Analyzing Residential End-Use Energy Consumption Data to Inform Residential Consumer Decisions and Enable Energy Efficiency Improvements

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Abstract

While renewable energy is in the process of maturing, energy efficiency improvements may provide an opportunity to reduce energy consumption and consequent greenhouse gas emissions to bridge the gap between current emissions and the reductions necessary to prevent serious effects of climate change and will continue to be an integral part of greenhouse gas emissions policy moving forward. Residential energy is a largely untapped source of energy reductions as consumers, who wish to reduce energy consumption for monetary, environmental, and other reasons, face barriers. One such barrier is a lack of knowledge or understanding of how energy is consumed in a home and how to reduce this consumption effectively through behavioral and technological changes.

One way to improve understanding of residential energy consumption is through the creation of a model to predict which appliances and electronics will be present and significantly contribute to the electricity consumption of a home on the basis of various characteristics of that home. The basis of this model is publically available survey data from the Residential Energy Consumption Survey (RECS). By predicting how households are likely to consume energy, homeowners, policy makers, and other stakeholders have access to valuable data that enables reductions in energy consumption in the residential sector. This model can be used to select homes that may be ripe for energy reductions and to predict the appliances that are the basis of these potential reductions. This work suggests that most homes in the U.S. have about eight appliances that are responsible for about 80% of the electricity

consumption in that home. Characteristics such as census region, floor space, income, and total electricity consumption affect which appliances are likely to be in a home, however the number of appliances is generally around 8. Generally it takes around 4 appliances to reach the 50% threshold and 12 appliances to reach 90% of electricity consumption, which suggests significant diminishing returns for parties interested in monitoring appliance level electricity consumption.

Another way to improve understanding of residential energy consumption is through the development of residential use phase energy vectors for use in the Economic Input-Output Life Cycle Assessment (EIO-LCA) model. The EIO-LCA model is a valuable scoping tool to predict the environmental impacts of economic activity. This tool has a gap in its capabilities as residential use phase energy is outside the scope of the model. Adding use phase energy vectors to the EIO-LCA model will improve the modeling, provide a more complete estimation of energy impacts and allow for embedded energy to be compared to use phase energy for the purchase of goods and services in the residential sector. This work adds 21 quads of energy to the residential energy sector for the model and 15 quads of energy for personal transportation. These additions represent one third of the total energy consumption of the United States and a third of the total energy in the EIO-LCA model. This work also demonstrates that for many products such as electronics and household appliances use phase energy demands are much greater than manufacturing energy demands and dominate the life cycles for these products.

A final way in which this thesis improves upon the understanding of how use phase energy is consumed in a home is through the exploration of potential energy reductions in a home. This analysis selects products that are used or consumed in a home, and explores the potential for reductions in the embedded manufacturing and use phase energy of that product using EIO-LCA and the energy vectors created in Chapter 3. The results give consumers an understanding of where energy is consumed in the lifecycle of products that they purchase and provide policy makers with valuable information on how to focus or refocus policies that are aimed and reducing energy in the residential sector. This work finds that a majority of the energy consumed by retail products is consumed in the use phase of electronics and appliances. Consequently the largest potential reductions in residential energy use can be found in the same area. The work also shows that targeting reductions in the manufacturing energy for many products is likely to be an ineffective strategy for energy reductions with the exception of a select few products. Supply chain energy reductions may be more promising than manufacturing energy reductions, though neither is likely to be as effective as strategies that target use phase energy reductions.

Table of Contents

List of Tables

List of Figures

Chapter 1. Motivations and Research Questions

1. Motivations

While renewable energy is in the process of maturing, energy efficiency improvements may provide an opportunity to reduce energy consumption and consequent greenhouse gas emissions to bridge the gap between current emissions and the reductions necessary to prevent serious effects of climate change as predicted by the Intergovernmental Panel on Climate Change (IPCC) [1]. Energy efficiency improvements exist that are readily available, can have negative costs, and can immediately reduce energy consumption and consequent greenhouse gas emissions as has been demonstrated by Enkvist (in what has now become known as the "McKinsey Curve") as well as by Rubin and others [2][3][4][5]. Unfortunately, without a better understanding of energy consumption these improvements may not be fully realized.

In order for energy efficiency investments to be effectively implemented, stakeholders need better information about the whole lifecycle, i.e., both embedded and use-phase energy for products and services. Better data about energy consumption can empower consumers and policy makers to more efficiently facilitate reductions in energy consumption. This knowledge can also provide a better focus of resources to either target upstream embedded energy or downstream use-phase energy depending on the product or service. It can also give policy makers the necessary understanding to craft effective energy efficiency programs. Without first understanding how energy is currently being used it is unlikely that consumers and policy makers can maximize energy consumption reductions. It is also important to have access to this baseline data in order to properly gauge the effectiveness of energy efficiency programs.

Many consumers desire to reduce energy consumption and consequent greenhouse gasses but lack the knowledge, resources, and capital to do so. In this thesis several novel improvements are presented to the current state of knowledge on residential energy consumption that will help users, policy makers, and other stakeholders to gain information that will empower them to reduce consumption. The reasons that stakeholders wish to reduce energy consumption vary widely, however regardless of motivation, without a better understanding of energy consumption, efficiency improvements will be difficult or impossible [6][7].

One area in which there is both a need for and a demand for better data is residential energy consumption. Consumer understanding of how and why we consume energy in homes is lacking [8][9]. Attari et. al. showed that consumers tend to overestimate the energy use of low-energy electronics while underestimating the energy use of larger consuming appliances [10]. There is also a desire amongst homeowners and energy consumers to reduce consumption for a plethora of reasons including monetary savings and environmental concerns amongst others [6][7].

This market for energy savings remains generally untapped for a variety of reasons such as the relatively poor understanding by both policy makers and consumers about how and why consumers use energy [10], the relative newness of energy monitoring devices such as The Energy Detective and the Efergy Energy Monitor [11][12], the spread of energy use amongst many devices as shown in the Residential Energy Consumption Survey (RECS) [13], and the relatively low share of energy costs compared to other consumer expenditures as shown in the Bureau of Economic Analysis Consumer Expenditure Survey [14].

Numerous studies have explored how better data and better feedback for users may result in reduced energy consumption over various periods of time [15][16][17]. There is no guarantee that the better data identified in this thesis will result in reduced consumption as rebound effects may occur [18] or the data may not reach a wide enough audience to make a significant impact. Regardless of these potential shortcomings, without knowledge of energy consumption we can be sure that stakeholders cannot consciously alter energy consumption behaviors to reduce energy use, consequent greenhouse gas emissions, or money.

Another way in which policy makers and researchers currently gain insight into energy use and greenhouse gas emissions is through life-cycle assessment (LCA) models. One type of LCA model is a process LCA model. Process models itemize the energy and material inputs and outputs for each step in the production of a good or service [19] and then aggregate them for total results (i.e., from the bottom up). Process models offer benefits over other LCA models in that they are comprehensive and can be made very specific to model a given product. They also can model all phases of a life cycle, from cradle to cradle or cradle to grave. Though these models can be comprehensive, they can also require more time, effort, and resources than other models. Another kind of LCA model is an input-output (IO) LCA model. These models work by modeling all monetary transactions between sectors of an economy across the supply chain in order to produce a given valued output (i.e., a top down basis) [19]. Environmental and energy impacts per monetary unit are applied to each sector in the economy in order for the model to estimate impacts. These models offer a more streamlined approach to LCA modeling than their process-based counterparts, though they also generally have larger uncertainty associated with them. A third type of model exists that combines process models with input-output models into a hybrid LCA model. These models combine the potential for specific data for a product or process with the comprehensiveness of EIO models for the rest of the economic sectors. This research will deal specifically with EIO-LCA models. The research presented in this thesis focuses on the improvement of EIO-LCA modeling to move beyond the traditional cradle to gate or cradle to consumer screening process to include the use-phase in this screening process.

One of the most comprehensive and popular IO-LCA models is the EIO-LCA model developed by researchers at the Green Design Institute at Carnegie Mellon University (www.eiolca.net) [20]. Unfortunately, as is the case with many input-output (IO) models, the scope of this model only encompasses products and services from cradle to gate or cradle to consumer in the case of purchaser price basis models. This is acceptable for many products and services that do not have large use-phase energy consumption components to their life cycles. However, for other products and services whose life-cycle energy use is dominated by the use-phase (such as many household appliances which form the core of residential consumption) [21], IO models do a poor job estimating true life-cycle impacts.

Finally, a potential means to reduce energy use arises through the improvement of knowledge of energy consumption across the lifecycle of retail products and services. This improved knowledge could be intended for consumers or for corporate or policy decision makers. An example of such an improvement of consumer knowledge could come through the implementation of carbon or energy footprint labels for retail products. The underlying hypothesis is that if consumers were to select products and services based on minimizing embedded and use phase energy and greenhouse gas emissions, the manufacturing energy for products and services could shift from the average to the best practices and use phase energy could be decreased. Few carbon labels have been implemented to date and those that have are still too young to draw any conclusions about effectiveness [22][23][24]. Instead we can look at similar labeling efforts to explore the effectiveness of labeling efforts in general. The most obvious program to draw parallels to is the Energy Star program, which was predicted by Brown et. al. in 2002 to save 150 million tons of carbon dioxide equivalents between 2001 and 2010 [25]. According to the Energy Star website's "Fact Sheet", in 2006 alone, Energy Star saved the United States 37 million tons of carbon dioxide equivalent emissions [26]. Understanding the potential for an energy labels program to reduce energy and consequent greenhouse gas emissions is important to the success of such a program. A more comprehensive review of carbon and energy footprint labels is provided later in this thesis.

While not a lifecycle tool, Lawrence Berkeley National Lab's Home Energy Saver offers baseline and predictive capabilities at a much more detailed level than the RECS-based predictive tool described in Chapter 2 [27]. What differentiates this work from the Home Energy Saver is the intended user of the model. Home Energy Saver is designed to be a predictive tool with several user inputs about appliances and other characteristics of a home for the purpose of describing to the end user potential energy savings potentials from technology upgrades in the home. The RECS based tool created in Chapter 2 is intended for a higher level audience than the Home Energy Saver, such as local or state policy makers, or researchers who may be interested in locating a specific group of homes that may benefit from an electrical appliance based modeling system such as nonintrusive load monitoring (NILM).

The RECS-based model created in Chapter 2 offers insight into how a typical household may consume electricity at the appliance level given various simple attributes of that home (such as household income level, census division, total floor space, or total electricity consumption) which are inputs that most people would be able to identify immediately. The RECS-based model, unlike Home Energy Saver, does not require multiple inputs about which appliances are present in the home, ZIP code, number of residence by age group, age of the home, foundation type, insulation in the home, etc. as all of these attributes of the typical home for this census region are already accounted for in the segmentation of the RECS data. The RECS based model is not intended to accurately describe a single user's electricity profile, but rather provide insight for policy makers, utilities, and researchers who may be interested in how a typical home in this region is likely to be consuming electricity at the appliance level. This type of analysis may be difficult to extract from the Home Energy Saver model which is targeted for a different audience for energy and greenhouse gas emissions savings, not necessarily electricity consumption. Home Energy Saver also has limited breakdown capabilities for electricity consumption, often to aggregated end-uses that are bigger than the appliance or device level. Likewise, tailoring the model described in Chapter 2 for individual household use may be difficult as the model in its current iteration is designed to model the typical home in a given subset of the national data without inquiring about specific details of a given home. For these purposes, something like the Home Energy Saver model is more appropriate.

2. Research Questions

This research attempts to answer several important questions that affect knowledge and understanding of residential energy consumption towards making efficient reductions. These questions guide the research presented in this thesis.

2. 1. How can we use aggregated data such as the RECS to predict the quantity and which appliances are likely to be present in a specific household? (Chapter 2)

This research utilizes publically available data from RECS to provide estimates for how many and which appliances are likely to contribute significantly to a household's electricity consumption given varying characteristics of a home such as income, size, census region, etc. This research moves beyond simple "average" home estimates, which may misrepresent energy consumption in a typical home, and develops estimates for the typical home as well as homes that utilize natural gas appliances and homes that use electrical appliances. This information is useful for researchers who are trying to develop in-home electricity monitors to further inform consumers in an attempt to enable electricity reductions. This work is also useful for policy makers who are also trying to incentivize and enable energy reductions in the residential sectors.

2. 2. How can we predict differences in appliance ownership and use based on various factors including geography, socioeconomic status, housing size, or total energy consumption? (Chapter 2)

RECS tracks many characteristics for each household sampled in the survey. This work segregates the data based on these characteristics to provide predictions for potential households' likely appliances that contribute to their electricity consumption. These predictions include both which appliances and how many appliances may significantly contribute to a household's electricity consumption.

2. 3. What data sources are available to create use-phase energy vectors that are applicable to EIO-LCA models and where are the significant gaps in the data? (Chapter 3)

Residential use phase energy is outside of the scope of traditional environmental IO models. Using publically available data sources from federal level U.S. organizations such as the Department of Energy, the Census, the Federal Trade Commission, the Environmental Protection Agency, and ENERGY STAR; as well as state and local municipalities, companies, trade unions, and foreign governments, residential use phase energy data is collected regarding the lifetime of appliances, energy consumption, expected increases in consumption over time (degradation), and yearly shipments. This data is then used to calculate lifetime use phase estimates for residential appliances and electronics. These estimates are combined with Bureau of Economic Analysis data on industrial outputs to create use phase energy estimates at the same level of aggregation as the EIO-LCA model. Significant gaps in data are found for some devices and IO sectors.

These gaps are filled with annual energy consumption under the assumption that for these sectors the annual consumption for entire fleet of devices is approximately equal to the lifetime consumption of all of the devices sold in that year.

2. 4. What is the uncertainty associated with use phase energy data and how does it compare across sectors and energy impacts in the EIO-LCA model? (Chapter 3)

Uncertainty in the use phase energy modeling and uncertainty in the manufacturing energy modeling are both explored in this research to give the user an indication of likely and potential use of manufacturing energy estimates. Uncertainty associated with degradation of appliances over time, lifetimes, behavioral issues, and efficiency all contribute to the uncertainty of these estimates. Despite the large uncertainties with the modeling, the total residential consumption in the model is reasonably consistent with top down approach estimates for residential energy consumption.

2. 5. What is the maximum reasonable expectation for short-term energy reductions if consumers are given better information regarding retail goods and services to enable consumers to reduce energy? (Chapter 4)

Building on prior work for the California Air Resources Board (CARB) and the California Environmental Protection Agency (EPA), and using the EIO-LCA model and the energy vectors developed in Chapter 3, we explore the maximum reasonable expectation for short-term energy reductions for energy footprint labels or a similar consumer information program to reduce energy. This work demonstrates the ability of the use phase energy vectors to handle important modeling tasks such as this one and provides a maximum reasonable expectation potential for short-term energy reductions given an effective energy footprint label and easy to implement manufacturing improvements with short term pay-back periods of three years or less.

2. 6. What are the particular sets of goods or services that are particularly well suited for better consumer awareness to reduce lifecycle energy on the basis of variation in manufacturing and use phase energy? (Chapter 4)

Exploring a diverse set of 20 products in the U.S. and modeling their potential reductions in the supply chain, final manufacturing sector, and use phase allows us to predict which residential goods and services may be well suited for reductions given improved consumer awareness. This assessment also shows which life-cycle phase offers the largest potential for reductions for a given product. This analysis could be used or replicated to shape policies that could maximize the potential for information campaigns to reduce residential energy consumption.

The next 3 chapters (as identified above) address the methods and results related to the research questions. Chapter 5 summarizes results of this thesis including an explicit listing of results by research question as well as discussions of future work and contributions.

