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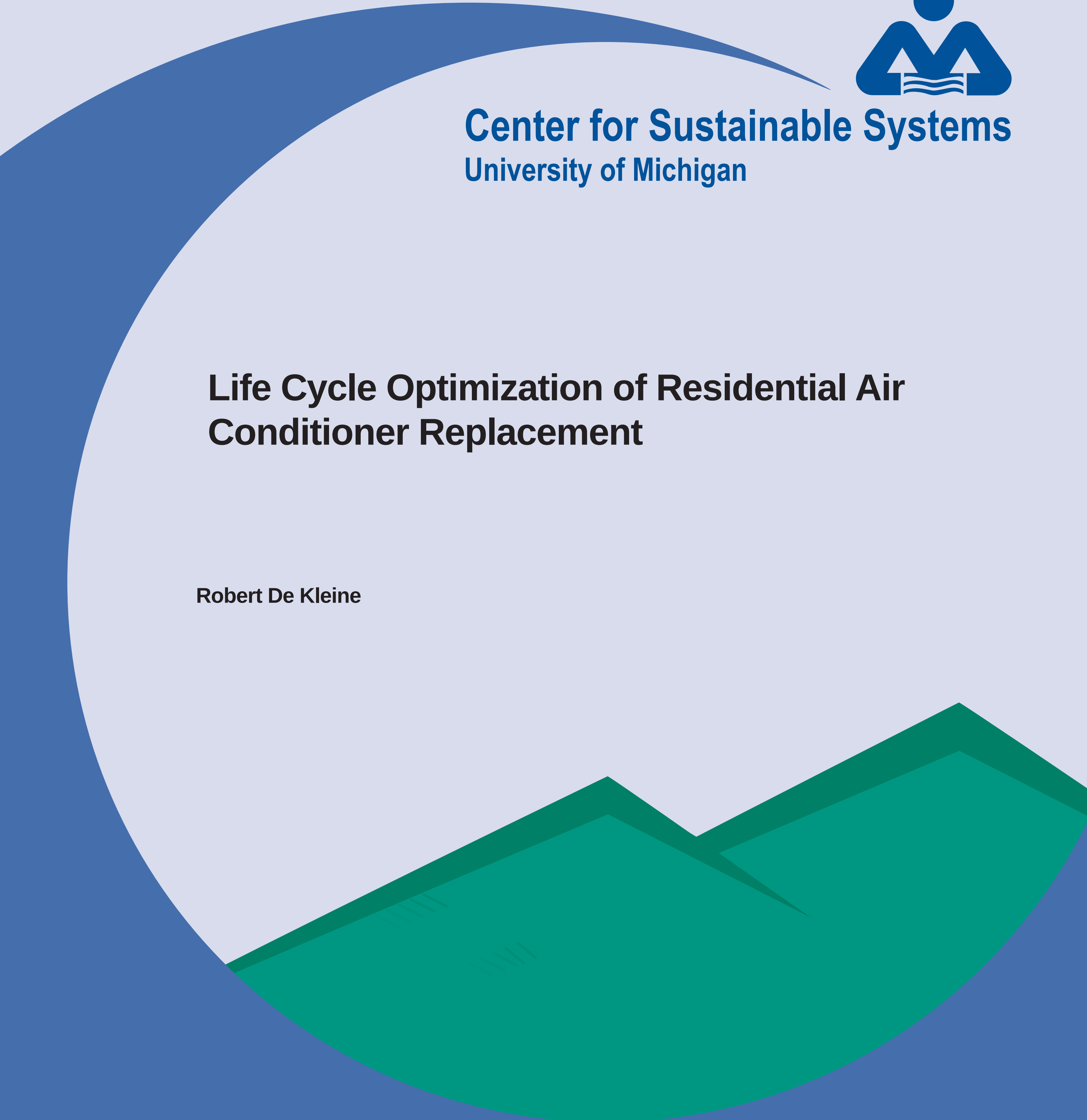

# Life Cycle Optimization of Residential Air Conditioner Replacement

Robert De Kleine

# Life Cycle Optimization of Residential Air Conditioner Replacement

By:

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for the degree of Master of Science
(Natural Resources and Environment)

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# Abstract

Utilizing more efficient central air conditioning equipment is one strategy to curb residential energy consumption. The average efficiency of air conditioning units sold tends to increase gradually over time, so replacing old units can reduce energy consumption during operation, but these energy savings must be weighed against the energy associated with the creation of a new unit and disposal of the existing unit. A model based on the lifecycle inventories for each model year of a typical 3 ton central air conditioning unit was developed to find replacement schedules that minimize the (1) energy consumption, (2) greenhouse gas emissions and (3) cost to the homeowner over a period from 1985 thru 2025 for 6 cities across the United States. Dynamic variables such as changes in raw material energy intensity, refrigerant market share, and cost of electricity over time were considered.

Over the 41 year time horizon, energy minimization required 7 to 15 units, greenhouse gas (GHG) minimization required 3 to 5 replacements, while cost minimization required 3 units for the various cities examined. The cost of replacing according to an energy optimal schedule was between 11 to 57% more than the cost optimal schedule for the same city. Locations with the hottest climates required the most replacements. Financial incentives were introduced as negative costs into the model to align the optimal cost schedule with energy and GHG optimal schedules. These incentives were substantial. Often, they were in the range of $1000 to $2000 per replacement.

The model demonstrates the benefits of optimal replacement under several scenarios including an increase in the federal efficiency standard in 2016, the adoption of a regional efficiency standard, and the replacement of existing central air conditioners with Energy Star units instead of units at the federal minimum efficiency standard. For example, when starting with model years older than 2005, optimal replacement with Energy Star units in Ann Arbor, MI offers the potential for 8% energy savings and 5% GHG savings versus replacing with units at the federal minimum efficiency standard from 2009-2025.

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I want to thank Frank Johnson and Jake Even at Robertson Morrision Heating and Cooling for their help in coordinating the disassembly of an air conditioning unit.

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## Nomenclature

| | |
|---|---|
| ACCA | Air Conditioning Contractors of America |
| AEO | Annual Energy Outlook |
| AER | Annual Energy Review |
| AHRI | Air-Conditioning, Heating and Refrigeration Institute [formerly American Refrigerant Institute (ARI)] |
| ASHRAE | American Society of Heating, Refrigerating and Air-Conditioning Engineers |
| BTU | British Thermal Unit |
| CAC | Central Air Conditioner |
| CDD | Cooling Degree Days (base 65 F) |
| CLH | Cooling Load Hours |
| DOE | Department of Energy |
| EER | Energy Efficiency Ratio |
| EIO-LCA | Economic Input-Output Life Cycle Assessment |
| EPA | Environmental Protection Agency |
| GHG | Greenhouse Gas |
| HFC | Hydrofluorocarbon |
| HVAC | Heating, Ventilation and Air Conditioning |
| ISO | International Organization for Standardization |
| LCA | Life Cycle Assessment |
| LCI | Life Cycle Inventory |
| LCO | Life Cycle Optimization |
| MECS | Manufacturing Energy Consumptions Survey |
| NAICS | North American Industry Classification System |
| NERC | North American Electricity Reliability Corporation |
| SEER | Seasonal Energy Efficiency Ratio |
| TEWI | Total Environmental Warming Impact |
| TMY3 | Typical Meteorological Year 3 Database |

# 1 Introduction

Mechanical air conditioning dates back to 1902 when Willis Carrier built a cooling system to regulate the temperature and humidity within a publishing plant in order to help maintain a consistent paper size for the printing machines (Carrier Corp., 2002). From these beginnings, air conditioning has grown to become an expected feature in American homes. Today, 70% of adults consider air conditioning to be a necessity compared to 1973 when 72% considered it a luxury (Taylor, Funk, & Clark, 2006).

As air conditioning has grown into a mainstream technology, the environmental and financial consequences of air conditioning have also increased. Residential air conditioning demands about 2.67 quadrillion BTUs of energy and emits the equivalent of 43.6 million metric tons of carbon dioxide per year (DOE, 2007). Figure 1.1 shows that space cooling accounts for 13% of all the primary energy consumed by the residential sector in the United States. Nationally, it is also responsible for about 13% of the sector's greenhouse gas (GHG) emissions, but this proportion varies by region as shown in Figure 1.2. Beyond these impacts, there is a significant financial cost to the consumer. In 2005, the average household cost of electricity for central air conditioning was $335 (EIA, 2009a). In the Southern Census Region, these costs are even higher at $448 per year (EIA, 2009a).

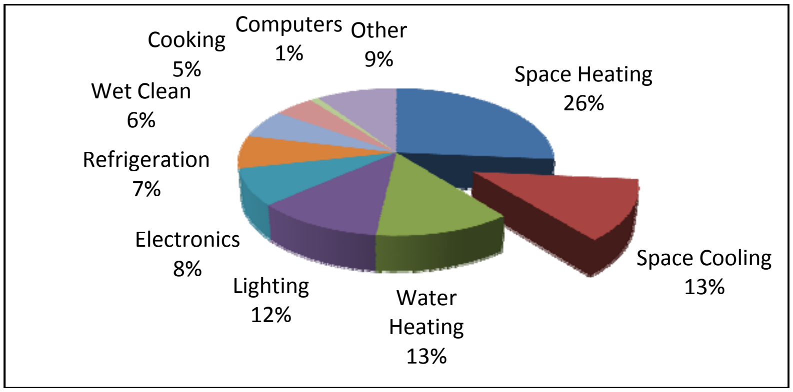

**Figure 1.1: Primary Energy Usage of Residential Sector (DOE, 2008)**

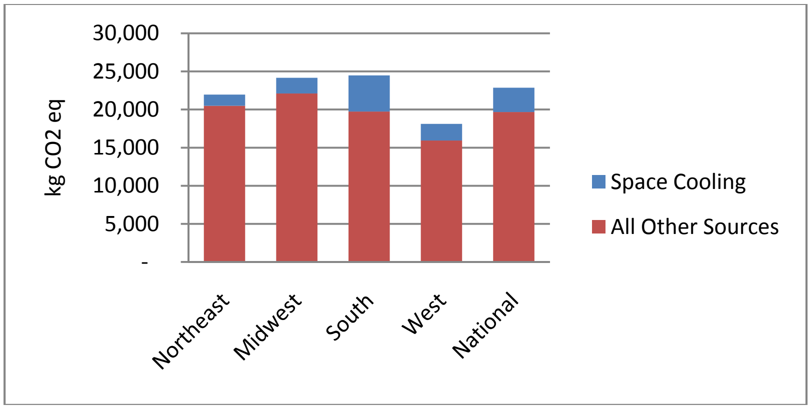

**Figure 1.2: Carbon Dioxide Emissions of an Average Household by Census Region (DOE, 2008)**

Creating a more efficient installed base of air conditioners in the residential sector can be an important strategy for conserving energy. Encouraging homeowners to accelerate the replacement of inefficient units with new, efficient units can save operational energy. However, as with any product system, the real environmental burden is the accumulation of the burdens associated with the creation, use, and retirement of that product. The potential benefits from replacing an air conditioner with a more efficient unit must be weighed against the added burden associated with the creation of a new unit and disposal of the old unit. Just as one can calculate an economic payback period from an investment in a product with lower operating costs, one can also calculate an environmental payback period from expending more energy to manufacture an efficient product that will save on operating energy. In both cases, the product must be held at least as long as the payback period in order to be beneficial. It is difficult to know when to replace products like air conditioners in order to minimize total environmental impact and cost. This research seeks to help consumers, manufacturers, and policy makers understand the best times for typical homeowners to replace their air conditioners in order to minimize energy consumption, greenhouse gas (GHG) emissions, or cost to the consumer.

## 1.1 Air Conditioning Trends

Central air conditioning has grown substantially in the last two decades while the number of homes relying exclusively on room air conditioners for cooling has remained relatively stable. Figure 1.3 summarizes the growth of air conditioning in American households.

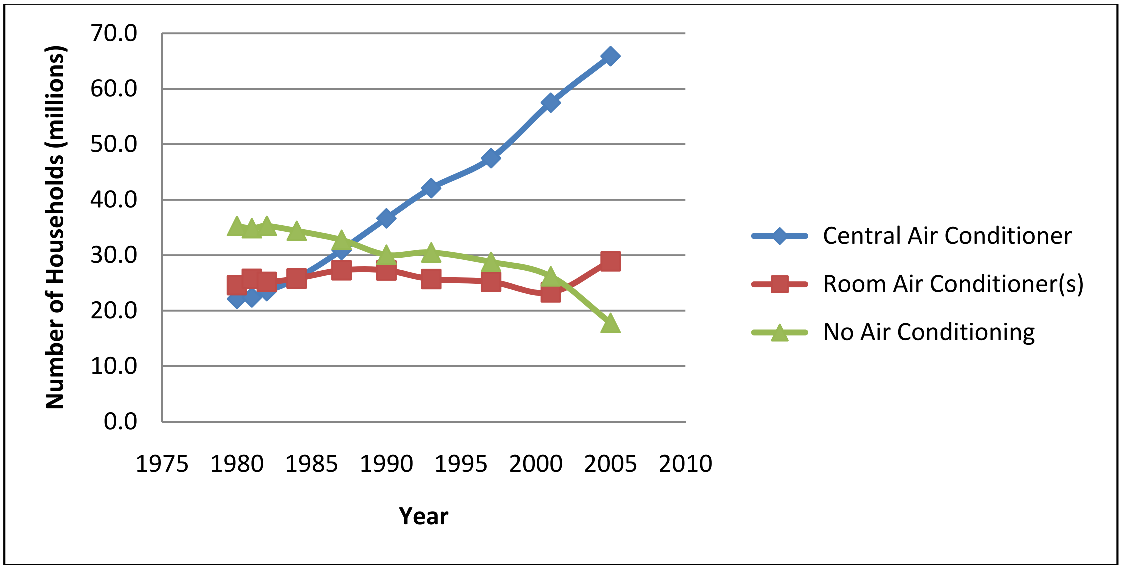

**Figure 1.3: Changes in American Household Access to Air Conditioning (EIA, 2000; EIA, 2009e)**

New home construction is one factor that is driving the market penetration of central air conditioning. Nationally, 90% of new single family homes are constructed with central air conditioning while in the south it is included in virtually all new homes (US Census Bureau, 2006).

The overall demand for space cooling stands to increase due to high population growth in regions with hot climates. Table 1.1 shows the four states projected to grow the fastest are also among the states with the highest cooling degree days (using a base 65°F). A cooling degree day (CDD) is a measure of the cooling demand of a climate. It is calculated by summing the number of degrees the average daily temperature exceeds the base temperature over the course of a year.

**Table 1.1: Cooling Load of States with Fastest Population Growth (US Census Bureau, 2005; NCDC, 2002)**

| | Projected Growth Rate (2000-2030) | Average Population Weighted Cooling Degree Days | Ranking of States with Highest Average Cooling Degree Days |
|---|---:|---:|---:|
| **Nevada** | 114.3 % | 1921 | 7 |
| **Arizona** | 108.8 % | 2861 | 3 |
| **Florida** | 79.5 % | 3420 | 1 |
| **Texas** | 59.8 % | 2648 | 4 |

These four states alone account for about 40% of the projected growth in the US population from 2000 to 2030. If these projections are correct, the average American will go from living in a 1250 CDD climate in 2000 to a 1360 CDD climate by 2030. This assumes that climate patterns will remain stable in the coming decades. The prospect of higher summertime temperatures resulting from climate change would further increase the amount of cooling required. Climate change also stands to increase the saturation of air conditioning as households that previously had no air conditioning equipment become unwilling to deal with higher summer temperatures (Sailor & Pavlova, 2003).

## 1.2 History of Federal Standards

Beginning in the 1970's various states began implementing their own minimum efficiency standards for appliances. The Energy Policy and Conservation Act of 1975 called for national appliance efficiency targets. The National Appliance Energy Conservation Act of 1987 established national standards for several classes of household appliances including room and central air conditioners and called for the Department of Energy to review and revise the standards in the future (DOE, 2008). Central air conditioner (CAC) efficiency is usually measured by the seasonal energy efficiency ratio (SEER), which represents the average number of BTUs of cooling per Wh of electricity input over a typical cooling season. The initial efficiency level was set at 10 SEER and took effect for split system CACs manufactured on or after January 1, 1992. The Department of Energy published a revised standard for CACs on January 22, 2001 which took effect in January 2006. This new rule raised federal energy efficiency standards 30% to 13 SEER. As Figure 1.4 shows, this change has significantly boosted the average efficiency of central air conditioners being sold. It continued to increase very gradually after the federal standard was implemented. According to the US Department of Energy, this more stringent standard will save 4.2 quads (quadrillion BTUs) of energy by 2030 (DOE, 2005). A new rule making process is currently underway with a final rule to be established by June 2011, which will take effect in June of 2016 (DOE, 2008).

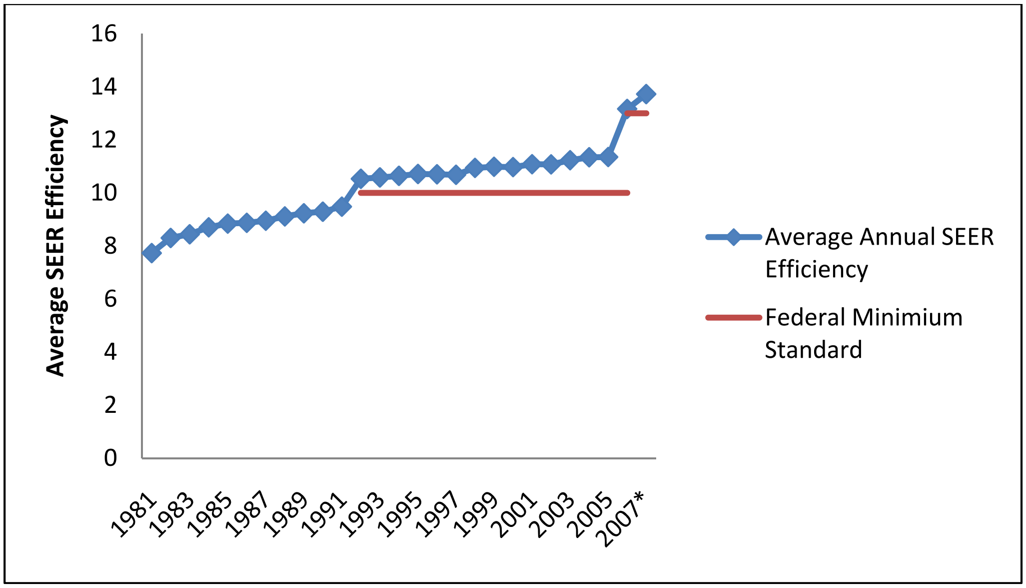

**Figure 1.4: Average SEER of Central Air Conditioning Units Shipped (Skaer, 2007)**
* based on sales figures from January to June

## 1.3 A Typical Central Air Conditioning

Air conditioning equipment can take many forms. The method used in the United States for most single-family homes is a split system central air conditioner using a vapor compression cycle. This air conditioning system is composed of both an outdoor and an indoor unit. The outdoor unit is a condensing unit composed mainly of a compressor, condenser coils, and a fan. Homes that have forced air furnaces typically have an indoor evaporator coil that is embedded within or mounted above the furnace. Homes without forced air furnaces will use an air handler composed of an evaporator coil and fan. A set of refrigerant lines allows the refrigerant to circulate between the indoor and outdoor units.

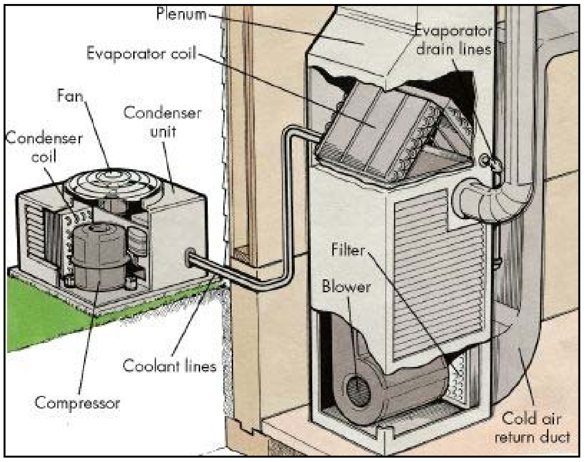

**Figure 1.5: Diagram of a Typical Central Air Conditioning System.**
*(Source: http://paprikalab.com/blog/wp-content/uploads/2008/06/air_conditioner.jpg)*

Cooling is provided when the liquid refrigerant is delivered to the indoor evaporator coil. The refrigerant begins to evaporate, thus cooling the coil and the air that is blown across the coil. This cold air is blown through the home's ductwork into the living spaces. After passing through the indoor coil, the heat absorbed from the air causes the refrigerant to vaporize. The refrigerant vapor is drawn outside to the compressor in the outdoor unit. The compressor raises the pressure of the refrigerant and discharges it to the condenser coils. The refrigerant in the coils loses heat to the outside air being blown across the coils causing the refrigerant to condense to a liquid. This liquid then enters the refrigerant lines where it travels back into the home and through an expansion device, which reduces the pressure allowing the refrigerant to vaporize in the evaporative coil, and thus repeat the process. The process is summarized in Figure 1.6.

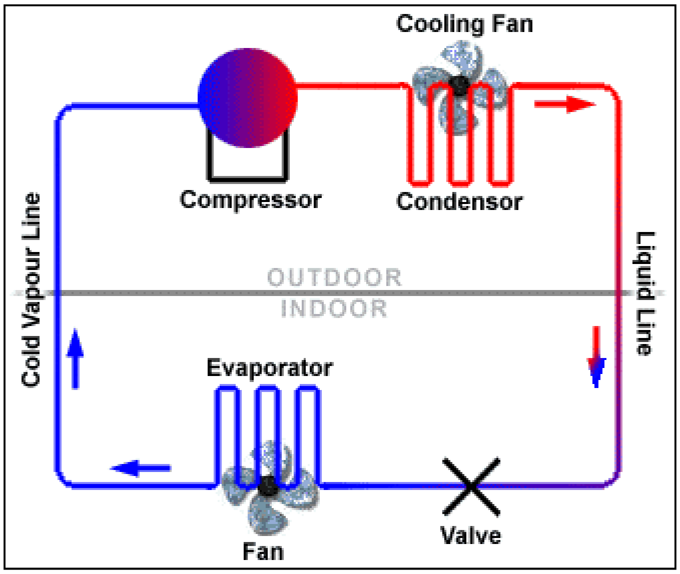

**Figure 1.6: Diagram of the Basic Refrigeration Cycle (Complete HVAC Services, 2009)**

In addition to lowering the dry bulb temperature of the air in the home, central air conditioners are effective at lowering the humidity in the home. Moisture in the air condenses forming water droplets when it comes into contact with the cold evaporator coils. These droplets run off the coil and are discharged to the house's drain system. Removing the humidity is a big component of increasing the comfort of homes in many areas of the country. This process is referred to as latent cooling, where as the process of lowering the dry bulb temperature is referred to a sensible cooling.

## 1.4 Problem Statement

At any point in the lifetime of an air conditioner, a homeowner has the option of replacing an older unit with a new model. On average that new model will be more efficient, but manufacturing the new model consumes energy and produces emissions. This thesis explores how different policies and strategies can be used to reduce the burdens associated with residential central air conditioning.

A model was developed to investigate how the replacement schedule of a CAC impacts the (1) energy usage, (2) GHG emissions and (3) cost to the consumer over the course of a 41 year period from the start of 1985 to the end of 2025. Using life cycle optimization, the replacement strategy that minimizes the objective is identified by accounting for all the impacts of the air conditioning unit and modeling how these impacts change with time. These results are dependent on the climate where the unit operates, thus customer location must be taken into account.

The model is then used to explore how different policies and replacement strategies impact these objectives. First, the optimization is completed using different scenarios for the next federal standard. Next, carbon pricing and the impact on the optimal cost replacement are analyzed. Then, financial incentives are introduced into the model as negative costs in order to examine how the optimal cost schedule can be aligned with the optimal energy and GHG schedules. Next, an example of a regional standard is investigated to see what kind of environmental and cost savings can be achieved. Finally, the model's time horizon is shortened to 2009 thru 2025 in order to compare the results of replacing an existing unit with an Energy Star CAC instead of a unit that only meets the minimum standard.

## 1.5 Thesis Outline

Chapter 2 begins by describing the basic methodology behind life cycle assessment (LCA) and how this is extended through the use of dynamic life cycle inventories to complete the life cycle optimization (LCO).

Chapter 3 applies LCA methods for evaluating central air conditioners. It presents both an economic input-output approach and a process-based approach for modeling the production of a CAC. Energy consumed, GHG emitted, and cost to the consumer associated with the other life cycle phases such as shipping, use, and end of life are calculated.

In Chapter 4, the dynamic parameters of the LCO are introduced. Factors used in the model like increasing unit efficiency, phasing out of ozone depleting refrigerants, and the changing energy intensity of material production are explored.

Results of the analysis are presented in Chapter 5. The optimal replacement schedules for various efficiency forecasts are evaluated. Also, the impact of putting a price on carbon production is analyzed in the cost optimization.

Chapter 6 extends the existing model to investigate how financial incentives can be use to align the cost optimization schedule with optimal energy and GHG replacement schedules. The potential savings of implementing a regional standard is calculated. Finally, a comparison of the impacts from replacing with an Energy Star CAC to the impacts from replacing with a minimum efficiency CAC is presented.

Research conclusions, limitations, and potential policy implications are discussed in Chapter 7.

# 2 Methodology

## 2.1 Life Cycle Assessment

Life cycle methods look at the entire impact of a product or service over its lifetime. Decision makers often focus on one aspect of the life cycle typically the impacts of using a product or service, but in order to truly understand the significance, a “cradle to grave” approach must be used.

The International Organization for Standardization (ISO) describe the purpose of life cycle assessment (LCA) as the evaluation of the environmental burdens associated with a product, process, or activity by (1) identifying and quantifying energy and materials used and wastes released to the environment, (2) assessing the impact of the energy and materials used and released to the environment, and (3) identifying and evaluating opportunities for environmental improvements (ISO, 1997).

The ISO approach to conducting an LCA is initially to define the goal of the analysis and to decide which aspects will be included and excluded in the study. From this point, the inputs and outputs are quantified during each phase of the life cycle and summed together. In the impact assessment, the results of the inventory are used to evaluate the benefit or damage to the environment. After this is completed, the results can be interpreted and utilized. The LCA process is not necessarily linear. Each step often helps to shape and refine both the previous and future steps. The ISO framework for conducting a LCA is summarized in Figure 2.1.

