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Optimal replacement of residential air conditioning equipment to minimize energy, greenhouse gas emissions, and consumer cost in the US

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ABSTRACT

A life cycle optimization of the replacement of residential central air conditioners (CACs) was conducted in order to identify replacement schedules that minimized three separate objectives: life cycle energy consumption, greenhouse gas (GHG) emissions, and consumer cost. The analysis was conducted for the time period of 1985–2025 for Ann Arbor, MI and San Antonio, TX. Using annual sales-weighted efficiencies of residential CAC equipment, the tradeoff between potential operational savings and the burdens of producing new, more efficient equipment was evaluated. The optimal replacement schedule for each objective was identified for each location and service scenario. In general, minimizing energy consumption required frequent replacement (4–12 replacements), minimizing GHG required fewer replacements (2–5 replacements), and minimizing cost required the fewest replacements (1–3 replacements) over the time horizon. Scenario analysis of different federal efficiency standards, regional standards, and Energy Star purchases were conducted to quantify each policy's impact. For example, a 16 SEER regional standard in Texas was shown to either reduce primary energy consumption 13%, GHGs emissions by 11%, or cost by 6–7% when performing optimal replacement of CACs from 2005 or before. The results also indicate that proper servicing should be a higher priority than optimal replacement to minimize environmental burdens.

1. Introduction

Space cooling currently accounts for about 13% of the residential sector's primary energy consumption and greenhouse gas (GHG) emissions (DOE, 2007). About 36% of central air conditioners (CACs) used in single family homes are at least one decade old (EIA, 2009b). Meanwhile, the typical CAC purchased today is rated to be about 25% more efficient than systems purchased 10 years ago (Skaer, 2007). There is an opportunity to reduce energy consumption and GHG emissions by replacing older air conditioning systems with new, more efficient systems. However, replacing equipment consumes energy and generates GHG from the production of new equipment. A life cycle framework that evaluates the production, use, and disposal of equipment is required to explore this tradeoff.

Federal minimum efficiency standards have helped to dramatically improve the efficiency of the average central air conditioner (CAC) sold. The first federal standard, which called for a Seasonal Energy Efficiency Ratio (SEER) of 10 (coefficient of performance $=10/3.412=2.93$) went into effect in 1992. The SEER metric represents the ratio of BTUs of cooling per watt-hour of electricity consumed for a typical American climate. Average energy efficiency of purchased CACs improved about 0.07 SEER per year while the 10 SEER standard was in effect as more consumers purchased higher efficiency units. In 2006, the 10 SEER standard was superseded by a 13 SEER standard. Following the implementation of this standard, about 5 out 6 CACs sold were minimum efficiency units (Skaer, 2007). For the purposes of the study, it is assumed that in the future the average sales weighted efficiency will continue to increase at the same rate as under the 10 SEER standard.

Since the average efficiency of air conditioning equipment increases over time, when the typical household replaces a CAC, it will be upgrading its system with more efficient equipment. Given the environmental tradeoff associated with upgrading, it is difficult for homeowners to know when to replace their CAC.

Previous research efforts related to the energy efficiency of air conditioning equipment have focused on impacts from the adoption or revision of minimum efficiency standards and the effectiveness of labeling programs. Studies have estimated energy, carbon dioxide, and cost savings for new and revised energy efficiency standards in the United States for a series of residential and commercial products including air conditioning equipment (Meyers et al., 2003; Rosenquist et al., 2006). Similar studies have been conducted internationally to evaluate the benefits of standards for air conditioning equipment in China (Lu, 2007) and

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Malaysia (Mahlia et al., 2001, 2004; Saidur et al., 2007). Other work has evaluated labeling programs that promote higher efficiency products. In the United States, research has explored the energy savings resulting from the Energy Star program (Webber et al., 2000; Sanchez et al., 2008).

These analyses assume that the service life of the new products remains the same and that existing products are replaced at the end of their typical service life. Thus, the replacement interval is assumed to be independent of efficiency trends and policy. Furthermore, these studies have focused on the energy, GHG, and cost savings from the operation of such equipment. They do not consider the larger system impacts such as the energy penalty to manufacture more efficient equipment.

A life cycle optimization framework can provide guidance about when products like CACs should replace equipment in order to minimize environmental or economic costs (Kim et al., 2003, 2006; Bole, 2006). This study determines when the typical homeowner should replace CAC equipment in order to minimize life cycle: (1) energy consumption, (2) GHG emissions, and (3) consumer cost. Objectives were examined separately, and thus separate replacement schedules were developed.