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Chapter 2. One Size Does Not Fit All: Averaged Data on Household Electricity is Inadequate for Residential Energy Policy and Decisions[1]

1. Introduction

Residential energy consumption in the United States accounted for 23% of all energy consumption in 2010 [1]; yet this sector is perhaps the least understood. A similar scenario describes the situation in many other countries. The vast majority of the information that is available for characterizing it is aggregate or indirect in nature (e.g., surveys, monthly utility bills, etc.). A growing number of applications, services and policies, such as automated demand response and energy efficiency upgrades require a more detailed comprehension of energy use than the available aggregate data.

Estimating the end-use energy consumption of residential households is a topic of interest for many stakeholders including utilities, customers, policy makers and appliance manufacturers among other parties, and it has been an active topic of research for at least four decades [2][3][4]. Two distinct modeling approaches can be used to categorize the existing practices: top-down and bottom-up. Bottom-up approaches are better suited for creating detailed models of the time-dependent behavior of individual end-use loads, but require significant input data resulting from measurements and surveys [5]. Top-down approaches attempt to infer the end-use behavior from high-level variables such as macroeconomic indicators, weather, etc.

Each of these approaches has its advantages and limitations, and there is a

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symbiotic relationship between them: results gathered from one can inform ways to improve the other. We posit that a first step towards this (i.e., achieving a more symbiotic relationship) is to analyze the existing data from surveys to understand what it can tell us about the nature of the demand and about how to optimize both future deployments of sub-metering equipment to expand the existing datasets, and the design of top-down approaches based on high-level indicators.

Furthermore, we show that, if not carefully analyzed, some summary statistics from these surveys can be misleading. For instance, average appliance energy consumption based on RECS data may be misunderstood if one does not pay attention to the variation in the housing stock.

2. Materials and Methods

Residential energy consumption information is useful to both end-customers and utilities or third parties, even though the significance and applications for each one of these stakeholders may be different. For consumers, this information is generally used to inform energy efficiency and saving strategies, while for utilities and other interested parties the objectives are varied and may not necessarily include efficiency and curtailment.

2.1 Related Work

Previous studies show that improved knowledge by consumers about their consumption patterns can lead to reductions in electricity consumption of between 0% and 15% [6][7][8]. However, the small sample sizes and the short time frames of these studies are often insufficient to assess general long-term savings. Peschiera et. al. found that initial energy savings from feedback diminished between four and fifteen months after feedback was initiated [9]. Parker et. al. also found that energy efficiency improvements from feedback were not permanent when they performed a follow-up evaluation three years after their study concluded [10]. Studies warn that initial energy reductions that are behaviorally based tend to last for a short period [9] and that without continued eduation, incentives, or disincentives, consumers revert back to old higher consuming behaviors [11].

Top-down residential energy models are popular for a variety of reasons and they serve a number of purposes generally dealing with demand forecasting [5]. Top-down models tend to treat the energy sector as an energy sink. These models rely on historical energy demands and account for other input factors such as GDP, employment, price indices, climate, construction rates, appliance ownership, and housing stock changes. Two types of top-down models exist: econometric and technological models. Econometric models are typically based on prices of appliances and energy while technological models are based on other factors such as appliance ownership changes and changes in housing stock. While top-down energy models have been used for residential energy demand forecasting for decades [12][13] a particular type of top-down model has been used with success to disaggregate electricity consumption into individual appliances. This method is known as conditional demand analysis. Aigner et. al. [14], Blaney et. al [15], Tiedmann [16], and others have successfully demonstrated the ability of conditional demand analysis to disaggregate total energy consumption into component parts. Unfortunately for users, conditional demand analysis cannot be used to disaggregate specific household loads.

Because of the limitations of the consumption information reported by utilities to their customers, much work has been done to provide better, disaggregated (i.e., appliance-specific) electricity consumption data for residential customers using a variety of techniques and systems that build from the bottom up, or what is commonly referred to as the Engineering Method [5][17]. An example of this comes from Mihalakakou et. al. who have created a neural network model that predicts energy consumption hourly on the basis of meteorological inputs [18]. Yao et. al. have also created a bottom-up statistical model of household energy use in the United Kingdom, however issues regarding how to deal with ownership rates or penetration rates continue to exist in many statistical models that make them difficult for individual homeowner use. Similarly, Chiou et. al. have created a residential time of use energy model at the sub-house level to more accurately predict household consumption and potential improvements which generally come in increments at a sub-house level [19]. Paatero et. al. deal with aggregation issues similarly in that many households are simulated in a way that each house is given a probability to own and use an appliance that is set equal to the ownership rate for that appliance [20]. The results of this are well suited for decisions at a higher level than the household but do little for aiding individuals in reducing energy use. Bottom-up models appear to be better suited to answer the questions posed in this research than top-down models by nature, however they are not without flaws. Kavgic et. al highlight the strengths and weaknesses of bottom-up models citing a lack of transparency and quantification of uncertainties as being the major flaws in many bottom-up models [21].

Furthermore, there is a collection of signal processing and machine learning techniques for disaggregating these aggregate measurements of electricity consumption, known as non-intrusive load monitoring (NILM) techniques [2][22][23][24][25]. NILM works by monitoring an electric circuit with multiple appliances using automated computer analysis of current and voltage waveforms in order to characterize and break down the total electric load into component appliances that contribute to the total load. There are also commercial and research ventures developing plug-through power meters to monitor individual appliances, or products for analyzing electricity consumption patterns at higher points of the load distribution tree such as the electric circuits or panels.

It is important for researchers interested in the development of any of these systems and techniques to understand which appliances are significant and how many of them need to be disaggregated or individually monitored. The answer to these two questions is also important for researchers and consumers who may not be directly interested in technologies, for example those who seek to develop effective energy efficiency policies or to reduce household electricity consumption.

Understanding which appliances are important is only the first step to improving residential energy efficiency. The next step after identifying these "hot-spots" of energy consumption is reconciling with cost-effective opportunities to reduce consumption. For example, knowing that air conditioning accounts for a significant portion of one's electricity bill is only helpful if there is an opportunity to reduce this load. It is not helpful to know that air-conditioning is a large consumer of electricity if an efficient air conditioning model is already installed and behavioral change is not an option. In this case it is more useful to identify smaller appliances that have larger potentials for energy reduction. Once the potentials for reduction have been identified, behaviors may be modified and equipment may be replaced to reduce energy consumption.

In this study we analyze existing data about end-use consumption in the US to provide initial answers to the questions posed above and, in doing so, help guide future developments in top-down and bottom-up approaches for residential end-use load modeling and forecasting. The model proposed in the research presented in this paper uniquely deals with ownership rates of appliances to deliver realistic potential households for analysis. We begin by describing the datasets that were used and the methods we applied to it.

This work is not intended to estimate the specific consumption patterns for a specific household, but rather the likely home given certain attributes, such as location, household income, total electricity consumption, and floor space. For more detailed models to predict household electricity, natural gas, and related greenhouse gas emissions, one might consult a model such as Lawrence Berkeley National Lab's Home Energy Saver which has detailed inputs about attributes of a home intended for modeling [26]. This model is intended more for the use of state, local, and regional policy makers and researchers, such as those interested in nonintrusive load monitoring, for predicting how and where typical homes consume electricity, given certain characteristics of those homes. This model also breaks electricity use down to a bit more detail than the Home Energy Saver. For example, the RECS based model estimates electricity use for televisions, VCRs, and DVD players; while the Home Energy Saver aggregates several devices into an entertainment end-use in the small appliance energy consumption.

2.2 Data

The Residential Energy Consumption Survey (RECS) is a survey for occupied primary housing units with a focus on energy use [27]. The survey was started in 1978 and was in its thirteenth iteration as of 2009 (though the 2009 results are not completely available as of the time of this manuscript). RECS provides high level published summaries and a *microdata* set that is the publically available underlying data used to create many of the reports and figures. The microdata contains complete responses from all of the 4,382 housing units surveyed and is weighted to represent the 111 million homes found in the United States at the time of the 2005 survey. It is these responses that are the basis for all of the RECS summary data tables. While the dataset is regarded as reliable, the dataset itself is small with each home in the dataset representing around 25,000 homes, so the potential for error is quite large. The RECS microdata also contains a number of obvious errors and missing pieces of data, which is expected for a spreadsheet that contains more than 4.7 million cells.

The Federal Trade Commission (FTC) also publishes yearly data for all of the appliances sold in the United States [28], however the data is impossible to use in this work without supplemental data on ownership of each model appliance. For this reason RECS was determined to be a much better source than the FTC data for this research.

The 2005 RECS microdata was used as the basis for electricity consumption estimates by appliance, supplemented with the 2001 RECS End-Use Survey [29] when the microdata was insufficient. While the 2001 End-Use Survey is over ten years old, it is the best supplemental data available for the purposes of this study. The RECS Residential End Use Survey for 2001 estimates the average consumption of 42 unique appliances contributing to the average household's electric load. Of these 42 appliances, 23 contribute at least 0.1% of the average electricity demand in one or more of the U.S. Census divisions. The data is first broken down by census division in order to highlight potential differences that may result from geographical location. Subsequent breakdowns of the data will explore household size, income, and total electricity use and will be displayed in the appendix. Anything that contributes less than 0.1% of the electricity load is ignored for simplicity of this study.

Despite the fact that there is uncertainty associated with the data used in this research, the results are still applicable to current household electricity consumption. Both trends in appliance energy consumption and energy standards indicate that the energy consumption of appliances decreases over time. Using more current data would likely indicate slightly different results, smaller totals for each appliance, more appliances in each household, and a higher total consumption per residence [30][31][32]. Myers et. al. indicate that federal appliance standards will reduce appliance consumption by 8%-9% by the year 2020 compared to appliance consumption in the absence of these standards [30][31]. In general however, the authors do not expect that the number or appliances or the relative contribution of appliances to significantly change, especially given adoption rates for appliances and the uncertainty of relative ages of appliances in a given home.

2.3 Methods

To answer the questions of how many and which appliances were the primary contributors the electricity demand in US households, it was necessary to first define what would constitute the basis for determining this list (i.e., what portion of the total household demand we were interested in finding contributors for). Thus, consumption thresholds for this research were set at 50%, 80%, and 90%.

The first, 50%, was chosen to determine how many appliances would have to be monitored in order to account for half of all of the electricity consumption in a household. It is a reasonable assumption that any of various monitoring techniques are going to have to encompass at least half of the electricity load in order to be considered useful/effective. It is also unlikely that a consumer is willing to spend time and money on a product or service that cannot guarantee at least half of an electric load will be covered.

The 80% threshold was chosen based on the "80/20 rule", the idea that 80% of a result is produced by 20% of a cause. If the 80/20 rule proves true in this instance, we could expect to monitor four-fifths of the electric load of a given house by monitoring a select one fifth of the appliances in that home. A quick analysis on the RECS data indicates that this rough approximation holds true. The RECS End-Use Consumption of 2001 lists 42 unique appliances and a 43rd category labeled "residual." 20% of the appliances in the RECS would correspond to between 8 and 9 appliances. In reality the top 20% of the appliances correspond to 76%-78% of the total residential electricity consumption in the study (76% if "residual" electricity consumption is included, 78% if "residual" is not considered to be an appliance). While it appears that the "80/20 rule" holds true in this case, there is significant variation as to which appliances are actually present in a home.

Finally, the 90% threshold was chosen to illustrate the challenge created by diminishing returns of monitoring more appliances. We can consider the 90% threshold a toned-down frontier that represents all of the electric appliances in a home given that

100% of the electric load is an unrealistic goal (e.g., there are small electronics that will get "lost in the noise" of the electric load). This threshold also serves to show the diminishing returns of disaggregating 10% of the load between 80% and 90%. The same can also be observed in the jump from the 50% to 80% thresholds.

Even though we have exact targets set at 50%, 80%, and 90%; the idea is not that the target thresholds are important. Rather, they serve to illustrate the notion that it requires increasingly more appliances to monitor higher thresholds, that this is a problem of diminishing returns, and that a select few appliances generally do not dominate electric loads in a household. Instead, most households' electricity consumptions are widely spread amongst many appliances, which makes disaggregation a complex problem [29]. Given this premise, the goal of this research is not to perfectly calculate the number of appliances to achieve a given frontier, but rather to generalize the complexity of the problem, and to gain insight into how many and which appliances are important to household electricity consumption for those working on energy management systems.

2.4 Scenarios

Four national and regional scenarios are explored in this study. The first two scenarios are meant to illustrate the difference between an actual household's electricity consumption (can be thought of as the median household) and the average household reported in the RECS summary data. These two theoretical households are labeled *average* and *typical* and are explained in more detail in sections 2.4.1 and 2.4.2. Additionally two scenarios are included to show what happens at the extremes; when households rely heavily on electricity (electric space heating, water heating, clothes dryers, central air, etc.) for core appliances and when they rely heavily on other fuels such as natural gas or if they lack these appliances. These two theoretical households are labeled *electric* and *gas* and are further explained in sections 2.4.3 and 2.4.4. None of these scenarios are intended to represent specific real households, but rather they are hypothetical scenarios that are intended to encompass the ranges of realistic households that may exist while highlighting the differences. A brief summary of the scenarios can be seen in Table 2-1.

Table 2-1. Summary of the four scenarios used in this study.

Average	**Typical**	**Electric**	**Natural Gas**
Average household based on RECS data from 2001 and 2005.	Typical household based on RECS data with adjusted penetration rates to whole numbers to reflect the most likely household appliances that are owned in a given region.	Electric household is an extreme case in which the typical house is given various electric appliances (clothes dryer, space heater, water heater, oven, stove)	Natural gas household is an extreme case in which the typical house is assumed not to have various electric appliances (clothes dryer, space heater, water heater, oven, stove).

2.4.1 Average Scenario

The *average* scenario is based on average consumption of a household as reported in the RECS data. This scenario ranks appliance electricity consumption based on either average appliance-level consumption, which is multiplied by the percentage of households that have this appliance, or the sum of all electricity consumption by a given appliance divided by the total number of houses (with or without that given appliance). This is demonstrated in Equations 1 and Equation 2 where E_{Ai} is the electricity consumption of appliance *i*, $E_{01\ RECS}$ is the electricity per appliance as estimated by the 2001 RECS, H_A is the number of homes that have a given appliance according to the 2001 RECS, and the H_{T01} is the total number of homes in the United States at the time of the 2001 RECS.

$$E_{Ai} = \frac{E_{01\ RECS} * H_A}{H_{T01}} \quad (1)$$

Equation 2 is the average scenario when energy estimates are available from 2005 RECS Microdata regression model where $E_{05\ RECS}$ are the estimates given by the 2005 RECS Microdata and H_{T05} is the total number of homes as of the 2005 RECS.

$$E_{Ai} = \frac{\sum E_{05\ RECS}}{H_{T05}} \quad (2)$$

A first example of this can be observed using data on coffee makers. Using the RECS End-Use Consumption of Electricity 2001 data we can see that a coffee maker consumes, on average, 116 kWh annually (i.e. $E_{01\ RECS}$ = 116 kWh). We can gather from the 2005 RECS Microdata that 67.2 million of the 111 million homes in the US have coffee makers (i.e., H_{T05} = 111 million and H_A = 67.2 million). Applying all of this to equation 1, we can see that the "average" household would consume 70.1 kWh annually as a result of using coffee makers, far less than what an actual coffee maker is expected to consume.

A second example is refrigerators for which we have RECS data on how much electricity households dedicate to their use ($E_{05\ RECS}$ =151 TWh) as well as the number of appliances (138 million) and the number of homes in the US that either have at least one refrigerator (H_{T05} = 111 million). From this we can apply equation 2 and discover that the average household consumes 1,360 kWh annually for refrigeration purposes.

This *average* scenario is only slightly different than the 2001 and 2005 RECS data as it is presented. We have simply adjusted the data by removing the category of consumption labeled as *residual* without adjusting the total consumption value. This is done because the so-called *residual* appliances are either (a) extremely small on the micro-level and thus do not consume much electricity or (b) they are small on the macro-level (i.e. few people own them). Main-space heating and central air conditioners were originally assumed to have equivalent efficiency throughout the U.S. by the authors, but they were used in proportion to the number of heating degree days and cooling degree days respectively. This was found to be inconsistent with the data from the 2005 RECS data, which is based on a non-linear regression model. We have taken the regression of the RECS microdata to be more accurate than the more simple proportionality method originally used.