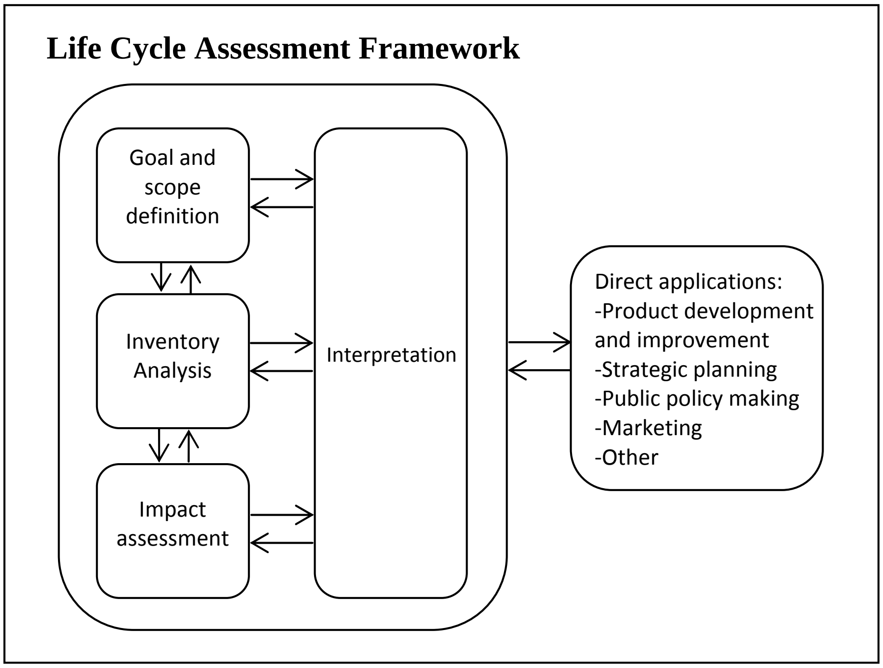

**Figure 2.1: International Standards Organization Life Cycle Analysis Framework (ISO, 1997)**

## 2.2 Scope and Boundaries

This study considered the burdens associated with a typical CAC used to provide cooling service to a single family home over the time period from 1985-2025. These burdens were in the form of energy consumed, greenhouse gasses emitted, and financial cost to the consumer. Homes were considered in the different areas of the 48 contiguous states.

Several types and sizes of air conditioning units are available on the market. This research will consider electrically-powered, split system CACs that utilize vapor-compression refrigeration since it is the most common type used for single-family residential space cooling. These units typically range from 1.5 tons to 5 tons of cooling capacity with each ton representing 12,000 BTUs of cooling. The most common size, 3 tons, will be considered in this study. Air conditioning methods that do not fit this profile such as evaporative coolers and single package units are excluded.

Many factors beyond the CAC itself, such as the heat transfer and infiltration through the building envelope, leakage in the ductwork, and occupant behavior can significantly alter a buildings air conditioning system performance. Variables such as these that do not relate directly to the CAC were excluded to make the study analysis feasible, but these factors and their potential impact on the study's findings are discussed in Section 7.2

## 2.3 Dynamic Life Cycle Inventory

The typical life cycle inventory ignores changes that occur in a product system over time. Instead, it usually represents a snapshot in time of the system. In reality, many factors are constantly changing various aspects of this product system. In order to better account for the actual performance of a system over time, a dynamic life cycle inventory is required to reflect these changes. For example, regulations and consumer purchasing behavior have been responsible for improving the average efficiency of air conditioners sold in the past. The cost of new CAC units and the cost of energy are also variable. These and other factors presented in Chapter 4 can significantly change the result of the analysis. Exploring these changes is necessary for understanding the tradeoffs associated with the timing of replacement.

## 2.4 Life Cycle Optimization Model

In the case of products that are responsible for significant environmental impacts during their use, the option of when to replace can lead to many different outcomes over the time horizon being examined. Figure 2.2 shows a representation of a product system with four different replacement paths. On the y-axis is the cumulative environmental burden associated with the product. This environmental burden could include any number of factors such as energy usage, greenhouse gas emissions, solid waste generation, water consumption, habitat loss, etc. At time 0, there is an initial burden associated with the creation of the product. This burden then gradually increases over time resulting from the use of the product. A consumer has various opportunities to replace the product, which results in another jump in the burden, but replacement can provide the opportunity to acquire a product that is less harmful during its use. The total burdens of the various replacement paths are denoted by $B_n$ along the right of the chart. Replacing a product with a more efficient one can result in a lower total burden at the end of the period. This can be observed when comparing $B_1$ to $B_4$. A key point to consider is that the relative results from the various paths are dependent on the time period being considered. For instance, one could imagine that if the time period being considered in Figure 2.2 were extended, the burden associated with $B_2$ could surpass the burden of $B_3$.

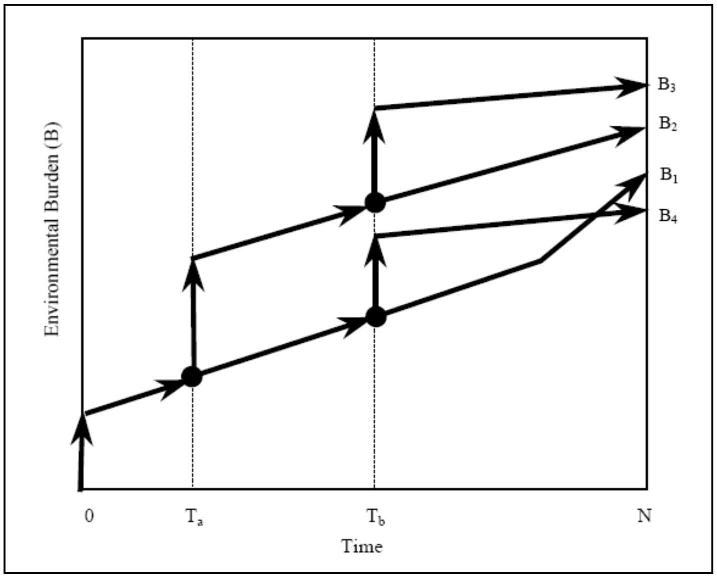

**Figure 2.2: A Schematic Diagram Demonstrating Various Burden Outcomes from Product Use and Replacement (Kim H. C., 2003)**

The goal of life cycle optimization is to determine the best path of replacement to minimize the particular burdens being examined. With the creation of dynamic life cycle inventories and the use of dynamic programming algorithms the system life cycle can be optimized by selecting the best replacement schedule for the system. This approach was initially developed to study the replacement of a mid-size automobile (Kim, Keoleian, Grande, & Bean, 2003) and later used to study the replacement of household refrigerators (Kim, Keoleian, & Horie, 2006) and clothes washers (Bole, 2006).

# 3 Air Conditioner Life Cycle Inventories

## 3.1 Material Production and Manufacturing

The material composition of CACs was sought from industry groups, individual manufacturers, and appliance recyclers. These groups were either unwilling or unable to provide data related to the material composition. Similar requests for data on manufacturing energy were also unsuccessful. Other methods had to be employed to complete this portion of the inventory. Both an economic input-output life cycle assessment (EIO-LCA) approach and a process-based life cycle analysis approach were used to account for the production burdens.

In most cases, it is necessary to replace both the indoor and outdoor components together in order to allow the system to achieve its intended efficiency. It was assumed in this study that both components were always replaced together.

### 3.1.1 EIO-LCA Inventory

One strategy used to conduct a life cycle assessment is an economic input-output approach. This method relies on databases created by deconstructing economic transactions throughout the supply chain into inputs and outputs between the sectors within an economy. These results can be used in conjunction with information about the environmental impacts associated with these sectors to find the impact of a product produced by these sectors. However, because it utilizes producer price data to determine the product impacts, this approach is limited to producing results based on industry sector averages and not based on product specifics.

In an attempt to get the most accurate results, component data was used to calculate the energy and GHG emissions for the indoor and outdoor components of the CAC rather than simply using the cost of the unit as a whole. Doing the analysis on a component level reduces some of the variability of using the average energy and GHG intensities for the HVAC equipment manufacturing sector, which not only includes residential HVAC equipment, but also commercial and industrial heating and cooling equipment as well as drinking fountains and soda dispensers. The component data was based on the reverse engineering analysis from the DOE (2000). The data presented the producer cost of the components based on the efficiency of the units ranging from 10 to 14 SEER.

Each component was assigned to an appropriate NAICS category so an energy and GHG multiplier could be obtained for that category using the Department of Commerce 1997 dataset (Carnegie Mellon University Green Design Institute, 2008). It was calculated that the cost of the coils was composed of 55% copper costs and 45% aluminum costs based on an assumption of equal mass proportions and a 20% higher price for copper per unit of mass than for aluminum (USGS, 2009). All the other components were assigned to a single category as shown in Table 3.1.

**Table 3.1: CAC Components and Designated NAICS Code**

| | Component | NAICS Code |
|---|---|---|
| **Outdoor Unit** | Coil Materials | 331421 Copper Rolling, Drawing, and Extruding<br>331315 Aluminum Sheet, Plate, and Foil Manufacturing |
| | Electrical Materials | 331422 Copper Wire (except Mechanical) Drawing |
| | Misc Materials | 33272 Turned Product and Screw, Nut, and Bolt Manufacturing |
| | Fan Materials | 333996 Fluid Power Pump and Motor Manufacturing |
| | Cabinet Materials | 331221 Rolled Steel Shape Manufacturing |
| | Plumbing Materials | 331421 Copper Rolling, Drawing, and Extruding |
| | Compressor Materials | 333912 Air and Gas Compressor Manufacturing |
| **Indoor Unit** | Coil Materials | 331421 Copper Rolling, Drawing, and Extruding<br>331315 Aluminum Sheet, Plate, and Foil Manufacturing |
| | Electrical Materials | 331422 Copper Wire (except Mechanical) Drawing |
| | Misc Materials | 33272 Turned Product and Screw, Nut, and Bolt Manufacturing |
| | Fan Materials | 333996 Fluid Power Pump and Motor Manufacturing |
| | Cabinet Materials | 331221 Rolled Steel Shape Manufacturing |
| | Plumbing Materials | 331421 Copper Rolling, Drawing, and Extruding |
| **Direct Labor (incl. benefits)** | | 81141 Home and Garden Equipment and Appliance Repair and Maintenance |
| **Overhead (incl. benefits)** | | 55111 Management of Companies and Enterprises |

The energy and GHG results from each of these components were summed together to create the life cycle inventories. The burdens for producing refrigerant were considered in a separate analysis presented in Section 3.1.4.

### 3.1.2 Process LCI

The second approach to estimating the production of the CAC was based on a process LCA approach. The burdens associated with the material production, the fabrication of those materials into components, and the final assembly of the products were considered.

*Outdoor Unit*

In order to estimate the material composition of the outdoor unit, a retired unit was dissembled and the components were weighed to determine their mass. The unit was a 3-ton, 10 SEER unit (Byrant Model 561CJ036-C). Based on the model revision number, it is estimated that this unit was likely manufactured around 2001. Table 3.2 shows the breakdown of the weights of the various components. The refrigerant used in the unit was considered separately.

Table 3.2: Component Weights (in kg) of Deconstructed Outdoor CAC Unit

| | |
|---|---|
| Compressor | 29.3 |
| Coil Assembly | 7.9 |
| Fan Motor | 4.3 |
| Unit Wall | 3.1 |
| Base | 2.7 |
| Top Cover | 1.9 |
| Fan Guard | 1.6 |
| Refrigerant Lines | 1.0 |
| Wire Guard | 0.8 |
| Fan Blade | 0.6 |
| Misc Fasteners | 0.3 |
| Capacitor | 0.3 |
| Relay Switch | 0.2 |
| Copper Wiring | 0.2 |
| **Total** | **54.3** |

Many of the raw materials used in these components were easily identified. A section of the coil assembly was further deconstructed to determine that the coil assembly was composed of approximately 50% copper tubing and 50% aluminum fins. Materials for other components had to be estimated. The fan motor was assumed to have a composition of 25% copper wire, 72% steel, and 3% polyamide based on values in the literature (Klausner, Grimm, & Hendrickson, 1998). The refrigerant tubing included brass service values and it was assumed that half of this weight was due to these valves. The relay switch and capacitor were a small portion of the overall weight of the unit thus the relay switch was modeled simply as half copper wiring and half nylon polymer and the capacitor was modeled as half sheet metal and half paraffin.

With the dominant portion of the outdoor unit mass coming from the compressor and the difficulty in physically deconstructing the compressor, data from Harabut's LCA of a rotary compressor (2004) was used to better account for the impacts of this component. Since the compressor in that study was significantly smaller than the reciprocating compressor found in the deconstructed unit, the mass of the materials used in that study were scaled up by a factor of 3.52 to match the mass of the compressor in the deconstructed unit.

Using the databases in SimaPro 7.1, these components were modeled. When available, simple processing techniques were included in the inventory to account for some of the processing of the materials into tubing, wire, and sheet metal.

To try to capture some of the burdens associated with assembly, the same EIO-LCA factors were applied to the direct labor and overhead portion of manufacturing costs to calculate energy consumed and GHG emissions generated during the final assembly.

*Indoor Unit*

The indoor unit was assumed to consist of a sheet metal case and a coil assembly with the same copper and aluminum mass proportions as the outdoor coil assembly. Using results from various product data sheets for indoor units sold in both cased and uncased versions, the weight of the steel casing and coil assembly was estimated at 7.0 kg and 15.9 kg, respectively, for models currently available that would likely be matched with a 13 SEER unit. Indoor component cost values from the reverse engineering cost analysis were used to scale these values to 5.7 kg and 9.9 kg for a unit that would be part of a 10 SEER system. Just as with the outdoor unit, some of the basic processing was included in the SimaPro model and again the remainder of the processing and assembly burden was modeled using the EIO-LCA approach based on labor and overhead costs.

### 3.1.3 Comparison of EIO-LCA and Process-based Production Results

Using two different approaches to model the production burdens associated with creating a new CAC yielded two significantly different sets of results. Using the EIO-LCA approach to model a 10 SEER unit resulted in 2,850 MJ of primary energy demand and 248 kg of $CO_2$ equivalent GHG emissions. For the process LCA approach based on the deconstructed outdoor unit and a corresponding indoor unit, the total primary energy demand is 5,710 MJ. The overall GHG associated with producing the system is 317 kg $CO_2$ eq. A breakdown of these energy and GHG values is shown in Figure 3.1 and Figure 3.2.

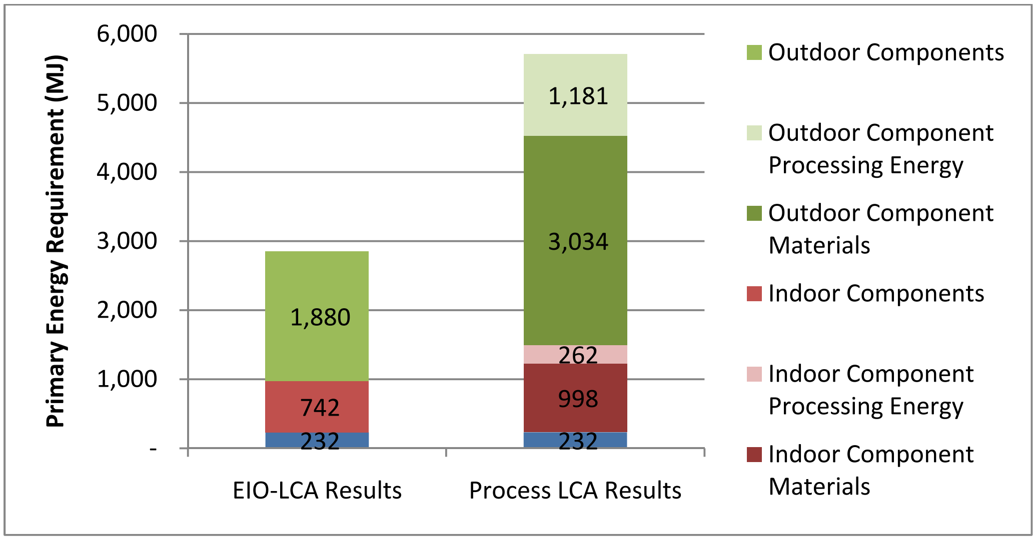

**Figure 3.1: Material and Manufacturing Energy Inventory Summary for 10 SEER, 3-ton CAC**

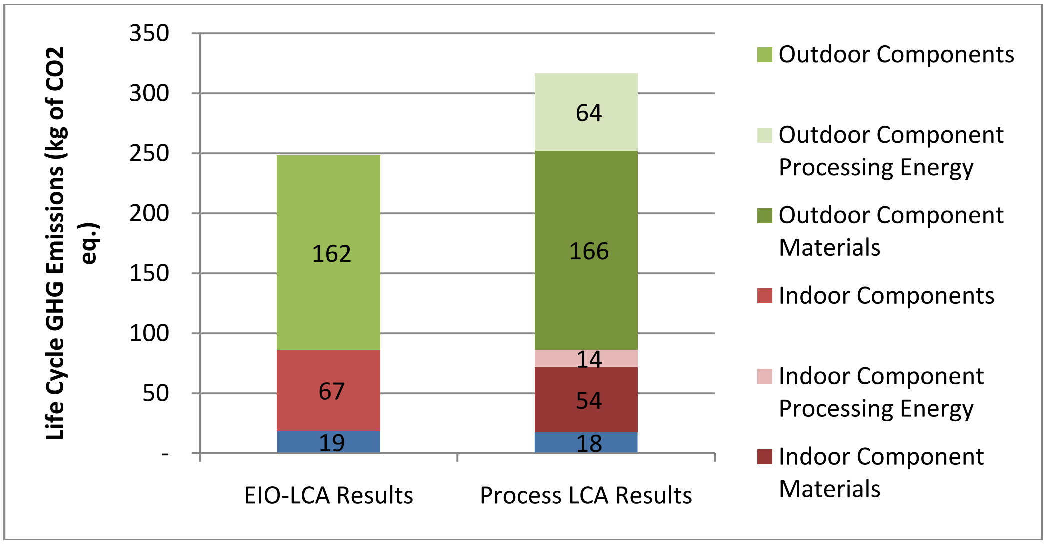

**Figure 3.2: Material and Manufacturing GHG Emission Inventory Summary for 10 SEER, 3-ton CAC**

These results reflect the modeling of a 10 SEER unit. The burdens of other efficiency CACs were determined by using the relative difference in DOE cost data as a proxy for relative mass difference which in turn is a proxy for the relative environment burdens. This method was applied to both the EIO-LCA results and the process LCA results. In the case of the outdoor units, weight data from a survey of air conditioner datasheets available online for various models of condenser units from several different brands ranging in efficiency from 10 to 18 SEER and ranging in capacity from 1.5 to 5 tons of cooling were used to create a weight function based on the nominal efficiency of the outdoor unit. The resulting weight function for a 3 ton unit was

$$m_{outdoor} = 17.1\eta - 31.6$$

where $m_{outdoor}$ is the mass of the outdoor unit, and $\eta$ is the efficiency in SEER. The producer cost data was used to create a cost index and weight function was used to create a weight index for the outdoor unit. Figure 3.3 show good agreement between the cost and weight indices. Creating a weight function for indoor evaporators coils based on efficiency is difficult. Indoor units are not marketed in terms of SEER efficiency like outdoor units, thus it was not possible to do an accurate comparison between cost and weight for indoor units.

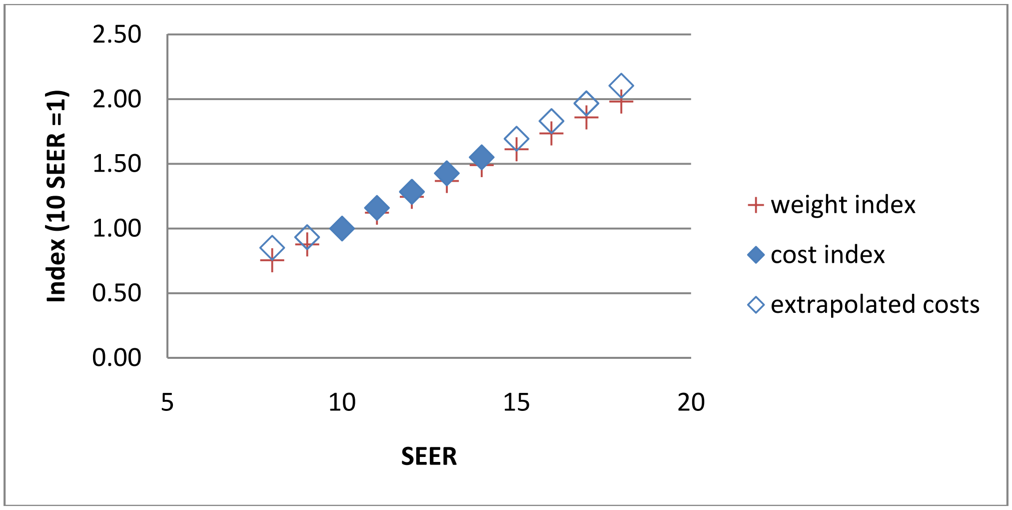

**Figure 3.3: Comparison of the Producer Cost and Weight Index for an Outdoor Unit based on Efficiency**

### 3.1.4 Refrigerants and Refrigerant Lines

*Refrigerants*

Refrigerants were considered separately from the other components in the CAC. The mass of refrigerant charge was estimated from product specification sheets. From these datasheets, the following exponential curve was fitted to create a refrigerant mass function:

$$m_{refrig} = (1.124^{\eta} + 1.019^{c} + 0.7489)\ lbm$$

where $m_{refrig}$ is the mass of refrigerant, $\eta$ is efficiency in terms of SEER, and c is unit capacity in 1000s of BTUs ($R^2 = 0.60$). Improving efficiency and increasing capacity of CAC units tend to increase the size of the coils for the outdoor units and more coil volume tends to increase the mass of refrigerant required (Skaer, 2005).

Outdoor units typically come pre-charged with enough refrigerant to operate with a 15 to 20 foot lineset connecting the indoor and outdoor components. Installers must frequently adjust the level of refrigerant based on the particular installation configuration. It was assumed the refrigerant pre-charge serves as a good approximation for the total mass of refrigerant in most home CAC systems.

Two types of refrigerants were considered in the analysis, R-22 and R-410a. Historically, R-22 has dominated the residential CAC market. R-22 is a hydrochlorofluorocarbon (HCFC) and as such poses a threat to the stratospheric ozone when released into the air with an Ozone Depletion Potential of approximately 0.05 (Süss & Staub, 2009). HCFCs are being phased out by the EPA to comply with amendments to the Montréal Protocol. As part of this phase out process, R-22 will no longer be used in new CACs after January 1, 2010. Chemical manufactures will still be allowed to produce limited amounts of R-22 to service old units until 2020.

Virtually all new CACs after 2009 will use R-410a instead of R-22. R-410a is a hydrofluorocarbon (HFC) and the absence of chlorine means it does not deplete ozone when released, but like R-22 it does have high global warming potential (GWP). R-410a is not interchangeable with R-22 so R-410a cannot be used in equipment designed for R-22 (Süss & Staub, 2009). R-410a must be maintained at higher pressures, but at these higher pressures it has a higher heat capacity and as a result R-410a can utilize smaller coil tubing and fewer coil circuits theoretically reducing the mass of the outdoor unit and reducing the amount of refrigerant required (Beeton, Buynacek, & Monnier, 2008). Neither of these effects was consistently nor strongly observed in the available product data thus the amount of refrigerant and the size of the unit was assumed to be independent of the refrigerant used.

A life cycle inventory of the production of several refrigerants including R-22 and R-134a was conducted by Campbell and McCulloch (1998). Since no lifecycle inventory is available for the production of R-410a, it has been assumed in recent studies (Arthur D. Little, Inc., 2002; Bovea, Cabello, & Querol, 2007) that R-134 and R-410a have a similar embodied energy since both are HFCs. The GHG emissions resulting from this embodied energy remain the same and the fugitive emissions are calculated as 0.3% of the GWP. This same approach was used in this analysis with the values given in Table 3.3.

**Table 3.3: Environmental Characteristics of CAC Refrigerants (Campbell & McCulloch, 1998; IPCC, 2007)**

| Refrigerant | 100 yr. GWP | Processing Energy (MJ/kg) | Estimated Manufacturing CO2 eq. warming (kg CO2/kg refrigerant) |
|---|---|---|---|
| **R-22** | 1810 | 36 | 393 |
| **R-410a** | 2090[a] | 84.5[b] | 13.8[b] |

a) based on a blend of 50% Difluoromethane and 50% Pentafluoroethane by weight

b) values from HFC-134a Route A and B from Campbell & McCulloch, 1998 were averaged

*Refrigerant Lines*

As part of the installation of a CAC system, refrigerant lines are used to connect the outdoor and indoor units. The energy and emissions associated with the production of a 20 foot refrigerant lineset and a corresponding weight of 4.5 kg (W.W. Grainger, Inc., 2009) was modeled using SimaPro 7.1.

### 3.1.5 Initial Costs

Modeling the cost of CACs is difficult due to the fact that homeowners typically purchase the components from HVAC contractors who quote a price based on the particular project which includes both the equipment and installation. The retail cost is not accessible like appliances that are sold directly to consumers in stores. The DOE (2002) analyzed the cost structure of the CAC market as part of the federal standard rule making process. By estimating the average markup from the manufacturer, the distributor, and the dealer, the equipment costs were determined. The installation costs were estimated from public sources and surveying HVAC contractors. These DOE results were used to estimate initial CAC costs for 10-14 SEER units.

Producer costs for higher and lower efficiency units were extrapolated to higher and lower efficiency units. These results were then approximated by the linear regression in Figure 3.4.

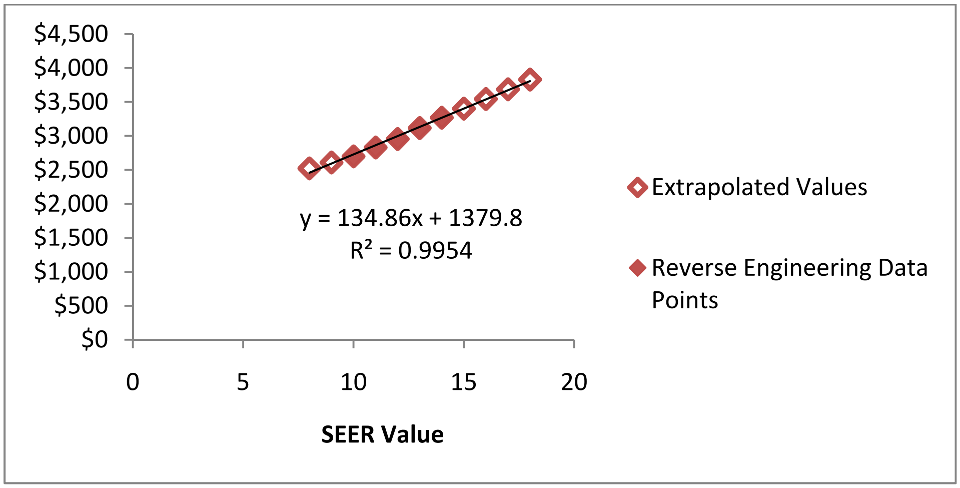

**Figure 3.4: Consumer Price Model for CAC Purchase and Installation**

## 3.2 Shipping

To estimate the shipping distance each unit traveled, the locations of several major manufacturing facilities producing residential central air conditioning units were located by searching manufacturers' websites and annual reports. The results are presented in Table 3.4.

