comes to energy efficiency.

Third, when a refrigerator, water heater, or other appliance breaks down, the tendency among many consumers is to view the purchase as a replacement like any household repair — to be done quickly and with minimum expenditure. Moreover, non-energy related factors such as appearance, durability, brand name, and dealer recommendation may be paramount in the purchase decision [1]. For these and other reasons, a study by the National Academy of Sciences concluded "to view energy users as only investors leads to an inaccurate account of individual behavior, even with respect to capital goods" [18].

Finally, some people move relatively frequently and hold appliances for only a fraction of their useful life. They may not be able to recover the extra first costs for efficient appliances when they sell their houses. Those expecting to hold an appliance temporarily are likely to

TABLE II
COST EFFECTIVENESS OF SOME HIGHLY EFFICIENT APPLIANCES AND LIGHT BULBS IN THE U.S. (A)

Model	Increased first cost (b) (1985 $)	Annual electr. savings (kWh/yr)	Simple payback period (yrs)	Internal rate of return (%/yr)
Whirlpool ET17HK1M refrigerator/freezer	60	330	2.4	45
DEC International heat pump water heater	1200	2500 (c)	6.3	15
Lenox HS-14 Power Saver central air conditioner	1000	2100 (c)	6.3	14
Friedrich SM10G10 room air conditioner	130	210 (c)	8.1	12
Philips SL18 compact fluorescent lamp (d)	18	57	4.0	24
Panasonic 17 W fluorescent lamp (e)	10	43	3.0	34

(a) Based on a first year electricity price of $0.076/KWh and a 2%/yr real electricity price escalation rate. The first year electricity price was the national average in 1984 and the escalation rate is based on utility industry forecasts.
(b) The cost difference is relative to a model of standard efficiency made by the same manufacturer. Cost data were obtained from dealers and contractors in the Washington D.C. area.
(c) For air conditioning and hot water heating, the estimated use in a typical U.S. household is assumed.
(d) It is asusmed that this 18 watt fluorescent bulb replaces a 75 watt incandescent bulb and is used for about 2.7 hours/day.
(e) It is assumed that this 17 watt fluorescent bulb replaces a 60 watt long-life incandescent bulb and is used for about 2.7 hours/day.

minimize first cost, even though the payback on an efficient appliance is very rapid in some cases (see TABLE II).

V. MINIMUM EFFICIENCY STANDARDS: A REGULATORY APPROACH

Given the enormous energy and cost savings opportunities and the barriers to achieving them in the unregulated marketplace, it is reasonable for states or the federal government to impose appliance efficiency standards. By barring the sale of models that fail to achieve some minimum level of efficiency, standards eliminate the worst models and overcome the problem of third party purchases. If standards are set at a very stringent level with manufacturers given sufficient time to upgrade their product offerings, standards could stimulate product development and innovation.

The U.S. Congress first provided federal energy officials with the authority to set minimum efficiency standards for appliances in 1975. The National Energy Conservation Policy Act of 1978 went further and required the U.S. Department of Energy (DOE) to establish standards that would bar the sale of models that fail to achieve the maximum level of efficiency technically achievable and economically justified [19].

Federal standards were nearly completed for eight major appliances when the Carter Administration left office in January 1981. The Reagan Administration, under pressure from some appliance manufacturers, postponed promulgation of standards beyond legal deadlines. Most manufacturers oppose national standards, although a few manufacturers such as Carrier and Amana are supportive.

Forced by lawsuits to take some form of action, DOE came up with a "no standards" proposal, concluding that minimum efficiency standards were not justified for any product on the basis of insignificant savings, adverse impacts on manufacturers, and other factors [20]. This proposal was put forward in spite of DOE's own analysis showing that even very modest standards could reduce residential energy demand by over six percent and save consumers $10 – 16 billion by 2005 [21]. A final "no standards" regulation went into effect in August, 1983.

In order to avoid a patchwork of state standards, federal standards preempt state standards under the 1978 law. By issuing "no standards," the federal government overturns state standards unless a waiver is granted. Ironically, a law that was meant to stimulate energy conservation could have exactly the opposite effect.

But the story is not over yet. DOE's "no standards" ruling was challenged in the U.S. Court of Appeals by the Natural Resources Defense Council, Consumers Union, then Congressman Richard Ottinger of New York, and several states. In July 1985, the Court of Appeals strongly rejected DOE's no standards ruling, calling it "unsupported by substantial evidence" and "contrary to law" [22].

Assuming that the Appeals Court decision is not overturned by the Supreme Court (reversal is an unlikely event because the decision was unanimous and establishes no new legal principles), states can proceed with their own appliance standards until new federal standards are completed. DOE is required to reexamine and reissue federal standards with new conditions that make it very difficult for them to circumvent the law again. However, a new ruling on national appliance standards is not required before 1988.

State officials, frustrated by the failure of the federal government to enact meaningful appliance standards, are increasingly moving forward on their own. California first adopted comprehensive appliance standards in 1976. These standards are considered the most effective conservation program in the state, having cumulatively saved over 1000 MW of peak demand since 1977 [23].