2.4.2 Typical Scenario

The typical household scenario was created to illustrate the difference between average and typical consumption. This scenario treats penetration rates for each appliance in a conditional fashion. If an appliance has a penetration rate (number of appliances divided by total number of households) of 50% or greater, it is assumed that our hypothetical "actual" house will have that appliance as seen in equation 3, where P is the penetration rate for an appliance and A_T is the total number of the particular appliance in the 2005 RECS. In this case, the penetration rate is set to 1. Similarly, if fewer than 50% of homes have a given appliance, that appliance is assumed not to be present in a typical home. Thus, in this case, the penetration rate is set to 0. In cases where more than one appliance is owned, the penetration rate is rounded to the nearest whole number. In the absence of 2005 RECS data we rely on the estimates from the 2001 End-Use Report produced by RECS.

$$E_{Ai} = \begin{cases} \sum \frac{E_{RECS\,05}}{A_T}, & P > 50\% \\ 0, & P \leq 50\% \end{cases} \quad (3)$$

$$\text{where } P = \frac{A_T}{H_{T05}}$$

In this scenario we eliminate rare appliances like pool heaters and ensure that an entire central air-conditioning system is accounted for, avoiding a model where an "average" home has 3% of a pool heater and 58% of a central-air conditioning system. An example of this can be seen in central air conditioners. In New England, only 13% of homes have a central air conditioning unit. Applying the equation 3, we assume that the typical home in New England consumes no electricity for central air conditioning. Alternatively, we see that 63% of homes in the same region own coffee makers. Applying the equation above we see that the 50% cutoff is met and we apply the 2001 End-Use data on coffee makers which shows that each coffee maker consumes 116 kWh annually. Thus, the typical home in New England in our study has one coffee maker that consumes 116 kWh each year. Contrast this with the average scenario where we see that the average New England housing unit consumes about 2% of their electricity from central air conditioning systems, a value that is grossly watered down because of the low penetration rate of these systems in the New England region.

2.4.3 Electric Scenario

The third scenario explores a hypothetical house where natural gas is not utilized. All of the appliances in RECS that typically may be powered by either natural gas or electricity are powered by electricity. These electric appliances include water heaters, main space heaters, clothes dryers, stoves, and ovens. This scenario also utilizes the conditional from of equation 3 applied to the typical household scenario to eliminate appliances that are present in fewer than 50% of homes. This scenario is intended to represent an extreme possibility, though this is a realistic extreme. 24% of homes in the East South Central Census Division fit into this "extreme" scenario and own all five of these electric appliances as seen in Table 2-2. By contrast, only 6% of homes in the Middle Atlantic Census Division have all five of these electric appliances.

Table 2-2. Percentage of homes that own electric clothes dryers, stoves, ovens, water heaters, and space heaters and thus qualify as part of the Electric Scenario by Census Region.

New England	Middle Atlantic	East North Central	West North Central	South Atlantic	East South Central	West South Central	Mountain	Pacific
6%	6%	9%	7%	21%	24%	8%	7%	5%

2.4.4 Natural Gas Scenario

The fourth and last scenario intends to explore another hypothetical extreme: a house with all gas appliances of the same types as in the Electric Appliances Scenario above. The same equation applies to this scenario with electricity consumption set to zero for water heaters, main space heaters, clothes dryers, stoves, and ovens. This could also represent a home that does not have these appliances, but regardless of the case, the electricity consumption is zero. We observe in the RECS microdata summarized in Table 2-3 that 27% of homes in the Middle Atlantic Census Division contain none of the five electric appliances listed above either because they do not own them or they are powered by another fuel. At the other end of the spectrum, only 3% of the homes in the East South Central Census Division meet these same criteria.

Table 2-3. Percentage of homes that do not own electric clothes dryers, stoves, ovens, water heaters, and space heaters and thus qualify as part of the Natural Gas Scenario by Census Region.

New England	Middle Atlantic	East North Central	West North Central	South Atlantic	East South Central	West South Central	Mountain	Pacific
11%	27%	18%	8%	4%	3%	5%	12%	18%

The specific scenarios are not intended to represent any real houses but rather various ranges and frontiers for possible scenarios. While there are a vast number of potential combinations of electric appliances that may or may not be present in a home, it is hoped that the four scenarios in this study are sufficient to answer questions about how many appliances may need to be monitored in a home to account for 50-90% of total use. We seek to identify the number of important appliances in a home, as this is important and relevant for parties seeking to reduce energy consumption in a home.

The final component to this model explores the differences between the four scenarios across the nine U.S. Census divisions using the U.S. RECS microdata for each household surveyed. Regional differences for fuel use and appliance ownership, if large enough, can highlight any aspects important to consider in designing data or technology to educate users across the U.S.

3. Results

As shown in Table 2-4, in the *average* scenario, we estimate that the number of appliances required to reach 80% of a household's electricity consumption is 12 for the aggregate United States, but ranges between 10 and 14 for each of the nine census divisions. This represents the result achievable by casually using the RECS data. We see that, not surprisingly, finding 50% of household electricity is much easier than obtaining 80% of the electricity consumption, requiring only between 3 and 5 appliances for the 9 census divisions. This also indicates that the 4 appliances with the highest consumption account for half of the total electricity consumption in an average household in the United States, while 8 appliances account for the next 30% (see Figure 2-1). To be clear, it is not necessarily the same 4 appliances in all average households across the census divisions (see Figure 2-2). Please note that there is no rearrangement of appliances in Figure 2-2 for ease of reading. This means that central air-conditioners are always on the bottom of the stacked bars even though they are not always the largest consumers of electricity. For this reason, we have included separate Figure 2-1 to quickly determine the actual number of appliances needed to reach certain thresholds regardless of what these appliances are. Figure 2-2 clearly shows diminishing returns for the number of appliances requiring monitoring given that the appliances with the largest electric load are monitored first. Exploring the 90% threshold further reinforces this diminishing returns theory. In six of the nine census divisions, getting to the 90% threshold requires monitoring more than 18 appliances, which is equivalent to saying that the next 6 appliances (appliances 13-18) account for only 10% of the electric load.

Table 2-4. Number of appliances to reach thresholds by Census Region for the average scenario. Additional information on specific appliances can be found in Figure 2-3.

	New England	Pacific	Middle Atlantic	East North Central	Mountain	USA	West North Central	West South Central	South Atlantic	East South Central
50%	5	5	3	4	4	5	4	3	4	5
80%	14	13	10	12	13	14	12	10	10	14
90%	21	20	15	18	19	21	18	16	15	21

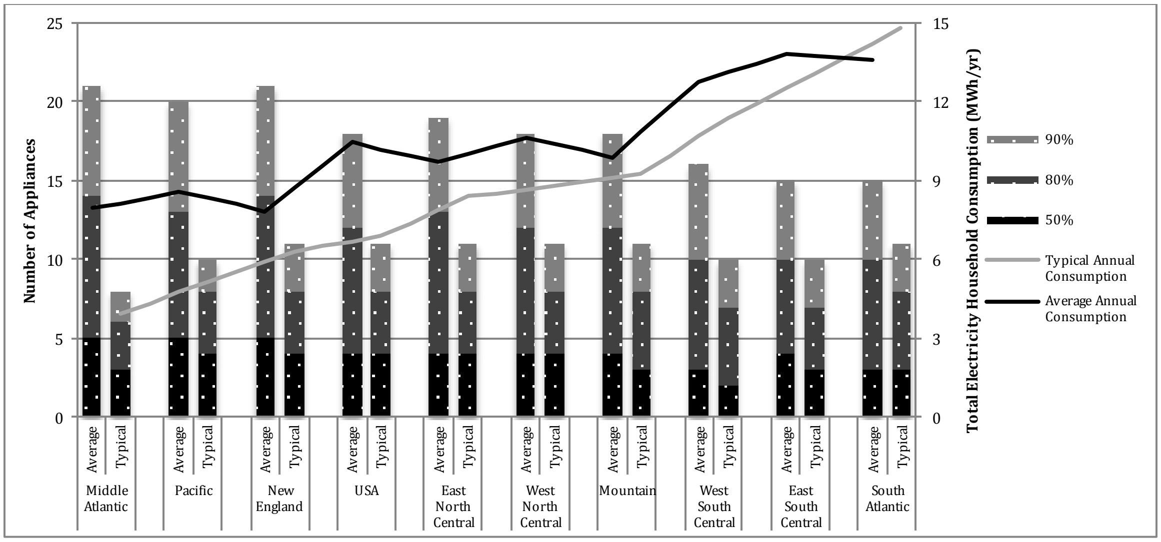

Figure 2-1. Number of appliances (bars on first Y-axis) to reach 50%, 80%, and 90% threshold of total household electricity consumption for the nine United States Census divisions and the country as a whole. On the second Y-axis (lines) household electricity consumption is displayed in MWh per year.

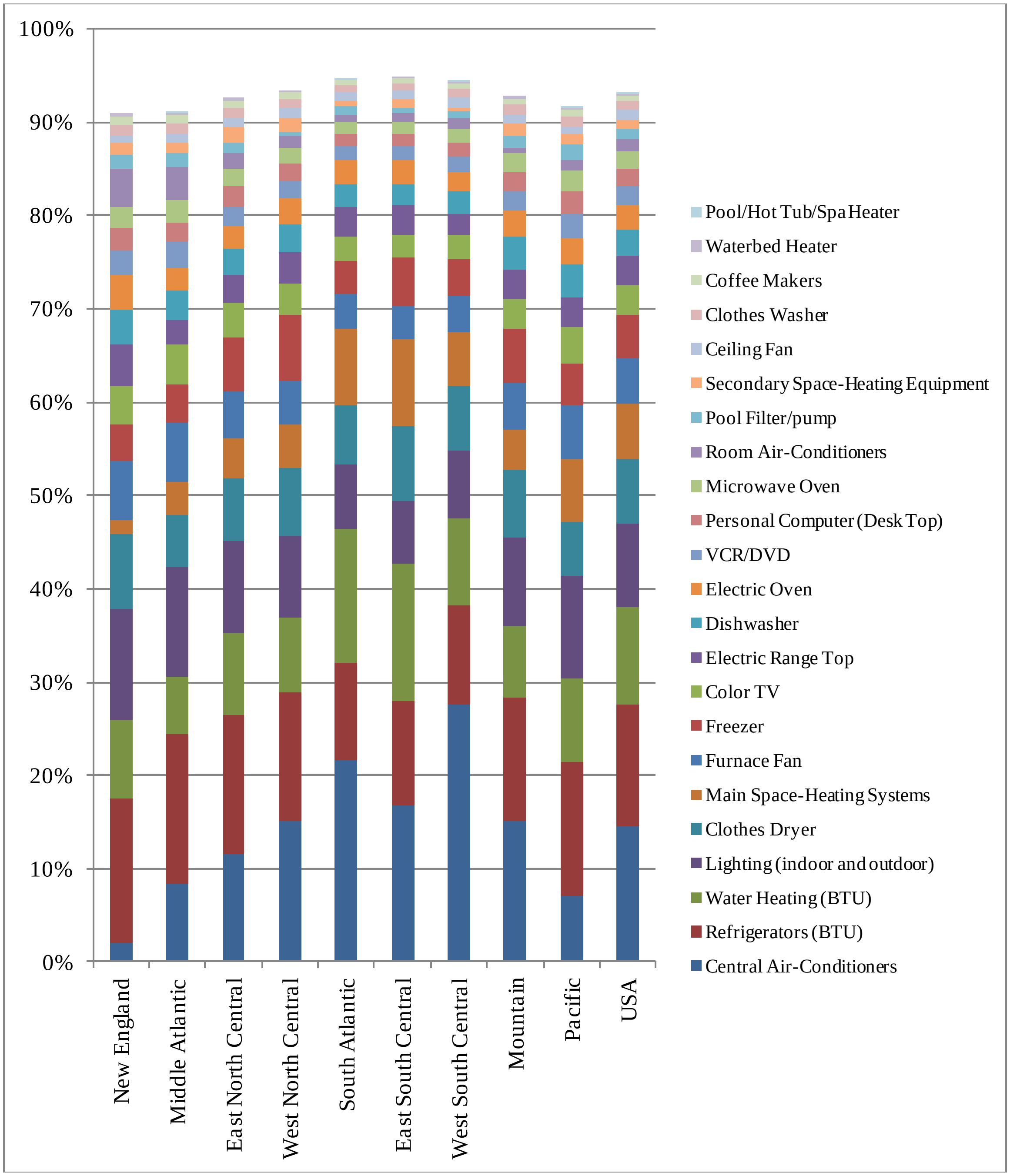

Figure 2-2. Cumulative Electricity Consumption by appliance and U.S. Census Region for the Average Scenario.

The idea that there is no average house and that the averaged RECS data is misleading for policy decisions is illustrated in Table 2-5 and Figures 1 and 3. We can see that the average scenario is vastly different than the typical scenario as well as the two extreme scenarios for gas and electric appliances. For both the 80% and 90% thresholds the average scenario requires significantly more appliances than the other three cases by 4 or 5 appliances at the 80% mark and 7-9 appliances when targeting the 90% threshold. These differences are also highlighted in Figure 2-4 which shows not only how many appliances it takes to reach each threshold, but specifically what these appliances are expected to be. The specific appliances at the national level are also identified in Table 2-5. These appliances, while showing some overlap at the national level for the summary scenarios (central air conditioners in all four scenarios and lighting and refrigerators for the average, typical, and gas scenarios), are dependent on appliance ownership at the household level. The remaining top four appliances for the four scenarios vary as demonstrated in Table 2-5.

Table 2-5. Predicted appliances to reach thresholds for aggregate U.S. for four theoretical scenarios. Further information regarding specific appliances that contribute to each scenario can be found in Figure 2-4.