**Table 3.4: Major Residential Air Conditioner Manufacturing Locations**

| Location | Manufacturer | Source | Latitude | Longitude |
|---|---|---|---|---|
| **Marshalltown, IA** | Lennox | Company Website | 42.1 | -92.9 |
| **Tyler, TX** | Trane | 2006 Annual Report | 32.4 | -95.3 |
| **Houston, TX** | Goodman | 2008 Annual Report | 29.8 | -95.4 |
| **Fayetteville, TN** | Goodman | 2008 Annual Report | 35.2 | -86.6 |
| **Fort Smith, AR** | Rheem | Company Website | 35.4 | -94.4 |

The approximate latitude and longitude for each location being modeled was used to determine the distance, d, between the destination of each manufacturing site using the haversine formula,

$$\mathrm{d} = \cosh^{-1}(\sin(lat_1)) \times \sin(lat_2) \times \cos(lat_1) \times \cos(\, lat_2) \times \cos(lon_2 - lon_1) \times 6371\ km$$

where $lat_1$ and $lon_1$ refers to the latitude and longitude of the origin and the $lat_2$ and $lon_2$ refers to the latitude and longitude of the destination.

The distance values from the function given above were compared to driving distances found with Google maps. As a result, it was found that a multiplier of 1.25 could be used to better approximate the additional distance required by road travel. The weight function described in Section 3.1.3 was used to approximate the shipping weight of the outdoor units. The weight of the indoor unit was estimated at 19.5 kg for 3 ton units based on averages from product data sheets.

These distance and weight values along with the energy and greenhouse gas intensity factors for a 28 metric ton diesel truck from the SimaPro database were used to model transportation burdens.

## 3.3 Use

The annual energy use of the unit was calculated by multiplying the efficiency of the unit by the estimated cooling load hours of each location. Cooling load hours (CLH) are an estimate of the number of hours an air conditioning unit would need to run continuously at a full load to consume the equivalent of its annual energy demand. Figure 3.5 is an example of a CLH map published by the American Heating and Refrigeration Institute (2008). The values used in this study where drawn from the DOE energy savings calculator for Energy Star CACs which agree with the AHRI CLH map values.

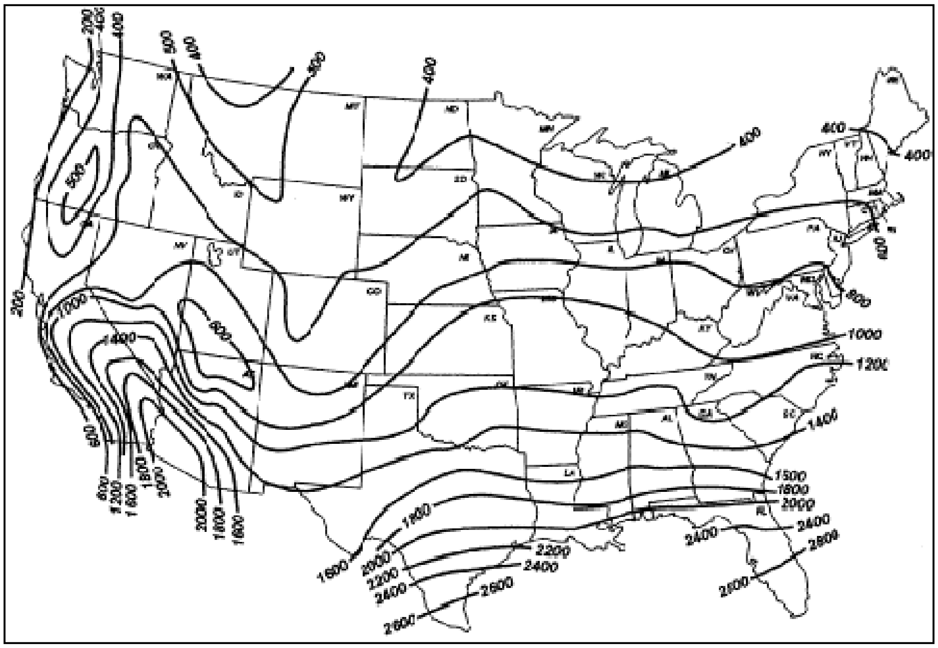

Figure 3.5: Cooling Load Hours for the United States (AHRI, 2008)

The impact of electricity generated to power CACs is evaluated based on that region's NERC grid as shown in Figure 3.6. Factors for calculating the primary energy consumed and GHG emitted for each kWh of electricity delivered was based on life cycle inventories by Kim and Dale (2005).

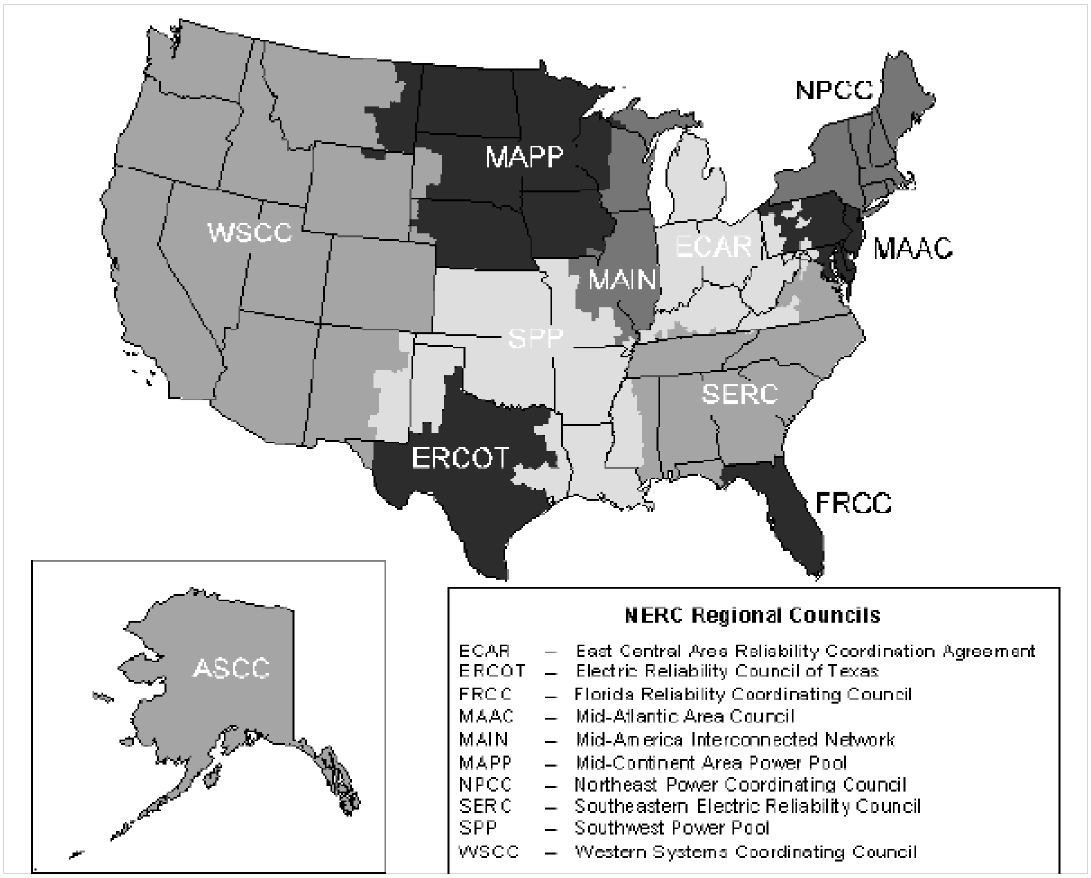

**Figure 3.6: North American Electric Reliability Corporation Grids for the Contiguous United States and Alaska**[a]

a) Grid regions frequently change as a result of restructuring and individual utilities switching between regions. Most notability in 2006, MAAC, ECAR, and portions of MAIN merged to form the ReliabilityFirst Corporation (RFC). EIA data and publications continue to use the old grid divisions and thus these old regions were used in this analysis as well.

In terms of GHG emissions, both the indirect emissions from electricity generation and the direct emissions from refrigerant leakages are accounted for in order to find the total environmental warming impact (TEWI) for the operation of the equipment. The direct emissions are dependent on the leakage rate of the unit. Based on input from AHRI, Sand et al. (1997) used annual leak rates of 4% of refrigerant charge for 1996 model year equipment and 2% for 2005 model year equipment when calculating GHG impacts of residential air conditioning equipment. It was assumed that through better product engineering and improved manufacturing techniques the rate of refrigerant loss would decline. In this analysis, a 4% leakage rate was used for years prior to and including 1996 and a 2% rate was used for the years 2005 and after with a linear interpolation used to calculate rates from 1997 to 2004.

It was assumed that the refrigerant leakage is discovered and corrected during the course of periodic maintenance servicing. While in reality, the typical CACs may not be serviced annually, the model allocates the energy and CO2 emissions associated with replacing lost refrigerant to the year in which the refrigerant is lost. The energy and GHG burdens for the replacement refrigerant are the same as those for the initial refrigerant manufacture.

### 3.3.1 Season Energy Efficiency Ratio

In 1979, the Seasonal Energy Efficiency Ratio (SEER) metric was established as an efficiency measure for central air conditioning equipment. Previously, the efficiency of CACs was only measured using the Energy Efficiency Ratio (EER). EER is a steady-state efficiency measure of BTUs of cooling provided per kWh of electricity consumed at an outdoor temperature of 95°F. This metric continues to be used for measuring the efficiency of room air conditioners. Since a CAC's efficiency varies based on outdoor temperature (the cooler the outdoor temperature the greater the efficiency of the unit, the hotter the less efficient), the SEER metric was created to provide a better indicator of the overall efficiency experienced over the course of an entire cooling season for a typical U.S. climate. For most CAC units, 82°F is used as an average operating condition thus the SEER is the based on the EER at that temperature with some correction for inefficiency from cycling on and off that occurs while operating at part load conditions.

A major criticism of the SEER metric is that by designing it for a typical US climate, it does not represent the performance of an air conditioner in more extreme climates. The southwestern United States tends to be hot and dry and thus requires more sensible cooling, while the southeast it tends to be hot and humid requiring more latent cooling. In cities like Las Vegas and Fresno where a significant portion of the cooling load occurs at or above 95°F, the performance of a CAC is often significantly lower than the nominal SEER value (Henderson & Sachs, 2006).

In an effort to account for these differences, a simple submodel was developed to better predict the actual performance of an air conditioner based on the climate of a particular location. The model uses an alternative AHRI rating procedure to create a modified SEER based on the location being modeled instead of a national average. This bin-based calculation method of SEER has been used by Henderson and Sacs (2006) in studying the performance of CAC in various US cities. The method involves collecting weather data to create temperature bins for temperatures above 65°F in 5 degree increments. The efficiency and capacity of the unit is known for each of the temperature bins. The number of hours in each bin is used to find an expected efficiency of the unit over the course of the cooling season. A summary of the bin-based SEER calculation method is shown in Table 3.5.

**Table 3.5: Summary of Bin-Based Methods to Calculate SEER (Henderson & Sachs, 2006)**

$$SEER_{bin} = \frac{Annual\ Cooling}{Annual\ Energy\ Use} = \frac{\sum q(T_j) \times n_j \times CLF}{\sum e\,(T_j) \times n_j \times \frac{CLF}{PLF}}$$

where:

$q(T_j)$ - trend for AC cooling capacity as a function of ambient temperature
$e(T_j)$ - trend for AC cooling energy used as a function of ambient temperature
$T_j$ - ambient temperature in the j$^{th}$ bin
$n_j$ - number of hours in the j$^{th}$ bin

and where:

$$CLF = \frac{BL(T_j)}{q(T_j)}$$

$$BL(T_j) = \frac{q(95)}{1.1} \times \frac{(T_j - 65)}{(95 - 65)}$$

$$PLF = 1 - C_d \times (1 - CLF)$$

$CLF$ - cooling load fraction
$PLF$ - part load fraction (degrades efficiency at part load)
$BL(T_j)$ – building cooling load line
(assuming the AC unit is 10% oversized at 95°F and load goes to zero at 65°F)
$C_d$ – cooling degradation factor (assumed to be 0.10 in this study)

In the submodel, weather profiles based on meteorological data from 1961 to 2005 found in the Typical Meteorological Year 3 (TMY3) database were used to create temperature bins for the various locations (NREL, 2008). For the submodel, a 0.1 cyclical degradation factor was assumed (Doughery, Filliben, & Aviles, 2002). The efficiency and capacity of R-410a units decreases more quickly at higher ambient temperatures than for R-22 units and as a result separate performance curves were used. The actual capacity and efficiency performance curves were derived from results from Payne and Domanski (2002) for both R-22 and R-410a units. Multipliers to correct the nominal SEER were found using this method for each location. The outcome for cities considered is shown in Table 3.6.

**Table 3.6: SEER Adjustment Factors Derived from Bin Calculations**

| | R-22 | R-410a |
|---|---|---|
| **Ann Arbor** | 1.010 | 1.040 |
| **Los Angeles** | 1.051 | 1.098 |
| **Miami** | 0.991 | 1.013 |
| **New York** | 1.002 | 1.028 |
| **San Antonio** | 0.975 | 0.990 |
| **Wichita** | 0.977 | 0.994 |

These values are similar to those calculated by Henderson and Sacs (2006) using their bin analysis. For instance, their analysis resulted in a 1.010 adjustment factor for Miami, 1.026 for

New York, and 1.030 for Ann Arbor (Detroit). The analysis did not specify what refrigerants were being considered, but they appear closer to the R-410a values calculated in this research.

### 3.3.2 Deterioration of Energy Performance

Many factors can contribute to changes in the operating performance of a CAC over time. Fouling of the coils reduces heat transfer lowering system efficiency. The loss of refrigerant can reduce the performance of the system especially in the case of fixed orifice expansion controls (PG&E, 2001). These factors leading to performance degradation stem from a lack of maintenance. A properly maintained system should not suffer a performance drop off. In this research, regular maintenance is assumed and thus no deterioration in energy performance is expected.

## 3.4 Repair and Maintenance

Repair and maintenance activities were modeled based on data from the DOE rulemaking analysis (2002). Maintenance includes tasks like checking refrigerant levels and cleaning coils. It is assumed that average annual cost of maintenance is $46 regardless of the unit. Repairs include replacing any damaged or failed components in the system. This excludes the cost of a replacement compressor, which is modeled separately in Year 14. The repair costs are assumed to increase with increasing unit efficiency. In the DOE analysis, the repair cost remained constant from year to year. In this study, the repair cost was assumed to increase linearly with the age of the unit, but the overall repair cost over the life of the unit remained the same. This was done to acknowledge that units are more likely to fail as they age and that repairs early in the product's lifetime are typically covered by product warranties.

Energy and GHG emissions associated with the replacement of the compressor were included in the analysis and assumed to be the same as the initial compressor sold with the unit. Energy and GHG emissions associated with other maintenance and repair activities were assumed to be negligible. Figure 3.7 shows the maintenance, repair, and compressor replacement cost for a 13 SEER CAC over its lifetime.

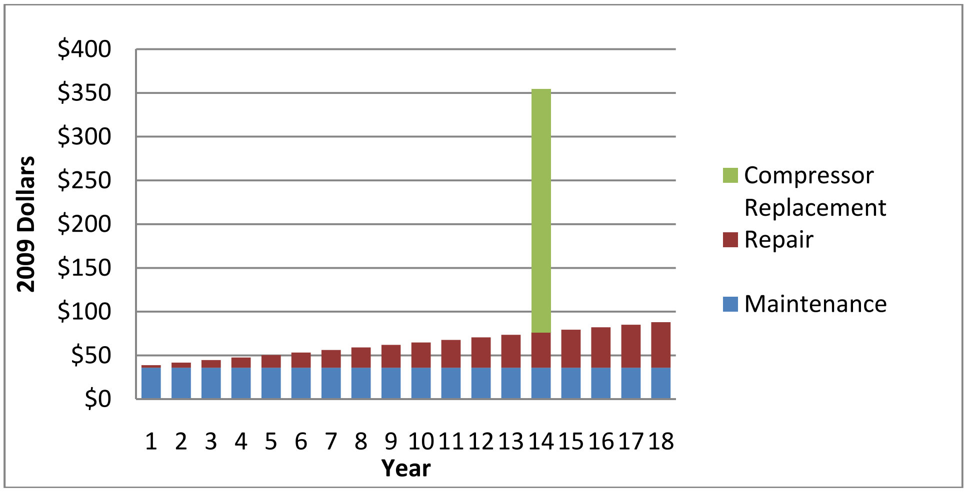

Figure 3.7: Lifetime Repair and Maintenance Cost Distribution of 13 SEER CAC

## 3.5 End-of-Life

It was assumed that the CAC unit is removed at the end of life and 85% of the refrigerant is recovered (Arthur D. Little, Inc., 2002). Since the units are constructed from highly recyclable metals, it is assumed that 90% of the unit is recycled at end of life. The remaining material is assumed to be landfilled. The energy and GHG emission factors compiled by Kim (2003) were used to calculate the burdens associated with disposal.

## 3.6 Life Cycle Energy and GHG Profiles

The energy, GHG emissions, and consumer costs associated with an average 2009 CAC unit (SEER = 13.9) operating in Ann Arbor are shown in Figure 3.8 and Figure 3.9 below for the various phases of the lifecycle. These results include the dynamic parameters presented in Chapter 4 in order to model the 2009 unit.

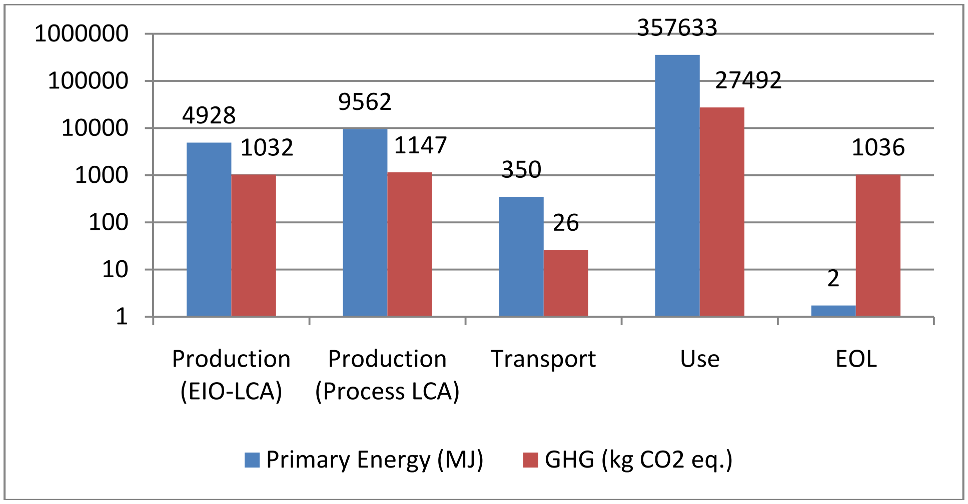

**Figure 3.8: Life Cycle Energy Consumption and GHG Emissions of New Unit in Ann Arbor, MI (2009 -2025)**

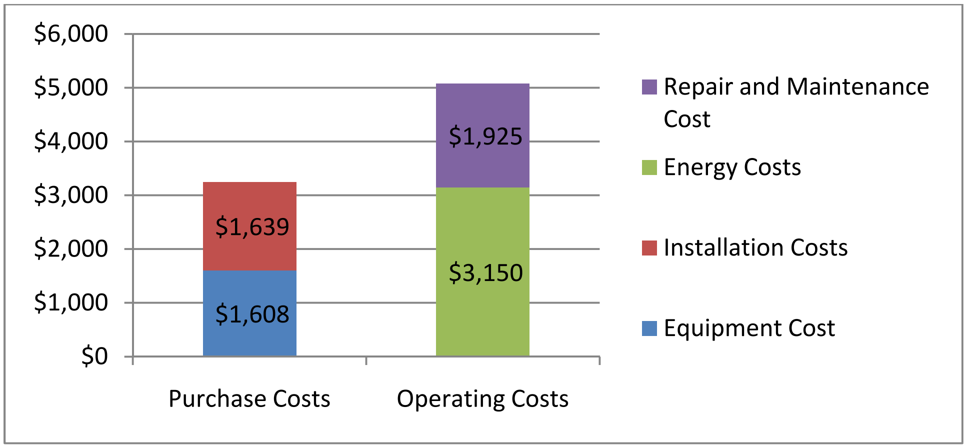

**Figure 3.9: Life Cycle Cost of New Unit in Ann Arbor, MI (2009-2025)**

# 4 Dynamic Life Cycle Inventory Parameters

## 4.1 Energy Efficiency

The vast majority of consumers purchase CAC units at the level of the minimum standard. In 2007, the year following the establishing of the new 13 SEER standard about 5 out of 6 units sold were 13 SEER units (Skaer, 2007). Following the establishment of the 10 SEER standard, gradually a larger segment of homeowners began to purchase higher efficiency units thus raising the average efficiency of units sold in the following years. It is expected that the average efficiency of units sold will continue to increase in the similar manner. The increase in average efficiency following the previous federal standard, approximately 0.07 SEER per year, was used to project the rate of average efficiency growth in this research. Several scenarios were created to anticipate the effects of the next federal standard scheduled to take effect in June of 2016. The base case assumes that no new standard is adopted and efficiency continues to increase along the same trajectory. The remaining scenarios consider the adoption of a new standard of 15, 16, or 17 SEER. These efficiency scenarios are represented in Figure 4.1.

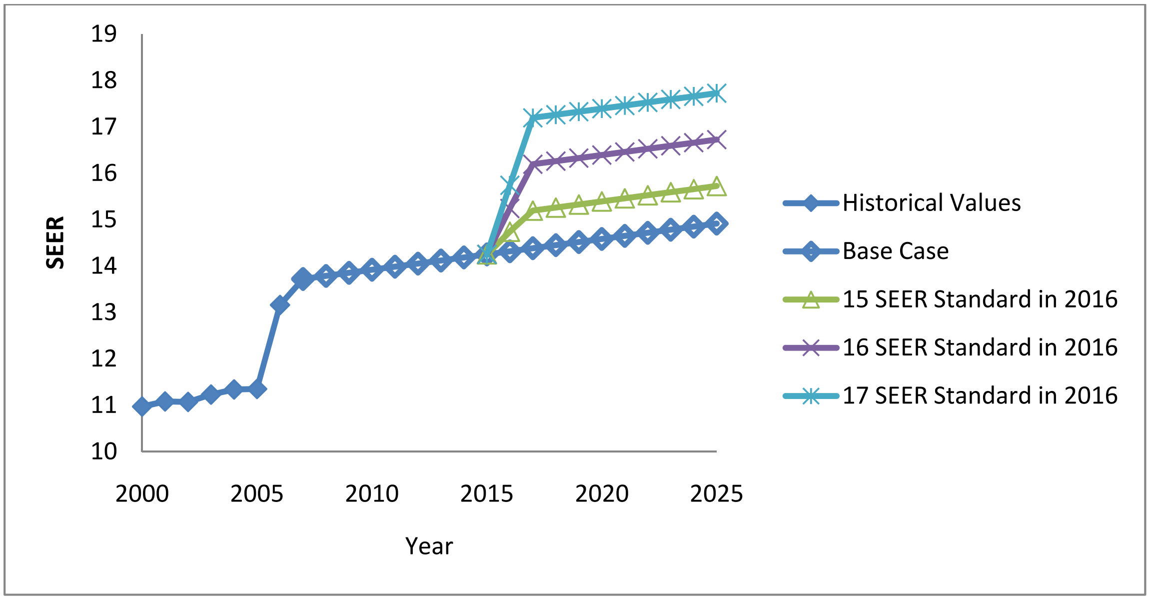

**Figure 4.1: Average CAC Efficiency Improvement Scenarios**

## 4.2 Material Contents

The mass, design, and cost of the components of the CAC are assumed to be dependent on the efficiency of the unit being considered not on the year of manufacture. The assumption is that improving efficiency forces units to become larger thus demanding more energy and generating more GHG emissions during the production of the unit. Since the average annual efficiency tends to increase, the burdens of producing a new unit tends to increase over time as well. Variability in commodity prices and their effect on the ultimate consumer cost are ignored.

*Refrigerants*

As described in Section 3.3, the leakage was assumed to decrease from 4% to 2% of refrigerant mass during the time period of the study. In addition, the refrigerant was modeled as completely changing over from R-22 to R-410a by 2010. Figure 4.2 shows the changeover model based on estimates from the industry (Zellmer, 2008).

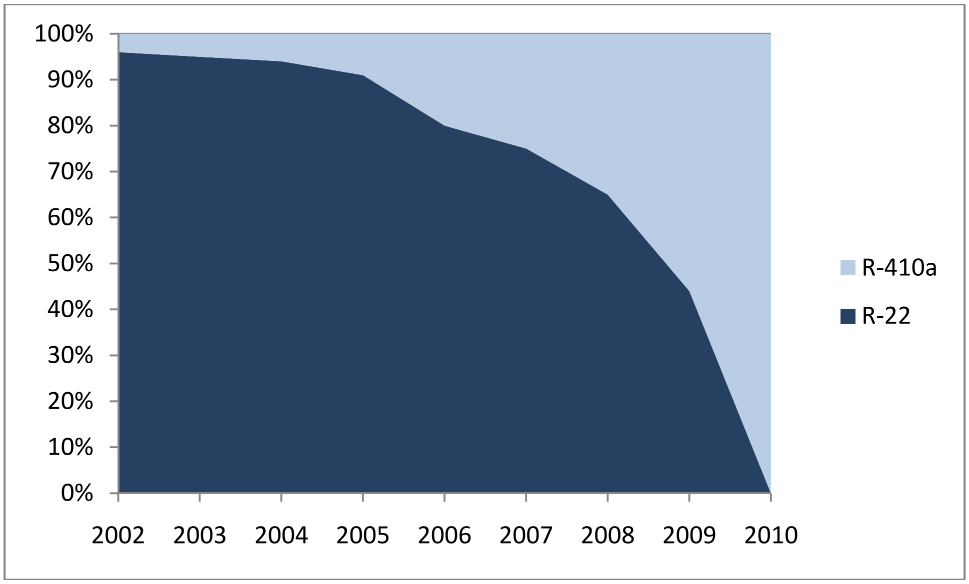

**Figure 4.2: Growth in R-410a Market Share of Residential CAC Market**

## 4.3 Energy Intensity

Over time the energy required to produce goods generally decreases as processes are streamlined, waste is reduced, and new more efficient manufacturing technologies emerge. A method for estimating the changes in energy intensity of basic materials was utilized by Kim while modeling the life cycle of a mid-sized car (2003). These values were used in this study for the period from 1985 to 1998. Values after 1998 were updated with actual data that has become available since Kim's work. The same techniques for estimating future energy intensities were also used to extend the index to 2025. A more detailed description of the various data sources used and the resulting material index is given in the Appendix. This decrease in the energy and GHG intensity of the raw materials used to make the CAC components counteracts the tendency of increasing environmental burdens due to the need to make larger, more energy efficient components.