California substantially upgraded its standards on refrigerators, freezers, air conditioners and heat pumps in 1984 – 85. The new refrigerator and freezer standards are particularly ambitious, requiring efficiencies by the early 1990s that are greater than those of appliances now widely available in the U.S. [24].

Maine adopted comprehensive minimum efficiency standards in 1985. They are less aggressive than California's new standards, but they do ban the sale of "energy guzzling" products. New York recently strengthened its minimum standards for air conditioners and heat pumps. Numerous other states are considering new appliance standards as well [25].

VI. UTILITY REBATES: AN INCENTIVES APPROACH

In the absence of federal standards or widespread state standards, many utilities offer incentives to their customers to promote the purchase of more efficient appliances. Utility incentive programs primarily involve rebate payments to those who buy qualifying models; in a few cases low interest loans are offered. Utility incentive programs have proliferated very rapidly — a survey conducted in 1983 showed that incentive programs are reaching up to 60 percent of all households in the country [26].

Air conditioners and heat pumps are the most commonly covered products in utility rebate programs, although a few utilities provide rebates for more efficient refrigerators, freezers, and water heaters also [26]. Qualification levels and rebate payments vary from program to program. In some cases, fixed rebates are given for any model that qualifies; in other cases the payment depends on the efficiency of the unit. The latter "sliding scale" approach rewards the purchaser for the amount of energy and/or peak demand saved and serves as an incentive for the production and purchase of very efficient models. It is preferred by manufacturers; however, some utilities prefer fixed rebates due to their simplicity [27].

There have been relatively few rigorous evaluations of utility rebate programs. Unfortunately, many utilities perform crude program evaluations without quantitative data or with flawed assumptions (e.g., assuming there would be no purchase of highly efficient products in the absence of rebates) [27].

Northern States Power (NSP) in Minnesota extensively studied their pilot appliance rebate programs taking into account the incremental number of purchases of high efficiency models after the rebates began [28]. NSP found that rebates for some products (e.g. air conditioners) were cost-effective for the utility while rebates for other products (e.g. water heaters) were not. NSP also found that many appliance purchasers eligible for rebates did not apply, and that getting appliance dealers to stock and promote qualifying models is critical to program success [28].

Utilities are generally pleased with their rebate programs and plan to expand them [26]. This is understandable since utilities estimate they are typically paying $100 – 300 per KW of reduced peak demand and that on the order of 50 percent of sales are qualifying for rebates in some cases [27]. However, it is likely that further program experimentation and evaluation could increase the energy savings and cost-effectiveness of utility incentive programs.

VII. WHERE DO WE GO FROM HERE?

A national strategy which promotes energy-efficient appliance technologies is in the best interests of everyone: appliance users, who benefit from lower energy bills; ratepayers, who won't have to shoulder the costs of additional power plants needed to run inefficient appliances; utilities, who avoid having to build costly and risky new generating plants; and appliance manufacturers, who benefit from a more certain marketplace and uniform national standards. Such a strategy should, at a minimum, contain the following four elements: (1) increased support for R&D; (2) better consumer information on appliance efficiency; (3) expanded and improved utility rebate programs; and (4) the adoption of meaningful federal appliance efficiency standards.

In the past, research funded by DOE and other organizations has directly led to the development and commericalization of innovative, highly efficient appliances. Further R&D should be supported by government institutions since technological and economical opportunities still abound [11]. Some examples include smart controls for appliances (e.g., controls that defrost R/Fs and freezers when needed), advanced insulating materials for R/Fs and freezers, variable-speed drives for air conditioners and heat pumps, microwave and heat pump clothes dryers, and "integrated appliances" that perform multiple functions such as refrigeration and water heating. Given the constraints of the marketplace, this work might not be carried out without partial public support.

Accurate and easily understood operating cost information is essential for appliance purchasers who are interested in buying on the basis of life-cyle cost. It would be helpful to require efficiency and operating cost labels on all major products, conduct an educational campaign in conjunction with the labeling program, and provide life-cyle cost estimates or simple methods for computing life-cycle costs to purchasers.

Early experience with utility rebate programs appears to be positive. These programs should be expanded and viewed as a "first resort" power planning option throughout the nation. At the same time, it is likely that utility incentive programs could be improved through increased research and evalution. There is a need to test different rebate levels and program designs, collecting "before and after" sales data in order to accurately assess program impacts. Also, rebate programs targeted at parties other than consumers (e.g., builders, landlords, or appliance dealers) might prove useful.

The adoption of federal appliance efficiency standards can ensure that manufacturers and purchasers move closer to cost-effective efficiency levels. Federal standards are preferred to state standardsd, since the latter are piecemeal and possibly inconsistent. The recent Court of Appeals decision should finally lead to national standards after many years of delay. In the mean time, stepped up action on the part of states should help convince policymakers and manufacturers that uniform federal standards are preferable.

The different policy options outlined here serve different but complementary objectives. Government-supported R&D helps bring advanced technologies to the marketplace; better information and consumer education raise awareness among purchasers; standards remove "energy guzzling" appliances from the market; and utility rebates stimulate the purchase of highly efficient models. A comprehensive national strategy for energy efficient appliances should include all of these options.

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