Threshold	50%	80%	90%
Average	Central Air-Conditioners Refrigerators Water Heating Lighting	Clothes Dryer Main-Space Heating Furnace Fan Freezer Color TV Electric Range Top Dishwasher Electric Oven	VCR/DVD Personal Computer Microwave Oven Room-Air Conditioner
Typical	Central Air-Conditioners Refrigerators Lighting Electric Range Top	Dishwasher Furnace Fan Electric Oven Color TV	Personal Computer VCR/DVD Electric Oven
Gas	Central Air-Conditioners Refrigerators Lighting Dishwasher	Furnace Fan Color TV Personal Computer	VCR/DVD Microwave Oven
Electric	Water Heating Main Space-Heating Central Air-Conditioners Clothes Dryer	Refrigerators Lighting Electric Range Top Dishwasher	Furnace Fan Electric Oven Color TV

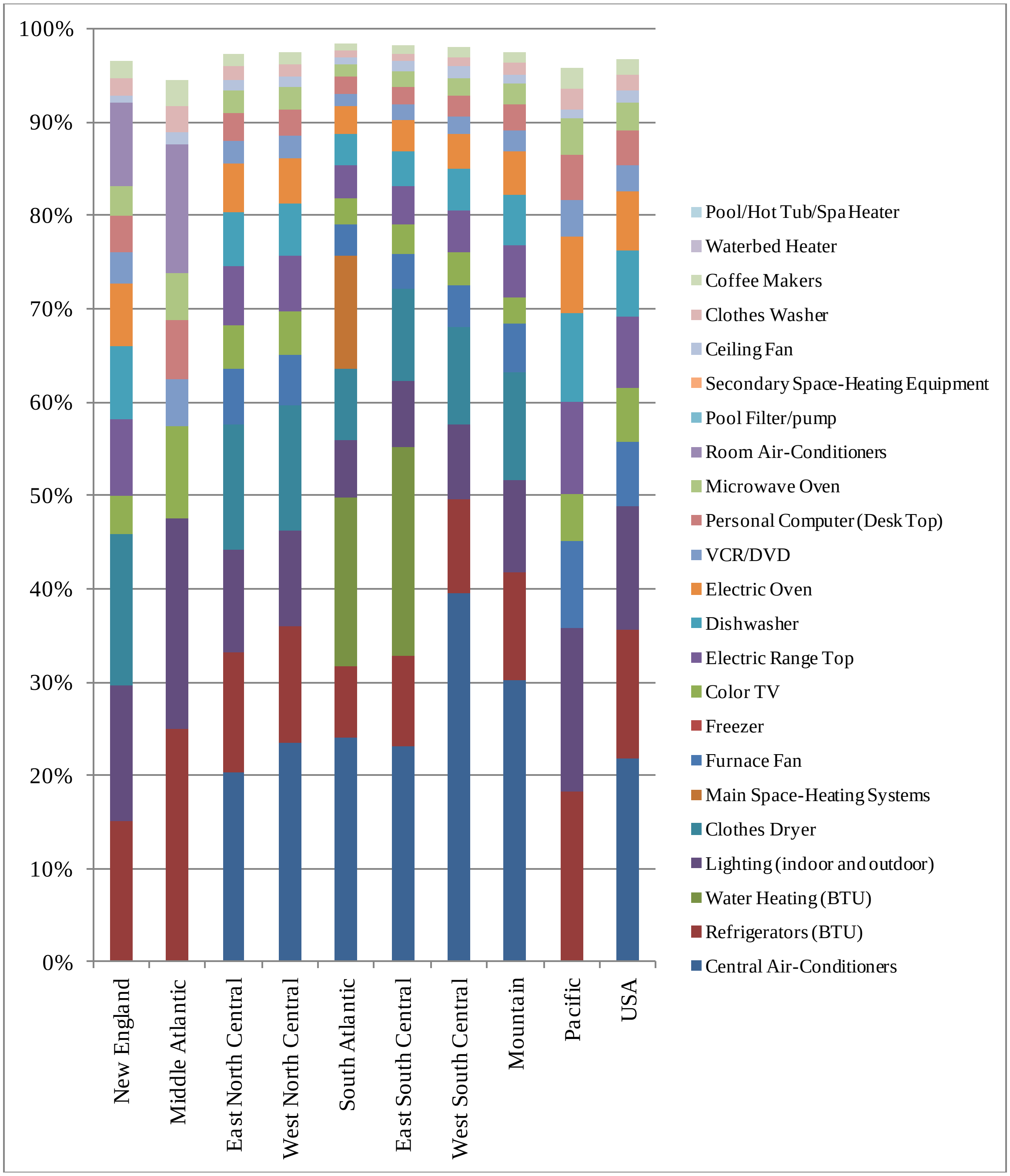

Figure 2-3. Typical Household Cumulative Electricity Consumption by Census Region and Appliance.

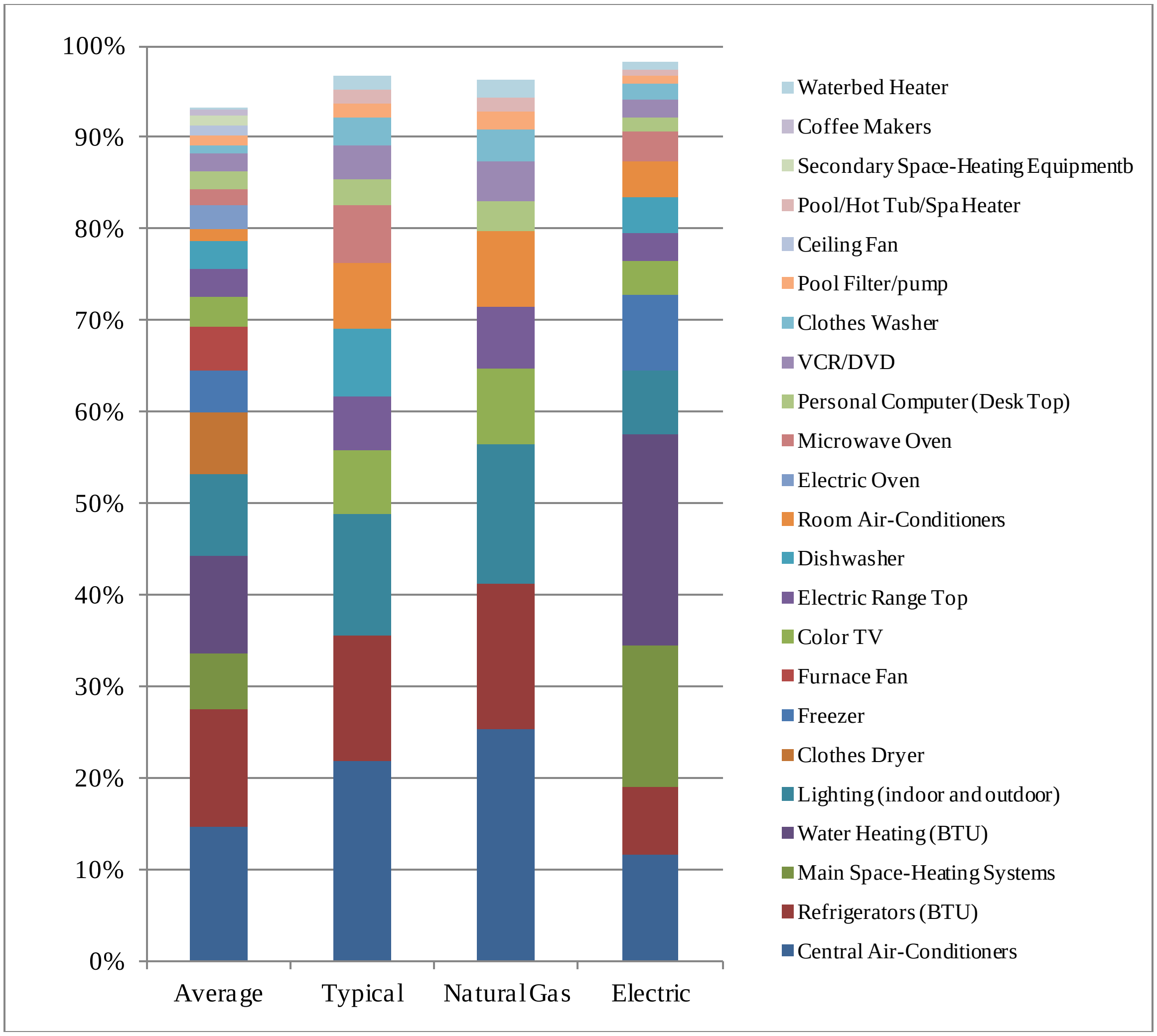

Figure 2-4. Specific appliances and their contributions to household electricity consumption for the average, actual, gas, and electric scenarios at the national level.

Looking specifically at electric main space heating system we can begin to understand why the average scenario overestimates the number of appliances needed to reach a given threshold. In the average scenario main space heating systems account for 6% of the household consumption, however fewer than half of the households in the U.S. have electric heating. Looking at the electric scenario, we would expect a household with an electric heating system to consume more electricity than the average scenario shows (15% in the average scenario). Because appliances have less significant impacts on the total household consumption in the average scenario, more appliances are required to reach a given threshold.

In reality, we can only make educated guesses as to which appliances are going to be important for end-use sub-metering prior to performing the disaggregation itself based on data from other appliances and homes. We can also pick appliances randomly or based on those that are easier to monitor. For example, in the case of NILM, we could pick appliances that have easily recognizable transients, or appliances that already exist in a given signature database. Regardless of how the appliances are picked, there is no guarantee that we can select the largest electricity consuming appliances without monitoring them a priori or monitoring the entire electric load of a household. Figures 5 and 6 show how the optimal and least optimal selection of appliances affects the number of appliances necessary to monitor a given portion of a household's electricity consumption. These graphs take the cumulative appliance electricity consumption separately for each of the two scenarios both in increasing (optimal selection of appliances to monitor) and decreasing (least optimal) order. Realistically one should expect a path that is somewhere between the optimal and least optimal lines with the goal of optimal appliance selection. Regardless, we can see from these figures that the appliances that we choose to monitor directly influence the portion of the household electricity consumption that we should expect to capture. The inability to ensure that the largest consumers are captured in the monitoring makes all of the scenarios presented in this research technically infeasible, but useful as best case scenarios. In reality, the number of appliances to achieve a given threshold in a given scenario would be the minimum number of appliances necessary to disaggregate if the appliances happen to be selected in descending order, from largest consumers to smallest. If they are selected in a different order, we would see a different path than the optimal line shown in figures 5 and 6. It is worth mentioning that the selection order of appliances matters regardless of the scenario we choose to explore as demonstrated in figures 5 and 6. Tables 6 and 7 correspond to figures 5 and 6 showing the expected contributions for each appliance in the average and typical scenarios. Table 2-8 shows the top ten expected appliances for a given census division in the typical scenario. A map of the United States Census Divisions can be found in observed in Figure 2-7.

Table 2-6. Appliances listed in decreasing order of consumption for the average scenario.

Central Air-Conditioners	15%
Refrigerators	13%
Water Heating	10%
Lighting (indoor and outdoor)	9%
Clothes Dryer	7%
Main Space-Heating Systems	6%
Furnace Fan	5%
Freezer	5%
Color TV	3%
Electric Range Top	3%
Dishwasher	3%
Electric Oven	3%
VCR/DVD	2%
Personal Computer (Desk Top)	2%
Microwave Oven	2%
Room Air-Conditioners	1%
Pool Filter/pump	1%
Secondary Space-Heating Equipment	1%
Ceiling Fan	1%
Clothes Washer	1%
Coffee Makers	1%
Waterbed Heater	0%
Pool/Hot Tub/Spa Heater	0%

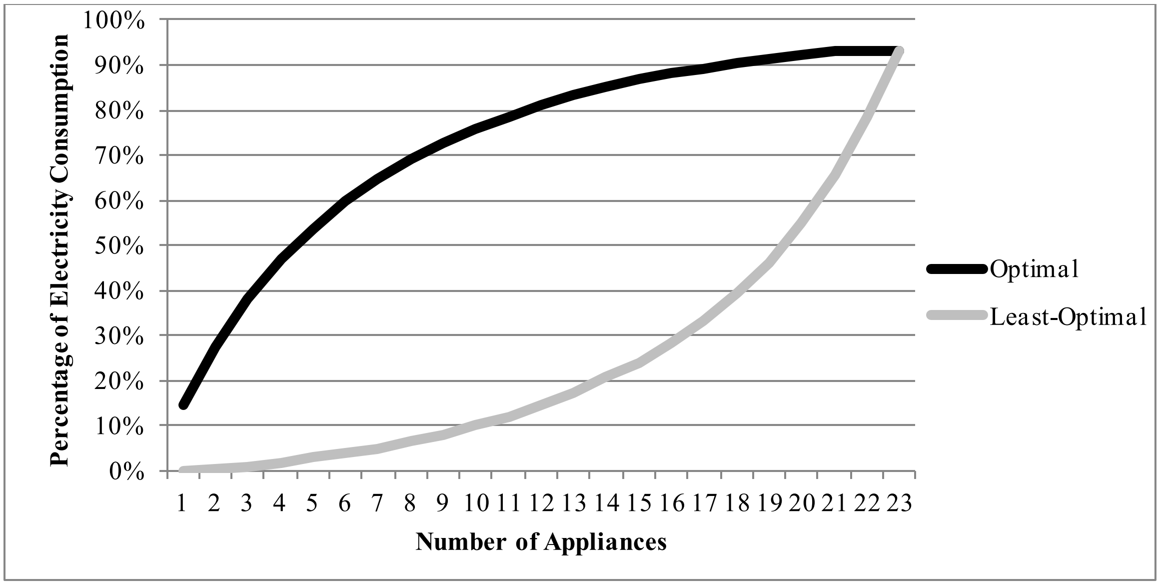

Figure 2-5. Optimal and least-optimal selection of appliances to monitor in the average scenario. See Table 2-6 for a list of corresponding appliances.

Table 2-7. Appliances listed in decreasing order of consumption for the typical scenario.

Central Air-Conditioners	22%
Refrigerators	14%
Lighting (indoor and outdoor)	13%
Electric Range Top	8%
Dishwasher	7%
Furnace Fan	7%
Electric Oven	6%
Color TV	6%
Personal Computer (Desk Top)	4%
VCR/DVD	3%
Electric Oven	3%
Clothes Washer	2%
Coffee Makers	2%
Ceiling Fan	1%

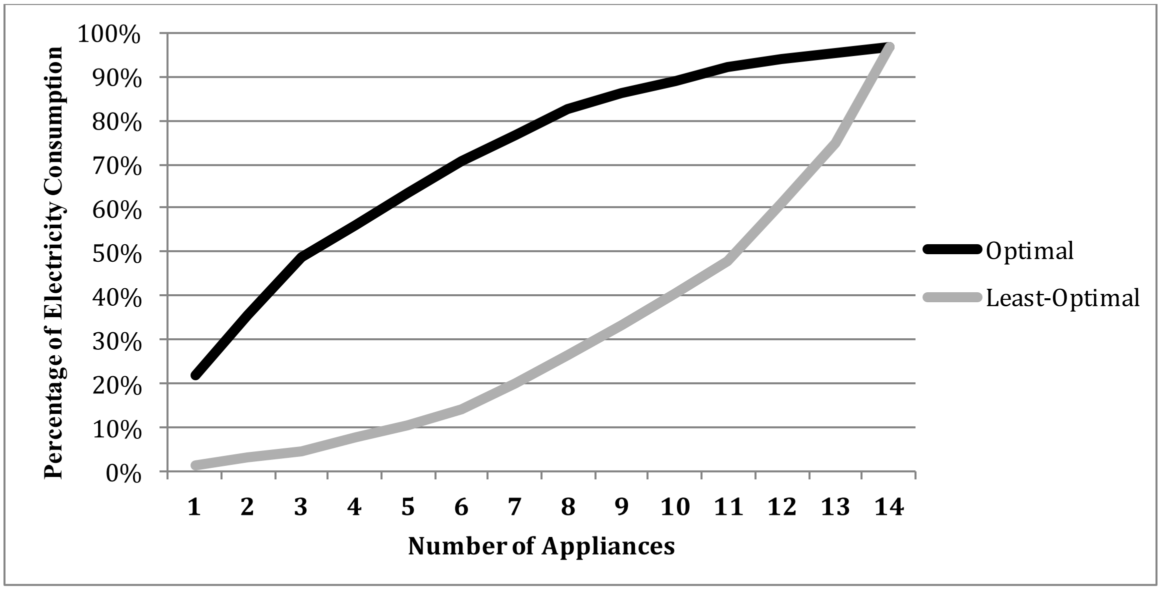

Figure 2-6. Optimal and least-optimal selection of appliances to monitor in the typical scenario. See Table 2-7 for a list of corresponding appliances.

Table 2-8. Ranked order of most likely top ten consuming appliances in a given U.S. Census Region for the *typical scenario*.