The proportion of energy required and GHG emitted from the production of each major type of raw material and from the manufacturing of the components was found from the SimaPro analysis of the outdoor unit and indoor unit. This allowed for scaling of the energy and GHG burdens associated with the CAC components for each model year based on the changing energy intensity of the raw materials and manufacturing in that particular year.

## 4.4 Life-Cycle Cost Analysis

In the model, it is assumed that the initial cost depends only on unit efficiency. Therefore, average CAC efficiency growth translates into price increases over time. The DOE (2002) engineering analysis, which served as the basis for this relationship, modeled the producer cost of several different basic units of various efficiencies produced at very high volumes.

*Electricity grid*

The primary energy consumption and GHG emissions associated with the individual NERC grids were assumed to remain constant until 2007. Afterward, the primary energy input and GHG output for the use phase were scaled based on projections from the Annual Energy Outlook (AEO) for fossil fuel intensity and for GHG intensity of each grid until 2025 (2009).

Changes in the cost of electricity were also considered. Historical, electricity costs are based on monthly, state-level residential prices dating back to 1990 (EIA, 2009d). TMY3 temperature data was used to develop a monthly profile of the proportion of annual CDDs for each location to estimate the expected electricity price for an air conditioner over the course of a year. Prior to 1990, the local electricity price is assumed to fluctuate in proportion to the national annual average residential electricity price (EIA, 2009c). Future projections for prices at the NERC level were taken from AEO (2009). All costs were adjusted to 2009 dollars based on GDP deflating factors in the Annual Energy Review (2008) and AEO (2009).

# 5 Results and Discussion

## 5.1 Model Application to Central Air Conditioning Units

The LCO method was used to find the optimal replacement timelines for a residential CAC in order to minimize energy consumption, GHG emissions, and cost to the consumer between 1985 and 2025. The DOE assumes the expected lifetime of a CAC is 18.4 years (DOE, 2002). Since the opportunity to replace was evaluated at the beginning of each year, an 18 year lifetime was used instead. It was assumed that a CAC could not exceed this lifetime.

The model was applied to six US cities: Ann Arbor, MI; Los Angeles, CA; Miami, FL; New York, NY; San Antonio, TX; and Wichita, KS. These cities were chosen to sample a variety of climates, states, and NERC regions. Both the process LCA and EIO-LCA results for the creation of the unit as described in Sections 3.1.1 and 3.1.2 were used separately to compare the impacts on the results.

## 5.2 Optimal Lifetimes of Central Air Conditioning Units

The optimal replacement schedules for a CAC operating in Ann Arbor and San Antonio assuming no updated standard in 2016 is shown in Table 5.1 and Table 5.2 below. Results for other cities are presented in the Appendix. Starting with the assumption that a new unit was purchased at the start of 1985, the table lists the year a unit should be replaced in order to minimize each objective. The energy, GHG, and cost impacts for each of the 3 optimal replacement schedules are shown. The percentage increase over the optimum is also presented. Both the process-based and EIO results for the production burdens where used in the analysis and the results are given separately.

**Table 5.1: LCO Results for Ann Arbor and San Antonio Using Process LCA Results**

| | | | Life Cycle Impacts | | | % Deviation from the Optimum | | |
|---|---|---|---|---|---|---|---|---|
| **City** | **Objective** | **Schedule** | **Energy (MJ)** | **GHG (kg CO2 eq.)** | **Cost (2009$)** | **Energy** | **GHG** | **Cost** |
| **Ann Arbor** | **Energy** | 1985, 1992, 1998, 2007, 2014 | 1,063,000 | 90,300 | 26,500 | --- | 2.4 % | 22.3 % |
| | **GHG** | 1985, 1992, 2010 | 1,081,000 | 88,300 | 22,000 | 1.6 % | --- | 1.7 % |
| | **Cost** | 1985, 1995, 2008 | 1,084,000 | 89,100 | 21,600 | 2.0 % | 1.0 % | --- |
| **San Antonio** | **Energy** | 1985, 1989, 1992, 1998, 2006, 2007, 2012, 2019 | 3,586,000 | 218,400 | 58,000 | --- | 2.0 % | 27.3 % |
| | **GHG** | 1985, 1992, 2006, 2010 | 3,631,000 | 214,100 | 48,100 | 1.2 % | --- | 5.5 % |
| | **Cost** | 1985, 1995, 2008 | 3,709,000 | 217,400 | 45,600 | 3.4 % | 1.5 % | --- |

**Table 5.2: LCO Results for Ann Arbor and San Antonio Using EIO-LCA Results[a]**

| City | Objective | Schedule | Life Cycle Impacts | | | % Deviation from the Optimum | | |
|---|---|---|---|---|---|---|---|---|
| | | | Energy (MJ) | GHG (kg CO2 eq.) | Cost (2009$) | Energy | GHG | Cost |
| Ann Arbor | Energy | 1985, 1989, 1992, 1998, 2006, 2010, 2018 | 1,042,000 | 92,600 | 32,000 | --- | 5.4 % | 47.9 % |
| | GHG | 1985, 1992, 2010 | 1,066,000 | 87,800 | 22,000 | 2.4 % | --- | 1.7 % |
| | Cost | 1985, 1995, 2008 | 1,071,000 | 88,800 | 21,600 | 2.8 % | 1.1 % | --- |
| San Antonio | Energy | 1985, 1988, 1989, 1992, 1995, 1998, 2003, 2006, 2007, 2010, 2015, 2020 | 3,549,000 | 224,100 | 69,300 | --- | 4.9 % | 52.0 % |
| | GHG | 1985, 1992, 2006, 2010 | 3,612,000 | 213,600 | 48,100 | 1.8 % | --- | 5.5 % |
| | Cost | 1985, 1995, 2008 | 3,696,000 | 217,000 | 45,600 | 4.2 % | 1.6 % | --- |

a) EIO-LCA results refer to modeling of the unit production. See Section 3.1 for details.

The replacement intervals to minimize energy are much shorter than when minimizing GHG or cost in both the Ann Arbor and San Antonio scenarios. This frequent replacement leads to a significant increase in cost ranging from 22 to 52% companied to the cost optimal solutions in each case. The GHG replacement schedules are the same across both scenarios. Switching from a cost optimal solution to a GHG optimal solutions results in a more modest 1.7-5.5% increase in cost. The optimal cost replacement schedules are also the same since cost to the consumer is independent of the assumptions made for production burdens.

Across all the locations examined, the energy optimal replacement schedule always required the most replacements ranging from 5 to 15 total units owned. The GHG optimal solution required between 3 to 5 units and the cost optimal solution required 3 units in all cases. In fact, the cost optimal solution for all cites called for the first replacement to occur in 1995 and the second to occur in 2008 with the exception of Miami, where the first replacement would occur in 1992. It is interesting to note that for most locations, the holding period to minimize consumer cost requires that each new unit be held longer than the previous one starting with 10 years, then 13 years, and finally 18 years, which is the maximum assumed life span. This would suggest that there is a diminishing financial return from replacing with progressively higher efficiency units that makes it more cost effective to hold on to each CACs longer. For instance after the first replacement, a certain financial savings is realized, but this reduces the amount of financial savings that can be achieved from future replacements.

The locations with the highest demand for space cooling had the most replacements when optimizing for energy and GHG, while more moderate climates had fewer replacements. This result agrees with expectations. The more a CAC is used the larger the operating burdens are relative to the production and disposal burdens. It becomes more beneficial to upgrade to more efficient units more frequently, since savings in the operational burdens can offset these additional production and disposal burdens more quickly.

## 5.3 Comparing Optimal Replacement to Typical Replacement Patterns

It is useful to compare the optimal results obtained in Section 5.3 to those for a typical replacement pattern. It is difficult to know the typical age at replacement. Industry officials contend that the average age of replacement is anywhere between 11 to 15 years (DOE, 2008). A typical lifetime of 13.67 years was chosen because it allows for three units to be purchased and used between 1985 and the end of 2025. If another length of time was selected, the results may have been subject to distortion since at least one unit would have to be disposed of prematurely. For instance, if a 12 year lifetime was selected replacements would occur in 1997, 2009, and 2021. However, the 2021 unit would only be in use for 5 years before retiring it again at the end of 2025 and the full benefits of the operational savings of energy, GHG emissions, and cost would not be realized.

Since the model only allowed for replacement at the start of each year, three scenarios were created where the CAC was replaced after every 14 years with one interval of 13 years that rotated between the first, second, and third period in the respective scenarios. The impacts generated from these three replacement schedules were very similar and thus they were averaged together to represent a single typical replacement scenario.

The optimal results were then compared to the impacts that were associated with a typical replacement pattern starting in 1985. These results are shown for Ann Arbor and San Antonio in Table 5.3 and Table 5.4. Results for other locations are given in the Appendix.

**Table 5.3: Comparison of Optimal Replacements to Typical Replacement Scenario Using Process LCI Data**

| | | Life Cycle Impacts of Typical Replacement | | | Savings from Optimal vs. Typical Replacement | | |
|---|---|---|---|---|---|---|---|
| City | Objective | Energy (MJ) | GHG (kg CO2 eq.) | Cost (2009$) | Energy | GHG | Cost |
| Ann Arbor | Energy | 1,115,000 | 90,400 | 22,200 | 4.7 % | 0.1 % | (19.3 %) |
| | GHG | 1,115,000 | 90,400 | 22,200 | 3.1 % | 2.4 % | 0.8 % |
| | Cost | 1,115,000 | 90,400 | 22,200 | 2.8 % | 1.4 % | 2.4 % |
| San Antonio | Energy | 3,818,000 | 222,400 | 46,700 | 6.1 % | 1.8 % | (24.2 %) |
| | GHG | 3,818,000 | 222,400 | 46,700 | 4.9 % | 3.7 % | (2.9 %) |
| | Cost | 3,818,000 | 222,400 | 46,700 | 2.8 % | 2.3 % | 2.5 % |

**Table 5.4: Comparison of Optimal Replacements to Typical Replacement Scenario Using EIO-LCA Results**

| | | Life Cycle Impacts of Typical Replacement | | | Savings from Optimal vs. Typical Replacement | | |
|---|---|---|---|---|---|---|---|
| City | Objective | Energy (MJ) | GHG (kg CO2 eq.) | Cost (2009$) | Energy | GHG | Cost |
| Ann Arbor | Energy | 1,101,000 | 90,000 | 22,200 | 5.4 % | (2.9 %) | (44.3 %) |
| | GHG | 1,101,000 | 90,000 | 22,200 | 3.1 % | 2.4 % | 0.8 % |
| | Cost | 1,101,000 | 90,000 | 22,200 | 2.7 % | 1.3 % | 2.4 % |
| San Antonio | Energy | 3,803,000 | 222,000 | 46,700 | 6.7 % | (1.0 %) | (48.3 %) |
| | GHG | 3,803,000 | 222,000 | 46,700 | 5.0 % | 3.8 % | (2.9 %) |
| | Cost | 3,803,000 | 222,000 | 46,700 | 2.8 % | 2.2 % | 2.5 % |

a) EIO-LCA results refer to modeling of the unit production. See Section 3.1 for details.

The replacement of CACs according to the optimal patterns offers the potential to reduce each objective between 2.4 to 6.7 % for these two cities. Again, the frequent replacement for energy optimization leads to a significant cost penalty compared to a typical replacement pattern.

## 5.4 Impact of Future Federal Standards

The same analysis was repeated for the various scenarios modeling the adoption of a new federal efficiency standard in 2016. New efficiency standards of 15, 16, and 17 SEER were modeled for the various cities. Figure 5.1 and Figure 5.2 show the potential reductions in energy consumption and GHG emissions that could be achieved using LCO under these federal standard scenarios in Ann Arbor and San Antonio. The results of the optimal cost replacement schedules did not change as a result of increasing the efficiency standard. Since the final replacement occurs in 2008 in the cost optimal schedule, increasing the minimum efficiency standard in 2016 has no effect on lifecycle cost from 1985 through 2025.

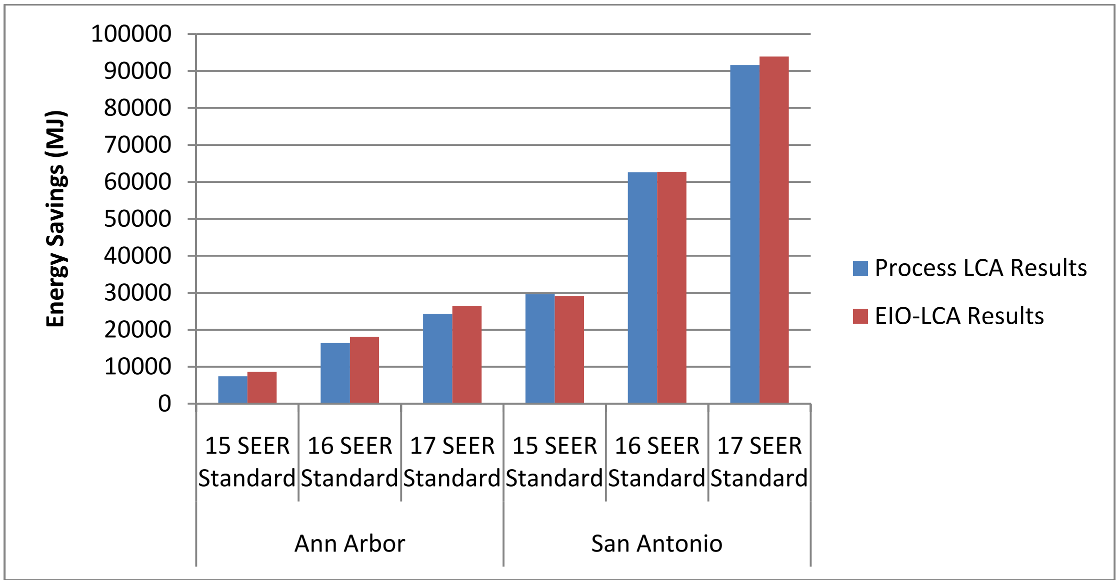

**Figure 5.1: Potential Energy Savings Using LCO under Different Federal Efficiency Standard Scenarios**

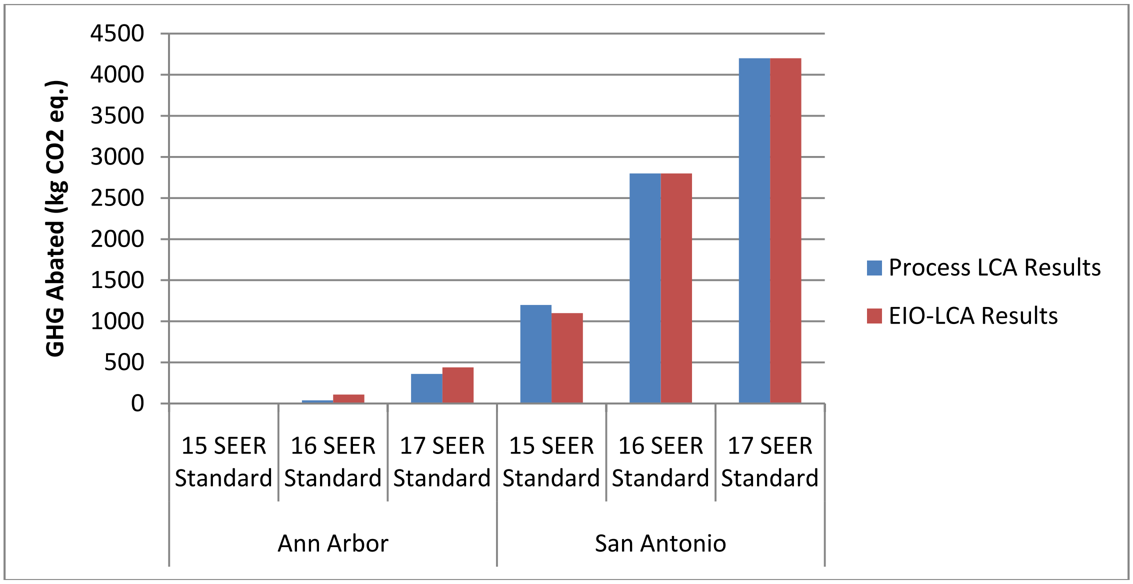

**Figure 5.2: Potential GHG Avoided Using LCO under Different Federal Efficiency Standard Scenarios**

The optimal replacement results are shown for a 16 SEER CAC in Ann Arbor and San Antonio in Table 5.5 and Table 5.6. Results for the other efficiency scenarios are given in the Appendix.

**Table 5.5: LCO Results for Ann Arbor and San Antonio with an Updated 16 SEER Standard Using Process LCI Results**

| | Objective | Schedule | Life Cycle Impacts | | | % Deviation from the Optimum | | |
|---|---|---|---|---|---|---|---|---|
| | | | Energy (MJ) | GHG (kg CO2 eq.) | Cost (2009$) | Energy | GHG | Cost |
| **Ann Arbor** | **Energy** | 1985, 1992, 1998, 2007, 2017 | 1,047,000 | 89,600 | 26,500 | --- | 1.5 % | 22.7 % |
| | **GHG** | 1985, 1992, 2007, 2017 | 1,051,000 | 88,200 | 24,400 | 0.4 % | --- | 12.6 % |
| | **Cost** | 1985, 1995, 2008 | 1,084,000 | 89,100 | 21,600 | 3.6 % | 1.0 % | --- |
| **San Antonio** | **Energy** | 1985, 1989, 1992, 1998, 2006, 2007, 2011, 2017 | 3,524,000 | 215,200 | 57,600 | --- | 1.9 % | 26.4 % |
| | **City** | 1985, 1992, 2007, 2017 | 3,570,000 | 211,300 | 47,100 | 1.3 % | --- | 3.5 % |
| | **Cost** | 1985, 1995, 2008 | 3,709,000 | 217,400 | 45,600 | 5.3 % | 2.9 % | --- |

**Table 5.6: LCO Results for Ann Arbor and San Antonio with an Updated 16 SEER Standard Using EIO-LCA Results**[a]

| | Objective | Schedule | Life Cycle Impacts | | | % Deviation from the Optimum | | |
|---|---|---|---|---|---|---|---|---|
| | | | Energy (MJ) | GHG (kg CO2 eq.) | Cost (2009$) | Energy | GHG | Cost |
| **Ann Arbor** | **Energy** | 1985, 1989, 1992, 1998, 2006, 2010, 2017 | 1,024,000 | 91,700 | 32,100 | --- | 4.5 % | 48.3 % |
| | **GHG** | 1985, 1992, 2007, 2017 | 1,032,000 | 87,700 | 24,400 | 0.8 % | --- | 12.6 % |
| | **Cost** | 1985, 1995, 2008 | 1,071,000 | 88,800 | 21,600 | 4.6 % | 1.2 % | --- |
| **San Antonio** | **Energy** | 1985, 1988, 1989, 1992, 1995, 1998, 2003, 2006, 2007, 2010, 2016, 2017 | 3,486,000 | 221,100 | 69,000 | --- | 4.9 % | 51.5 % |
| | **GHG** | 1985, 1992, 2007, 2017 | 3,552,000 | 210,800 | 47,100 | 1.9 % | --- | 3.5 % |
| | **Cost** | 1985, 1995, 2008 | 3,696,000 | 217,000 | 45,600 | 6.0 % | 3.0 % | --- |

a) EIO-LCA results refer to modeling of the unit production. See Section 3.1 for details.

By comparing the optimal results for the energy and GHG objectives among the different scenarios, it is evident that progressively higher efficiency standards from 15 SEER to 16 SEER to 17 SEER will reduce environmental burdens over the time horizon. In the case of the GHG optimization for Ann Arbor, a 15 SEER standard has no effect because the final replacement occurs in 2010, before the new standard takes effect. This boundary effect would disappear if the time horizon was extended. In the 16 SEER scenario, the increase in efficiency and corresponding reduction in GHG emissions during the use phase becomes large enough that it is beneficial to replace after 2017 thus yielding a reduction in GHG emissions.

The results from the efficiency scenario analysis are similar to those in the base case, which did not account for a new efficiency standard. For instance, in the 16 SEER scenario, the energy objective still requires the most replacements and as a result raises the cost dramatically. With the exception of going from 3 to 4 total units in order to minimize GHG emissions in Ann Arbor, the number of replacements does not change in these scenarios relative to the original efficiency scenario.

## 5.5 Impact of Carbon Price

To evaluate the impact of potential carbon pricing, either in the form of a carbon tax or under a cap and trade system, four different carbon costs were assigned to a ton of CO2 equivalent starting in 2009 through 2025. This analysis assumed the full costs of carbon are ultimately passed on to the consumer and no portion of the carbon cost is absorbed by the manufacturer, contractor, or utility. The effect on the optimal cost solution is shown in Table 5.7.

**Table 5.7: Impact of Carbon Price on Cost Optimal Solution**

| City | Carbon Cost (\$/ton of $CO_2$ eq.) | Schedule | Life Cycle Cost (2009\$) |
|---|---|---|---|
| **Ann Arbor** | No Tax | 1985, 1995, 2008 | \$21,600 |
| | \$50 | 1985, 1995, 2008 | \$23,000 |
| | \$100 | 1985, 1995, 2008 | \$24,300 |
| | \$200 | 1985, 1995, 2008 | \$27,000 |
| **San Antonio** | No Tax | 1985, 1995, 2008 | \$45,600 |
| | \$50 | 1985, 1995, 2008 | \$49,200 |
| | \$100 | 1985, 1995, 2008 | \$52,800 |
| | \$200 | 1985, 1995, 2008 | \$60,100 |

Creating a cost of carbon up to \$200 per ton of carbon dioxide had no impact on the actual replacement dates. Since the final replacement date remains 2008, the carbon cost introduced in 2009 would only serve to raise the cost of operating the unit from 2009 until the end of the time horizon.

It is important to note that the model does not reflect changes to the forecast for average efficiency of units sold as a result of carbon pricing. This model also does not reflect changes in the emission factors of the electricity grid as a result of carbon pricing. It is likely that less carbon intensive generation methods would be adopted since a carbon price of \$200 per ton could double or triple the price of electricity in most NERC grids. Finally, these dramatic increases in the price of carbon would also change consumer patterns and reduce air conditioning demand in favor of ceiling fans and other methods of cooling. All of these factors greatly limit the accuracy of the optimization for forecasting actual lifecycle costs under a carbon pricing regime. Instead, these results should be viewed as an upper bound of lifecycle costs over the time horizon.

# 6 Model Extensions

## 6.1 Aligning Cost with Energy and GHG

The results from the optimization of the replacement schedules demonstrate that in every location, optimizing for energy requires much more frequent replacement than when optimizing for GHG or cost. Minimizing GHG emissions in some cases requires more replacements than the cost optimal solution, but more often it requires the same number of replacements, but the timing of those replacements is not the same.

Most consumers are likely to act to minimize their costs. In situations where there is a misalignment between the optimal cost replacement schedules and the other objectives, it is helpful to explore how financial incentives could be used to align the cost optimal solution with the other two objectives. Determining this level of financial incentives, whether they be in the form of utility rebates or tax credits and deductions, is helpful for policy makers looking to influence consumer behavior.

A negative cost was introduced into the model to represent financial incentives available to the consumer for replacing an existing unit. This was done for the specific years in which a replacement was desirable from either an energy or GHG standpoint. A simple algorithm increased the incentive amount in each targeted year until it triggered a replacement in each of those years in the model. The analysis was done using the process LCA results for the production phase. The incentive amount for the base case scenario and a 16 SEER standard scenario are represented in Figure 6.1 and Figure 6.2 respectively.

