Opportunities for Improving the Energy-Efficiency of Window-Type Room Air Conditioners

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As required by the National Appliance Energy Conservation Act (NAECA), minimum energy efficiency standards ranging from 8.0 to 9.0 EER went into effect for window-type room air conditioners on January 1, 1990. But by incorporating commonly used technologies such as high-efficiency rotary compressors, grooved refrigerant tubing, slit-type fins, subcoolers, and permanent split capacitor fan motors, 10.0 EER efficiency levels can be achieved for the most popular classes of room air conditioners without having to increase chassis size. Even greater efficiency increases can be realized with brushless permanent magnet fan motors, enlarged heat exchanger coils, and variable speed compressors. Efficiency increases were estimated through the use of a calibrated computer simulation model. To assess the cost-effectiveness of the above design options, their impact on manufacturing cost was estimated with data supplied by both room air conditioner manufacturers and component suppliers. New minimum efficiency standards set at levels requiring approximately a 10.0 EER for the most popular classes would result in the following projected benefits: (1) national energy savings of 0.69 Quads over the period 1999–2030, (2) SO_2, NO_x, and CO_2 emission reductions of 111 kt, 104 kt, and 57 Mt, respectively, over the period 1999–2030, and (3) peak demand savings of 2.17 GW by the year 2025. For the consumer, a ‘‘10.0 EER’’ minimum standard yields the lowest life-cycle cost and the corresponding payback period is no greater than six years for the most popular classes.

INTRODUCTION

A room air conditioner is an encased assembly designed as a unit to be mounted in a window or through a wall. It is designed primarily to provide cooled and dehumidified air to an enclosed space, room, or zone. Some window units provide space heating in addition to space cooling. Heat is provided by heat pump operation, electric resistance elements, or by a combination of both.

A room air conditioner consists of refrigerant-side and air-side components all contained within a single cabinet. For cooling-only units, the refrigerant-side components are the evaporator (indoor conditioning coil), the compressor, the condenser (outdoor coil), and the capillary tube. These components are all connected via refrigerant tubing. The air-side components consist of the fan motor, the evaporator fan, and condenser fan. One fan motor is used to drive both fans. The cabinet, which contains these components, is split into an indoor and outdoor side. The two sides are separated by a divider wall, which is usually insulated. The insulation reduces heat transfer between the two sides. The indoor components are the evaporator and evaporator fan. The outdoor components are the compressor, condenser, capillary tube, fan motor, and condenser fan.

Background

The present test procedure for rating room air conditioners is a steady-state test which establishes an energy-efficiency ratio (EER) for the unit being tested (U.S. Office of the Federal Register 1995a). The EER is obtained by dividing the measured cooling capacity of the unit (Btu/hr) by its total electrical input (Watts). The outdoor ambient temperature during the test is maintained at 95° F. A seasonal rating procedure has not been adopted for room air conditioners because cycling effects (where the unit turns off and on to meet temperature set point) are believed to be small. When room units are turned on, the room temperature is likely to be high, thus reducing the amount of cycling as compared to central air-conditioning systems.

The National Appliance Energy Conservation Act (NAECA) establishes minimum efficiency standards for 12 product classes of room air conditioners (NAECA 1987). These 12 product classes apply to units that are designed to be installed in single- or double-hung windows and are defined according to the following criteria: (1) cooling capacity, (2) whether the outside portion of the cabinet has louvered sides (louvered sides are stamped on the outdoor portion of the cabinet allowing for better airflow over the outside condenser coil and, thus, improving system performance), and (3) whether a reversing valve is present (i.e., whether the unit operates as a heat pump). In the Department of Energy’s (DOE) Notice of Proposed Rulemaking (NOPR) for room air conditioners (U.S. Office of the Federal Register 1994), two additional classes were established for units that are designed to be installed in casement-slider and casement-only windows. Table 1 provides a list of the 14 product classes with their accompanying existing minimum efficiency standards.

***Table 1.** Room Air Conditioner Product Classes and Existing Minimum Efficiency Standards*

Product Class	EER (Btu/W·hr)
Without Reverse Cycle and with Louvered Sides	
Less than 6000 Btu/hr	8.0
6000 to 7999 Btu/hr	8.5
8000 to 13,999 Btu/hr	9.0
14,000 to 19,999 Btu/hr	8.8
20,000 Btu/hr and over	8.2
Without Reverse Cycle and without Louvered Sides	
Less than 6000 Btu/hr	8.0
6000 to 7999 Btu/hr	8.5
8000 to 13,999 Btu/hr	8.5
14,000 to 19,999 Btu/hr	8.5
20,000 Btu/hr and over	8.2
With Rev. Cyc., with Louv. Sides	8.5
With Rev. Cyc., without Louv. Sides	8.0
Casement-Only	NA
Casement-Slider	NA

Source: NAECA 1987.