Rank	New England	Middle Atlantic	East North Central	West North Central	South Atlantic	East South Central	West South Central	Mountain	Pacific	USA
1	Clothes Dryer	Refrigerators	Central Air-Conditioners	Central Air-Conditioners	Central Air-Conditioners	Central Air-Conditioners	Central Air-Conditioners	Central Air-Conditioners	Refrigerators	Central Air-Conditioners
2	Refrigerators	Lighting	Clothes Dryer	Clothes Dryer	Water Heating	Water Heating	Clothes Dryer	Clothes Dryer	Lighting	Refrigerators
3	Lighting	Room Air-Conditioners	Refrigerators	Refrigerators	Main Space-Heating Systems	Clothes Dryer	Refrigerators	Refrigerators	Electric Range Top	Lighting
4	Room Air-Conditioners	Color TV	Lighting	Lighting	Clothes Dryer	Refrigerators	Lighting	Lighting	Dishwasher	Electric Range Top
5	Electric Range Top	Personal Computer	Electric Range Top	Electric Range Top	Refrigerators	Lighting	Electric Range Top	Electric Range Top	Furnace Fan	Dishwasher
6	Dishwasher	VCR/DVD	Dishwasher	Dishwasher	Lighting	Electric Range Top	Dishwasher	Dishwasher	Electric Oven	Furnace Fan
7	Electric Oven	Microwave Oven	Furnace Fan	Furnace Fan	Electric Range Top	Dishwasher	Furnace Fan	Furnace Fan	Color TV	Electric Oven
8	Color TV	Clothes Washer	Electric Oven	Electric Oven	Dishwasher	Furnace Fan	Electric Oven	Electric Oven	Personal Computer	Color TV
9	Personal Computer	Coffee Makers	Color TV	Color TV	Furnace Fan	Electric Oven	Color TV	Color TV	VCR/DVD	Personal
10	VCR/DVD	Ceiling Fan	Personal Computer	Personal Computer	Electric Oven	Color TV	Personal Computer	Personal Computer	Microwave Oven	VCR/DVD

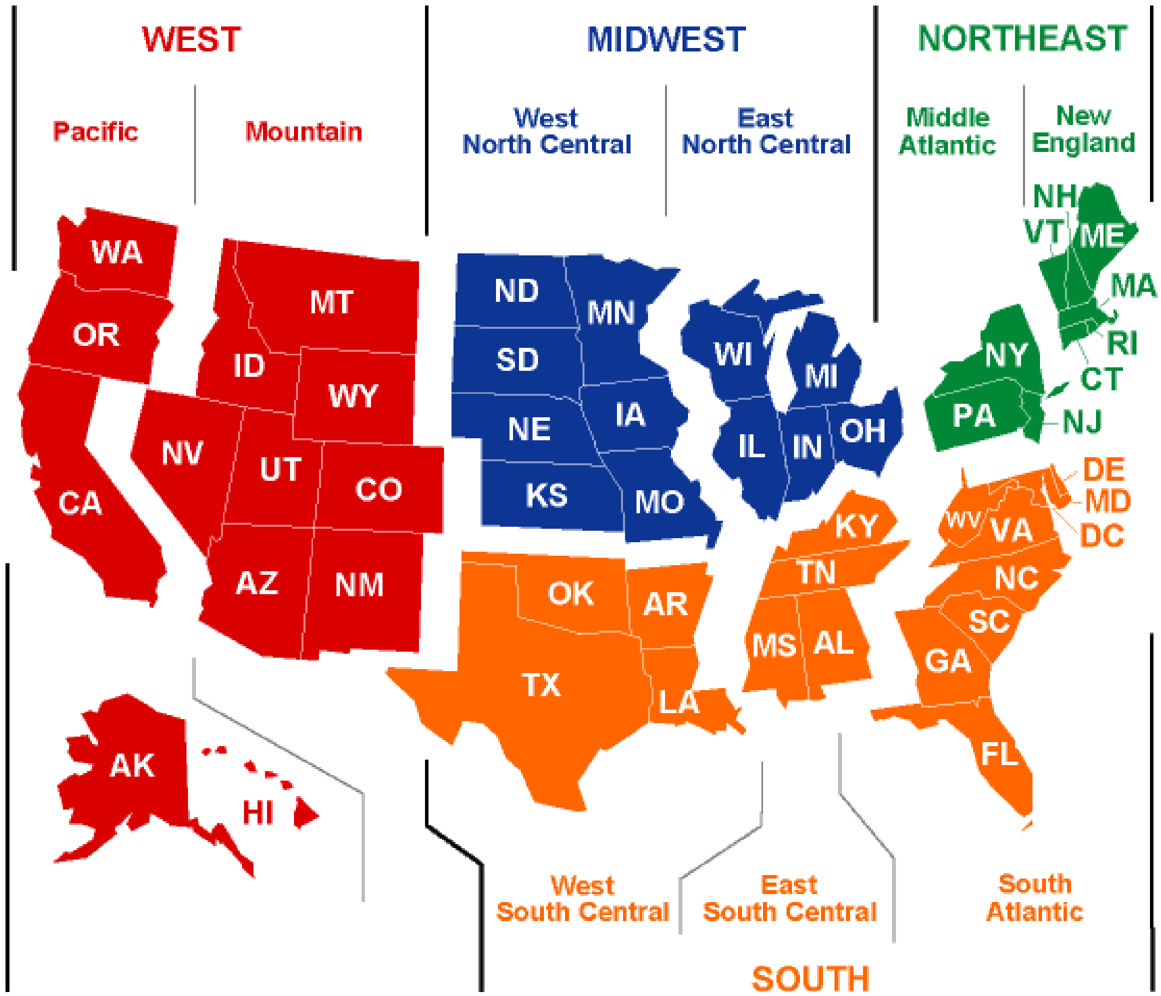

Figure 2-7. Map of the United States split into Census Regions [33].

3.1 Alternative Household Energy Use Assessments

United States Census divisions are not the only way in which we can characterize and analyze the data. We also have explored household income, total floor space, and total electricity consumption to identify other relevant differences. A few notable differences that are similar to the results previously shown can be observed between the different methods of household classification. First, households that have lower incomes generally consume less electricity and thus the number of appliances is slightly lower than households with higher incomes. This can be observed in Figure 2-8, which shows how household income affects the number of appliances to reach various thresholds, similar to the graph seen in Figure 2-3. Using floor space to analyze the data yields similar results as seen in Figure 2-9. There is an obvious correlation between income and total floor space and also between floor space and electricity consumption. Similarly to the results seen in Figure 2-8, we see that smaller homes not only have lower total electricity loads but also require fewer appliances to reach the 80% threshold. The data gets more interesting when it is analyzed using total electricity as the classifier. We not only see the increase in number of appliances at the lower end of the spectrum as we saw in figures 8 and 9, but we also see a decrease in number of appliances at the high end of the spectrum. This is explained by the fact that these very high end consumers have large appliances like electric hot water heaters and electric space heaters which not only drive the total electric load for the household up, but also these appliances account for a larger portion of the electric load so fewer appliances are required to reach the 80% threshold. This phenomenon can be observed in Figure 2-10 when data is organized by total electricity consumption for the typical scenario, however the average scenario does not show the original increase in number of appliances at the lower end of the spectrum.

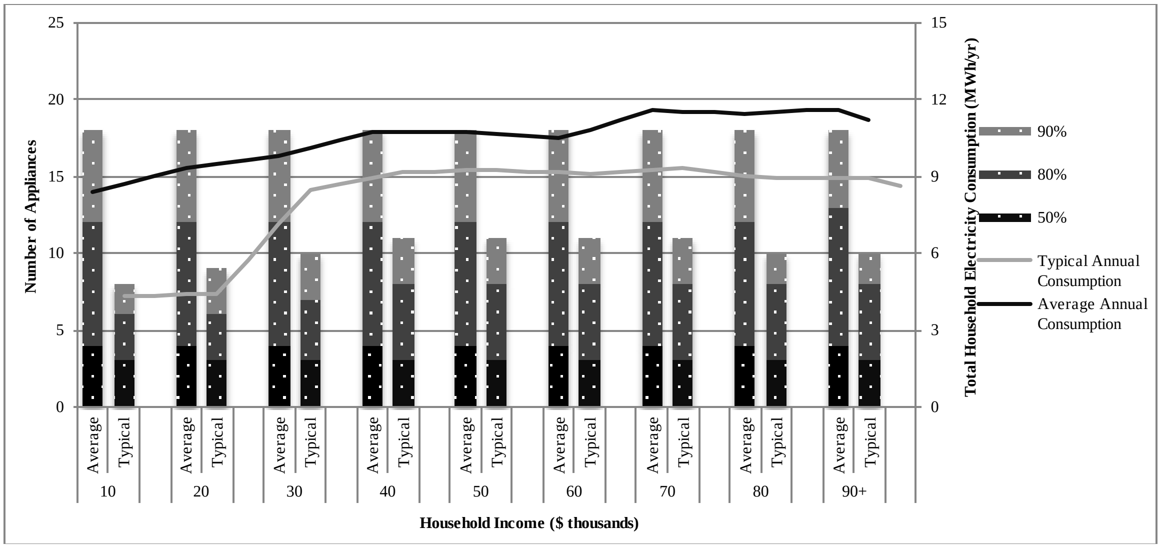

Figure 2-8. Number of appliances (bars on first Y-axis) to reach 50%, 80%, and 90% threshold of total household electricity consumption for varying household income levels. On the second Y-axis (lines) household electricity consumption is displayed in MWh per year.

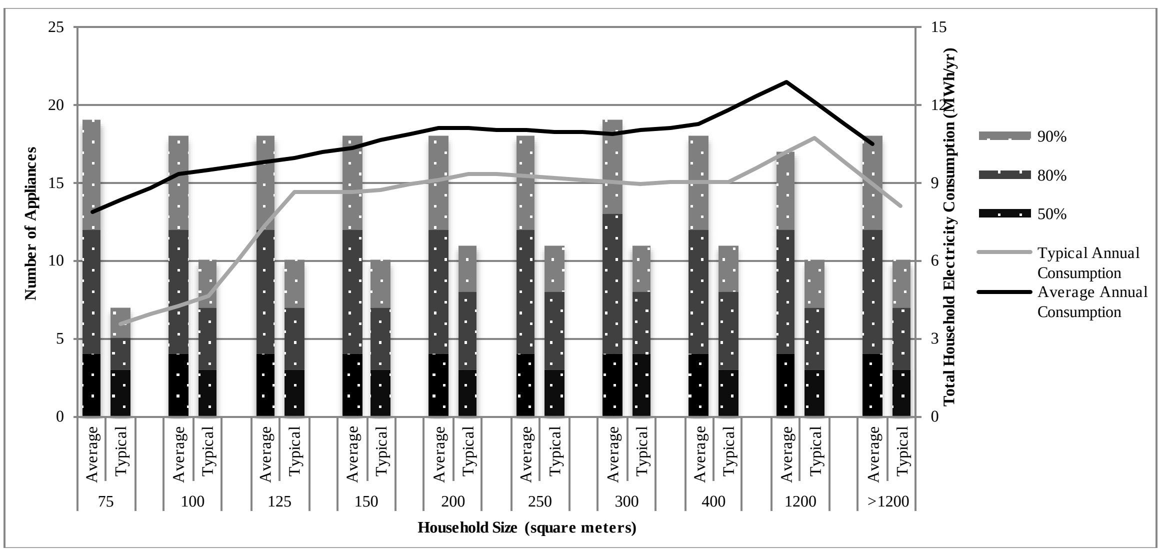

Figure 2-9. Number of appliances (bars on first Y-axis) to reach 50%, 80%, and 90% threshold of total household electricity consumption for varying household sizes. On the second Y-axis (lines) household electricity consumption is displayed in MWh per year.

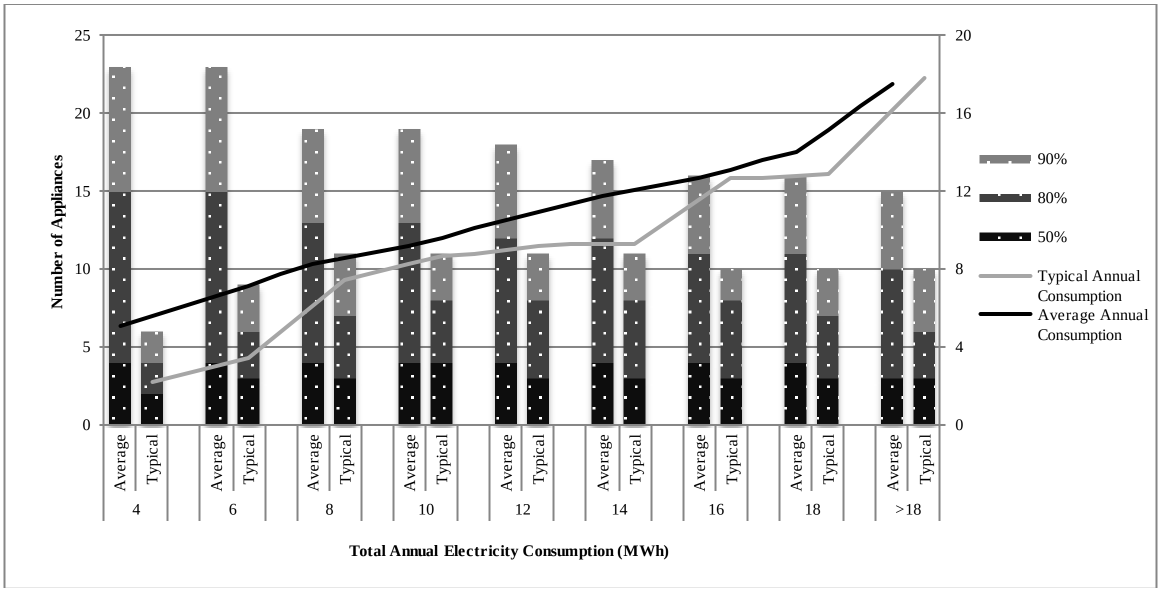

Figure 2-10. Number of appliances (bars on first Y-axis) to reach 50%, 80%, and 90% threshold of total household electricity consumption for varying total annual household electricity consumption. On the second Y-axis (lines) household electricity consumption is displayed in MWh per year.

4. Conclusions

This research demonstrates the need for the careful consideration of the difference between average appliance electricity consumption and actual appliance consumption. If household level policy is crafted for average household consumption, the importance of uncommon, large consumers of electricity may be neglected or underestimated. Similarly, more common appliances that have a larger electric load may be overestimated. Alternatively, if appliance or household level data on electricity consumption is used to craft regional or national policy, the effects of larger, rare appliances may be overestimated, while the more common, smaller appliances may be severely underestimated.

This approach is easily demonstrated with examples. For this, we will look at refrigerators and electric pool heaters. Refrigerators have a penetration rate of more than 99% while electric pool heaters have a penetration rate of less than 3%. If a household level decision, such as the decision of where to install a limited number of plug-through power sub-meters, were to be improperly developed around average consumption data, appliances with large consumptions like the pool heater may be ignored as they account for less than one-tenth of one percent of the average electricity consumption in the United States. This would be fine for the greater than 99% of homes that do not electric pool heaters, however any successful disaggregation method necessarily must be able to account for a pool heater which on average consumes about 2,300 kWh annually [29]. Refrigerators on the other hand, accounted for roughly half of the electricity consumption that pool heaters are responsible for (1,240 kWh per year). Given that on a per unit basis, refrigerators consume so much less electricity, the penetration rate of nearly 100% make refrigerators much more important on an average consumption basis (roughly 12 percent of the average household electricity load in 2005). National or regional policy created based on the average consumption would overstate the effects of refrigerators and underestimate the effects of pool heaters in a home that has both devices.

Another interesting piece of this study shows that there are important regional differences in the way households consume electricity and energy in aggregate. This is expected, as there are major differences in climate, housing characteristics, and available fuels. One of the biggest differences in the way that electricity is consumed between U.S. Census divisions is the amount of electricity on average each house consumes. On average, homes in the East South Central Census Division consume more than 1,750 kWh while houses in the New England Census Division consume less than 850 kWh as seen in Figure 2-2. This is likely due to the fact that the average home in the East South Central Region has about 1,900 cooling degree days (CDD) while the average home in

New England has about 720 CDD. The difference in CDDs is often compensated for with the use of electric air conditioners. The other climate difference is in heating degree days (HDD). New England has about twice as many heating degree days as the East South Central Census Division (6,750 and 3,400 respectively). Heating demands, unlike cooling demands, may be met with a plethora of fuels. Main space and secondary heating fuels include electricity, kerosene, propane, natural gas, wood, pellets, coal, and solar. Because of the wide range of fuels available for heat, less electricity is required for heating needs than is required for cooling needs, which accounts for some of the large difference in electricity demands. Many other differences exist between homes in different regions, some of which are likely to be captured at the U.S. Census division level such as differences in residential building insulation, window u-values, and appliance penetration rates.