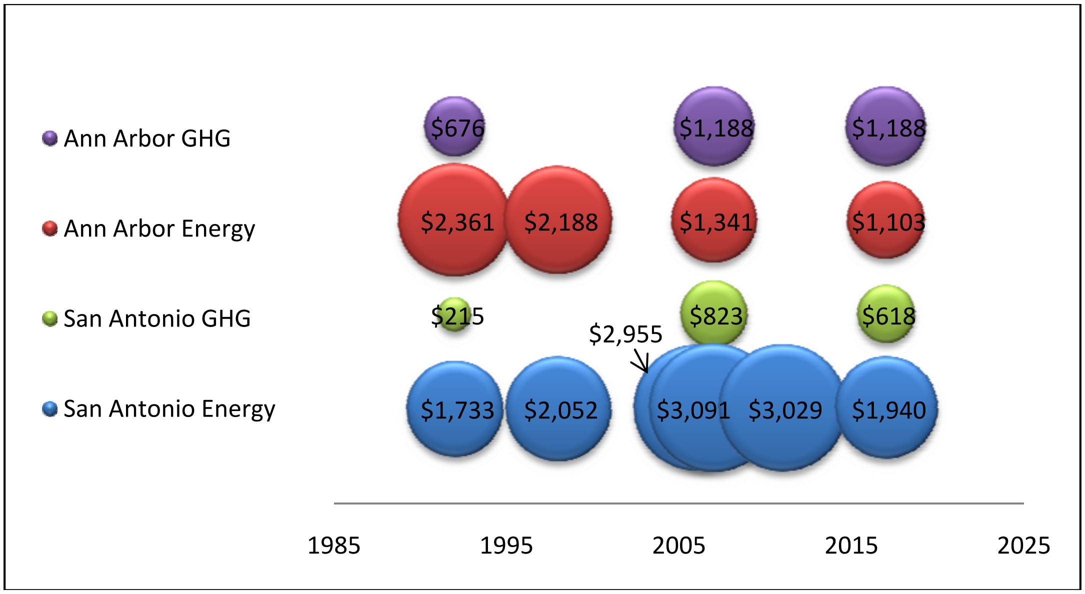

**Figure 6.1: Incentive Level Required to Align Cost Schedule with Energy and GHG Replacement Schedules Assuming Base Case Efficiency Scenario**

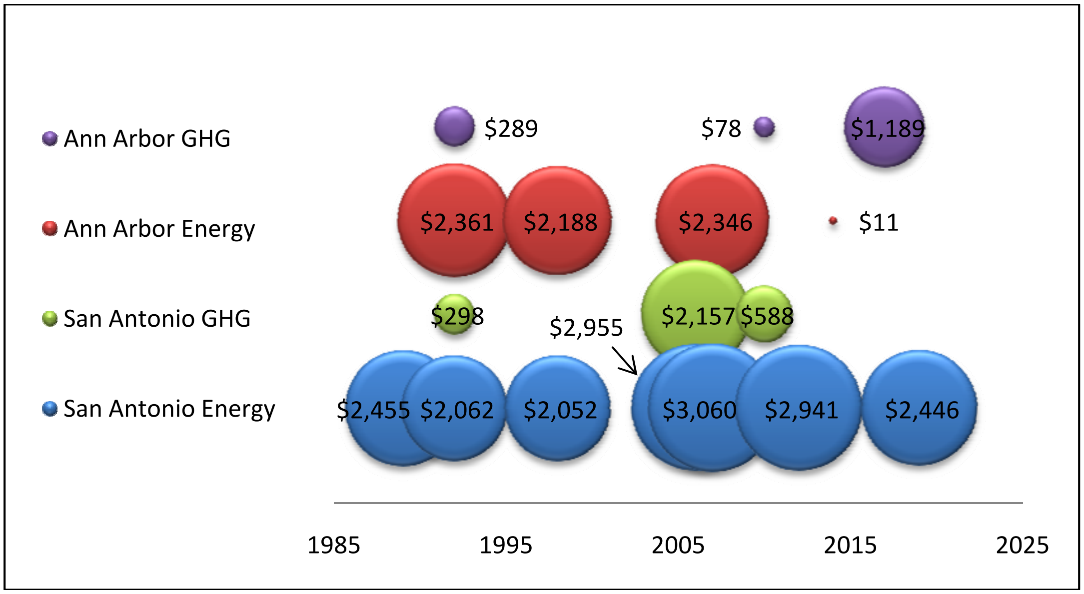

**Figure 6.2: Incentive Level Required to Align Schedule Cost with Energy and GHG Replacement Schedules Assuming 16 SEER Efficiency Scenario**

The time between desired replacements has a significant effect on the magnitude of the incentives that are required to trigger replacement. The closer the replacement years are to one another, the larger the incentives must be to trigger a replacement. For instance, forcing a system replacement after one year of use will require that the incentive be nearly as large as the entire cost of the new system. Consider the base case scenario, the total cost of the incentives for 4 replacements to optimize for energy in Ann Arbor is $6900 while the cost of 7 replacements for San Antonio is $18,000. The more frequent replacement in the case of San Antonio means more incentives are required and because they are closer together means the individual incentives themselves must be larger.

It is useful to understand how effective incentives can be at reducing GHG emissions. The total of all the incentives over the time horizon were calculated for Ann Arbor and San Antonio. Using the corresponding reductions in GHG emissions in going from the original cost optimal schedule to a GHG optimal schedule in both the base case and the 16 SEER efficiency scenario, it was possible to calculate the cost of reducing each metric ton of emitted carbon dioxide. The results are presented in Table 6.1.

**Table 6.1: Cost of Carbon Reduction from Incentives for Accelerated Replacement (in 2009$/mton of $CO_2$ abated)**

| | The Base Case | 16 SEER in 2016 |
|---|---|---|
| **Ann Arbor** | $3,480 | $1,700 |
| **San Antonio** | $510 | $500 |

For the scenarios examined, it would be much more cost effective to provide financial incentives in San Antonio to reduce carbon emissions than to do so in Ann Arbor. While the financial costs are greater for San Antonio, the GHG reductions are even more substantial.

## 6.2 Regional Standards

Under the Energy Independence and Security Act of 2007, the Department of Energy now has the ability to establish one or two regional standards that exceed the federal minimum standard. The creation of a regional standard requires a significant energy savings and be economically justified. To explore this scenario, the southeast region of the country was selected as a potential region for a separate regional standard. States were selected based on CDD and geographic proximity. These are shown in Figure 6.3 below.

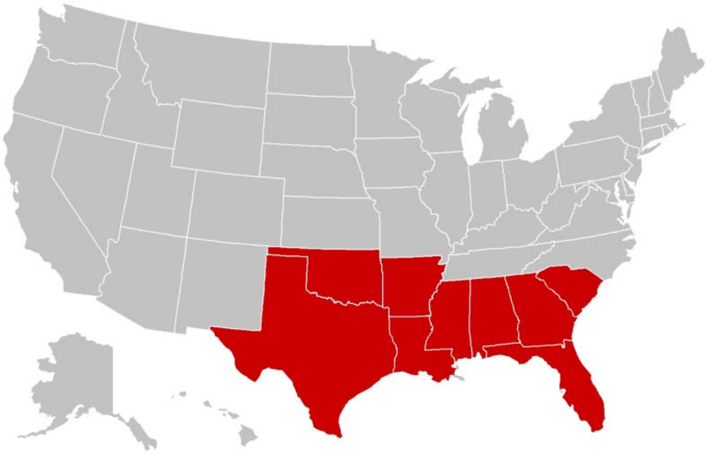

**Figure 6.3: States Considered in a Regional Standards Analysis**

The southwest region, including areas of California, Nevada, Arizona, and New Mexico, could also be a candidate for a separate regional standard, but due to the lower humidity in that region such a standard might also include other cooling metrics in addition to SEER in order to emphasize sensible cooling capacity. The model only uses SEER to model efficiency and thus a regional standard based only on SEER is necessary for evaluation so the southeastern region was selected.

Unlike the previous analysis which assumed a new unit was purchase at the start of 1985, this analysis was done in order to evaluate the impacts from different aged systems from 2009 till 2025. In essence, the model was modified by decreasing the time horizon to start at 2009 and examining the results till 2025. In this case, the environmental burdens and consumers expenses that occur before 2009 are ignored, but the burdens and costs thereafter are considered. The process LCA results are used to model the burdens from the production of subsequent units.

Location profiles were created for each of the states in the region. A population weighted cooling load hour average (U.S. Census Bureau, 2009; Energy Star, 2009) was found for each state. The national temperature distribution was used to calculate the effective SEER for all the states. The largest NERC region by area was used for each state in states where more than one NERC region was present.

It was assumed that a new regional standard of 16 SEER would take place at the start of 2009. While it is more likely that such a standard would be implemented in 2016 along with a revised national standard, this is only 10 years before the end of the time horizon and thus in many optimization scenarios the final replacement would occur before such a regional standard was adopted. Thus for the purposes of understanding the impact of a regional standard, the 16 SEER standard was assumed to begin at the start of 2009. Process LCA results were used for the analysis. The results for selected initial model years for selected states in the region are shown in Table 6.2. Results for all states are given the Appendix.

**Table 6.2: LCO Savings from Regional Standard Compared to Base Case Efficiency Scenario for Select States and Initial Model Years.**

| State | Year of CAC in 2009 | Objective | Base Case Efficiency | | 16 SEER Regional Standard | | Savings from Regional Standard |
|---|---|---|---|---|---|---|---|
| | | | Dates of Optimal Replacement | | Objective | Dates of Optimal Replacement | |
| **AL** | **1997 or before** | **Energy (MJ)** | 2009, 2016 | 913,000 | 2009, 2017 | 793,000 | 13.2 % |
| | | **GHG (CO2 eq.)** | 2009 | 52,700 | 2009 | 46,800 | 11.2 % |
| | | **Cost (2009$)** | 2009 | $13,500 | 2009 | $12,810 | 5.1 % |
| | **2003** | **Energy (MJ)** | 2009, 2016 | 913,000 | 2009, 2017 | 793,000 | 13.2 % |
| | | **GHG (CO2 eq.)** | 2009 | 52,700 | 2009 | 46,800 | 11.2 % |
| | | **Cost (2009$)** | 2003, 2013 | $13,190 | 2003, 2013 | $12,700 | 3.7 % |
| | **2008** | **Energy (MJ)** | 2008, 2015 | 907,000 | 2009, 2017 | 793,000 | 12.6 % |
| | | **GHG (CO2 eq.)** | 2008, 2015 | 51,200 | 2008, 2011 | 46,500 | 9.2 % |
| | | **Cost (2009$)** | 2008, 2016 | $12,610 | 2008, 2013 | $12,190 | 3.4 % |
| **FL** | **1997 or before** | **Energy (MJ)** | 2009, 2013, 2019 | 1,455,000 | 2009, 2017 | 1,260,000 | 13.4 % |
| | | **GHG (CO2 eq.)** | 2009 | 72,200 | 2009 | 63,500 | 12.0 % |
| | | **Cost (2009$)** | 2009 | $20,550 | 2009 | $18,850 | 8.2 % |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **FL** | **2003** | **Energy (MJ)** | 2009, 2013, 2019 | 1,455,000 | 2009, 2017 | 1,260,000 | 13.4 % |
| | | **GHG (CO2 eq.)** | 2009 | 72,200 | 2009 | 63,500 | 12.0 % |
| | | **Cost (2009$)** | 2003, 2013 | $20,430 | 2009 | $18,850 | 7.7 % |
| | **2008** | **Energy (MJ)** | 2008, 2012, 2019 | 1,448,000 | 2009, 2017 | 1,260,000 | 13.0 % |
| | | **GHG (CO2 eq.)** | 2008, 2015 | 70,300 | 2008, 2011 | 63,400 | 9.8 % |
| | | **Cost (2009$)** | 2008, 2016 | $19,510 | 2008, 2013 | $18,340 | 6.0 % |
| **TX** | **1997 or before** | **Energy (MJ)** | 2009, 2016 | 1,084,000 | 2009, 2017 | 939,000 | 13.3 % |
| | | **GHG (CO2 eq.)** | 2009 | 66,200 | 2009 | 58,400 | 11.8 % |
| | | **Cost (2009$)** | 2009 | $16,600 | 2009 | $15,470 | 6.8 % |
| | **2003** | **Energy (MJ)** | 2009, 2016 | 1,084,000 | 2009, 2017 | 939,000 | 13.3 % |
| | | **GHG (CO2 eq.)** | 2009 | 66,200 | 2009 | 58,400 | 11.8 % |
| | | **Cost (2009$)** | 2003, 2013 | $16,360 | 2009 | $15,470 | 5.4 % |
| | **2008** | **Energy (MJ)** | 2008, 2012, 2019 | 1,077,000 | 2009, 2017 | 939,000 | 12.8 % |
| | | **GHG (CO2 eq.)** | 2008, 2015 | 64,300 | 2008, 2011 | 58,100 | 9.8 % |
| | | **Cost (2009$)** | 2008, 2016 | $15,640 | 2008, 2013 | $14,880 | 4.9 % |

The results for all of the states showed that units older than 2003 should be replaced at the start of the time horizon in order to minimize energy or GHG emissions under the base case scenario. Units older than 1997 should also be replaced in 2009 in order to minimize cost. The first replacement follows a similar pattern in the regional standard scenario, but in this case all existing units would be replaced in 2009 in order to minimize energy.

For the model years evaluated, the results under this example regional standard scenario show that consumers in these southeast states who follow a optimal replacement pattern starting in 2009, could expect to reduce life cycle energy consumption by about 13%, GHG emissions by about 9-12%, or cost by 2-8%.

## 6.3 Replacing with Higher Efficiency Units

It is helpful for homeowners with existing CAC units to know when they should replace their CACs. The same time horizon modifications to the model used in the regional standard analysis described in Section 6.2 were also used in this analysis. The 2009 to 2025 time horizon was used to compare the results of purchasing a new unit at the minimum standard or at a higher efficiency unit such as an Energy Star model for homeowners with existing CACs of various model years. It was assumed that in either case the homeowner started out with a unit that had an efficiency of the average unit sold in the year it was purchased. All subsequent purchases were either made at the minimum efficiency level or at the minimum Energy Star qualifying level. This analysis was done assuming a 16 SEER standard in 2016 and that the Energy Star standard would increase to 17.5 SEER at that time. However, since the new standard is scheduled to take effect in June, it was assumed that homeowners would have the opportunity to purchase units at the start of 2016 before the new standard took effect. As a result, 2017 is actually the first year when the standards would change the purchasing decision. According to

Energy Star, the average premium for an Energy Star CAC is $556 (Energy Star, 2009). It was assumed that this price premium would remain constant through 2025. The result for selected model years evaluated in Ann Arbor and San Antonio are shown in Table 6.3 and Table 6.4.

**Table 6.3: Comparison of Impacts of Replacing with a Baseline Model (Assuming 16 SEER Scenario) and an Energy Star Model Under Optimal Replacement in Ann Arbor for Select Years**

| Year of CAC in 2009 | Objective | Baseline Model | | Energy Star Model | | Savings from Energy Star |
|---|---|---|---|---|---|---|
| | | Dates of Units Used | Objective | Dates of Units Used | Objective | |
| **1992** | **Energy (MJ)** | 2009, 2017 | 344,000 | 2009, 2017 | 316,000 | 8.2 % |
| | **GHG (CO2 eq.)** | 2009, 2017 | 29,600 | 2009 | 28,100 | 5.3 % |
| | **Cost (2009$)** | 2009 | $8,240 | 1992, 2010 | $8,830 | (7.1 %) |
| **1997** | **Energy (MJ)** | 2009, 2017 | 344,000 | 2009, 2017 | 316,000 | 8.2 % |
| | **GHG (CO2 eq.)** | 2009, 2017 | 29,600 | 2009 | 28,100 | 5.3 % |
| | **Cost (2009$)** | 1997, 2010 | $8,230 | 1997, 2013 | $8,790 | (6.8 %) |
| **2002** | **Energy (MJ)** | 2009, 2017 | 344,000 | 2009, 2017 | 316,000 | 8.2 % |
| | **GHG (CO2 eq.)** | 2009, 2017 | 29,600 | 2009 | 28,100 | 5.3 % |
| | **Cost (2009$)** | 2002, 2013 | $7,800 | 2002, 2013 | $8,290 | (6.2 %) |
| **2006** | **Energy (MJ)** | 2006, 2017 | 335,000 | 2009, 2017 | 316,000 | 5.6 % |
| | **GHG (CO2 eq.)** | 2006, 2017 | 27,600 | 2006, 2017 | 27,100 | 1.7 % |
| | **Cost (2009$)** | 2006, 2019 | $7,140 | 2006, 2019 | $7,630 | (7.0 %) |

**Table 6.4: Comparison of Impacts of Replacing with a Baseline Model (Assuming 16 SEER Scenario) and an Energy Star Model Under Optimal Replacement in San Antonio for Select Years.**

| Year of CAC in 2009 | Objective | Baseline Model | | Energy Star Model | | Savings from Energy Star |
|---|---|---|---|---|---|---|
| | | Dates of Units Used | Objective | Dates of Units Used | Objective | |
| **1992** | **Energy (MJ)** | 2009, 2017 | 1,131,000 | 2009, 2017 | 1,028,000 | 9.1 % |
| | **GHG (CO2 eq.)** | 2009, 2017 | 69,200 | 2009, 2017 | 64,100 | 7.4 % |
| | **Cost (2009$)** | 2009 | $17,720 | 2009 | $17,330 | 2.2 % |
| **1997** | **Energy (MJ)** | 2009, 2017 | 1,131,000 | 2009, 2017 | 1,028,000 | 9.1 % |
| | **GHG (CO2 eq.)** | 2009, 2017 | 69,200 | 2009, 2017 | 64,100 | 7.4 % |
| | **Cost (2009$)** | 2009 | $17,720 | 2009 | $17,330 | 2.2 % |
| **2002** | **Energy (MJ)** | 2009, 2017 | 1,131,000 | 2009, 2017 | 1,028,000 | 9.1 % |
| | **GHG (CO2 eq.)** | 2009, 2017 | 69,200 | 2009, 2017 | 64,100 | 7.4 % |
| | **Cost (2009$)** | 2002, 2013 | $17,610 | 2002, 2013 | $17,320 | 1.6 % |
| **2006** | **Energy (MJ)** | 2006, 2017 | 1,119,000 | 2009, 2017 | 1,028,000 | 8.1 % |
| | **GHG (CO2 eq.)** | 2006, 2017 | 66,900 | 2009, 2017 | 64,100 | 4.3 % |
| | **Cost (2009$)** | 2006, 2017 | $15,680 | 2006, 2017 | $15,800 | (0.8 %) |

These results show that purchasing Energy Star CACs using LCO schedules result in energy and GHG savings for both Ann Arbor and San Antonio, however the percentage of savings are larger in the case of San Antonio than for Ann Arbor. Generally, replacing with Energy Star units also yielded a cost savings for the homeowners in San Antonio, but in Ann Arbor purchasing Energy Star CACs results in a higher overall cost.

# 7 Conclusions

## 7.1 Key Findings

The use of air conditioning in the residential sector consumes significant energy resources and produces significant GHG emissions. There are also significant costs associated with air conditioning homes. Over time the average efficiency of a CAC gradually increases, which creates an opportunity to reduce these impacts. Federal efficiency standards have played a major role in increasing this average efficiency level. To fully understand the impact of CACs, all of the phases of the lifecycle were examined including the production of the unit, transport, use, and disposal. When considering all of these phases, there is a tradeoff that consumers are confronted with while deciding when to replace their CACs. A newer, more efficient unit will use less power, and as a result, GHG emissions at the power plant decline and the homeowner's energy cost will be lower. However, the production of a new unit requires more energy to be expended to produce that new unit, which in turn generates more GHG emissions. The initial cost of the new unit is also significant. This research explored how the decision of when to replace a CAC can reduce the environmental burdens and cost to the consumer.

At the core of this research, was a lifecycle optimization of the replacement in order to minimize three objectives: (1) energy consumption, (2) GHG emissions, and (3) cost to the consumer. This method entailed creating life cycle inventory profiles for each year of the time horizon from 1985 thru 2025. Both process LCA and EIO-LCA methods were used to account for the energy and GHG burdens of producing the units. The operating climate and its impact on the efficiency of the CAC were considered. Dynamic parameters including CAC energy efficiency; energy intensity of raw materials and manufacturing; and primary energy, GHG emissions, and consumer cost associated with electricity generation and delivery were modeled.

Across the various efficiency scenarios using both the process LCA and EIO-LCA methods, energy minimization required more replacements than the other objectives. For the various cities examined, between 5 and 15 units were required. The EIO-LCA data for the production of a new CAC resulted in lower energy and GHG burdens for the production of a new unit. Therefore, when these results were used in the LCO model more replacements were required (7-15 units) than when the process-LCA results were used (5-11 units). The lower the initial burdens, the more beneficial it is to upgrade frequently since the lower production burdens can be more quickly offset by operating efficiency gains.

When GHG emissions were minimized, 3 to 5 units were required. The results of the GHG inventory using both the process LCA and EIO-LCA were similar, so there were no differences in the number of replacements between these two cases.

The most consistent result was for the cost objective. With the exception of Miami, all the locations called for replacements in 1995 and 2008 regardless of the efficiency scenario when trying to minimize consumer cost. It is interesting to note that for these locations the optimal holding period for minimizing cost increased from 10 years to 13 years to 18 years. This suggests that there is a diminishing financial return from replacing with progressively higher efficiency units that makes it more cost effective to hold on to each new CACs longer than the previous one.

Since the GHG optimal schedules have far fewer replacements than the energy optimal schedules, the cost optimal schedules do a better job of approximating the GHG optimal schedules than the energy optimal schedules. In the base case, replacing according to the optimal cost schedule would lead to a 1.0-2.0% increase in the level of GHG emissions compared to replacing according to the optimal GHG schedule. Comparing the energy results of the optimal cost to the optimal energy schedule results in 2.0-4.2% increased energy required. These differences tend to increase as higher efficiency scenarios are considered. On the other hand, the consumer cost of implementing an energy optimal replacement schedule resulted in large cost premiums of 10.9-57.4% over the optimal cost case.

By comparing the optimal results to a typical replacement pattern for a homeowner from 1985 thru 2025, we can see the opportunity for savings from optimizing replacement. In the base case scenario, the optimal replacement schedules can reduce energy by 4.7-7.3%, GHG emissions by 2.3-4.5% or cost by 2.4-2.6% compared to the typical replacement schedule. In this case, a homeowner starting with a new unit in 1985 and replacing that with a new unit every 13 or 14 years thereafter can come reasonably close to achieving the lowest impacts without following an optimal replacement schedule. The results from a typical replacement schedule do not change under the adoption of a new federal standard because the final replacement occurs before 2016. However, the analysis showed that increasing the federal standard can reduce the energy and GHG burdens when using optimal replacement. Therefore, the differences between the typical replacement and optimal replacement will tend to increase for energy and GHG when a new federal standard is considered.

## 7.2 Research Scope and Limitations

Modeling the life cycle impacts of central air conditioning is challenging. Boundaries must be created and assumptions made in order to make the analysis feasible. It is important to examine these limitations and how they can impact the results. First the life cycle optimization requires the selection of a specific time horizon. In this analysis, a 41 year time horizon from 1985 thru 2025 was selected. For a homeowner who installed a CAC in 1985 and expects to vacate the home at the end of 2025, these results will indicate the optimal replacement schedules. Other time horizons will yield different results.

Furthermore, modeling air conditioner performance presents its own set of challenges. The ability of a CAC to provide space cooling is dependent on the building where it is used. The CLH values used for calculating use phase impacts require that cooling equipment is sized according to the load of the building, and therefore, it was assumed that the units throughout this study were sized correctly. An oversized CAC will need to operate for shorter periods than a correctly sized unit in order to deliver the necessary cooling. Therefore, the hours an oversized unit operates will be fewer, but it will consume more energy when is does operate. Oversized units are generally less efficient because more frequent cycling on and off reduces the amount of time a CAC operates at full efficiency, which occurs several minutes after the unit turns on (Proctor, Katsnelson, & Wilson, 1995).

There many studies to suggest that there is a significant tendency to oversize CAC units in residential applications. Neme, Proctor, and Nadel (1999) did a literature review of studies which compared actual CAC sizing compared to the cooling loads calculated using the Air Conditioning Contractors of America (ACCA) Manual J, the standard method of sizing cooling loads for residences. The average study found 47% of home CACs were oversized by an average of 0.91 tons. Since customers are prone to complain when CACs fail to provide adequate cooling, HVAC contractors have an incentive to erring on the side of over-sizing equipment in order to minimize callbacks. Also, some contractors use heuristic methods to size equipment, rather than calculating cooling loads, which can also lead to oversizing (Proctor, Katsnelson, & Wilson, 1995). Because oversized units are less efficient, and the energy consumption, GHG emissions, and operating costs would be higher, but it is not clear how this would change the optimal replacement schedule if subsequent replacements were also oversized.

Using cooling load hours to estimate energy use eliminates the need to model the specific buildings where the cooling is provided. This greatly simplifies the analysis. However, this fact is also a limitation since different buildings in the same location are capable of having very different cooling demands due to differences in building envelope, size, orientation, and shading as well as differences in occupant behavior. Since the goal of this analysis was not to model specific buildings, but rather compile a life cycle inventory for a “typical” home, using CLH was determined to be an acceptable approach, but because it is a general approach, the results will not be accurate for all homes.

Another problem with modeling the performance of a CAC is modeling the interaction with the homes ductwork. About 15 to 20% of energy spent on space cooling could be saved by preventing leakage in the duct system (Neme, Proctor, & Nadel, 1999). These leaks increase the operating time of the air conditioning system. As a result, it would be expected that in homes with leaky ductwork that the optimal replacement schedules would resemble the optimal replacement schedules of warmer climates where the number of replacements tends to be higher and the lifecycle impacts tend to be greater. In this analysis, the ductwork was not modeled and was instead assumed to deliver all of the cold air to the living spaces.

Beyond just the performance of the system, behavioral considerations limit the accuracy of the results. Individual households have different set points on their thermostats. In Wisconsin for instance, the thermostat setting for most homes surveyed ranged from 71.8 $^{o}$F to 78.5$^{o}$F (Pigg, 2008). Having a higher or lower set point than the average will again impact that the actual operating time of the system and as a result the optimal replacement results. Another behavior phenomena often referred to as the rebound effect often limits the benefits of utilizing more efficient products because consumers tend to use these products more than their less efficient predecessors. In this case, a homeowner that replaces and old CAC with a newer, more efficient system will be paying less to cool his or her home, but as a result that homeowner might be inclined to use the system more by setting the thermostat to a lower set point thus offsetting some to the potential cost savings. This type of behavioral response was not modeled in this analysis, instead in was assumed the homeowners behavioral patterns as they related the air conditioning system were constant.

## 7.3 Policy Implications

This research holds several implications for policy related to air conditioning. Comparing the LCO results of the various efficiency scenarios for Ann Arbor and San Antonio showed that increasing the federal standard in 2016 offered the potential for reducing energy and GHG emissions over the time horizon. Of the scenarios investigated for the next federal standard, a 17 SEER standard offered the greatest potential for reducing environmental impacts followed by 16 SEER and then 15 SEER. In each case the added environmental burdens from creating a higher efficiency unit were offset by energy and GHG reductions in the use phase.

The impact of carbon pricing on the optimal cost results was briefly explored. A carbon price of \$200 per ton of $CO_2$, either from a carbon tax or cap and trade regime, introduced in 2009 did not alter the cost replacement schedule for either Ann Arbor or San Antonio. It only served to increase the life cycle costs by about \$5,400 and \$14,500 respectively. However, this analysis has limited usefulness due to limitations in the modeling. It is likely that such a carbon tax would dramatically increase the average efficiency of new units sold as well as decrease the carbon intensity of the electricity grid. Both of these trends would tend to reduce the level of GHG emissions and thus carbon costs, but neither was able to be modeled. Instead these results should be interrupted as an upper bound for the lifecycle costs under a carbon pricing regime.

Financial incentives can be used to make the energy and GHG optimization replacement schedules cost effective, but the total cost of these incentives can be very large. Incentives can be in the form of utility rebates or tax credits. Incentives for Ann Arbor and San Antonio were explored for both the base case scenario and the 16 SEER scenario. The typical incentive required to trigger an individual replacement in the case of energy optimization is on the order of \$1000 to \$3000 dollars. With respect to a GHG optimization, the level of incentive required per replacement is typically less than \$1000 dollars with several instances being less than \$300 dollars. The carbon incentives were more cost effective in San Antonio than in Ann Arbor. In San Antonio, the reduction of one metric ton of $CO_2$ costs approximately \$500. In the base case in Ann Arbor, the cost was about \$3,500 per metric ton, and in the case of a 16 SEER standard the cost was less than half at \$1,700. The 16 SEER standard created an opportunity for greater reductions in GHG emissions making the incentives more cost effective.