In DOE's NOPR, new minimum efficiency standards were proposed for the 12 product classes established by NAECA (no standards were proposed for the casement-only and casement-slider classes). The proposed standards were based on a technical analysis conducted by DOE's contractor, Lawrence Berkeley National Laboratory (LBNL). DOE received extensive comments, primarily from the room air conditioner industry, regarding the proposed standards and the technical analysis which they were based upon. A reanalysis was conducted incorporating these comments resulting in revised estimates of the efficiency increases possible in room air conditioners (U.S. DOE 1996a; U.S. DOE 1996b).

Scope

This paper summarizes the reanalysis for the four most popular classes of room air conditioners (i.e., the classes without reverse cycle, with louvered sides, and with capacities below 20,000 Btu/hr). These four classes comprised over 90% of room air conditioner shipments in 1993 (AHAM 1993). Thus, the technical data presented in this paper represent an overwhelming majority of the room air conditioners shipped in the United States. The technical data presented for the four most popular classes includes (1) manufacturer cost, (2) efficiency, (3) life-cycle cost, and (4) payback period. In addition, national energy savings, air-borne emission reductions, and electric utility peak demand savings resulting from the implementation of the most cost-effective energy efficiency levels for all room air conditioner product classes are presented.

METHODOLOGY

The first step in assessing efficiency improvements for room air conditioners is to identify the possible design options for improving efficiency. Next, baseline models for each product class (models with efficiencies close to the existing minimum efficiency standard) are identified and characterized for the purpose of determining which design options can be applied to them to improve their efficiency. Manufacturer cost data obtained through surveys of room air conditioner manufacturers and component suppliers are used to determine the cost impacts of increasing system efficiency. A simulation model (validated with manufacturer test data) estimates the efficiency increases associated with each design option. The design options applied to each baseline model are ordered based on simple payback period. Once the manufacturer cost and efficiency data are assembled for each baseline model, life-cycle costs are determined. From this, forecasts of national energy savings, reduced air-borne emissions, and utility peak demand savings are made.

Design Options

Several design options were analyzed for the purpose of establishing what efficiency increases were possible in room air conditioners. Methods for improving the efficiency of room air conditioners are identified in the following discussion.

Heat Exchanger Improvements. All U.S. room air conditioner manufacturers produce their heat exchangers ''in-house''. The research and development of new heat exchanger improvements are usually conducted ''in-house'' as well. Methods for improving the performance of the heat exchanger coils include the following: (1) increasing the frontal coil area, (2) increasing the depth of the coil (adding tube rows), (3) increasing the fin density, (4) improving the fin design, (5) improving the tube design, (6) adding a subcooler (for the condenser coil only), and (7) spraying condensate onto the condenser coil.

Increase Frontal Coil Area and Increase Tube Rows. Increasing the total evaporator or condenser coil surface area by adding tube rows or increasing the frontal area is limited by the chassis in which the room air unit is constructed. A larger chassis is typically required to accommodate a larger face area or more tube rows as the coils usually have been maximized for the greatest face area and depth. Units with the highest efficiency (12.0 EER) have relatively large coils for their capacity size. All 12.0 EER units have relatively low cooling capacities (8800 to 10,500 Btu/hr). Since manufacturers produce three to four standard chassis sizes, the 12.0 EER units are usually the smallest capacity model to be installed in a particular chassis size. Thus, their high efficiency is due in large part to the higher ''coil size-to-capacity'' ratio.

Increase Fin Density. Increasing the fin density is another option for increasing the total surface area. But most coil designs already have the maximum fins per inch allowable. Any further increases might lead to premature coil degradation as dirt particles could more easily lodge between the tightly packed fins.

Improve Fin and Tube Design. Heat exchanger coils in U.S. room air conditioners are made of aluminum fins and copper refrigerant tubing. Most, if not all, high efficiency room air conditioner models (EERs of at least 10.0) use slit-type fins and grooved tubing. The slit-type fin surface usually consists of small strips raised from the base plate fin surface. These surfaces increase the air turbulence over the coil and, thus, increase the air-side heat transfer coefficient. Slit-type fins yield better results than wavy or corrugated fin designs (Nakayama & Xu 1983; Webb 1990; Beecher & Fagan 1987). Each room air conditioner manufacturer has developed a unique fin design to achieve the desired heat transfer improvement. Grooved refrigerant tubing (also referred to as rifled tubing) has its interior surface augmented with spiral grooves. The added surface area created by the grooves improves the refrigerant-side heat transfer coefficient (Schlager et al. 1990).