Other secondary factors influence the ownership of appliances and the behaviors of their users as well, both of which directly influence the number of appliances in a home that contribute significantly to its annual electricity consumption. These secondary factors include geographical factors, socioeconomic status, fuel availability and price, and political and social ideologies. Regional differences may be important in terms of what appliances may be common and what fuels are used to power them. This is observable in the differences in average electricity consumption for the different census divisions, as the average home in the East-South Central Census Division consumes more than twice as much electricity annually as the average home in the New England Census Division. This regional difference likely stems from the fact that electric air-conditioning is more frequently used in the East-South Central Census Division while more natural gas fueled space heating is used in the New England Census Division amongst other factors. Some of the differences in number of appliances required to reach the thresholds set in this research can be seen in Figure 2-1. The differences in actual appliances by census divisions can be seen in figures 2 and 3. Other differences may be too localized to capture at the census division like age of homes, attitudes toward energy conservation, and affluence. While these other factors are most certainly interesting, they lie outside the scope of this research.

Estimating the number of significant appliances in a household can be viewed as a design problem. If the goal is to develop a system for disaggregating electricity consumption into component appliances, it is necessary to understand how many appliances and which appliances are likely to be important to account for enough of the electricity consumption for the system to be effective (e.g., how many appliance signatures to embed in a system). With no preset notion of the appropriate thresholds, we show results for three reasonable thresholds (50, 80, and 90 percent capture of consumption). Results for other thresholds can be interpolated using the results from the three thresholds used in this study.

5. Conclusions

Understanding the difference between average residential electricity consumption and actual residential consumption is very important when looking at common data like the RECS microdata and the RECS End Use Table. A party interested in systems to monitor household consumption should not make policy or decisions based on the RECS average data, which would overestimate the number of contributing appliances to a household electric load. Likewise, one should be careful when using household or appliance level data when crafting policy at a level that is higher than the household.

Estimating the number of appliances that contribute to a home's electricity consumption is a difficult, complex problem that many parties are interested in, including national, state, and local policy makers as well as utilities that wish to perform peak shaving and consumers of electricity who may wish to reduce consumption for economical and environmental concerns. Electricity consumption in a household is spread widely amongst many appliances and electronics, but in reality the number of appliances that consume significant electricity in a home is much lower than the average home that is depicted by RECS. Our results suggest it generally requires only 8 appliances to reach 80% of a household's total electricity consumption but this number varies significantly depending on the appliance ownership and usage. To hit the 50% threshold, generally only the four biggest appliances need to be monitored, but this number drops as low as 2 in the West South Central where central air conditioners typically constitute 40% of a household electric bill. By simply using data from RECS to discover the number of appliances and types of appliances one might expect to find in a home is not sufficient as in the average scenario we see that it takes 12 appliances to reach the 80% threshold. We find that there is not a big difference in the number of appliances to reach the 50% and 80% thresholds for the typical, natural gas, and electric scenarios with the electric scenario requiring 3 appliances to reach 50% and 8 appliances to reach 80% of the household electricity consumption. The natural gas house requires three appliances to reach 50%, but only 7 to reach the 80% threshold. All three of these scenarios require significantly fewer appliances than the average scenario depicts suggesting that using aggregate, national data is inaccurate for decisions at the household level.

The RECS dataset and summary reports rely on relatively few data points and contain errors. Hopefully the RECS will continue to grow in sample size and improve in data quality as it moves from the 2005 survey to the 2009 survey and beyond. Regardless of improvements that may be made to the RECS dataset, it is vital that stakeholders are able to distinguish between the average home and what an actual home may consume in terms of electricity in order to better facilitate reductions in electricity consumption. Careful analysis of RECS, the most comprehensive national survey regarding energy consumption, reveals important details about which appliances we expect will be significant consumers in households. This information can be used to further develop disaggregation techniques such as NILM, which in turn will help stakeholders make informed decisions in regards to energy use. This data can also be used to further improve the next iteration of RECS and other top-down energy models, thereby continuing the symbiotic improvement of both top-down and bottom-up residential energy models.

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Chapter 3. Estimates of Residential Use Phase Energy for Economic Input-Output Life Cycle Assessment

Input-output models are valuable scoping tools for many applications. Unfortunately, residential use phase energy and personal transportation fall outside the scope of these models and must be separately modeled. By combining use phase energy data from a variety of publically available sources with economic data from the Bureau of Economic Analysis (BEA), the use phase energy vectors can be created as complements to IO-LCA models. These vectors can make input-output modeling more complete from a product lifecycle perspective, more accurate for products with large use phase impacts, and applicable for scoping and decision support activities that assess residential use phase energy. Results of the combined model can quickly show energy use differences between manufacturing and use phase.

1. Economic Input Output models Review

Economic Input-Output Life Cycle Assessment (EIO-LCA) is a tool to estimate the materials, emissions and energy requirements from economic activity. EIO-LCA was adopted from Economic Input-Output (EIO) models, which were originally created in the 1930s by Wassily Leontief in order to determine the change in demand for inputs that comes about because of a change in production [1][2]. The method has been adapted to predict the environmental impacts by adding vectors of environmental impact data per dollar of economic activity for each of the sectors of the economy.

EIO-LCA models have been used as a scoping tool to identify portions of a product's life cycle that most negatively impact the environment [3]. These models have also been used to compare different products that serve the same purpose to identify which is more environmentally benign [4][5]. Similarly, EIO has been used in the design and redesign of products in order to minimize environmental impacts [6]. For instance, car manufacturers may wish to decide to explore replacing steel parts with plastic or aluminum parts based on results from EIO-LCA models. These models may also be used to identify “hot-spots” where manufacturers may reduce environmental impacts [7][8].

Current Input-Output (IO) LCA models predict environmental impacts and economic activity from cradle-to-gate for producer price based models or cradle-to-consumer for consumer price based models. In other words, the impacts for a given purchase are estimated from the origins of a product or service up to where a service or product is purchased for the producer price model (for example the grocery store) or where the product or service is delivered (for example the consumer’s home).

While IO-LCA models have advantages in that they streamline the estimation of environmental impacts, they are incomplete in that within their usual boundary they do not consider use-phase and the end-of-life impacts without any modifications. IO-LCA models may do an adequate job scoping the impacts for some products and services that have relatively small use phase and end of life impacts. For other products and services that have large use-phase or end-of-life impacts, IO-LCA models have not been capable of estimating the total life cycle environmental impacts. Hybrid modeling approaches have been used which augment IO-LCA models with end of life data, though these models still require time and effort to find data to augment the models [9][10].

Economic Input-Output (EIO) models estimate the purchases in a supply chain leading up to final production in an industry. When an EIO model is used with environmental impact data, it can be used to estimate upstream life-cycle environmental impacts of production activities of any sector in the economic model. The basic EIO model derives the economic purchases, or supply chain, required to make a desired output. Once the supply chain has been estimated, environmental emissions can be estimated by multiplying the output of each sector by its environmental impact per dollar of output using Eq. 3-1.

$$b_i = R_i(I + A + AA + AAA + \ldots)y = R_i(I - A)^{-1}y \qquad \textbf{\textit{Eq. 3-1}}$$

In Eq. 3-1, b_i is the vector of environmental burdens (such as GHG emissions for each production sector), R_i is a matrix with diagonal elements representing the emissions per dollar of output for each sector, I is the identity matrix (a table of all zeros except for the diagonal entries containing a 1), A is the direct requirements matrix (with rows representing the required inputs from other sectors to make a unit of output), and y is the vector of desired production or "final demand." Terms in Eq. 3-1 represent the production of the desired output itself (I*y), contributions from the direct or first level ("tier-1") suppliers (A*y), those from the second level ("tier-2") indirect suppliers (A*A*y), and so on.

2. Uncertainties in Input-Output Models

As with any calculation based on EIO-LCA methods, this method has substantial uncertainties related to sectoral aggregation; price, temporal, and spatial variation; and several other issues, as discussed elsewhere [11][12][13]. As these uncertainties are not unique to this model, this section will focus on the uncertainties associated with use phase energy and the implementation of this vector into the model.

Sector aggregation occurs when operations that are technically and environmentally different are aggregated into a single sector or groups of sectors [14]. For this IO model, sector aggregation is dictated by the BEA in the IO tables created from survey data. Generally, more detailed disaggregated IO data is not available. Because energy consumption data sources may be organized by different classification systems than IO sectors (e.g., appliance level energy consumption), bridging this data with IO sectors results in the loss of information about more detailed sectors, and in some cases, introduces additional uncertainties from forced disaggregation of data.

The environmental data used in the model is a national average of all the companies in a given IO sector. It does not account for the differences in various companies' actual environmental impacts. For example, the carbon intensity of electricity production can vary significantly depending on the geographic region and the electricity grid portfolio in that region. Similarly, a nationally focused use-phase energy vector will not account for the different energy efficiencies that a sector may have, which fuel is utilized, and the fuels used in the regional electricity grid. For example, as shown in Chapter 2, a home in the South Atlantic Census Region is more likely to heat a home with electricity than a home in the New England Census Region, which is more likely to utilize natural gas. Instead, the average home will reflect that some fraction of its space heating comes from each source proportional to the amount of energy spent at the national level on residential space heating. Various uncertainties and variability relevant to estimating use phase energy have been incorporated in this work and are discussed. Further discussion of potential uncertainties from this national model in estimating regional use phase impacts is below.

3. Development of Primary Use-Phase Energy Vectors

Traditionally, IO-LCA models are constructed and used to estimate impacts with boundaries of cradle-to-gate or cradle-to-consumer impacts for products and services. Even the broader cradle-to-consumer boundary excludes effects occurring in the use or end of life phases of the product. Such a default IO-LCA boundary may be sufficient for applications to many products and services that do not have large use-phase energy components to their lifecycle, however it underestimates the impacts of products that have significant use-phase energy components. By incorporating use phase energy, the utility of EIO models could be improved. Masanet et. al. demonstrate the dominance of use phase energy on the life cycle on several products such as hot water heaters and refrigerators with use phase estimates that are developed externally to the IO model used for manufacturing energy requirements [15]. Similarly, Matthews et. al. show that the use-phase dominates the life-cycle of several lighting technologies, though as efficiencies improve the importance manufacturing energy increases [16].

One exception to the traditional cradle-to-gate or cradle-to-consumer framework is the "Open IO" IO-LCA model. Open IO is an open source model made available through The Sustainability Consortium (www.sustainabilityconsortium.org/open-io/) [17]. Open IO estimates the use-phase impacts for many goods and services based on estimates at a disaggregated level. This level of disaggregation is based on 2,923 product "bricks" identified in the Global Production Classification code. Open IO estimates on energy consumption, lifetime, price, and use are gathered from a variety of sources ranging from http://pottery.about.com to analyst estimates. These estimates are then aggregated to the IO sectoral level that is found in the model. Only the sectors that have some sort of direct energy use have use-phase impacts estimated in the model. Open IO does not differentiate between residential energy and energy consumed in other sectors and does not include personal transportation energy. A comparison of the results for EIO-LCA use phase energy to the same sectors in Open IO can be found in a later subsection that compares the EIO-LCA energy vectors to Open IO energy vectors in Table 3-8.

There are three things that distinguish this work from that of Open IO. First, the Open IO model deals in a different, more detailed level of sectoral disaggregation than the EIO-LCA model used by Green Design Institute at Carnegie Mellon University to estimate use-phase energy. Because the Open IO estimates are derived from bottom up estimates of energy use rather than top down estimates, uncertainty in the data necessarily increases with each assumption that is required. The uncertainty is displayed in the documentation spreadsheets as high and low estimates around the point estimates. Each estimate is derived from energy estimates for thousands of product "bricks" which are highly disaggregated from the IO sectors used in the model. For example, audio and video equipment sector is broken down into nearly 150 types of products. Secondly, the impacts (energy, greenhouse gas emissions, etc.) estimated by the Open IO model are more aggregated than the Carnegie Mellon University EIO-LCA model. The Open IO model has a single impact category for energy use while this work will separately estimate total energy, coal, petroleum, natural gas, non-fossil electricity, and biomass/waste fuels.

4. Use Phase Energy Sectors: A Focus on Residential Equipment

This model focuses on residential energy consumption for two major reasons. First, residential energy consumption is a relatively untapped source of energy reductions in the United States that is poorly understood at the household level [18]. This market for energy savings remains generally untapped for a variety of reasons such as the relatively poor understanding by both policy makers and consumers about how and why consumers use energy [19], the relative newness of energy monitoring devices such as The Energy Detective and the Efergy Energy Monitor [20][21], and the spread of energy use amongst many devices as shown in the Residential Energy Consumption Survey (RECS) [22]. The second reason why this work focuses on residential energy is for completeness of the EIO-LCA model. The portions of energy that are included and missing from the model are further described in this subsection.

Aside from being outside the scope of this research, which is focused on residential energy, the need for manufacturing use phase energy vectors can be eliminated from industrial equipment manufacturing sectors as this poses a double-counting dilemma. Energy used to operate industrial equipment is already accounted for in the products and services that they provide. This can be illustrated through an example such as milk, using the EIO-LCA model. For every $1,000 spent on milk (fluid milk and butter manufacturing), about $2.33 is spent on farm machinery and equipment manufacturing, about $30.13 is spent on petroleum refineries, and roughly $39.95 is spent on power generation and supply [1]. Much of the purchases that go to petroleum refineries and power generation and supply are used for fuel and electricity to operate the farm equipment and machinery required to produce $1,000 worth of milk. Thus, the use-phase energy associated with the farm equipment and machinery sector is already accounted for in the food products and services that the equipment is used to manufacture. Adding a use-phase energy estimate for the farm machinery and equipment manufacturing sector would thus count the energy that is already accounted for as use-phase energy as well and thus would be double counted in the model. This double counting issue eliminates the need to apply use-phase energy to industrial sectors where Manufacturing Energy Consumption Survey (MECS) already accounts for energy purchases [23].

While the commercial sector is also outside of the scope of a residential energy vector, it is still important to briefly discuss. A commercial use phase energy vector, like manufacturing sectors, would introduce double counting into the EIO-LCA model. Instead future work on use phase energy vectors should focus on what level of aggregation energy use should be allocated. For instance, in the residential sector we have allocated appliance use-phase energy to the appliance manufacturing sectors themselves. In the commercial sector, this may or may not be possible pending what data is available. Instead the model will likely have to settle for the way that energy is currently allocated, which is to a sector that is one level higher than the appliance sector. This is a result of data available at the building level through the Commercial Building Energy Consumption Survey (CBECS) [24], which allows for the allocation of energy use to commercial sectors such as hotels and fast food restaurants. The implications of this are two-fold. First, this means that energy that is used by appliances in a commercial building is allocated directly to the purchase of the hotel room or the restaurant service that is purchased rather than the purchase of the appliance that is using the energy. This is one level higher than the residential use-phase vector that is being developed in this work. The second implication is that the use-phase estimate for a given appliance or electronic device that is purchased by residential users as well as commercial and industrial users will be skewed toward a lower estimate as some of the energy that is consumed will be allocated to an upstream commercial or industrial sector. The implication here is that there is overlap in some of the appliances and electronics that are purchased by both the residential and commercial or industrial sectors.

The remaining sectors that are not accounted for in the EIO-LCA model are residential transportation sectors. The model has already considered all of the transportation upstream of the purchase of a product in a store, so ultimately the only unaccounted for transportation is personal and recreational transportation. This includes personal watercraft, residential lawn mowers, cars, light trucks, and personal gardening and farming equipment. Gasoline and petroleum expenditure data is available from the Consumer Expenditure Survey [25], however data on how this gasoline and petroleum is used will have to come from alternate sources.