A regional standard has the potential to reduce environmental impacts and consumer cost in areas with high cooling demands. The study explored a scenario modeling an example regional standard of 16 SEER beginning in 2009 for nine south central and south eastern states. By comparing the energy consumption, GHG emissions, and consumer cost from a LCO from 2009 to 2025 with and without such a regional standard, it was possible to calculate the savings for each. For the states considered, a 13% reduction in energy consumption, 9-12% reduction in GHG, and a 3.4-8.2% reduction in cost were observed depending on the objective being minimized when starting with units older than 2003.

Most of the analyses explored the impacts of replacing an older CAC with a new unit of an average efficiency for all the CACs sold in that year. From a consumer's perspective, it is beneficial to know not only when the best time to replace an existing unit is, but also whether or not it is beneficial to replace with a higher efficiency model such as an Energy Star model. The research explored the optimal replacement schedule of CACs with minimum efficiency models and Energy Star models from 2009 to 2025 in Ann Arbor and San Antonio. For Ann Arbor, when replacing with a minimum efficiency unit, an existing unit older than 2006 should be replaced to minimize energy, a unit older than 2003 should be replaced to minimize GHG emitted, and a unit older than 1997 should be replaced to minimize consumer cost. For San Antonio, units produced before 2006 should be replaced to minimize energy and GHG emissions, and units made before 2005 should be replaced to minimize cost. These results differ slightly for homeowners considering Energy Star upgrades, but in all cases doing an optimal replacement with Energy Star units will yield energy and GHG reductions. For units 2005 and older, there is an 8% energy savings and 5% GHG savings in Ann Arbor. While in San Antonio, there is a 9% energy savings and 7% GHG savings. For homes in San Antonio with units 2004 or newer, purchasing Energy Star units has the potential to save on cost, but a home in Ann Arbor is financially better off replacing with minimum efficiency units regardless of the age of the existing unit.

Currently, some states and utilities offer rebates for upgrading with higher efficiency central air conditioners. The results from a survey of the CAC rebate programs are provided in the Appendix. Typically, these rebates programs offer between $200 and $500 depending on efficiency. These programs can encourage homeowners to replacement with Energy Star units by making it more cost effective.

One policy consideration concerning the replacement of CACs that was not considered in this analysis is the prevention of ozone depletion. R-22, the dominant refrigerant used in residential central air conditioners until about 2009, causes ozone damage when released into the atmosphere. Air conditioning policies seeking to protect the ozone layer would seek to replace units that use R-22, which were most of the units sold before 2009, in order to prevent this refrigerant from escaping through leaks in the system.

## 7.4 Future Research

The lack of material and production data in this study meant that various methods need to be used to estimate the life cycle inventory for these stages. Much of this analysis used data from the DOE (2002) rulemaking process for the current federal standard, and as a result, the data was not current. The research would benefit from further life cycle analyses conducted with more accurate and up-to-date data sources to model the material and manufacturing phases. Furthermore, better data on refrigerant leakage and end of life refrigerant recovery rate would also allow for more accurate modeling.

There are several areas of the incentive analysis that deserve further exploration. It is unrealistic that an incentive program would be structured in such a way that incentives would be offered only in certain years and at potentially dramatically different levels. The analysis presented here can be extended to examine how rebate programs could be structured in order to make them practical to implement. Future research should also explore how consumers would actually respond to different rebate levels.

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# Appendix

## A.1 Energy Intensity

Much of the data and methods pertaining to energy intensity factors were taken from Kim's *Shaping Sustainable Vehicle Fleet Conversion Policies Based on Life Cycle Optimization and Risk Analysis* (2003). Various data sources were used to update Kim's values to reflect new data available since the time his dissertation. These data sources as well as the energy intensity values used are given below.

*Iron and Steel*

Kim's original values were based on Manufacturing Energy Consumptions Survey (MECS) from 1985 to 1998. This same technique was used to extend the data using data from the 2002 and 2006 MECS. This approach allowed for calculation of energy intensity based on mass (MJ/kg). An economic energy intensity (MJ/$ of shipments) was used as a proxy from 2007 to 2025 based on projection of the reference case of the AEO 2009.

*Aluminum*

Again Kim's values based on the MECS were used till 1998. Extending this with 2002 and 2006 MECS data was problematic due to electricity being withheld from the 2002 MECS, and in the MECS 2006, the 'Primary Aluminum' category was not reported. Instead, data from the International Aluminium Institute on the electrical power used per metric ton of primary aluminum produced in North America was used to extend the index to 2007. The AEO 2009 reference case was used to project the energy intensity to 2025.

*Plastic*

Kim's values were used for plastics thru 2006 and updated using the AEO 2009 reference case from 2007 to 2025.

*Copper*

As opposed to aluminum, historically the energy intensity on a mass basis of copper has remained relatively stable (Ruth, 1995). As a result of this stability and the lack of relevant copper data, the energy intensity of copper is assumed to remain the same during the time horizon.

*Manufacturing*

Energy intensity indicators calculated by the DOE (2008) for the manufacturing sector were used to calculate the manufacturing energy intensity index thru 2004. The energy intensity data of 'Fabricated Metal Products' from the 2009 AEO reference case was used to complete the manufacturing index.

### Table A.0.1: Energy Intensity Index

| 2001=1 | Ferrous Materials | Aluminum | Plastics | Copper | Manufacturing |
|---|---|---|---|---|---|
| 1985 | 1.542 | 1.201 | 1.008 | 1.000 | 1.001 |
| 1986 | 1.528 | 1.180 | 1.008 | 1.000 | 1.107 |
| 1987 | 1.513 | 1.158 | 1.008 | 1.000 | 1.122 |
| 1988 | 1.499 | 1.137 | 1.008 | 1.000 | 1.095 |
| 1989 | 1.453 | 1.130 | 1.008 | 1.000 | 1.094 |
| 1990 | 1.408 | 1.122 | 1.008 | 1.000 | 1.114 |
| 1991 | 1.364 | 1.115 | 1.008 | 1.000 | 1.104 |
| 1992 | 1.347 | 1.113 | 1.008 | 1.000 | 1.096 |
| 1993 | 1.332 | 1.111 | 1.008 | 1.000 | 1.206 |
| 1994 | 1.316 | 1.109 | 1.008 | 1.000 | 1.115 |
| 1995 | 1.272 | 1.093 | 1.008 | 1.000 | 1.070 |
| 1996 | 1.229 | 1.078 | 1.008 | 1.000 | 1.099 |
| 1997 | 1.186 | 1.064 | 1.008 | 1.000 | 1.065 |
| 1998 | 1.144 | 1.049 | 1.008 | 1.000 | 1.085 |
| 1999 | 1.096 | 1.011 | 1.008 | 1.000 | 1.099 |
| 2000 | 1.048 | 1.038 | 1.003 | 1.000 | 1.068 |
| 2001 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| 2002 | 0.952 | 1.002 | 0.997 | 1.000 | 0.986 |
| 2003 | 0.899 | 1.022 | 0.994 | 1.000 | 0.997 |
| 2004 | 0.847 | 1.027 | 0.989 | 1.000 | 0.979 |
| 2005 | 0.794 | 1.023 | 0.986 | 1.000 | 0.955 |
| 2006 | 0.742 | 1.017 | 0.984 | 1.000 | 0.926 |
| 2007 | 0.743 | 1.018 | 0.968 | 1.000 | 0.914 |
| 2008 | 0.730 | 0.925 | 0.953 | 1.000 | 0.899 |
| 2009 | 0.736 | 0.981 | 0.930 | 1.000 | 0.970 |
| 2010 | 0.731 | 0.934 | 0.925 | 1.000 | 0.955 |
| 2011 | 0.715 | 0.895 | 0.918 | 1.000 | 0.933 |
| 2012 | 0.698 | 0.860 | 0.913 | 1.000 | 0.926 |
| 2013 | 0.682 | 0.833 | 0.907 | 1.000 | 0.920 |
| 2014 | 0.672 | 0.823 | 0.895 | 1.000 | 0.907 |
| 2015 | 0.665 | 0.820 | 0.884 | 1.000 | 0.896 |
| 2016 | 0.656 | 0.813 | 0.874 | 1.000 | 0.886 |
| 2017 | 0.645 | 0.799 | 0.865 | 1.000 | 0.872 |
| 2018 | 0.635 | 0.782 | 0.856 | 1.000 | 0.858 |
| 2019 | 0.627 | 0.765 | 0.847 | 1.000 | 0.842 |
| 2020 | 0.619 | 0.754 | 0.840 | 1.000 | 0.818 |
| 2021 | 0.613 | 0.753 | 0.836 | 1.000 | 0.807 |
| 2022 | 0.608 | 0.753 | 0.833 | 1.000 | 0.800 |
| 2023 | 0.602 | 0.747 | 0.830 | 1.000 | 0.797 |
| 2024 | 0.597 | 0.742 | 0.828 | 1.000 | 0.793 |
| 2025 | 0.593 | 0.743 | 0.826 | 1.000 | 0.790 |

## A.2 LCO Results of Standard Efficiency Improvement Scenario

**Table A.0.2: LCO Results for Standard Efficiency Improvement Scenario Using Process LCI Data**

|  |  |  | Life Cycle Impacts |  |  | % Deviation from the Optimum |  |  |
|---|---|---|---|---|---|---|---|---|
| City | Objective | Schedule | Energy (MJ) | GHG (kg CO2 eq.) | Cost (2009$) | Energy | GHG | Cost |
| **Ann Arbor** | **Energy** | 1985, 1992, 1998, 2007, 2014 | 1,063,000 | 90,300 | 26,500 | --- | 2.4 % | 22.3 % |
|  | **GHG** | 1985, 1992, 2010 | 1,081,000 | 88,300 | 22,000 | 1.6 % | --- | 1.7 % |
|  | **Cost** | 1985, 1995, 2008 | 1,084,000 | 89,100 | 21,600 | 2.0 % | 1.0 % | --- |
| **Los Angeles** | **Energy** | 1985, 1989, 1992, 1998, 2006, 2010, 2018 | 1,693,000 | 105,300 | 49,000 | --- | 4.3 % | 24.0 % |
|  | **GHG** | 1985, 1992, 2010 | 1,733,000 | 100,900 | 39,700 | 2.3 % | --- | 0.5 % |
|  | **Cost** | 1985, 1995, 2008 | 1,740,000 | 101,900 | 39,500 | 2.8 % | 1.0 % | --- |
| **Miami** | **Energy** | 1985, 1989, 1992, 1995, 1998, 2003, 2006, 2007, 2010, 2015, 2020 | 6,218,000 | 312,600 | 92,100 | --- | 2.4 % | 27.6 % |
|  | **GHG** | 1985, 1992, 1998, 2006, 2010 | 6,278,000 | 305,200 | 76,000 | 1.0 % | --- | 5.3 % |
|  | **Cost** | 1985, 1992, 2008 | 6,416,000 | 308,700 | 72,200 | 3.2 % | 1.2 % | --- |
| **New York** | **Energy** | 1985, 1992, 1998, 2007, 2014 | 1,540,000 | 80,600 | 42,900 | --- | 3.0 % | 10.9 % |
|  | **GHG** | 1985, 1992, 2010 | 1,573,000 | 78,300 | 39,000 | 2.1 % | --- | 0.7 % |
|  | **Cost** | 1985, 1995, 2008 | 1,577,000 | 79,000 | 38,700 | 2.4 % | 0.9 % | --- |
| **San Antonio** | **Energy** | 1985, 1989, 1992, 1998, 2006, 2007, 2012, 2019 | 3,586,000 | 218,400 | 58,000 | --- | 2.0 % | 27.3 % |
|  | **GHG** | 1985, 1992, 2006, 2010 | 3,631,000 | 214,100 | 48,100 | 1.2 % | --- | 5.5 % |
|  | **Cost** | 1985, 1995, 2008 | 3,709,000 | 217,400 | 45,600 | 3.4 % | 1.5 % | --- |
| **Wichita** | **Energy** | 1985, 1989, 1992, 1998, 2006, 2010, 2018 | 2,176,000 | 172,400 | 38,200 | --- | 1.8 % | 36.1 % |
|  | **GHG** | 1985, 1992, 2006, 2010 | 2,195,000 | 169,400 | 31,100 | 0.9 % | --- | 10.7 % |
|  | **Cost** | 1985, 1995, 2008 | 2,237,000 | 171,500 | 28,100 | 2.8 % | 1.3 % | --- |

## Table A.0.3: LCO Results for Standard Efficiency Improvement Scenario Using EIO LCI Data

| | | | Life Cycle Impacts | | | % Deviation from the Optimum | | |
|---|---|---|---|---|---|---|---|---|
| City | Objective | Schedule | Energy (MJ) | GHG (kg CO2 eq.) | Cost (2009$) | Energy | GHG | Cost |
| **Ann Arbor** | **Energy** | 1985, 1989, 1992, 1998, 2006, 2010, 2018 | 1,042,000 | 92,600 | 32,000 | --- | 5.4 % | 47.9 % |
| | **GHG** | 1985, 1992, 2010 | 1,066,000 | 87,800 | 22,000 | 2.4 % | --- | 1.7 % |
| | **Cost** | 1985, 1995, 2008 | 1,071,000 | 88,800 | 21,600 | 2.8 % | 1.1 % | --- |
| **Los Angeles** | **Energy** | 1985, 1989, 1992, 1998, 2006, 2010, 2018 | 1,665,000 | 104,600 | 49,000 | --- | 4.1 % | 24.0 % |
| | **GHG** | 1985, 1992, 2006, 2010 | 1,683,000 | 100,400 | 42,100 | 1.0 % | --- | 6.4 % |
| | **Cost** | 1985, 1995, 2008 | 1,727,000 | 101,600 | 39,500 | 3.7 % | 1.1 % | --- |
| **Miami** | **Energy** | 1985, 1988, 1989, 1991, 1992, 1995, 1998, 2001, 2004, 2006, 2007, 2010, 2014, 2018, 2022 | 6,168,000 | 318,300 | 103,300 | --- | 4.5 % | 43.0 % |
| | **GHG** | 1985, 1992, 1998, 2006, 2010 | 6,257,000 | 304,600 | 76,000 | 1.4 % | --- | 5.3 % |
| | **Cost** | 1985, 1992, 2008 | 6,402,000 | 308,300 | 72,200 | 3.8 % | 1.2 % | --- |
| **New York** | **Energy** | 1985, 1989, 1992, 1998, 2006, 2010, 2018 | 1,514,000 | 82,900 | 48,300 | --- | 6.6 % | 24.9 % |
| | **GHG** | 1985, 1992, 2010 | 1,558,000 | 77,800 | 39,000 | 2.9 % | --- | 0.7 % |
| | **Cost** | 1985, 1995, 2008 | 1,564,000 | 78,600 | 38,700 | 3.3 % | 1.0 % | --- |
| **San Antonio** | **Energy** | 1985, 1988, 1989, 1992, 1995, 1998, 2003, 2006, 2007, 2010, 2015, 2020 | 3,549,000 | 224,100 | 69,300 | --- | 4.9 % | 52.0 % |
| | **GHG** | 1985, 1992, 2006, 2010 | 3,612,000 | 213,600 | 48,100 | 1.8 % | --- | 5.5 % |
| | **Cost** | 1985, 1995, 2008 | 3,696,000 | 217,000 | 45,600 | 4.2 % | 1.6 % | --- |
| **Wichita** | **Energy** | 1985, 1989, 1992, 1998, 2003, 2006, 2007, 2012, 2019 | 2,147,000 | 175,500 | 44,200 | --- | 3.9 % | 57.4 % |
| | **GHG** | 1985, 1992, 2006, 2010 | 2,176,000 | 168,900 | 31,100 | 1.3 % | --- | 10.7 % |
| | **Cost** | 1985, 1995, 2008 | 2,224,000 | 171,200 | 28,100 | 3.6 % | 1.4 % | --- |

a) EIO-LCA results refer to modeling of the unit production. See Section 3.1 for details.

## A.3 Comparison of Optimal to Typical Replacement in Base Case

Table A.0.4: Comparison of Optimal to Typical Replacement Using Process LCI Data

| | | Life Cycle Impacts | | | Savings from Optimal vs. Typical Replacement | | |
|---|---|---|---|---|---|---|---|
| City | Objective | Energy (MJ) | GHG (kg CO2 eq.) | Cost (2009$) | Energy | GHG | Cost |
| **Ann Arbor** | **Energy** | 1,115,000 | 90,400 | 22,200 | 4.7 % | 0.1 % | (19.3 %) |
| | **GHG** | 1,115,000 | 90,400 | 22,200 | 3.1 % | 2.4 % | 0.8 % |
| | **Cost** | 1,115,000 | 90,400 | 22,200 | 2.8 % | 1.4 % | 2.4 % |
| **Los Angeles** | **Energy** | 1,790,000 | 103,500 | 40,500 | 5.5 % | (1.7 %) | (21.0 %) |
| | **GHG** | 1,790,000 | 103,500 | 40,500 | 3.2 % | 2.5 % | 2.0 % |
| | **Cost** | 1,790,000 | 103,500 | 40,500 | 2.8 % | 1.6 % | 2.5 % |
| **Miami** | **Energy** | 6,667,000 | 319,400 | 74,200 | 6.7 % | 2.1 % | (24.2 %) |
| | **GHG** | 6,667,000 | 319,400 | 74,200 | 5.8 % | 4.4 % | (2.5 %) |
| | **Cost** | 6,667,000 | 319,400 | 74,200 | 3.8 % | 3.3 % | 2.6 % |
| **New York** | **Energy** | 1,623,000 | 80,100 | 39,700 | 5.1 % | (0.6 %) | (8.2 %) |
| | **GHG** | 1,623,000 | 80,100 | 39,700 | 3.1 % | 2.3 % | 1.8 % |
| | **Cost** | 1,623,000 | 80,100 | 39,700 | 2.8 % | 1.4 % | 2.5 % |
| **San Antonio** | **Energy** | 3,818,000 | 222,400 | 46,700 | 6.1 % | 1.8 % | (24.2 %) |
| | **GHG** | 3,818,000 | 222,400 | 46,700 | 4.9 % | 3.7 % | (2.9 %) |
| | **Cost** | 3,818,000 | 222,400 | 46,700 | 2.8 % | 2.3 % | 2.5 % |
| **Wichita** | **Energy** | 2,303,000 | 175,300 | 28,800 | 5.5 % | 1.6 % | (32.6 %) |
| | **GHG** | 2,303,000 | 175,300 | 28,800 | 4.7 % | 3.4 % | (7.8 %) |
| | **Cost** | 2,303,000 | 175,300 | 28,800 | 2.8 % | 2.1 % | 2.6 % |

Table A.0.5: Comparison of Optimal to Typical Replacement Using EIO LCI Data

| | | Life Cycle Impacts | | | Savings from Optimal vs. Typical Replacement | | |
|---|---|---|---|---|---|---|---|
| City | Objective | Energy (MJ) | GHG (kg CO2 eq.) | Cost (2009$) | Energy | GHG | Cost |
| **Ann Arbor** | **Energy** | 1,101,000 | 90,000 | 22,200 | 5.4 % | (2.9 %) | (44.3 %) |
| | **GHG** | 1,101,000 | 90,000 | 22,200 | 3.1 % | 2.4 % | 0.8 % |
| | **Cost** | 1,101,000 | 90,000 | 22,200 | 2.7 % | 1.3 % | 2.4 % |
| **Los Angeles** | **Energy** | 1,776,000 | 103,100 | 40,500 | 6.2 % | (1.4 %) | (21.0 %) |
| | **GHG** | 1,776,000 | 103,100 | 40,500 | 5.2 % | 2.6 % | (3.8 %) |
| | **Cost** | 1,776,000 | 103,100 | 40,500 | 2.7 % | 1.5 % | 2.5 % |
| **Miami** | **Energy** | 6,652,000 | 318,900 | 74,200 | 7.3 % | 0.2 % | (39.3 %) |
| | **GHG** | 6,652,000 | 318,900 | 74,200 | 5.9 % | 4.5 % | (2.5 %) |
| | **Cost** | 6,652,000 | 318,900 | 74,200 | 3.8 % | 3.3 % | 2.6 % |
| **New York** | **Energy** | 1,608,000 | 79,700 | 39,700 | 5.9 % | (4.1 %) | (21.8 %) |
| | **GHG** | 1,608,000 | 79,700 | 39,700 | 3.1 % | 2.3 % | 1.8 % |
| | **Cost** | 1,608,000 | 79,700 | 39,700 | 2.8 % | 1.3 % | 2.5 % |
| **San Antonio** | **Energy** | 3,803,000 | 222,000 | 46,700 | 6.7 % | (1.0 %) | (48.3 %) |
| | **GHG** | 3,803,000 | 222,000 | 46,700 | 5.0 % | 3.8 % | (2.9 %) |
| | **Cost** | 3,803,000 | 222,000 | 46,700 | 2.8 % | 2.2 % | 2.5 % |
| **Wichita** | **Energy** | 2,288,000 | 174,800 | 28,800 | 6.2 % | (0.4 %) | (53.4 %) |
| | **GHG** | 2,288,000 | 174,800 | 28,800 | 4.9 % | 3.4 % | (7.8 %) |
| | **Cost** | 2,288,000 | 174,800 | 28,800 | 2.8 % | 2.1 % | 2.6 % |

a) EIO-LCA results refer to modeling of the unit production. See Section 3.1 for details.

## A.4 Optimization Results for Different Efficiency Scenarios

Table A.0.6: LCO Results for 15 SEER Scenario Using Process LCI Data

| City | Objective | Schedule | Life Cycle Impacts | | | % Deviation from the Optimum | | |
|---|---|---|---|---|---|---|---|---|
| | | | Energy (MJ) | GHG (kg CO2 eq.) | Cost (2009$) | Energy | GHG | Cost |
| **Ann Arbor** | **Energy** | 1985, 1992, 1998, 2007, 2017 | 1,056,000 | 90,000 | 26,500 | --- | 2.0 % | 22.4 % |
| | **GHG** | 1985, 1992, 2010 | 1,081,000 | 88,300 | 22,000 | 2.4 % | --- | 1.7 % |
| | **Cost** | 1985, 1995, 2008 | 1,084,000 | 89,100 | 21,600 | 2.7 % | 1.0 % | --- |
| **Los Angeles** | **Energy** | 1985, 1989, 1992, 1998, 2006, 2010, 2017 | 1,681,000 | 104,800 | 48,900 | --- | 3.9 % | 23.8 % |
| | **GHG** | 1985, 1992, 2010 | 1,733,000 | 100,900 | 39,700 | 3.1 % | --- | 0.5 % |
| | **Cost** | 1985, 1995, 2008 | 1,740,000 | 101,900 | 39,500 | 3.5 % | 1.0 % | --- |
| **Miami** | **Energy** | 1985, 1989, 1992, 1995, 1998, 2003, 2006, 2007, 2010, 2017 | 6,166,000 | 309,100 | 88,600 | --- | 2.0 % | 22.6 % |
| | **GHG** | 1985, 1992, 1998, 2006, 2010, 2017 | 6,199,000 | 303,100 | 77,700 | 0.5 % | --- | 7.6 % |
| | **Cost** | 1985, 1992, 2008 | 6,416,000 | 308,700 | 72,200 | 4.1 % | 1.9 % | --- |
| **New York** | **Energy** | 1985, 1992, 1998, 2006, 2010, 2017 | 1,528,000 | 81,400 | 45,700 | --- | 4.0 % | 18.1 % |
| | **GHG** | 1985, 1992, 2010 | 1,573,000 | 78,300 | 39,000 | 2.9 % | --- | 0.7 % |
| | **Cost** | 1985, 1995, 2008 | 1,577,000 | 79,000 | 38,700 | 3.2 % | 0.9 % | --- |
| **San Antonio** | **Energy** | 1985, 1989, 1992, 1998, 2006, 2007, 2011, 2017 | 3,557,000 | 216,900 | 57,800 | --- | 1.8 % | 26.9 % |
| | **GHG** | 1985, 1992, 2007, 2017 | 3,603,000 | 212,900 | 47,400 | 1.3 % | --- | 4.0 % |
| | **Cost** | 1985, 1995, 2008 | 3,709,000 | 217,400 | 45,600 | 4.3 % | 2.1 % | --- |
| **Wichita** | **Energy** | 1985, 1989, 1992, 1998, 2006, 2010, 2017 | 2,157,000 | 171,200 | 38,200 | --- | 1.6 % | 36.1 % |
| | **GHG** | 1985, 1992, 2007, 2017 | 2,176,000 | 168,400 | 30,500 | 0.9 % | --- | 8.9 % |
| | **Cost** | 1985, 1995, 2008 | 2,237,000 | 171,500 | 28,100 | 3.7 % | 1.9 % | --- |

**Table A.0.7: LCO Results for 16 SEER Scenario Using Process LCI Data**

| City | Objective | Schedule | Life Cycle Impacts | | | % Deviation from the Optimum | | |
|---|---|---|---|---|---|---|---|---|
| | | | Energy (MJ) | GHG (kg CO2 eq.) | Cost (2009$) | Energy | GHG | Cost |
| **Ann Arbor** | **Energy** | 1985, 1992, 1998, 2007, 2017 | 1,047,000 | 89,600 | 26,500 | --- | 1.5 % | 22.7 % |
| | **GHG** | 1985, 1992, 2007, 2017 | 1,051,000 | 88,200 | 24,400 | 0.4 % | --- | 12.6 % |
| | **Cost** | 1985, 1995, 2008 | 1,084,000 | 89,100 | 21,600 | 3.6 % | 1.0 % | --- |
| **Los Angeles** | **Energy** | 1985, 1989, 1992, 1998, 2006, 2010, 2017 | 1,668,000 | 104,400 | 48,800 | --- | 3.9 % | 23.5 % |
| | **GHG** | 1985, 1992, 2007, 2017 | 1,681,000 | 100,500 | 41,500 | 0.8 % | --- | 5.0 % |
| | **Cost** | 1985, 1995, 2008 | 1,740,000 | 101,900 | 39,500 | 4.3 % | 1.4 % | --- |
| **Miami** | **Energy** | 1985, 1989, 1992, 1995, 1998, 2003, 2006, 2007, 2010, 2017 | 6,108,000 | 306,700 | 88,000 | --- | 2.0 % | 21.9 % |
| | **GHG** | 1985, 1992, 1998, 2006, 2010, 2017 | 6,141,000 | 300,600 | 77,200 | 0.5 % | --- | 6.9 % |
| | **Cost** | 1985, 1992, 2008 | 6,416,000 | 308,700 | 72,200 | 5.0 % | 2.7 % | --- |
| **New York** | **Energy** | 1985, 1992, 1998, 2006, 2010, 2017 | 1,514,000 | 81,100 | 45,600 | --- | 3.6 % | 17.8 % |
| | **GHG** | 1985, 1992, 2010 | 1,573,000 | 78,300 | 39,000 | 3.9 % | --- | 0.7 % |
| | **Cost** | 1985, 1995, 2008 | 1,577,000 | 79,000 | 38,700 | 4.2 % | 0.9 % | --- |
| **San Antonio** | **Energy** | 1985, 1989, 1992, 1998, 2006, 2007, 2011, 2017 | 3,524,000 | 215,200 | 57,600 | --- | 1.9 % | 26.4 % |
| | **GHG** | 1985, 1992, 2007, 2017 | 3,570,000 | 211,300 | 47,100 | 1.3 % | --- | 3.5 % |
| | **Cost** | 1985, 1995, 2008 | 3,709,000 | 217,400 | 45,600 | 5.3 % | 2.9 % | --- |
| **Wichita** | **Energy** | 1985, 1989, 1992, 1998, 2006, 2010, 2017 | 2,136,000 | 169,900 | 38,200 | --- | 1.7 % | 36.1 % |
| | **GHG** | 1985, 1992, 2007, 2017 | 2,155,000 | 167,100 | 30,600 | 0.9 % | --- | 8.9 % |
| | **Cost** | 1985, 1995, 2008 | 2,237,000 | 171,500 | 28,100 | 4.7 % | 2.7 % | --- |