Add Subcooler to Condenser Coil. Few room air conditioners incorporate subcoolers. Most manufacturers attempt to get the amount of subcooling desired through redesign of the condenser before trying to incorporate one. Typically, subcoolers are added between the condenser outlet and the capillary tube inlet and are submerged near the condenser in the condensate produced by the evaporator. The effect of adding a subcooler is to increase the size of the condenser coil as it further cools the refrigerant coming out of the condenser.

Spraying Condensate onto Condenser Coil. All U.S. manufactured room air conditioners collect the condensate dripping off the evaporator coil and spray it onto the condenser coil. The spray improves the air-side heat transfer coefficient of the condenser (Tree et al. 1978).

Improve Compressor Efficiency. All U.S. room air conditioner manufacturers purchase their compressors from compressor manufacturers. Most manufacturers incorporate rotary compressors into their units. Although current maximum rotary compressor efficiencies range from 10.7 to 11.1 EER, at least one compressor manufacturer planned to develop rotary compressors with efficiencies of 12.0 EER by the year 1994 (Sanyo 1990). These development plans were canceled due to the difficulty of developing materials for a more efficient compressor motor. Although most rotary compressor manufacturers anticipate developments that will be able to yield compressor efficiencies of 11.1 to 11.3 EER, they state that this will require the development of high-efficiency motors, use of higher-grade materials in the rotary compressor mechanism, and new compressor production methods and equipment. Large capacity room air conditioners can use high-efficiency scroll and reciprocating compressors. Scroll compressors are available with efficiencies exceeding 11.0 EER while a technology developed by Bristol Compressors allows reciprocating compressor efficiencies to approach 12.0 EER (Duffy 1991). But since both scroll and reciprocating compressors are significantly larger and heavier than rotary compressors, room air conditioner manufacturers would incur significant application costs to incorporate these compressors into their current designs.

Improve Fan and Fan Motor Efficiency. Most efficiency improvement measures to the air delivery system are aimed at increasing the fan motor efficiency. Most U.S. room air conditioner manufacturers use permanent split capacitor (PSC) fan motors. PSC motors range in efficiency from 55 to 70%. Only a few room air models still use the low efficiency shaded pole motor (30 to 40% efficiency). The brushless permanent magnet motor (efficiency exceeding 70%) is presently much too expensive to be used in room air conditioners. Most fan motors are purchased from U.S. motor manufacturers.

Variable Speed Systems. Since cycling effects are small, designs which improve efficiency on a seasonal basis are probably not effective for room air conditioners. Variable speed systems (using both variable speed compressors and fan motors), thermostatic and electronic expansion valves, and thermostatic controls are all designs that improve the seasonal efficiency of central air conditioning systems. Variable speed systems reduce the energy consumption of central systems by as much as 40% (depending on climate location) (Henderson 1990; Bahel & Zubair 1989, Hori et al. 1985). Because some cycling probably occurs in room units, variable speed systems could very likely reduce their energy consumption.

Alternative Refrigerants. The refrigerant that is used in all room air conditioners is R-22. But because it is a hydrochloroflurocarbon (HCFC) and demonstrates ozone depletion potential (ODP), the Environmental Protection Agency (EPA) has banned its production and use by January 1, 2020 (U.S. Office of the Federal Register 1993). As a result, much research has been conducted by the air conditioning industry to find suitable replacements. Two alternatives have shown promise; (1) R-407C, a ternary blend of HFC-32/HFC-125/HFC-134a with composition of 23/25/52% by weight and (2) R-410A, an azeotrope of HFC-32/HFC-125 with composition of 50/50% by weight. But both have demonstrated short comings when compared to R-22. Systems with R-407C yield efficiencies that are approximately 5% less than those charged with R-22, while R-410A exhibits significantly higher compressor discharge pressures (Godwin 1994). Because of these problems, the analysis described here is based only on the use of R-22.

Surveys

In order to gather manufacturer cost data for the previously discussed design options, surveys of room air conditioner manufacturers and component suppliers were conducted. The surveys to manufacturers were conducted through their trade association (Association of Home Appliance Manufacturers (AHAM)). Surveys were also used to collect engineering data on baseline (minimum efficiency) units. This engineering data described the physical make-up and performance of the baseline units and was used to validate the performance of a computer simulation model. Once validated, the simulation model was used to estimate the efficiency improvements that result from incorporating design options into baseline units.