5. Data Sources and Conceptualization

Using publicly available data, use-phase energy vectors are created for the six existing energy categories that are tracked in the EIO-LCA model available at www.eiolca.net [1]. The energy categories contained in the model are natural gas, petroleum, coal, biofuels and waste, non-fossil electricity, and total energy use. The development of the use phase vector will be highlighted through the data and model for the *Household Refrigerator and Home Freezer Manufacturing* sector (NAICS 335222) [26]. This description will provide the most detail and examples, while methods for subsequent residential appliance types and sectors will provide less detail but use similar methods. Other IO sectors that have associated use phase energy will be developed similarly to the *Household Refrigerator and Home Freezer Manufacturing* sector and can be found following this section on refrigerators and freezers and in the Appendix. A mapping of household appliances to corresponding EIO-LCA sectors is shown in Table 3-1.

Table 3-1. Mapping from appliance to IO sectors.

IO Sector Number	**IO Sector**	**NAICS Sector Name**	**Included appliances (not an exhaustive list)**
214	333414	Heating equipment (except warm air furnaces) manufacturing	Heating equipment
215	333415	Air conditioning, refrigeration, and warm air heating equipment manufacturing	Air conditioners, forced air furnaces
234	334111	Electronic computer manufacturing	Desktops, Laptops
236	33411A	Computer terminals and other computer peripheral equipment manufacturing	Printers, Monitors, Speakers, Keyboards
237	334210	Telephone apparatus manufacturing	Cordless phones, answering machines
238	334220	Broadcast and wireless communications equipment	Satellite equipment, cell phones, cable boxes
239	334290	Other communications equipment manufacturing	Fire alarms, intercoms
240	334300	Audio and video equipment manufacturing	TVs, VCR/DVD, Stereos
260	335120	Lighting fixture manufacturing	Household lighting (indoor and outdoor)
261	335210	Small electrical appliance manufacturing	Vacuum cleaners, toasters, coffee makers, window fans, portable irons
262	335221	Household cooking appliance manufacturing	Stoves, ovens, microwaves, grills
263	335222	Household refrigerator and home freezer manufacturing	Refrigerators, freezers
264	335224	Household laundry equipment manufacturing	Washing machines, clothes dryers
265	335228	Other major household appliance manufacturing	Dishwashers, water heaters, garbage disposals/compactors

Data sources for 2002 are necessary to match the 2002 EIO-LCA model. Data estimating energy use by IO sector include the Department of Energy (DOE) Residential Energy Consumption Survey (RECS) [27] on appliance ownership, energy expenditures, and appliance age; DOE's RECS End-Use Consumption data on electricity consumption in 2001 by appliance and household [22]; FTC appliance energy data on an annual consumption per year basis for each model sold in 2003 [28]; AHAM data on shipments and appliance consumption by year [29][30]; Appliance Magazine estimates of shipments and appliance consumption [31]; and other various sources. Each of these data sources was free (with the exception of AHAM data on consumption per year [30]) and contains different data ranging from a yearly average of a single appliance's energy consumption to an appliance's total fleet consumption in a year to a yearly consumption estimate by appliance model. RECS End-Use Consumption data gives total energy consumption in 2001 by appliance for all of the appliances used in the US in 2001, yearly consumption by household, and yearly consumption by individual unit depending on the appliance [22]. The FTC gives appliance data for expected yearly consumption by model [28]. FTC data as old as 2003 is available on the web but to obtain data for earlier years a physical visit to Washington D.C. is required to access it. For the purposes of this model 2003 data is used and adjusted when necessary to match 2002 expected consumption. AHAM gives a point estimate for the energy use by year based on a sales weighted average [29]. AHAM also estimates yearly shipments of appliances, as does Appliance Magazine [30][31]. These data sources and their use in this work will be described more detail in subsequent sections of this chapter and can also be found in Table 3-2. None of these data sources estimate lifetime energy consumption for appliances and electronics sold in a given year. Instead each data source helps us to develop lifetime energy consumption estimates for appliances and electronics that will enable the development of use phase energy vectors for the EIO-LCA model. Lifetime energy consumption is the required metric for the inclusion of residential use phase energy in this model as the model represents the lifecycle demands of economic activity (i.e., all of the impacts from a given purchase), not the lifecycle demands of purchases in a given period of time (i.e. all of the electricity required to run an appliance in a given year).

Table 3-2. Mapping of data sources to IO sectors.

IO Sector	**Sector Name**	**Energy Use Estimates**	**Shipments**	**Lifetime**	**Use Phase Relative Standard Errors**
333414	Heating equipment (except warm air furnaces) manufacturing	Buildings and Energy Databook	Appliance Magazine	National Association of Home Builders	National Resources Canada & FTC Average
333415	Air conditioning, refrigeration, and warm air heating equipment manufacturing	Buildings and Energy Databook	N/A	N/A	National Resources Canada
334111	Electronic computer manufacturing	RECS	N/A	N/A	National Resources Canada
33411A	Computer terminals and other computer peripheral equipment manufacturing	Energy Star	N/A	N/A	National Resources Canada & FTC Average
334210	Telephone apparatus manufacturing	RECS	N/A	N/A	National Resources Canada
334220	Broadcast and wireless communications equipment	RECS	N/A	N/A	National Resources Canada & FTC Average
334290	Other communications equipment manufacturing	RECS	N/A	N/A	National Resources Canada & FTC Average
334300	Audio and video equipment manufacturing	RECS	N/A	N/A	National Resources Canada & FTC Average
335120	Lighting fixture manufacturing	RECS, Buildings and Energy Databook	N/A	N/A	National Resources Canada & FTC Average
335210	Small electrical appliance manufacturing	RECS	N/A	N/A	National Resources Canada & FTC Average
335221	Household cooking appliance manufacturing	Buildings and Energy Databook	N/A	N/A	National Resources Canada
335222	Household refrigerator and home freezer manufacturing	AHAM, FTC,	Appliance Magazine	DOE	Federal Trade Commission
335224	Household laundry equipment manufacturing	AHAM, FTC, NRDC, DOE	Appliance Magazine	DOE	National Resources Canada
335228	Other major household appliance manufacturing	RECS, DOE, AHAM	Appliance Magazine	NAHB	Federal Trade Commission

Degradation of the appliances must also be considered in this model as appliances tend to use more energy as they age [32]. In 1998 it was estimated by Miller and Pratt that refrigerators had an annual degradation factor of 1.37% based on 95 existing and 15 new refrigerators in New York, New York studied using in situ metering and a regression model [33]. This means that a one-year old refrigerator consumes 1.37% more energy than it did when it was new (age zero). The "2009 Second Refrigerator Recycling Program" in Nevada estimated a similar value of 1.25% based on methodology from a 2010 evaluation of the California Appliance Replacement Program [34][32]. We use the 1.25% estimate that is used by several refrigerator recycling programs throughout the country [34][32] though an analysis of Rhode Island's refrigerator turn-in program employed the 1.37% factor [35], but the overall effect of this alternate factor would be small. Table 3-3 shows degradation rates for appliances over time. With little evidence of a concrete degradation rate for other appliances, merely that one exists; the 1.25% estimate is used for all of the other residential appliances and equipment. Relative appliance energy use degradation will not change from appliance to appliance, only the absolute energy consumption changes. Table 3-3 show how different degradation rates increase the relative total energy consumption for an appliance over time. Future work on the degradation for other appliances would be beneficial for this and related research.

Table 3-3. Energy consumption increase relative to no degradation over time.

Degradation Rate	**1.25%**	**1.37%**	**2.00%**
10 years	6%	7%	11%
15 years	10%	11%	16%
20 years	14%	15%	23%

For the manufacturing portion of an IO-LCA model, manufacturing sectors either produce electricity on site or they purchase power from the "power generation and supply" sector. These purchases of power include the power that is delivered to the purchaser and also the power that is lost and used to deliver the energy services, called source energy. In our model, site energy consumption (i.e., residential use) similarly does not indicate the total energy use of these products and services. To account for these conversions and losses, we must apply a source to site ratio from "ENERGY STAR Performance Ratings Methodology for Incorporating Source Energy Use" [36]. The source to site ratios for various energy sources are in Table 3-4. For example, the national average for every kWh that is delivered to an end user site requires a total of 3.336 KWh at the source, 2.336 kWh of which are lost or used in the conversion, transmission and distribution of that electricity.

Table 3-4. Source to site ratios for various energy sources [36].

Fuel Type	**Source to Site Ratio**
Electricity (Grid Purchase)	3.336
Natural Gas	1.047
Fuel Oil	1.01
Propane & Liquid Propane	1.01
Wood	1.0
Coal/Coke	1.0
Other	1.0

6. Use Phase Energy Model Theory

If we have the annual consumption for each kind of appliance or equipment per appliance, the number of shipments in 2002 (the year of the EIO-LCA model), the expected lifetime for each appliance or equipment, the appliance or equipment degradation, and the 2002 industrial output, we can set up an equation (Eq. 3-2) to calculate the total use phase energy that looks similar to a future value equation from engineering economics.

$$FV(A) = A * \frac{(1+i)^n - 1}{i} \qquad \textbf{\textit{Eq. 3-2}}$$

In this case the future value (FV) will be replaced with our lifetime energy (LE). The annuity (A) is replaced with our annual consumption by the fleet of appliances sold in 2002. The interest rate (i) becomes our appliance degradation rate (d), or the rate at which our appliances consume more energy annually. Equation 3-3 shows these substitutions.

$$LE(A) = A * \frac{(1+d)^n - 1}{d} \qquad \textbf{\textit{Eq. 3-3}}$$

To calculate annual consumption we use Equation 3-4.

$$Annual\ consumption = \left(\frac{annual\ consumption}{appliance}\right) * 2002\ shipments \qquad \textbf{\textit{Eq. 3-4}}$$

7. Treatment of Uncertainty and Variability in the Model

There is significant uncertainty in the development of this model in addition to the uncertainties in IO models outlined above. Given the multitude of data sources and the fact that many of them do not explicitly outline uncertainties, uncertainty estimates must be constructed in other ways. Uncertainties that affect the use phase energy estimates in this model include uncertainties in appliance or electronic lifetime, behavioral uncertainty (i.e. how often a device is used), climate uncertainty (heating in warm versus cool climates), appliance efficiency, number of shipments, degradation, and other uncertainties. Uncertainties in appliance age and degradation rates for appliances are addressed above for the refrigerator and freezer sector. Each sector can be expected to see similar results in that if an appliance is used for fewer years, the lifetime energy use would be smaller. Similarly, a lower degradation rate would yield lower lifetime energy for a given appliance.

Uncertainty for each contributing variable (unit annual energy use, lifetime, shipments, and degradation) was modeled independently for each model. Energy use per unit was consistently found to be the most important variable for total lifetime energy consumption of all appliances sold in 2002. Uncertainty for each estimate is represented by relative standard errors generated from individual estimates of unit energy consumption. Because these estimates are for total national average energy consumption, it is less important to include all of the potential individual energy consumptions (combining all of the lowest estimates for degradation, energy use, shipments, and lifetime and combining all of the highest estimates). If the focus of this work were on modeling potential energy consumption for an individual appliance, the uncertainty bars would be significantly larger than they are in this analysis and simulations would be necessary for sensitivity analysis.

Inevitably, there is uncertainty with residential energy consumption as some of the products intended for use in the residential sector are purchased and used in the commercial and industrial sectors. An example of this might be the addition of a household style refrigerator to a university common area. Unfortunately there is little that can be done to account for this. While we do expect some spillover of energy that is accounted for in the residential sector to be actually consumed in the commercial sector and vice versa, we expect that these are relatively minor and are likely accounted for in the uncertainties of each of these estimates.

Relative standard errors for the use phase are developed from a variety of data sources that give annual use phase energy estimates for appliance or equipment models sold in a given year. Standard errors were developed from the Federal Trade Commission (FTC) [28] unweighted data for appliances sold in 2003 when available. 2002 data is available but requires a physical visit to Washington D.C. to obtain. It is assumed that the 2003 data is approximately the same as the 2002 data for this model. When FTC data is unavailable, ENERGY STAR's unweighted lists of appliances sold are accessed through U.S. ENERGY STAR data and Natural Resources Canada when the U.S. ENERGY STAR data was not available for devices [37]. It is assumed that the relative standard errors are unlikely to change significantly between devices sold in Canada and the United States. Standard errors were assumed to be 0% for cars, which is consistent with the Residential Transportation Energy Consumption Survey (RTECS) [38]. Other sectors with use phase energy consumption estimates of 30 TJ per million dollars that did not have standard errors readily calculable were assumed to have a relative standard error of 25%, the average standard error for the other sectors. 95% confidence intervals were developed by multiplying the relative standard errors by 1.96. Relative standard errors for manufacturing data and relative standard errors and their data sources for use phase relative standard errors are shown in Table 3-5 for comparison.

Table 3-5. Relative Standard Errors and 95% Confidence Errors for Use Phase and Manufacturing.

IO Sector	RSE Use Phase	95% CI Use Phase	RSE Manufacturing	95% CI Manufacturing	Use Phase RSE Data Source
Lawn and garden equipment manufacturing	25%	48%	7%	14%	Average
Heating equipment (except warm air furnaces) manufacturing	50%	97%	7%	14%	National Resources Canada
Air conditioning, refrigeration, and warm air heating equipment manufacturing	7%	14%	7%	14%	National Resources Canada
Power-driven handtool manufacturing	25%	48%	11%	22%	Average
Electronic computer manufacturing	17%	33%	11%	22%	National Resources Canada
Computer terminals and other computer peripheral equipment manufacturing	25%	48%	11%	22%	Average
Telephone apparatus manufacturing	25%	48%	11%	22%	Average
Broadcast and wireless communications equipment	25%	48%	11%	22%	Average
Other communications equipment manufacturing	25%	48%	11%	22%	Average
Audio and video equipment manufacturing	25%	48%	11%	22%	Average
Lighting fixture manufacturing	45%	88%	18%	35%	National Resources Canada
Small electrical appliance manufacturing	22%	43%	18%	35%	Federal Trade Commission
Household cooking appliance manufacturing	4%	7%	18%	35%	National Resources Canada
Household refrigerator and home freezer manufacturing	33%	64%	18%	35%	Federal Trade Commission
Household laundry equipment manufacturing	30%	59%	18%	35%	Federal Trade Commission
Other major household appliance manufacturing	15%	29%	18%	35%	Federal Trade Commission
Automobile Manufacturing	0%	0%	4%	8%	Residential Transportation Energy Consumption Survey
Boat building	25%	48%	4%	8%	Average
Motorcycle, bicycle, and parts manufacturing	25%	48%	4%	8%	Average

8. Residential Energy Use of Refrigerators and Freezers Sector

From the list of sectors above estimates will be made for lifetime energy use of all purchases in 2002. Refrigerators and freezers will be used as a template to demonstrate this process. Other devices are found in other IO sectors and can be found in the Appendix. These lifetime estimates are divided by Bureau of Economic Analysis (BEA) estimates of industrial output to yield energy use per dollar of output for a given IO sector, as done for other effects such as emissions.

The *Household Refrigerator and Home Freezer Manufacturing* sector (NAICS 335222) includes household refrigerator, refrigerator/freezer combinations (considered to be refrigerators), and freezers; all of which consume electricity in the use phase [26].

8. 1. Refrigerators Energy Use

Analysis of FTC's data on 2002 models of new refrigerators yields an unweighted average energy consumption of 520 kWh/model/year and a median consumption of 490 kWh/year [28]. AHAM provides a sales-weighted point estimate for refrigerator consumption for refrigerators sold in 2002 of 565 kWh/year [29], which means that the unweighted average of the FTC data is only 8% less than the AHAM estimate. The FTC minimum value for 2003 was 230 kWh and the maximum was 790 kWh. Applying a 1% average reduction in annual energy consumption for refrigerators between 2002 and 2003 [29], the 2002 average refrigerator consumption is calculated to be 526 kWh/year and the median is 496 kWh/year. The minimum is found to be 233 kWh/year and the maximum is found to be 799 kWh/year. The sales weighted point estimate of 565 kWh/unit/year is likely the most accurate of these values and thus the number used in the model, though the FTC data is reasonably consistent with this estimate.