**Table A.0.8: LCO Results for 17 SEER Scenario Using Process LCI Data**

| City | Objective | Schedule | Life Cycle Impacts | | | % Deviation from the Optimum | | |
|---|---|---|---|---|---|---|---|---|
| | | | Energy (MJ) | GHG (kg CO2 eq.) | Cost (2009$) | Energy | GHG | Cost |
| **Ann Arbor** | **Energy** | 1985, 1992, 1998, 2007, 2017 | 1,039,000 | 89,300 | 26,600 | --- | 1.5 % | 23.0 % |
| | **GHG** | 1985, 1992, 2007, 2017 | 1,043,000 | 87,900 | 24,400 | 0.4 % | --- | 12.9 % |
| | **Cost** | 1985, 1995, 2008 | 1,084,000 | 89,100 | 21,600 | 4.3 % | 1.4 % | --- |
| **Los Angeles** | **Energy** | 1985, 1989, 1992, 1998, 2006, 2010, 2017 | 1,657,000 | 104,000 | 48,800 | --- | 3.9 % | 23.4 % |
| | **GHG** | 1985, 1992, 2007, 2017 | 1,670,000 | 100,100 | 41,400 | 0.8 % | --- | 4.8 % |
| | **Cost** | 1985, 1995, 2008 | 1,740,000 | 101,900 | 39,500 | 5.0 % | 1.8 % | --- |
| **Miami** | **Energy** | 1985, 1989, 1992, 1995, 1998, 2003, 2006, 2007, 2010, 2016, 2017 | 6,054,000 | 306,000 | 90,900 | --- | 2.5 % | 26.0 % |
| | **GHG** | 1985, 1992, 1998, 2006, 2010, 2017 | 6,090,000 | 298,600 | 76,800 | 0.6 % | --- | 6.4 % |
| | **Cost** | 1985, 1993, 2006, 2017 | 6,210,000 | 301,100 | 72,200 | 2.6 % | 0.8 % | --- |
| **New York** | **Energy** | 1985, 1992, 1998, 2006, 2010, 2017 | 1,501,000 | 80,800 | 45,500 | --- | 3.3 % | 17.5 % |
| | **GHG** | 1985, 1992, 2007, 2017 | 1,509,000 | 78,200 | 40,500 | 0.5 % | --- | 4.7 % |
| | **Cost** | 1985, 1995, 2008 | 1,577,000 | 79,000 | 38,700 | 5.0 % | 1.0 % | --- |
| **San Antonio** | **Energy** | 1985, 1989, 1992, 1998, 2006, 2007, 2011, 2017 | 3,495,000 | 213,800 | 57,400 | --- | 1.9 % | 26.0 % |
| | **GHG** | 1985, 1992, 2007, 2017 | 3,541,000 | 209,900 | 47,000 | 1.3 % | --- | 3.1 % |
| | **Cost** | 1985, 1995, 2008 | 3,709,000 | 217,400 | 45,600 | 6.1 % | 3.6 % | --- |
| **Wichita** | **Energy** | 1985, 1989, 1992, 1998, 2006, 2010, 2017 | 2,117,000 | 168,800 | 38,200 | --- | 1.7 % | 36.2 % |
| | **GHG** | 1985, 1992, 2007, 2017 | 2,136,000 | 166,000 | 30,600 | 0.9 % | --- | 9.0 % |
| | **Cost** | 1985, 1995, 2008 | 2,237,000 | 171,500 | 28,100 | 5.7 % | 3.3 % | --- |

**Table A.0.9: LCO Results for 15 SEER Scenario Using EIO LCI Data**

| | | | Life Cycle Impacts | | | % Deviation from the Optimum | | |
|---|---|---|---|---|---|---|---|---|
| **City** | **Objective** | **Schedule** | **Energy (MJ)** | **GHG (kg CO2 eq.)** | **Cost (2009$)** | **Energy** | **GHG** | **Cost** |
| **Ann Arbor** | **Energy** | 1985, 1989, 1992, 1998, 2006, 2010, 2017 | 1,033,000 | 92,100 | 32,000 | --- | 4.9 % | 48.1 % |
| | **GHG** | 1985, 1992, 2010 | 1,066,000 | 87,800 | 22,000 | 3.2 % | --- | 1.7 % |
| | **Cost** | 1985, 1995, 2008 | 1,071,000 | 88,800 | 21,600 | 3.7 % | 1.1 % | --- |
| **Los Angeles** | **Energy** | 1985, 1989, 1992, 1998, 2006, 2010, 2017 | 1,653,000 | 104,100 | 48,900 | --- | 3.7 % | 23.8 % |
| | **GHG** | 1985, 1992, 2006, 2010 | 1,683,000 | 100,400 | 42,100 | 1.8 % | --- | 6.4 % |
| | **Cost** | 1985, 1995, 2008 | 1,727,000 | 101,600 | 39,500 | 4.5 % | 1.1 % | --- |
| **Miami** | **Energy** | 1985, 1988, 1989, 1991, 1992, 1995, 1998, 2001, 2004, 2006, 2007, 2010, 2013, 2017, 2021 | 6,117,000 | 316,200 | 102,900 | --- | 4.6 % | 42.5 % |
| | **GHG** | 1985, 1992, 1998, 2006, 2010, 2017 | 6,174,000 | 302,400 | 77,700 | 0.9 % | --- | 7.6 % |
| | **Cost** | 1985, 1992, 2008 | 6,402,000 | 308,300 | 72,200 | 4.7 % | 1.9 % | --- |
| **New York** | **Energy** | 1985, 1989, 1992, 1998, 2006, 2010, 2017 | 1,501,000 | 82,600 | 48,200 | --- | 6.1 % | 24.5 % |
| | **GHG** | 1985, 1992, 2010 | 1,558,000 | 77,800 | 39,000 | 3.8 % | --- | 0.7 % |
| | **Cost** | 1985, 1995, 2008 | 1,564,000 | 78,600 | 38,700 | 4.2 % | 1.0 % | --- |
| **San Antonio** | **Energy** | 1985, 1988, 1989, 1992, 1995, 1998, 2003, 2006, 2007, 2011, 2017 | 3,520,000 | 221,300 | 65,900 | --- | 4.2 % | 44.6 % |
| | **GHG** | 1985, 1992, 2007, 2017 | 3,585,000 | 212,500 | 47,400 | 1.8 % | --- | 4.0 % |
| | **Cost** | 1985, 1995, 2008 | 3,696,000 | 217,000 | 45,600 | 5.0 % | 2.2 % | --- |
| **Wichita** | **Energy** | 1985, 1989, 1992, 1998, 2003, 2006, 2007, 2011, 2017 | 2,128,000 | 174,200 | 44,200 | --- | 3.7 % | 57.4 % |
| | **GHG** | 1985, 1992, 2007, 2017 | 2,158,000 | 167,900 | 30,500 | 1.4 % | --- | 8.9 % |
| | **Cost** | 1985, 1995, 2008 | 2,224,000 | 171,200 | 28,100 | 4.5 % | 1.9 % | --- |

a) EIO-LCA results refer to modeling of the unit production. See Section 3.1 for details.

**Table A.0.10: LCO Results for 16 SEER Scenario Using EIO LCI Data**

| City | Objective | Schedule | Life Cycle Impacts | | | % Deviation from the Optimum | | |
|---|---|---|---|---|---|---|---|---|
| | | | Energy (MJ) | GHG (kg CO2 eq.) | Cost (2009$) | Energy | GHG | Cost |
| **Ann Arbor** | **Energy** | 1985, 1989, 1992, 1998, 2006, 2010, 2017 | 1,024,000 | 91,700 | 32,100 | --- | 4.5 % | 48.3 % |
| | **GHG** | 1985, 1992, 2007, 2017 | 1,032,000 | 87,700 | 24,400 | 0.8 % | --- | 12.6 % |
| | **Cost** | 1985, 1995, 2008 | 1,071,000 | 88,800 | 21,600 | 4.6 % | 1.2 % | --- |
| **Los Angeles** | **Energy** | 1985, 1989, 1992, 1998, 2006, 2010, 2017 | 1,640,000 | 103,600 | 48,800 | --- | 3.7 % | 23.5 % |
| | **GHG** | 1985, 1992, 2007, 2017 | 1,663,000 | 100,000 | 41,500 | 1.4 % | --- | 5.0 % |
| | **Cost** | 1985, 1995, 2008 | 1,727,000 | 101,600 | 39,500 | 5.3 % | 1.6 % | --- |
| **Miami** | **Energy** | 1985, 1988, 1989, 1991, 1992, 1995, 1998, 2001, 2004, 2006, 2007, 2010, 2016, 2017, 2021 | 6,057,000 | 314,000 | 102,700 | --- | 4.7 % | 42.2 % |
| | **GHG** | 1985, 1992, 1998, 2006, 2010, 2017 | 6,116,000 | 300,000 | 77,200 | 1.0 % | --- | 6.9 % |
| | **Cost** | 1985, 1992, 2008 | 6,402,000 | 308,300 | 72,200 | 5.7 % | 2.8 % | --- |
| **New York** | **Energy** | 1985, 1989, 1992, 1998, 2006, 2010, 2017 | 1,486,000 | 82,200 | 48,000 | --- | 5.6 % | 24.2 % |
| | **GHG** | 1985, 1992, 2010 | 1,558,000 | 77,800 | 39,000 | 4.8 % | --- | 0.7 % |
| | **Cost** | 1985, 1995, 2008 | 1,564,000 | 78,600 | 38,700 | 5.2 % | 1.0 % | --- |
| **San Antonio** | **Energy** | 1985, 1988, 1989, 1992, 1995, 1998, 2003, 2006, 2007, 2010, 2016, 2017 | 3,486,000 | 221,100 | 69,000 | --- | 4.9 % | 51.5 % |
| | **GHG** | 1985, 1992, 2007, 2017 | 3,552,000 | 210,800 | 47,100 | 1.9 % | --- | 3.5 % |
| | **Cost** | 1985, 1995, 2008 | 3,696,000 | 217,000 | 45,600 | 6.0 % | 3.0 % | --- |
| **Wichita** | **Energy** | 1985, 1989, 1992, 1998, 2003, 2006, 2007, 2011, 2017 | 2,106,000 | 172,900 | 44,200 | --- | 3.8 % | 57.4 % |
| | **GHG** | 1985, 1992, 2007, 2017 | 2,136,000 | 166,600 | 30,600 | 1.4 % | --- | 8.9 % |
| | **Cost** | 1985, 1995, 2008 | 2,224,000 | 171,200 | 28,100 | 5.6 % | 2.8 % | --- |

a) EIO-LCA results refer to modeling of the unit production. See Section 3.1 for details.

### Table A.0.11: LCO Results for 17 SEER Scenario Using EIO LCI Data

| | | | Life Cycle Impacts | | | % Deviation from the Optimum | | |
|---|---|---|---|---|---|---|---|---|
| **City** | **Objective** | **Schedule** | **Energy (MJ)** | **GHG (kg CO2 eq.)** | **Cost (2009$)** | **Energy** | **GHG** | **Cost** |
| **Ann Arbor** | **Energy** | 1985, 1989, 1992, 1998, 2006, 2010, 2017 | 1,015,000 | 91,300 | 32,200 | --- | 4.5 % | 48.6 % |
| | **GHG** | 1985, 1992, 2007, 2017 | 1,024,000 | 87,400 | 24,400 | 0.9 % | --- | 12.9 % |
| | **Cost** | 1985, 1995, 2008 | 1,071,000 | 88,800 | 21,600 | 5.5 % | 1.6 % | --- |
| **Los Angeles** | **Energy** | 1985, 1989, 1992, 1998, 2006, 2010, 2017 | 1,628,000 | 103,300 | 48,800 | --- | 3.7 % | 23.4 % |
| | **GHG** | 1985, 1992, 2007, 2017 | 1,651,000 | 99,600 | 41,400 | 1.4 % | --- | 4.8 % |
| | **Cost** | 1985, 1995, 2008 | 1,727,000 | 101,600 | 39,500 | 6.1 % | 2.0 % | --- |
| **Miami** | **Energy** | 1985, 1988, 1989, 1991, 1992, 1995, 1998, 2001, 2004, 2006, 2007, 2010, 2016, 2017, 2021 | 6,003,000 | 312,000 | 102,400 | --- | 4.7 % | 41.9 % |
| | **GHG** | 1985, 1992, 1998, 2006, 2010, 2017 | 6,064,000 | 297,900 | 76,800 | 1.0 % | --- | 6.4 % |
| | **Cost** | 1985, 1993, 2006, 2017 | 6,193,000 | 300,600 | 72,200 | 3.2 % | 0.9 % | --- |
| **New York** | **Energy** | 1985, 1989, 1992, 1998, 2006, 2010, 2017 | 1,474,000 | 81,900 | 47,900 | --- | 5.4 % | 23.9 % |
| | **GHG** | 1985, 1992, 2007, 2017 | 1,490,000 | 77,700 | 40,500 | 1.1 % | --- | 4.7 % |
| | **Cost** | 1985, 1995, 2008 | 1,564,000 | 78,600 | 38,700 | 6.1 % | 1.2 % | --- |
| **San Antonio** | **Energy** | 1985, 1988, 1989, 1992, 1995, 1998, 2003, 2006, 2007, 2010, 2016, 2017 | 3,455,000 | 219,700 | 68,900 | --- | 4.9 % | 51.2 % |
| | **GHG** | 1985, 1992, 2007, 2017 | 3,522,000 | 209,400 | 47,000 | 1.9 % | --- | 3.1 % |
| | **Cost** | 1985, 1995, 2008 | 3,696,000 | 217,000 | 45,600 | 7.0 % | 3.6 % | --- |
| **Wichita** | **Energy** | 1985, 1989, 1992, 1998, 2003, 2006, 2007, 2011, 2017 | 2,087,000 | 171,800 | 44,200 | --- | 3.8 % | 57.5 % |
| | **GHG** | 1985, 1992, 2007, 2017 | 2,117,000 | 165,500 | 30,600 | 1.4 % | --- | 9.0 % |
| | **Cost** | 1985, 1995, 2008 | 2,224,000 | 171,200 | 28,100 | 6.6 % | 3.4 % | --- |

a) EIO-LCA results refer to modeling of the unit production. See Section 3.1 for details.

## A.5 Comparison of Optimal to Typical Replacement in 16 SEER Scenario

**Table A.0.12: Comparison of Optimal Replacements to Typical Replacement Scenario Using Process LCI Data**

| City | Objective | Life Cycle Impacts | | | Savings from Optimal vs. Typical Replacement | | |
|---|---|---|---|---|---|---|---|
| | | Energy (MJ) | GHG (kg CO2 eq.) | Cost (2009$) | Energy | GHG | Cost |
| **Ann Arbor** | **Energy** | 1,115,000 | 90,400 | 22,200 | 6.1 % | 0.9 % | (19.7 %) |
| | **GHG** | 1,115,000 | 90,400 | 22,200 | 5.8 % | 2.4 % | (9.8 %) |
| | **Cost** | 1,115,000 | 90,400 | 22,200 | 2.8 % | 1.4 % | 2.4 % |
| **Los Angeles** | **Energy** | 1,790,000 | 103,500 | 40,500 | 6.8 % | (0.8 %) | (20.5 %) |
| | **GHG** | 1,790,000 | 103,500 | 40,500 | 6.1 % | 3.0 % | (2.4 %) |
| | **Cost** | 1,790,000 | 103,500 | 40,500 | 2.8 % | 1.6 % | 2.5 % |
| **Miami** | **Energy** | 6,667,000 | 319,400 | 74,200 | 8.4 % | 4.0 % | (18.7 %) |
| | **GHG** | 6,667,000 | 319,400 | 74,200 | 7.9 % | 5.9 % | (4.1 %) |
| | **Cost** | 6,667,000 | 319,400 | 74,200 | 3.8 % | 3.3 % | 2.6 % |
| **New York** | **Energy** | 1,623,000 | 80,100 | 39,700 | 6.7 % | (1.2 %) | (14.8 %) |
| | **GHG** | 1,623,000 | 80,100 | 39,700 | 3.1 % | 2.3 % | 1.8 % |
| | **Cost** | 1,623,000 | 80,100 | 39,700 | 2.8 % | 1.4 % | 2.5 % |
| **San Antonio** | **Energy** | 3,818,000 | 222,400 | 46,700 | 7.7 % | 3.2 % | (23.2 %) |
| | **GHG** | 3,818,000 | 222,400 | 46,700 | 6.5 % | 5.0 % | (0.9 %) |
| | **Cost** | 3,818,000 | 222,400 | 46,700 | 2.8 % | 2.3 % | 2.5 % |
| **Wichita** | **Energy** | 2,303,000 | 175,300 | 28,800 | 7.2 % | 3.1 % | (32.6 %) |
| | **GHG** | 2,303,000 | 175,300 | 28,800 | 6.4 % | 4.7 % | (6.1 %) |
| | **Cost** | 2,303,000 | 175,300 | 28,800 | 2.8 % | 2.1 % | 2.6 % |

**Table A.0.13: Comparison of Optimal Replacements to Typical Replacement Scenario Using EIO LCI Data**

| City | Objective | Life Cycle Impacts | | | Savings from Optimal vs. Typical Replacement | | |
|---|---|---|---|---|---|---|---|
| | | Energy (MJ) | GHG (kg CO2 eq.) | Cost (2009$) | Energy | GHG | Cost |
| **Ann Arbor** | **Energy** | 1,101,000 | 90,000 | 22,200 | 7.0 % | (1.9 %) | (44.7 %) |
| | **GHG** | 1,101,000 | 90,000 | 22,200 | 6.2 % | 2.5 % | (9.8 %) |
| | **Cost** | 1,101,000 | 90,000 | 22,200 | 2.7 % | 1.3 % | 2.4 % |
| **Los Angeles** | **Energy** | 1,776,000 | 103,100 | 40,500 | 7.7 % | (0.5 %) | (20.5 %) |
| | **GHG** | 1,776,000 | 103,100 | 40,500 | 6.4 % | 3.0 % | (2.4 %) |
| | **Cost** | 1,776,000 | 103,100 | 40,500 | 2.7 % | 1.5 % | 2.5 % |
| **Miami** | **Energy** | 6,652,000 | 318,900 | 74,200 | 9.0 % | 1.6 % | (38.5 %) |
| | **GHG** | 6,652,000 | 318,900 | 74,200 | 8.1 % | 5.9 % | (4.1 %) |
| | **Cost** | 6,652,000 | 318,900 | 74,200 | 3.8 % | 3.3 % | 2.6 % |
| **New York** | **Energy** | 1,608,000 | 79,700 | 39,700 | 7.6 % | (3.2 %) | (21.1 %) |
| | **GHG** | 1,608,000 | 79,700 | 39,700 | 3.1 % | 2.3 % | 1.8 % |
| | **Cost** | 1,608,000 | 79,700 | 39,700 | 2.8 % | 1.3 % | 2.5 % |
| **San Antonio** | **Energy** | 3,803,000 | 222,000 | 46,700 | 8.3 % | 0.4 % | (47.7 %) |
| | **GHG** | 3,803,000 | 222,000 | 46,700 | 6.6 % | 5.0 % | (0.9 %) |
| | **Cost** | 3,803,000 | 222,000 | 46,700 | 2.8 % | 2.2 % | 2.5 % |
| **Wichita** | **Energy** | 2,288,000 | 174,800 | 28,800 | 7.9 % | 1.1 % | (53.4 %) |
| | **GHG** | 2,288,000 | 174,800 | 28,800 | 6.6 % | 4.7 % | (6.1 %) |
| | **Cost** | 2,288,000 | 174,800 | 28,800 | 2.8 % | 2.1 % | 2.6 % |

b) EIO-LCA results refer to modeling of the unit production. See Section 3.1 for details.