Baseline Models. For each of the four most popular product classes, manufacturers provided a wealth of baseline unit data. Data were provided that described the physical characteristics of the baseline unit (e.g., coil size and compressor efficiency) as well as how it performed under DOE test procedure conditions. In consultation with AHAM, an actual baseline unit was selected for each class to be representative of most baseline units for that class. Baseline units were selected based on two criteria; the cooling capacity had to be representative of a majority of units in the class and the efficiency had to be close to the minimum allowed under NAECA effective in 1990. Table 2 lists some of the characteristics of the baseline units chosen for each of the four product classes.

Design Option Cost Data. Most of the cost data used in the analysis were provided by AHAM in response to DOE's proposed rulemaking for room air conditioners (AHAM 1994, 6–13). This data was an updated version of what AHAM had originally provided to LBNL for its technical analysis in support of DOE's proposed rulemaking. Only the cost data on improved reciprocating compressors were not provided by AHAM (Duncan 1994).

Simulation Model

Simulations were carried out using a modified version of the Oak Ridge Heat Pump Design Model, Mark III version (Fischer & Rice 1983; Fischer, Rice & Jackson 1988). The Oak Ridge Model is a comprehensive program for the simulation of an electrically driven, air-source heat pump. It is

Table 2. *Baseline Unit Characteristics*

	Product Class			
	Less than 6000	6000 to 7999	8000 to 13,999	14,000 to 19,999
EER (Btu/W·hr)	8.20	8.45	9.30	9.00
Capacity (Btu/hr)	5850	7480	12,155	17,965
Evaporator				
Area (sq.ft.)	0.87	0.87	1.06	1.56
Fin Design	Wavy	Wavy	Slit	Louver
Tube Design	Smooth	Smooth	Smooth	Groove
Condenser				
Area (sq.ft.)	1.68	1.68	1.81	2.54
Fin Design	Wavy	Wavy	Slit	Louver
Tube Design	Smooth	Smooth	Smooth	Groove
Compressor				
EER (Btu/W·hr)	10.8	10.9	10.3	10.61
Cap. (Btu/hr)	6670	8100	12,780	29,400

Source: U.S. DOE 1996a, 1-28.

Table 3. *Baseline Units: Test Data vs. Simulation Model Results*

Product Class		EER (Btu/W·hr)	Capacity (Btu/hr)	Comp Power (Watts)
Less than 6000	Test	8.20	5850	585
	Model	8.23	5852	586
	% Diff	0.4%	0.2%	0.2%
6000 to 7999	Test	8.45	7480	753
	Model	8.46	7481	753
	% Diff	0.1%	0.0%	0.0%
8000 to 13,999	Test	9.30	12,155	1128
	Model	9.32	12,153	1128
	% Diff	0.2%	0.0%	0.0%
14,000 to 19,999	Test	9.00	17,965	1698
	Model	9.00	17,966	1699
	% Diff	0.0%	0.0%	0.1%

Source: U.S. DOE 1996a, 1-33.

a steady-state model that is able to calculate the EER of the equipment being modeled at specified ambient conditions. Modifications were made to the simulation model in order to simulate the performance of room air conditioners (O'Neal & Penson 1988). These modifications included the following: (1) addition of routines to model subcoolers and condensate spray, (2) elimination of the reversing valve model, (3) modification of the capillary tube model, and (4) addition of adjustment factors to model grooved tubing.

Several additional modifications were made to the modified Oak Ridge Model based on comments provided by AHAM. AHAM's comments were based on (1) their review of the simulation model (AHAM 1990, 2–3) and (2) their review of simulation results produced in support of DOE's NOPR (AHAM 1994, 2–6). The most substantive changes involved modifications to the compressor subroutine and the addition of correction factors to assist in calibrating the model to test data (DOE 1996a).

Calibration Results. For each representative baseline unit chosen for each class, correction factors to adjust the calculated compressor power and refrigerant mass flow rate were used to match the predicted performance of the room air conditioner to that indicated by manufacturer supplied test data. In addition to the above correction factors, the length and/or the diameter of the capillary tube and the compressor shell heat loss were also adjusted to calibrate the model. Calibrations were conducted on the basis of matching the following ''primary'' quantities: (1) EER, (2) capacity, and (3) compressor power. Other ''secondary'' quantities (e.g., system refrigerant temperatures) were also considered in the calibrations, although the main objective was to achieve relatively small differences between the measured and simulated results for only the ''primary'' quantities.

For only the ''primary'' quantities, Table 3 presents a comparison between the manufacturers' test data and the data predicted from the simulation model for the four most popular product classes. Included in the comparison is the percentage difference between the two sets of values. After making all the necessary corrections and adjustments to the input files, both EER and capacity for all capacity classes were predicted to within 0.5% of values determined from test measurements.