This topic is of interest to both homeowners as well as the policy makers exploring programs to accelerate replacement of relatively inefficient product stock.

2. Scope

This study considered the environmental and economic burdens associated with a typical CAC used to provide space cooling to a single family home. This research considers electrically powered, forced air, split system CACs utilizing vapor-compression refrigeration with a cooling capacity of 3 tons (10.6 kW). The indoor unit (consisting mainly of an evaporator coil), the outdoor unit (consisting mainly of the compressor and condenser coils), and the refrigerant lines were modeled. Energy consumed by the blower motor was included, but the burden of producing the blower motor was excluded. Ann Arbor, Michigan was used to represent a relatively cool northern climate and San Antonio, Texas was used to represent a relatively hot southern climate in the model. Two different time horizons were used, 1985–2025 and 2010–2025. The first time horizon assumed a new CAC is purchased at the beginning of 1985 and the final CAC is retired at the end of 2025. This approach is helpful for exploring replacement trends over time. The second time horizon assumes that a homeowner in 2010 starts with an existing CAC whose previous production and operating burdens are ignored and only impacts beginning in 2010 are considered until the unit is retired at the end of 2025. This time frame provides insight on when homes with existing CACs should be replaced.

3. Methods

3.1. Life cycle optimization

Life cycle optimization (LCO) was used to determine the replacement schedule that minimized each objective. This method uses dynamic life cycle inventory profiles to represent each model year of a product. These dynamic life cycle inventories were used in conjunction with a dynamic programming model. In this model, a set of system characteristics is defined in the state of the system for each year. Decisions are made at the start of each year throughout the time horizon of optimization. In the present study, a state is defined by a vector (i,j) that represents model year i and age j of an air conditioner. The LCO model to find optimal air conditioner lifetimes for environmental criteria is constructed using the following notation and equations:

n: first year
N: last year
M: maximum physical life
BM(i): environmental burden (hereafter called burden) from the materials production of model year i
BA(i): burden of the manufacturing of model year i
BU(i,j): burden of the use phase during year j of model year i
BE(i,j): burden of the end-of-life stage of model year i retired at the end of year j
$u(i,j)$: cumulative burden of purchasing (producing) a new CAC at the start of year i and keeping it for j years. For any model year i, $u(i,0)=0$
$f(i)$: minimum possible burden accumulated from the start of year i through the end of year N given that a purchase is made at the start of year i.
x_i: number of years owning CAC of model year i.

$$u(i,j)=\begin{cases} B_M(i)+B_A(i)+B_E(i,i+j-1)+\displaystyle\sum_{k=1}^{j}B_U(i,k) & \text{if } j>0 \\ 0 & \text{if } j=0 \end{cases} \tag{1}$$

$$f(i)=\begin{cases} \displaystyle\min_{x_i\in\{1,2,\ldots,M\}}\{u(i,x_i)+f(i+x_i)\} & \forall i=n,\ldots,N \\ 0 & \forall i>N \end{cases} \tag{2}$$

For each criterion, this model seeks to minimize the burden from the life cycle of model years n to N by deciding x_i, the number of years before purchasing a new CAC.

This type of LCO approach was initially developed to study the replacement of mid-size automobiles (Kim et al., 2003) and was later applied to the replacement of household refrigerators (Kim et al., 2006) and household clothes washers (Bole, 2006). This article provides an overview of life cycle modeling of CACs, but a more detailed description of methods is provided in De Kleine et al. (2010).

3.2. Production modeling

Material composition for CAC production was estimated by disassembling a 3-ton, 10 SEER outdoor unit (Byrant Model #561CJ036-C) to identify the mass of the raw materials used in the components. Using the data of the material composition of the coil assembly from the outdoor unit along with product data sheets, the composition of the indoor unit was estimated. The overall material composition, by mass, of the outdoor, indoor, and refrigerant lines for this 10 SEER system was 74 kg. The raw material composition is presented in Fig. 1.

Using the databases in SimaPro 7.1, the components of the indoor and outdoor units along with the refrigerant line set were modeled to estimate the energy consumption and GHG emissions from raw material production and component manufacturing. Manufacturing processes were inventoried to account for processing materials into simple forms such as tubing, wire, and sheet metal. These processes represented about 18% of the total production energy of the 10 SEER model.

Producer cost data from a reverse engineering analysis of air conditioning equipment by the Department of Energy (2000) was utilized to model the production burdens of the equipment. First, producer utility costs were used to find energy consumed during assembly based on CAC efficiency. It was assumed that electricity was the dominant energy cost, and thus the cost was translated to electricity consumption based on industrial electricity pricing