## A.6 Regional Standard Analysis

**Table A.14: Comparison of Optimal Replacement under a 16 SEER Regional Standard to Base Case**

| State | Year of CAC in 2009 | Objective | Base Case | | 16 SEER Regional Standard | | Savings from Energy Star |
|---|---|---|---|---|---|---|---|
| | | | Dates of Optimal Replacement | | Objective | Dates of Optimal Replacement | |
| **Alabama** | **1992** | **Energy (MJ)** | 2009, 2016 | 913,000 | 2009, 2017 | 793,000 | 13.2 % |
| | | **GHG (CO2 eq.)** | 2009 | 52,700 | 2009 | 46,800 | 11.2 % |
| | | **Cost (2009$)** | 2009 | $13,500 | 2009 | $12,810 | 5.1 % |
| | **1997** | **Energy (MJ)** | 2009, 2016 | 913,000 | 2009, 2017 | 793,000 | 13.2 % |
| | | **GHG (CO2 eq.)** | 2009 | 52,700 | 2009 | 46,800 | 11.2 % |
| | | **Cost (2009$)** | 2009 | $13,500 | 2009 | $12,810 | 5.1 % |
| | **2003** | **Energy (MJ)** | 2009, 2016 | 913,000 | 2009, 2017 | 793,000 | 13.2 % |
| | | **GHG** | 2009 | 52,700 | 2009 | 46,800 | 11.2 % |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | **(CO2 eq.)** | | | | | |
| | | **Cost (2009$)** | 2003, 2013 | $13,190 | 2003, 2013 | $12,700 | 3.7 % |
| | **2008** | **Energy (MJ)** | 2008, 2015 | 907,000 | 2009, 2017 | 793,000 | 12.6 % |
| | | **GHG (CO2 eq.)** | 2008, 2015 | 51,200 | 2008, 2011 | 46,500 | 9.2 % |
| | | **Cost (2009$)** | 2008, 2016 | $12,610 | 2008, 2013 | $12,190 | 3.4 % |
| **Arkansas** | **1992** | **Energy (MJ)** | 2009, 2016 | 928,000 | 2009, 2017 | 805,000 | 13.2 % |
| | | **GHG (CO2 eq.)** | 2009 | 72,400 | 2009 | 63,700 | 11.9 % |
| | | **Cost (2009$)** | 2009 | $11,590 | 2009 | $11,180 | 3.6 % |
| | **1997** | **Energy (MJ)** | 2009, 2016 | 928,000 | 2009, 2017 | 805,000 | 13.2 % |
| | | **GHG (CO2 eq.)** | 2009 | 72,400 | 2009 | 63,700 | 11.9 % |
| | | **Cost (2009$)** | 2009 | $11,590 | 2009 | $11,180 | 3.6 % |
| | **2003** | **Energy (MJ)** | 2009, 2016 | 928,000 | 2009, 2017 | 805,000 | 13.2 % |
| | | **GHG (CO2 eq.)** | 2009 | 72,400 | 2009 | 63,700 | 11.9 % |
| | | **Cost (2009$)** | 2003, 2013 | $11,220 | 2003, 2013 | $10,930 | 2.6 % |
| | **2008** | **Energy (MJ)** | 2008, 2015 | 921,000 | 2009, 2017 | 805,000 | 12.6 % |
| | | **GHG (CO2 eq.)** | 2008, 2015 | 70,400 | 2008, 2011 | 63,500 | 9.8 % |
| | | **Cost (2009$)** | 2008, 2016 | $10,750 | 2008, 2013 | $10,520 | 2.1 % |
| **Florida** | **1992** | **Energy (MJ)** | 2009, 2013, 2019 | 1,455,000 | 2009, 2017 | 1,260,000 | 13.4 % |
| | | **GHG (CO2 eq.)** | 2009 | 72,200 | 2009 | 63,500 | 12.0 % |
| | | **Cost (2009$)** | 2009 | $20,550 | 2009 | $18,850 | 8.2 % |
| | **1997** | **Energy (MJ)** | 2009, 2013, 2019 | 1,455,000 | 2009, 2017 | 1,260,000 | 13.4 % |
| | | **GHG (CO2 eq.)** | 2009 | 72,200 | 2009 | 63,500 | 12.0 % |
| | | **Cost (2009$)** | 2009 | $20,550 | 2009 | $18,850 | 8.2 % |
| | **2003** | **Energy (MJ)** | 2009, 2013, 2019 | 1,455,000 | 2009, 2017 | 1,260,000 | 13.4 % |
| | | **GHG (CO2 eq.)** | 2009 | 72,200 | 2009 | 63,500 | 12.0 % |
| | | **Cost (2009$)** | 2003, 2013 | $20,430 | 2009 | $18,850 | 7.7 % |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | **2008** | **Energy (MJ)** | 2008, 2012, 2019 | 1,448,000 | 2009, 2017 | 1,260,000 | 13.0 % |
| | | **GHG (CO2 eq.)** | 2008, 2015 | 70,300 | 2008, 2011 | 63,400 | 9.8 % |
| | | **Cost (2009$)** | 2008, 2016 | $19,510 | 2008, 2013 | $18,340 | 6.0 % |
| **Georgia** | **1992** | **Energy (MJ)** | 2009, 2016 | 841,000 | 2009, 2017 | 731,000 | 13.1 % |
| | | **GHG (CO2 eq.)** | 2009 | 48,900 | 2009 | 43,500 | 11.0 % |
| | | **Cost (2009$)** | 2009 | $12,670 | 2009 | $12,100 | 4.5 % |
| | **1997** | **Energy (MJ)** | 2009, 2016 | 841,000 | 2009, 2017 | 731,000 | 13.1 % |
| | | **GHG (CO2 eq.)** | 2009 | 48,900 | 2009 | 43,500 | 11.0 % |
| | | **Cost (2009$)** | 2009 | $12,670 | 2009 | $12,100 | 4.5 % |
| | **2003** | **Energy (MJ)** | 2009, 2016 | 841,000 | 2009, 2017 | 731,000 | 13.1 % |
| | | **GHG (CO2 eq.)** | 2009 | 48,900 | 2009 | 43,500 | 11.0 % |
| | | **Cost (2009$)** | 2003, 2013 | $12,330 | 2003, 2013 | $11,930 | 3.2 % |
| | **2008** | **Energy (MJ)** | 2008, 2015 | 834,000 | 2009, 2017 | 731,000 | 12.4 % |
| | | **GHG (CO2 eq.)** | 2008, 2015 | 47,400 | 2008, 2011 | 43,100 | 9.0 % |
| | | **Cost (2009$)** | 2008, 2016 | $11,800 | 2008, 2013 | $11,460 | 2.9 % |
| **Louisiana** | **1992** | **Energy (MJ)** | 2009, 2013, 2019 | 1,318,000 | 2009, 2017 | 1,142,000 | 13.4 % |
| | | **GHG (CO2 eq.)** | 2009, 2016 | 100,700 | 2009 | 88,600 | 12.0 % |
| | | **Cost (2009$)** | 2009 | $14,800 | 2009 | $13,920 | 5.9 % |
| | **1997** | **Energy (MJ)** | 2009, 2013, 2019 | 1,318,000 | 2009, 2017 | 1,142,000 | 13.4 % |
| | | **GHG (CO2 eq.)** | 2009, 2016 | 100,700 | 2009 | 88,600 | 12.0 % |
| | | **Cost (2009$)** | 2009 | $14,800 | 2009 | $13,920 | 5.9 % |
| | **2003** | **Energy (MJ)** | 2009, 2013, 2019 | 1,318,000 | 2009, 2017 | 1,142,000 | 13.4 % |
| | | **GHG (CO2 eq.)** | 2009, 2016 | 100,700 | 2009 | 88,600 | 12.0 % |
| | | **Cost (2009$)** | 2003, 2013 | $14,540 | 2003, 2013 | $13,920 | 4.3 % |
| | **2008** | **Energy (MJ)** | 2008, 2012, 2019 | 1,311,000 | 2009, 2017 | 1,142,000 | 12.9 % |
| | | **GHG** | 2008, 2015 | 98,800 | 2008, 2011 | 88,500 | 10.4 % |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | **(CO2 eq.)** | | | | | |
| | | **Cost (2009$)** | 2008, 2016 | $13,880 | 2008, 2013 | $13,330 | 4.0 % |
| **Mississippi** | **1992** | **Energy (MJ)** | 2009, 2016 | 919,000 | 2009, 2017 | 797,000 | 13.2 % |
| | | **GHG (CO2 eq.)** | 2009 | 53,000 | 2009 | 47,100 | 11.2 % |
| | | **Cost (2009$)** | 2009 | $13,510 | 2009 | $12,820 | 5.1 % |
| | **1997** | **Energy (MJ)** | 2009, 2016 | 919,000 | 2009, 2017 | 797,000 | 13.2 % |
| | | **GHG (CO2 eq.)** | 2009 | 53,000 | 2009 | 47,100 | 11.2 % |
| | | **Cost (2009$)** | 2009 | $13,510 | 2009 | $12,820 | 5.1 % |
| | **2003** | **Energy (MJ)** | 2009, 2016 | 919,000 | 2009, 2017 | 797,000 | 13.2 % |
| | | **GHG (CO2 eq.)** | 2009 | 53,000 | 2009 | 47,100 | 11.2 % |
| | | **Cost (2009$)** | 2003, 2013 | $13,200 | 2003, 2013 | $12,720 | 3.7 % |
| | **2008** | **Energy (MJ)** | 2008, 2015 | 912,000 | 2009, 2017 | 797,000 | 12.6 % |
| | | **GHG (CO2 eq.)** | 2008, 2015 | 51,500 | 2008, 2011 | 46,700 | 9.2 % |
| | | **Cost (2009$)** | 2008, 2016 | $12,620 | 2008, 2013 | $12,200 | 3.4 % |
| **Oklahoma** | **1992** | **Energy (MJ)** | 2009, 2016 | 881,000 | 2009, 2017 | 765,000 | 13.2 % |
| | | **GHG (CO2 eq.)** | 2009 | 68,900 | 2009 | 60,800 | 11.8 % |
| | | **Cost (2009$)** | 2009 | $11,400 | 2009 | $11,010 | 3.4 % |
| | **1997** | **Energy (MJ)** | 2009, 2016 | 881,000 | 2009, 2017 | 765,000 | 13.2 % |
| | | **GHG (CO2 eq.)** | 2009 | 68,900 | 2009 | 60,800 | 11.8 % |
| | | **Cost (2009$)** | 2009 | $11,400 | 2009 | $11,010 | 3.4 % |
| | **2003** | **Energy (MJ)** | 2009, 2016 | 881,000 | 2009, 2017 | 765,000 | 13.2 % |
| | | **GHG (CO2 eq.)** | 2009 | 68,900 | 2009 | 60,800 | 11.8 % |
| | | **Cost (2009$)** | 2003, 2013 | $11,020 | 2003, 2013 | $10,750 | 2.4 % |
| | **2008** | **Energy (MJ)** | 2008, 2015 | 874,000 | 2009, 2017 | 765,000 | 12.5 % |
| | | **GHG (CO2 eq.)** | 2008, 2015 | 67,000 | 2008, 2011 | 60,500 | 9.7 % |
| | | **Cost (2009$)** | 2008, 2016 | $10,550 | 2008, 2013 | $10,350 | 2.0 % |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **South Carolina** | **1992** | **Energy (MJ)** | 2009, 2016 | 909,000 | 2009, 2017 | 789,000 | 13.2 % |
| | | **GHG (CO2 eq.)** | 2009 | 52,500 | 2009 | 46,600 | 11.2 % |
| | | **Cost (2009$)** | 2009 | $13,000 | 2009 | $12,390 | 4.7 % |
| | **1997** | **Energy (MJ)** | 2009, 2016 | 909,000 | 2009, 2017 | 789,000 | 13.2 % |
| | | **GHG (CO2 eq.)** | 2009 | 52,500 | 2009 | 46,600 | 11.2 % |
| | | **Cost (2009$)** | 2009 | $13,000 | 2009 | $12,390 | 4.7 % |
| | **2003** | **Energy (MJ)** | 2009, 2016 | 909,000 | 2009, 2017 | 789,000 | 13.2 % |
| | | **GHG (CO2 eq.)** | 2009 | 52,500 | 2009 | 46,600 | 11.2 % |
| | | **Cost (2009$)** | 2003, 2013 | $12,680 | 2003, 2013 | $12,250 | 3.4 % |
| | **2008** | **Energy (MJ)** | 2008, 2015 | 903,000 | 2009, 2017 | 789,000 | 12.6 % |
| | | **GHG (CO2 eq.)** | 2008, 2015 | 50,900 | 2008, 2011 | 46,300 | 9.2 % |
| | | **Cost (2009$)** | 2008, 2016 | $12,130 | 2008, 2013 | $11,750 | 3.1 % |
| **Texas** | **1992** | **Energy (MJ)** | 2009, 2016 | 1,084,000 | 2009, 2017 | 939,000 | 13.3 % |
| | | **GHG (CO2 eq.)** | 2009 | 66,200 | 2009 | 58,400 | 11.8 % |
| | | **Cost (2009$)** | 2009 | $16,600 | 2009 | $15,470 | 6.8 % |
| | **1997** | **Energy (MJ)** | 2009, 2016 | 1,084,000 | 2009, 2017 | 939,000 | 13.3 % |
| | | **GHG (CO2 eq.)** | 2009 | 66,200 | 2009 | 58,400 | 11.8 % |
| | | **Cost (2009$)** | 2009 | $16,600 | 2009 | $15,470 | 6.8 % |
| | **2003** | **Energy (MJ)** | 2009, 2016 | 1,084,000 | 2009, 2017 | 939,000 | 13.3 % |
| | | **GHG (CO2 eq.)** | 2009 | 66,200 | 2009 | 58,400 | 11.8 % |
| | | **Cost (2009$)** | 2003, 2013 | $16,360 | 2009 | $15,470 | 5.4 % |
| | **2008** | **Energy (MJ)** | 2008, 2012, 2019 | 1,077,000 | 2009, 2017 | 939,000 | 12.8 % |
| | | **GHG (CO2 eq.)** | 2008, 2015 | 64,300 | 2008, 2011 | 58,100 | 9.8 % |
| | | **Cost (2009$)** | 2008, 2016 | $15,640 | 2008, 2013 | $14,880 | 4.9 % |

## A.7 Energy Star Analysis

**Table A.15: Comparison of Impacts of Replacing with a Baseline Models to Energy Star Models under Optimal Replacement in Ann Arbor (Process LCA Results).**

| Year of CAC in 2009 | Objective | Baseline Model | | Energy Star Model | | Savings from Energy Star |
|---|---|---|---|---|---|---|
| | | Dates of Optimal Replacement | Objective | Dates of Optimal Replacement | Objective | |
| **1992** | **Energy (MJ)** | 2009, 2017 | 344,000 | 2009, 2017 | 316,000 | 8.2 % |
| | **GHG (CO2 eq.)** | 2009, 2017 | 29,600 | 2009 | 28,100 | 5.3 % |
| | **Cost (2009$)** | 2009 | $8,240 | 1992, 2010 | $8,830 | (7.1 %) |
| **1993** | **Energy (MJ)** | 2009, 2017 | 344,000 | 2009, 2017 | 316,000 | 8.2 % |
| | **GHG (CO2 eq.)** | 2009, 2017 | 29,600 | 2009 | 28,100 | 5.3 % |
| | **Cost (2009$)** | 2009 | $8,240 | 1993, 2010 | $8,820 | (7.0 %) |
| **1994** | **Energy (MJ)** | 2009, 2017 | 344,000 | 2009, 2017 | 316,000 | 8.2 % |
| | **GHG (CO2 eq.)** | 2009, 2017 | 29,600 | 2009 | 28,100 | 5.3 % |
| | **Cost (2009$)** | 2009 | $8,240 | 1994, 2010 | $8,820 | (7.0 %) |
| **1995** | **Energy (MJ)** | 2009, 2017 | 344,000 | 2009, 2017 | 316,000 | 8.2 % |
| | **GHG (CO2 eq.)** | 2009, 2017 | 29,600 | 2009 | 28,100 | 5.3 % |
| | **Cost (2009$)** | 1995, 2010 | $8,240 | 1995, 2010 | $8,810 | (7.0 %) |
| **1996** | **Energy (MJ)** | 2009, 2017 | 344,000 | 2009, 2017 | 316,000 | 8.2 % |
| | **GHG (CO2 eq.)** | 2009, 2017 | 29,600 | 2009 | 28,100 | 5.3 % |
| | **Cost (2009$)** | 2009 | $8,240 | 1996, 2013 | $8,800 | (6.8 %) |
| **1997** | **Energy (MJ)** | 2009, 2017 | 344,000 | 2009, 2017 | 316,000 | 8.2 % |
| | **GHG (CO2 eq.)** | 2009, 2017 | 29,600 | 2009 | 28,100 | 5.3 % |
| | **Cost (2009$)** | 1997, 2010 | $8,230 | 1997, 2013 | $8,790 | (6.8 %) |
| **1998** | **Energy (MJ)** | 2009, 2017 | 344,000 | 2009, 2017 | 316,000 | 8.2 % |
| | **GHG (CO2 eq.)** | 2009, 2017 | 29,600 | 2009 | 28,100 | 5.3 % |
| | **Cost (2009$)** | 1998, 2010 | $8,220 | 1998, 2013 | $8,760 | (6.6 %) |
| **1999** | **Energy (MJ)** | 2009, 2017 | 344,000 | 2009, 2017 | 316,000 | 8.2 % |
| | **GHG (CO2 eq.)** | 2009, 2017 | 29,600 | 2009 | 28,100 | 5.3 % |
| | **Cost (2009$)** | 1999, 2010 | $8,220 | 1999, 2013 | $8,740 | (6.4 %) |
| **2000** | **Energy (MJ)** | 2009, 2017 | 344,000 | 2009, 2017 | 316,000 | 8.2 % |
| | **GHG (CO2 eq.)** | 2009, 2017 | 29,600 | 2009 | 28,100 | 5.3 % |
| | **Cost (2009$)** | 2000, 2013 | $7,840 | 2000, 2013 | $8,330 | (6.2 %) |
| **2001** | **Energy (MJ)** | 2009, 2017 | 344,000 | 2009, 2017 | 316,000 | 8.2 % |
| | **GHG (CO2 eq.)** | 2009, 2017 | 29,600 | 2009 | 28,100 | 5.3 % |
| | **Cost (2009$)** | 2001, 2013 | $7,820 | 2001, 2013 | $8,300 | (6.2 %) |
| **2002** | **Energy (MJ)** | 2009, 2017 | 344,000 | 2009, 2017 | 316,000 | 8.2 % |
| | **GHG (CO2 eq.)** | 2009, 2017 | 29,600 | 2009 | 28,100 | 5.3 % |
| | **Cost (2009$)** | 2002, 2013 | $7,800 | 2002, 2013 | $8,290 | (6.2 %) |
| **2003** | **Energy (MJ)** | 2009, 2017 | 344,000 | 2009, 2017 | 316,000 | 8.2 % |
| | **GHG (CO2 eq.)** | 2003, 2011, | 29,600 | 2003, 2011 | 28,000 | 5.1 % |

|  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|
|  |  | 2017 |  |  |  |  |
|  | **Cost (2009$)** | 2003, 2013 | $7,770 | 2003, 2013 | $8,260 | (6.3 %) |
| **2004** | **Energy (MJ)** | 2009, 2017 | 344,000 | 2009, 2017 | 316,000 | 8.2 % |
|  | **GHG (CO2 eq.)** | 2004, 2011, 2017 | 29,500 | 2004, 2011 | 28,000 | 5.1 % |
|  | **Cost (2009$)** | 2004, 2013 | $7,750 | 2004, 2013 | $8,240 | (6.3 %) |
| **2005** | **Energy (MJ)** | 2009, 2017 | 344,000 | 2009, 2017 | 316,000 | 8.2 % |
|  | **GHG (CO2 eq.)** | 2005, 2017 | 29,400 | 2005, 2011 | 27,900 | 5.0 % |
|  | **Cost (2009$)** | 2005, 2013 | $7,730 | 2005, 2013 | $8,220 | (6.3 %) |
| **2006** | **Energy (MJ)** | 2006, 2017 | 335,000 | 2009, 2017 | 316,000 | 5.6 % |
|  | **GHG (CO2 eq.)** | 2006, 2017 | 27,600 | 2006, 2017 | 27,100 | 1.7 % |
|  | **Cost (2009$)** | 2006, 2019 | $7,140 | 2006, 2019 | $7,630 | (7.0 %) |
| **2007** | **Energy (MJ)** | 2007, 2017 | 328,000 | 2007, 2010, 2017 | 316,000 | 3.6 % |
|  | **GHG (CO2 eq.)** | 2007, 2017 | 27,100 | 2007, 2017 | 26,600 | 1.7 % |
|  | **Cost (2009$)** | 2007, 2020 | $7,040 | 2007, 2020 | $7,540 | (7.1 %) |
| **2008** | **Energy (MJ)** | 2008, 2017 | 326,000 | 2008, 2017 | 315,000 | 3.6 % |
|  | **GHG (CO2 eq.)** | 2008, 2017 | 27,000 | 2008, 2017 | 26,600 | 1.7 % |
|  | **Cost (2009$)** | 2008, 2021 | $7,020 | 2008, 2021 | $7,530 | (7.2 %) |
| **2009** | **Energy (MJ)** | 2009, 2017 | 344,000 | 2009, 2017 | 316,000 | 8.2 % |
|  | **GHG (CO2 eq.)** | 2009, 2017 | 29,600 | 2009 | 28,100 | 5.3 % |
|  | **Cost (2009$)** | 2009 | $8,240 | 2009 | $8,830 | (7.2 %) |

**Table A.16: Comparison of Impacts of Replacing with a Baseline Models to Energy Star Models under Optimal Replacement in San Antonio.**

| **Year of CAC in 2009** | **Objective** | **Baseline Model** |  | **Energy Star Model** |  | **Savings from Energy Star** |
|---|---|---|---|---|---|---|
|  |  | **Dates of Optimal Replacement** |  | **Objective** | **Dates of Optimal Replacement** |  |
| **1999 and before** | **Energy (MJ)** | 2009, 2017 | 1,131,000 | 2009, 2017 | 1,028,000 | 9.1 % |
|  | **GHG (CO2 eq.)** | 2009, 2017 | 69,200 | 2009, 2017 | 64,100 | 7.4 % |
|  | **Cost (2009$)** | 2009 | $17,720 | 2009 | $17,330 | 2.2 % |
| **2000** | **Energy (MJ)** | 2009, 2017 | 1,131,000 | 2009, 2017 | 1,028,000 | 9.1 % |
|  | **GHG (CO2 eq.)** | 2009, 2017 | 69,200 | 2009, 2017 | 64,100 | 7.4 % |
|  | **Cost (2009$)** | 2000, 2013 | $17,670 | 2009 | $17,330 | 1.9 % |
| **2001** | **Energy (MJ)** | 2009, 2017 | 1,131,000 | 2009, 2017 | 1,028,000 | 9.1 % |
|  | **GHG (CO2 eq.)** | 2009, 2017 | 69,200 | 2009, 2017 | 64,100 | 7.4 % |
|  | **Cost (2009$)** | 2001, 2013 | $17,620 | 2009 | $17,330 | 1.7 % |
| **2002** | **Energy (MJ)** | 2009, 2017 | 1,131,000 | 2009, 2017 | 1,028,000 | 9.1 % |
|  | **GHG (CO2 eq.)** | 2009, 2017 | 69,200 | 2009, 2017 | 64,100 | 7.4 % |
|  | **Cost (2009$)** | 2002, 2013 | $17,610 | 2002, 2013 | $17,320 | 1.6 % |
| **2003** | **Energy (MJ)** | 2009, 2017 | 1,131,000 | 2009, 2017 | 1,028,000 | 9.1 % |

| | | | | | | |
|---|---|---|---|---|---|---|
| | **GHG (CO2 eq.)** | 2009, 2017 | 69,200 | 2009, 2017 | 64,100 | 7.4 % |
| | **Cost (2009$)** | 2003, 2013 | $17,540 | 2003, 2013 | $17,260 | 1.6 % |
| **2004** | **Energy (MJ)** | 2009, 2017 | 1,131,000 | 2009, 2017 | 1,028,000 | 9.1 % |
| | **GHG (CO2 eq.)** | 2009, 2017 | 69,200 | 2009, 2017 | 64,100 | 7.4 % |
| | **Cost (2009$)** | 2004, 2017 | $17,100 | 2004, 2013 | $17,210 | (0.7 %) |
| **2005** | **Energy (MJ)** | 2009, 2017 | 1,131,000 | 2009, 2017 | 1,028,000 | 9.1 % |
| | **GHG (CO2 eq.)** | 2009, 2017 | 69,200 | 2009, 2017 | 64,100 | 7.4 % |
| | **Cost (2009$)** | 2005, 2017 | $17,060 | 2005, 2017 | $17,180 | (0.7 %) |
| **2006** | **Energy (MJ)** | 2006, 2017 | 1,119,000 | 2009, 2017 | 1,028,000 | 8.1 % |
| | **GHG (CO2 eq.)** | 2006, 2017 | 66,900 | 2009, 2017 | 64,100 | 4.3 % |
| | **Cost (2009$)** | 2006, 2017 | $15,680 | 2006, 2017 | $15,800 | (0.8 %) |
| **2007** | **Energy (MJ)** | 2007, 2017 | 1,094,000 | 2009, 2017 | 1,028,000 | 6.0 % |
| | **GHG (CO2 eq.)** | 2007, 2017 | 65,600 | 2007, 2017 | 63,600 | 3.1 % |
| | **Cost (2009$)** | 2007, 2017 | $15,490 | 2007, 2017 | $15,610 | (0.8 %) |
| **2008** | **Energy (MJ)** | 2008, 2017 | 1,091,000 | 2009, 2017 | 1,028,000 | 5.7 % |
| | **GHG (CO2 eq.)** | 2008, 2017 | 65,400 | 2008, 2017 | 63,400 | 3.2 % |
| | **Cost (2009$)** | 2008, 2017 | $15,490 | 2008, 2017 | $15,610 | (0.8 %) |
| **2009** | **Energy (MJ)** | 2009, 2017 | 1,131,000 | 2009, 2017 | 1,028,000 | 9.1 % |
| | **GHG (CO2 eq.)** | 2009, 2017 | 69,200 | 2009, 2017 | 64,100 | 7.4 % |
| | **Cost (2009$)** | 2009 | $17,720 | 2009 | $17,330 | 2.2 % |

## A.8 High Efficiency CAC Rebate Survey

| Investor Owned Utilities | Parent Company | Location | Minimum Required Efficiency | Rebate Amount | Sizing Requirement | Specified Contractor[2] | Comments |
|---|---|---|---|---|---|---|---|
| **AEP Ohio** | American Electric Power | OH | 14 SEER<br>16 SEER | $75<br>$150 | N | Y | |
| **Alabama Power** | Southern Company | AL | --- | None | | | |
| **Commonwealth Edison** | Exelon Company | IL | --- | None | | | |
| **Connecticut Light & Power** | Northeast Utilities Service Company | CT | 14.5 SEER / 12 EER | $500 | N | N | |
| **Consolidated Edison** | | NY | 15 SEER / 12.5 EER<br>16 SEER / 13 EER | $400<br>$600 | Y | Y | |
| **Consumers Energy** | | MI | --- | None | | | |
| **Detroit Edison** | DTE Energy | MI | --- | None[1] | | | |
| **Duke Energy** | | NC | 14 SEER w/ ECM fan motor | $200 Existing Home; $300 New | N | N | Valid for NC, SC, and OH |
| **Florida Power and Light** | | FL | 14 SEER to 20 SEER | Dependant on size and efficiency; e.g. 3-ton rebate ranges from $210 (14 SEER) to $1130 (20 SEER) | N | Y | |
| **Georgia Power** | Southern Company | GA | --- | None | | | |
| **North States Power Company-Minnesota** | Xcel Energy | MN | 14 SEER<br>15 SEER<br>16 SEER | $180<br>$280<br>$330 | | | |
| **North States Power Company-Wisconsin** | Xcel Energy | WI | --- | None | | | |
| **Ohio Edison** | FirstEnergy | OH | --- | None | | | |
| **Pacific Gas & Electric** | | CA | --- | None | | | |
| **PECO Energy** | Exelon Company | PA | --- | None | | | |
| **Progress Energy** | | NC/FL | --- | None | | | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Public Service Company of Colorado** | Xcel Energy | CO | 14.5 SEER / 12 EER<br>15 SEER / 12.5 EER<br>16 SEER / 13 EER | $250<br>$350<br>$500 | Y | Y | |
| **Public Service Electric & Gas** | | NJ | --- | None | | | |
| **Reliant Energy** | | TX | --- | None | | | |
| **Southern California Edison** | | CA | --- | None | | | |
| **Southwestern Power Service** | Xcel Energy | NM | --- | None | | | |
| **TXU Energy Retail** | | TX | --- | None | | | |
| **Virginia Electric & Power** | Dominion | VA | --- | None | | | |

| Publicly Owned Utilities | Service Area | Required Efficiency | Rebate Amount | Sizing Requirement | Specified Contractor[2] | Comments |
|---|---|---|---|---|---|---|
| **Austin Energy** | Austin, TX | 14 SEER / 11.5 EER | $180 | N | N | |
| | | 14 SEER / 12 EER | $300 | | | |
| | | 15 SEER / 12.5 EER | $480 | | | |
| **Colorado Springs Utilities** | Colorado Springs, CO | --- | None | | | |
| **CPS Energy** | San Antonio, TX | 15 SEER<br>16 SEER<br>17 SEER<br>18 SEER | $110/ton<br>$125/ton<br>$140/ton<br>$160/ton | N | N | |
| **JEA** | Jacksonville, FL | --- | None | | | |
| **Long Island Power Authority** | New York, NY | 14.5 SEER / 12 EER<br>15 SEER / 12.5 EER<br>16 SEER /13 EER | $250<br>$400<br>$600 | Y | Y | |
| **Los Angeles Department of Water & Power** | | 14 SEER | $100 | N | N | |

| | | | | | | |
|---|---|---|---|---|---|---|
| **Memphis Light, Gas and Water** | Memphis, TN. | --- | None | | | |
| **Nebraska Public Power District** | Nebraska | --- | None | | | |
| **Sacramento Municipal Utility District** | Sacramento, CA. | 14.5 SEER / 12 EER<br>15 SEER / 12.5 EER<br>16 SEER /13 EER | $400<br>$500<br>$650 | Y | Y | |
| **Salt River Project** | Phoenix, AZ | 17 Seer 17 / EER 13 | $400 | Y | Y, Licensed | Replacements Only |
| **Santee Cooper** | SE South Carolina | --- | None | | | |
| **Seattle City Light** | Seattle, WA | --- | None | | | |

| **State Programs** | | | | | | |
|---|---|---|---|---|---|---|
| **CoolAdvantage** | NJ | SEER 14.5 and EER 12 | $100 | Y | N | |
| | | SEER 15 and EER 12.5 | $150 | Y | N | |
| **Keystone HELP** | PA | Energy Star | 10% of cost up to 250 | N | Y | Also Loans for Energy Star |
| | | SEER ≥ 15.0, EER ≥ 12.5 | 10% of cost up to $500 | | | |
| **Focus on Energy** | WI | SEER 15 | $100 | N | N | Financing also available |

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1) Based on data collected from utility websites during June 20 – 24, 2009
2) Rebate program has a stated requirement that sizing calculations, such as those outlined in Manual J, be completed to qualify for the rebate. In certain cases when contractor participation is limited by the utility, contractors may receive training on or demonstrate the using of cooling load calculations or software.
3) Rebate program states the installation must be performed by contractor that has been approved by the utility and/or otherwise meets some type of selective criteria (e.g. NATE certification) in order to participate in the program.
4) Other AC programs such as tune-up rebates, low interest financing, and heat pump rebates not included.
5) Rebate program coming fall 2009