Energy Consumption

In order to determine the payback period and life-cycle cost of the various design options analyzed, it is necessary to determine their annual energy consumption. The DOE test procedure provides the following expression to determine a room air conditioner's annual energy consumption (U.S. Office of the Federal Register 1995b).

$$\mathrm{UEC} = \frac{\mathrm{Capacity}}{\mathrm{EER}} \bullet \mathrm{Hours} \bullet 0.001$$

where *UEC* = unit energy consumption (kWh/year)
Capacity = cooling capacity (Btu/hr)
EER = energy efficiency ratio (Btu/hr/Watt)
Hours = hours of compressor operation (750 hours/year)
0.001 = conversion factor (kW/W)

Recent field data indicate that the annual energy consumption of room air conditioners is significantly lower than that determined with DOE test procedure calculations based on an annual hours of operation of 750. (The value of 750 hours is the accepted national average for the annual hours of operation of a room air conditioner. It comes from an analysis AHAM performed to establish its value (AHAM 1982).) Field-based energy consumption data is shown to be approximately 71% of test procedure-based values (U.S. DOE 1996a, 1–36). This comparison implies that the annual hours of operation of room air conditioners have decreased by 71% from 750 hours to 533 hours. Thus, field-based energy

Table 4. *Less than 6,000 Btu/hr: Baseline and Design Option Analysis Data*

No.	Design Options	EER[a] (Btu/W·hr)	Mfg Cost	Retail Price	UEC Field[b] (kWh/yr)	PBP[c] (years)	LLC[d] @ 6%
0	Baseline	8.2	$179	$372	379	NA	$612
1	0 + Evap. & Cond. Slit-type Fins	8.7	$180	$373	358	0.4	$600
2	1 + PSC Fan Motor (50% efficiency)	9.3	$183	$378	334	1.7	$589
3	2 + Evap. & Cond. Grooved Tubes	9.7	$186	$383	321	2.5	$586
4	3 + Add Subcooler	10.0	$190	$390	312	3.6	$587
5	4 + Increase Evap. & Cond. Coil Area[e]	10.4	$217	$440	300	11.9	$630
6	5 + BPM Fan Motor (70% efficiency)	10.6	$277	$560	295	30.6	$747
7	6 + Variable-Speed Compressor	11.7	$401	$796	265	51.0	$964

Source: U.S. DOE 1996a, 1–37, 4–3.

Note: All dollar values in 1990$. Electricity price = 0.0735 $/kWh. Lifetime = 12.5 years.

[a] Design options with variable-speed compressors are rated with an SEER.

[b] Unit Energy Consumption is a field-based value.

[c] Payback Period determined with field-based energy consumption.

[d] Life-Cycle Cost determined with field-based energy consumption. Evaluated at a 6% discount rate.

[e] Evaporator face area increased from 0.87 to 1.13 ft^2. Condenser face area increased from 1.68 to 2.06 ft^2.

consumption values are determined by multiplying the DOE test procedure-based values by 71%.

RESULTS

Cost and Efficiency

Efficiency, energy consumption, manufacturer cost, retail price, payback period, and life-cycle cost data are presented for the four most popular room air conditioner product classes in Tables 4 through 7. Each of these results are discussed below.

Efficiency Results. With the exception of the variable-speed compressor design option, simulation modeling was used to determine the cooling capacity and efficiency of the baseline design and each design option. Simulated efficiency estimates for subcoolers were calibrated to test results provided by AHAM (AHAM 1994, 6). Efficiency estimates for the variable-speed compressors were based on a 10% reduction in energy use. Estimates of the cooling capacity can be found elsewhere (U.S. DOE 1996a, 1–37 to 1–40).

Energy Consumption Results. Only field-based energy consumption data are provided. Because the field-based energy data are based on information that is more recent than the energy consumption calculations used in the DOE test procedure, it is believed that the field-based data are more representative of actual room air conditioner energy consumption. Details on how the DOE-based energy consumption is determined for each design option can be found elsewhere (U.S. DOE 1996a, 1–34). As stated earlier, the field-based energy consumption is 71% of the DOE test procedure value. To determine the annual energy expense, the field-based energy consumption is multiplied by the electricity rate.

Manufacturer Cost and Retail Price Results. As stated earlier, manufacturer cost data were based on estimates provided by manufacturers and component suppliers. The Lawrence Berkeley Laboratory Manufacturer Analysis Model (LBL-MAM) was used to generate the retail price data. Based on its demand function, LBL-MAM calculates retail price based on, among other things, consumer purchase price elasticities, manufacturer cost, and annual energy expense. Energy expense is based on the field-based energy

Table 5. *6000 to 7999 Btu/hr: Baseline and Design Option Analysis Data*

No.	Design Options	EER[a] (Btu/W·hr)	Mfg Cost	Retail Price	UEC Field[b] (kWh/yr)	PBP[c] (years)	LLC[d] @ 6%
0	Baseline	8.5	\$199	\$404	471	NA	\$702
1	0 + Evap. & Cond. Slit-type Fins	8.8	\$200	\$405	453	1.1	\$692
2	1 + PSC Fan Motor (50% efficiency)	9.4	\$203	\$410	425	1.9	\$679
3	2 + Add Subcooler	9.7	\$207	\$417	412	3.0	\$678
4	3 + Evap. & Cond. Grooved Tubes	9.9	\$211	\$425	402	4.1	\$679
5	4 + Increase Evap. & Cond. Coil Area[e]	10.3	\$241	\$478	386	11.8	\$722
6	5 + BPM Fan Motor (70% efficiency)	10.5	\$302	\$599	379	28.9	\$839
7	6 + Variable-Speed Compressor	11.7	\$427	\$830	341	44.8	\$1,047

Source: U.S. DOE 1996a, 1–38, 4–4.

Note: All dollar values in 1990\$. Electricity price = 0.0735 \$/kWh. Lifetime = 12.5 years.

[a] Design options with variable-speed compressors are rated with an SEER.

[b] Unit Energy Consumption is a field-based value.

[c] Payback Period determined with field-based energy consumption.

[d] Life-Cycle Cost determined with field-based energy consumption. Evaluated at a 6% discount rate.

[e] Evaporator face area increased from 0.87 to 1.13 ft^2. Condenser face area increased from 1.68 to 2.06 ft^2.

consumption data. A complete description of how LBL-MAM determines retail prices for for room air conditioners can be found elsewhere (U.S. DOE 1996a; U.S. DOE 1996b).

Payback Period Results. As stated earlier, the design options are ordered based on simple payback period (PBP). Numerically, the PBP is the ratio of the increase in retail price (from the baseline to the design option) to the decrease in annual operating expenditures. PBPs are expressed in years. A PBP of three years means that the increased purchase price is recovered in approximately three years because of lower operating expenses. PBPs greater than the life of the product mean that the increased retail price is not recovered in reduced operating expenses. For the four most popular classes of room air conditioners, PBPs of less than half the product lifetime occur at efficiencies of approximately 10.0 EER.

Life-Cycle Cost Results. The life-cycle cost (LCC) is the sum of the retail price (*RP*) and the present value of operating expenses (*OE*) discounted over the lifetime (*N*) of the appliance. If operating expenses are constant over time, the LCC simplifies to:

$$LCC = RP + PWF \bullet OE$$

where we have defined the present worth factor:

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

The LCC is calculated for each class in the year standards are imposed, using a discount rate, *r*. In Table 4 through 7, the LCC is calculated at a discount rate of 6%. For the four most popular classes of room air conditioners, minimum LCCs occur at efficiencies of approximately 10.0 EER.

National Energy Savings, Emission Reductions, and Peak Demand Savings

Table 8 summarizes the efficiencies in which national energy savings, air-borne emission reductions, and peak demand

Table 6. *8000 to 13,999 Btu/hr: Baseline and Design Option Analysis Data*

No.	Design Options	EER[a] (Btu/W·hr)	Mfg Cost	Retail Price	UEC Field[b] (kWh/yr)	PBP[c] (years)	LLC[d] @ 6%
0	Baseline	9.3	\$257	\$495	694	NA	\$935
1	0 + 10.8 EER Compressor	9.7	\$263	\$506	666	5.3	\$928
2	1 + Add Subcooler	9.9	\$265	\$510	657	5.4	\$926
3	2 + Evap. & Cond. Grooved Tubes	10.1	\$270	\$518	640	5.8	\$924
4	3 + Increase Evap. & Cond. Coil Area[e]	11.0	\$304	\$577	590	10.7	\$951
5	4 + BPM Fan Motor (80% efficiency)	11.2	\$368	\$697	580	24.1	\$1,065
6	5 + Variable-Speed Compressor	12.4	\$499	\$929	522	34.4	\$1,260

Source: U.S. DOE 1996a, 1–39, 4–6.
Note: All dollar values in 1990\$. Electricity price = 0.0735 \$/kWh. Lifetime = 12.5 years.
[a] Design options with variable-speed compressors are rated with an SEER.
[b] Unit Energy Consumption is a field-based value.
[c] Payback Period determined with field-based energy consumption.
[d] Life-Cycle Cost determined with field-based energy consumption. Evaluated at a 6% discount rate.
[e] Evaporator face area increased from 1.06 to 1.50 ft^2. Condenser face area increased from 1.72 to 2.38 ft^2.

savings were determined for. Savings and emissions data were based on the most cost-effective energy efficiency levels for all room air conditioner classes (not just the most popular classes). The most cost-effective levels selected were based on those efficiencies which yield the lowest (or close to the lowest) LCC and have a payback period that is at most half the lifetime of the product. The lifetime of room air conditioners are approximately 12.5 years (U.S. DOE 1996a, 2–1). For product classes other than the four most popular, the data that served as the basis for the selection of the most cost-effective efficiency levels can be found elsewhere (U.S. DOE 1996a, 4–3 to 4–24).

National Energy Savings. Room air conditioners comprise 0.34 Quads (or 2.0%) of the total 1990 residential source energy consumption (Turiel et al. 1995, 3). Table 9 provides the national energy savings that are achieved by implementing as minimum efficiency standards the most cost-effective efficiency levels for room conditioners. These new standards are assumed to become effective in the year 1999. Cumulative energy savings between the years 1999 and 2030 are projected to be 0.69 Quads. As evidenced by Table 9, both central air conditioner and heat pump national energy use are impacted by increased room air conditioner standards. Retail prices for room air conditioners at the cost-effective efficiency levels are high enough to cause some consumers to switch over from room air conditioners to purchase central air conditioners or heat pumps for their space cooling needs. Thus, the national energy use due to central space cooling systems increases. The Lawrence Berkeley Laboratory Residential Energy Model (LBL-REM) was used to forecast the national energy savings. LBL-REM provides projections of the important characteristics of the residential appliance market by utilizing a database of significant determinants of the current residential appliance market, as well as parameters characterizing market decisions that will affect the energy consumption of future appliances (McMahon 1987). A complete description of the LBL-REM analysis for room air conditioners can be found elsewhere (U.S. DOE 1996a; U.S. DOE 1996b).

Emission Reductions. As discussed above, the impact of implementing minimum efficiency standards for room air conditioners is to reduce electricity demand growth. The main environmental effects of power plants on air and water quality result from emissions of SO_2, NO_x, and CO_2. With new efficiency standards lessening the need for electricity generation, power plant emissions would be reduced. A sec-

***Table 7.** 14,000 to 19,999 Btu/hr: Baseline and Design Option Analysis Data*

No.	Design Options	EER[a] (Btu/W·hr)	Mfg Cost	Retail Price	UEC Field[b] (kWh/yr)	PBP[c] (years)	LLC[d] @ 6%
0	Baseline	9.0	$328	$613	1,063	NA	$1,286
1	0 + 10.8 EER Compressor	9.7	$339	$632	987	3.5	$1,258
2	1 + Condenser Grooved Tubes	10.0	$343	$640	959	3.5	$1,247
3	2 + Add Subcooler	10.2	$348	$648	943	4.0	$1,245
4	3 + Increase Evap. & Cond. Coil Area[e]	10.7	$445	$812	891	15.7	$1,376
5	4 + 11.3 EER Compressor	11.1	$477	$870	863	17.5	$1,417
6	5 + 11.4 EER Compressor	11.2	$492	$897	856	18.7	$1,440
7	6 + BPM Fan Motor (79% efficiency)	11.5	$571	$1,039	832	25.2	$1,566
8	7 + Variable-Speed Compressor	12.8	$718	$1,295	749	29.6	$1,769

Source: U.S. DOE 1996a, 1–40, 4–8.
Note: All dollar values in 1990$. Electricity price = 0.0735 $/kWh. Lifetime = 12.5 years.
[a] Design options with variable-speed compressors are rated with an SEER.
[b] Unit Energy Consumption is a field-based value.
[c] Payback Period determined with field-based energy consumption.
[d] Life-Cycle Cost determined with field-based energy consumption. Evaluated at a 6% discount rate.
[e] Evaporator face area increased from 1.56 to 2.04 ft^2. Condenser face area increased from 2.54 to 2.86 ft^2.

ond source of these emissions is fuel-burning household appliances. Table 10 provides the emission reductions resulting from the implementation of the most cost-effective room air conditioner efficiency levels as efficiency standards. Cumulative emission reductions for SO_2, NO_x, and CO_2 between the years 1999 and 2030 are 111 kt, 104 kt, and 57 Mt, respectively. The primary source for these reductions are reduced power plant emissions. A complete description of the environmental analysis for room air conditioners can be found elsewhere (U.S. DOE 1996a: U.S. DOE 1996b).

Peak Demand Savings. Table 11 shows peak load reductions for room air conditioners at the most cost-effective efficiency levels. The base case peak load presented in Table 12 represents coincident peak load of all such appliances in the residential sector. Through the implementation of cost-effective efficiency levels for room air conditioners, peak load savings of 2.17 GW can be realized by the year 2025. The electric utility impact modeling analysis that was used to determine the peak load savings adopts the standard utility convention that the value of electricity savings, commonly called avoided cost, can be broadly separated into energy or variable cost savings, and capacity or fixed cost savings. A complete description of the electric utility impact modeling analysis can be found elsewhere (U.S. DOE 1996a; U.S. DOE 1996b).

CONCLUSIONS

For the four most popular product classes of room air conditioners, representing over 90% of U.S. room air conditioner shipments, efficiency levels of approximately 10 EER can be achieved cost-effectively without requiring chassis enlargement. This is accomplished through the use of high-efficiency rotary compressors, PSC fan motors, slit fin/grooved tube heat exchangers, and subcoolers. When compared to current minimum efficiency designs, 10 EER designs have a lower life-cycle cost and a payback period that is no greater than half the lifetime of the appliance.

Table 8. *Cost-Effective Efficiency Levels*

Product Class	EER (Btu/W·hr)
Without Reverse Cycle and with Louvered Sides	
Less than 6000 Btu/hr	10.0
6000 to 7999 Btu/hr	9.9
8000 to 13,999 Btu/hr	10.1
14,000 to 19,999 Btu/hr	10.2
20,000 Btu/hr and over	8.5
Without Reverse Cycle and without Louvered Sides[a]	
6000 to 7999 Btu/hr	9.2
8000 to 13,999 Btu/hr	9.1
With Rev. Cyc., with Louv. Sides	9.3
With Rev. Cyc., without Louv. Sides	8.9

Source: DOE 1996a, 4-3 to 4-24.

[a] Units with capacities less than 6000 Btu/hr and greater than 13,999 Btu/hr are currently not available.

Table 9. *National Energy Savings due to Cost-Effective Efficiency Levels*

Year	Room A/C (Quads)	Central A/C (Quads)	Central HP (Quads)	Total (Quads)
1999	0.01	0.00	0.00	0.01
2015	0.03	0.00	0.00	0.03
2030	0.03	−0.01	0.00	0.03
Cumulative 1999–2030	0.79	−0.09	−0.02	0.69

Source: U.S. DOE 1996a, 3-3 to 3-5.

Table 10. *Air-Borne Emission Reductions due to Cost-Effective Efficiency Levels*

	SO_2		NO_x		CO_2	
Year	(kt)[a]	(%)[b]	(kt)[a]	(%)[b]	(Mt)[c]	(%)[b]
2000	1.43	0.04	1.11	0.04	0.44	0.04
2010	5.04	0.18	4.38	0.16	1.93	0.14
2020	3.51	0.17	3.51	0.16	2.08	0.14
2030	2.41	0.18	2.90	0.15	2.40	0.15
Cumulative 1999–2030	111	—	104	—	57	—

Source: U.S. DOE 1996a, 7-3 to 7-7.

[a] kt = thousand metric tons

[b] Reduction as percent of total residential emissions

[c] Mt = million metric tons

Table 11. *Peak Demand Savings due to Cost-Effective Efficiency Levels*

Year	Peak Load (GW)	Savings (GW)
2000	26.95	0.36
2005	28.97	1.08
2010	30.38	1.81
2015	32.40	1.88
2020	34.61	1.95
2025	36.49	2.17
2030	38.51	2.17

Source: U.S. DOE 1996a, 6-2, 6-3.

When included with cost-effective designs for all other room air conditioner product classes, implementation of these efficiency levels as new minimum energy-efficiency standards are projected to provide cumulative national energy savings of 0.69 Quads between the years 1999 to 2030. As a result of reduced electrical generation, air-borne emissions of SO_2, NO_x, and CO_2 between the years 1999 and 2030 are reduced by 111 kt, 104 kt, and 57 Mt, respectively. In addition, electric utility peak demand savings of 2.17 GW are projected by the year 2015.

ACKNOWLEDGMENTS

This work was supported by the Assistant Secretary of Conservation and Renewable Energy, Office of Codes and Standards of the United States Department of Energy under Contract No. DE-AC0377SF00098. Thanks also go out to C. Keith Rice, of Oak Ridge National Laboratory, and Dennis O'Neal, of Texas A&M University, for several helpful discussions regarding the simulation model. In addition, Association of Home Appliance Manufacturer consultant William Beard is acknowledged for his work as serving as an intermediary in providing manufacturer data and providing critical review of the simulation model.

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