8. 2. Refrigerators Lifetime

Refrigerators last about 12 years [39], though the U.S. Department of Energy estimated in 2009 that 27% of refrigerators last 10-19 years and 8% of refrigerators last more than 20 years [40]. Young indicates with empirical evidence that Canadian households hold on to refrigerators much longer than other estimates would suggest [41]. Part of this is due to the lack of disposal of refrigerators when a new appliance is bought (i.e. the old refrigerator becomes a secondary appliance in the basement or garage for beverages and other items stored long term). The other hypothesis for this is that the models for appliance turnover may be incorrect. While this trend can only concretely be said to apply to Canada, the authors find little reason to believe that Canadian appliance replacement patterns would differ significantly than those in the U.S. Young's research found that more than half of Canadian refrigerators between 21 and 25 years old were still in use. The research also showed that 28% of refrigerators retired were between 16 and 20 years old and that only 40% of refrigerators were retired before they were 16 years old. Given this data, we will assume that the average age of retirement for refrigerators made in 2002 is 15 years, though it is reasonable that refrigerators may last or be used elsewhere longer. Other sources indicate various expected average lifetimes for refrigerators between 10 and 18 years [42][43][44][45]. Age (length of use) plays a significant role in the uncertainty of the lifetime energy use of refrigerators. This effect can be observed in Figures 3-1, 3-2, and 3-5.

8. 3. Refrigerator Shipments in 2002

In 2002, AHAM reports that 10.8 million refrigerators were shipped from US factories, including exports [30]. <u>Appliance Magazine</u> reported the number of refrigerator shipments, both U.S. made and imported for the U.S. market, not including exports, is 9.7 million refrigerators [31]. The Appliance Magazine and AHAM estimates are consistent both in the fact that they are reasonably consistent with each other and that the estimate excluding exports is slightly smaller than the estimate including exports. Given that the EIO-LCA model is for the energy use within the United States [1], the Appliance Magazine estimate of 9.7 million shipments is the number used for this model.

8. 4. Refrigerator 2002 Model Fleet Energy

Multiplying the average annual consumption of the refrigerator by the number of appliances sold in 2002, we can calculate the total electricity consumption associated with refrigerator use for the first year of use for these new appliances. Given the annual average consumption of 526 kWh/year and that 9.7 million refrigerators were sold for use in the U.S. market, refrigerators sold in 2002 consumed 5.1 TWh in their first year of use as observed in Eq. 3-5.

$$Annual\ consumption_{2002} = \left(526\ \frac{kWh}{unit\ year}\right) * 9.7\ million\ shipments_{2002} = 5.1\ TWh \qquad \textbf{Eq. 3-5}$$

Further multiplying this product by the average lifetime of a refrigerator will estimate the total lifetime electricity consumption by refrigerators. The final adjustment to this number is for the degradation of refrigerators over their lifetimes, as discussed above. Applying the 15-year lifetime and an appliance degradation rate of 1.25% per year we calculate an estimate of 84 TWh for the fleet of refrigerators sold in 2002 as observed in Eq. 3-6.

$$LE(5.1\ TWh) = 5.1\ TWh * \frac{(1+1.25\%)^{15}-1}{1.25\%} = 84\ TWh \qquad \textit{\textbf{Eq. 3-6}}$$

8. 5. Uncertainty in Refrigerator Energy Consumption

Several factors impact the uncertainty of the point estimates for lifetime refrigerator energy use developed above. Figure 3-1 shows the uncertainty associated with annual degradation rates between 0 and 2 percent for new refrigerators in 2002 over an uncertain lifetime between 1 and 25 years. Figure 3-2 shows the uncertainty of lifetime energy consumption given uncertain annual energy consumption (high, median, and low consuming refrigerators) over an uncertain lifetime between 1 and 25 years. The most likely value for the lifetime of the refrigerator is 15 years with high and low estimates of 10 and 20 years.

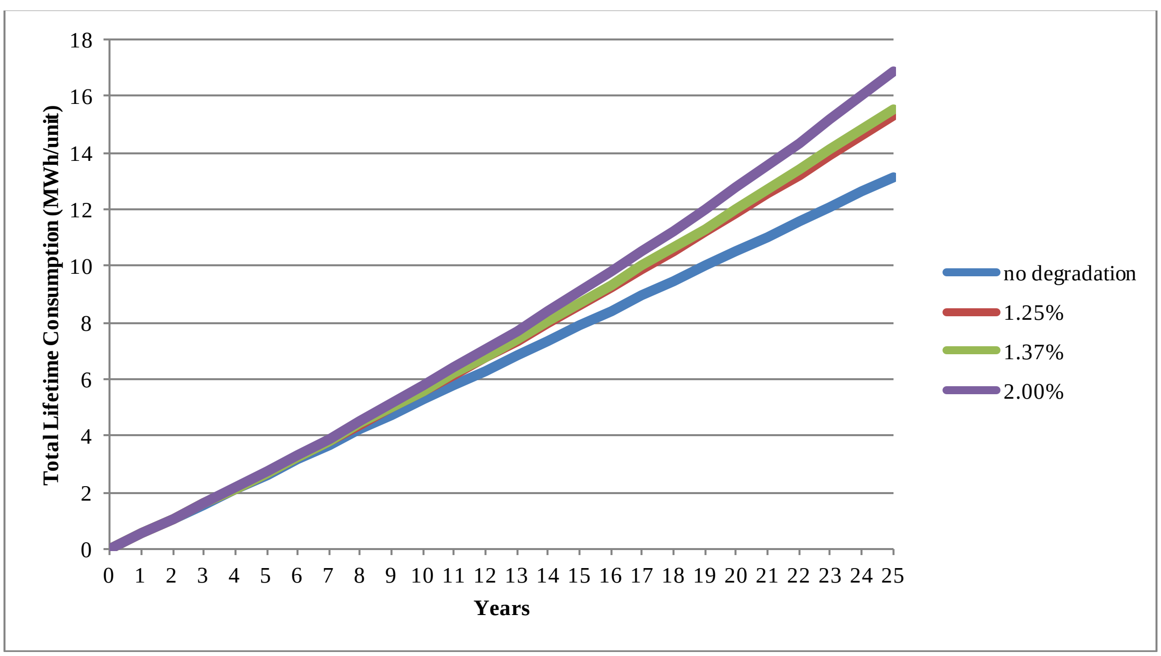

Figure 3-1. Uncertainty in refrigerator age and appliance degradation rate for a single average refrigerator sold in 2002 over an uncertain lifetime between 1 and 25 years.

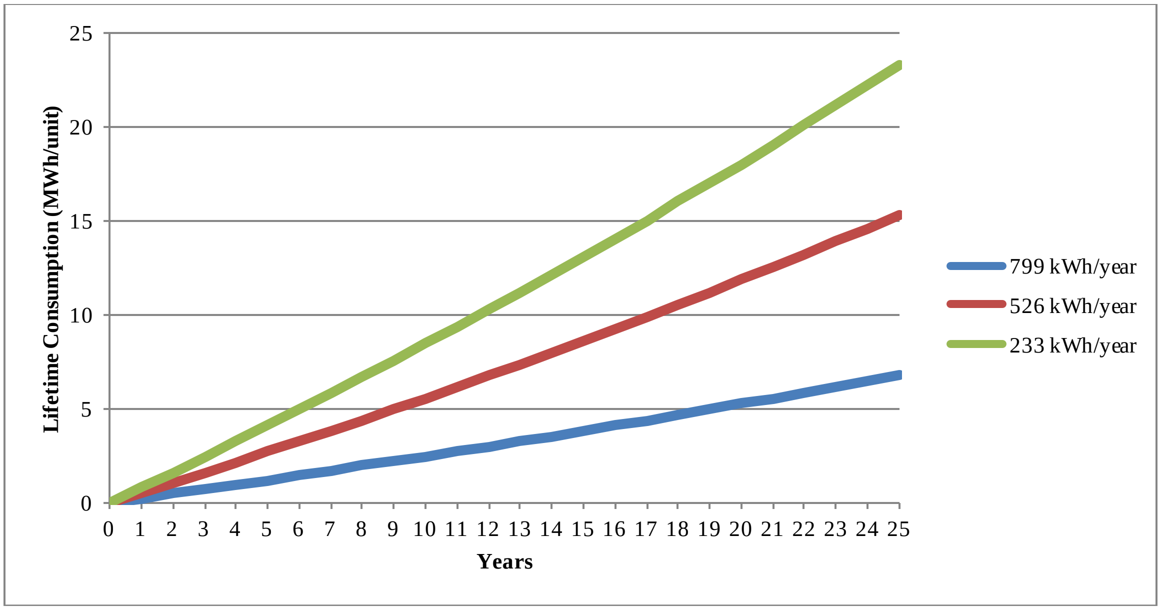

Figure 3-2. Lifetime energy consumption for a single refrigerator unit sold in 2002 at the high, median, and low consumption estimates with a 1.25% annual degradation rate in energy consumption over an uncertain lifetime between 1 and 25 years.

Uncertainty for each contributing variable (unit annual energy use, lifetime, shipments, and degradation) was modeled independently for each model. Energy use per unit was consistently found to be the most important variable for total lifetime energy consumption of all appliances sold in 2002. Uncertainty for each estimate is represented by relative standard errors generated from individual estimates of unit energy consumption. Because these estimates are for total national average energy consumption, it is less important to include all of the potential individual energy consumptions (combining all of the lowest estimates for degradation, energy use, shipments, and lifetime and combining all of the highest estimates). If the focus of this work were on modeling potential energy consumption for an individual appliance, the uncertainty bars would be significantly larger than they are in this analysis.

8. 6. Freezers Energy Use

Analysis of FTC's data on 2003 models of freezers yields an unweighted average energy consumption of 441 kWh/model/year and a median consumption of 397 kWh/year [28]. AHAM provides a sales weighted point estimate for freezer consumption in 2002 of 444 kWh/year [29], which means that the unweighted average of the FTC data is less than a tenth of a percent different than the AHAM estimate. The FTC minimum value for 2003 was 230 kWh and the maximum was 790 kWh. According to the AHAM data for freezers, there was no difference between the sales weighted average energy consumption in 2002 and 2003. The sales weighted point estimate of 444 kWh/unit/year is used in this model, though the FTC data is reasonably consistent with this estimate.

8. 7. Freezers Lifetime

The average lifetime of a freezer is about 15 years with a high estimate of 20 years and a low estimate of 12 years [42][43][44]. A range of 10-20 years is estimated by atdhomeinspection.com [46] and the National Association of Home Builders (NAHB) estimated the lifetime of freezers to be 16 years [44]. The 2000 U.S. Department of Housing and Urban Development's Residential Rehabilitation Inspection Guide estimated the average lifetime of a freezer to be 11 years based on a survey of manufacturers, trade associations, and product researchers [47]. Given multiple reports between a 10 and 20-year lifetime, 15 years is the value used in this estimate, though there is uncertainty about this value. The high and low estimates for the lifetime of refrigerators are assumed to be 10 and 20 years.

8. 8. Freezer Shipments in 2002

In 2002, AHAM reports that 2.8 million freezers were shipped from factories, including exports [30]. Appliance Magazine reported the number of freezer shipments, both U.S. made and imported for the U.S. market, not including exports, is 2.5 million freezers [31]. The Appliance Magazine and AHAM estimates are consistent both in the fact that they are reasonably close and that the estimate excluding exports is slightly smaller than the estimate including exports. Given that the EIO-LCA model is for the energy use within the United States, the Appliance Magazine estimate of 2.5 million shipments is used in this model.

8. 9. Freezer 2002 Model Fleet Energy

Multiplying the average annual consumption of a freezer by the number of appliances sold in 2002, we can calculate the total electricity consumption associated with freezer use for a single year. Further multiplying this product by the average lifetime of a freezer will give the total electricity consumption by the fleet of freezers sold in 2002. The final adjustment to this number is for the degradation of freezers over their lifetimes. Given the annual average consumption of 444 kWh/year and that 2.5 million freezers were sold for use in the U.S. market, freezers sold in 2002 consumed 1.1 TWh in their first year of use as observed in Eq. 3-7.

$$Annual\ consumption\ = (444\ kWh) * 2.5\ million\ shipments = 1.1\ \text{TWh} \qquad \textbf{\textit{Eq. 3-7}}$$

Multiplying the annual consumption by the 15-year lifetime and factoring in the 1.25% degradation rate for the appliances gives us a total lifetime consumption of 18 TWh for all of the 2.5 million freezers sold in 2002 in the United States as observed in Eq. 3-8.

$$LE(1.1\ TWh) = \ 1.1\ TWh * \frac{(1+1.25\%)^{15}-1}{1.25\%} = 18\text{ TWh} \qquad \textbf{\textit{Eq. 3-8}}$$

8. 10. Uncertainty in Freezer Energy Consumption

Several factors impact the uncertainty of the point estimates for lifetime refrigerator energy developed above. Figure 3-3 shows the uncertainty associated with annual degradation rates between 0 and 2 percent for new refrigerators in 2002 over an uncertain lifetime between 1 and 25 years. Figure 3-4 shows the uncertainty of lifetime energy consumption given uncertain annual energy consumption (high, median, and low consuming freezers) over an uncertain lifetime between 1 and 25 years. The expected lifetime for freezers is 15 years and the high and low estimates are 10 and 20 years.

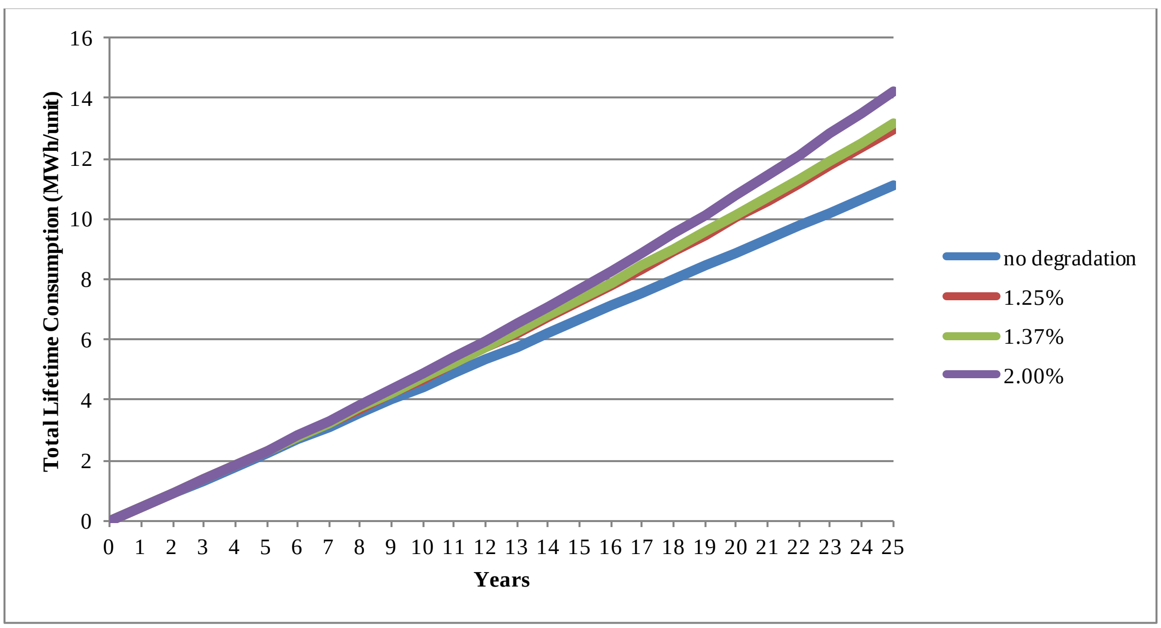

Figure 3-3. Effect of freezer age and appliance degradation rate for a single average freezer sold in 2002 on lifetime energy consumption per unit.

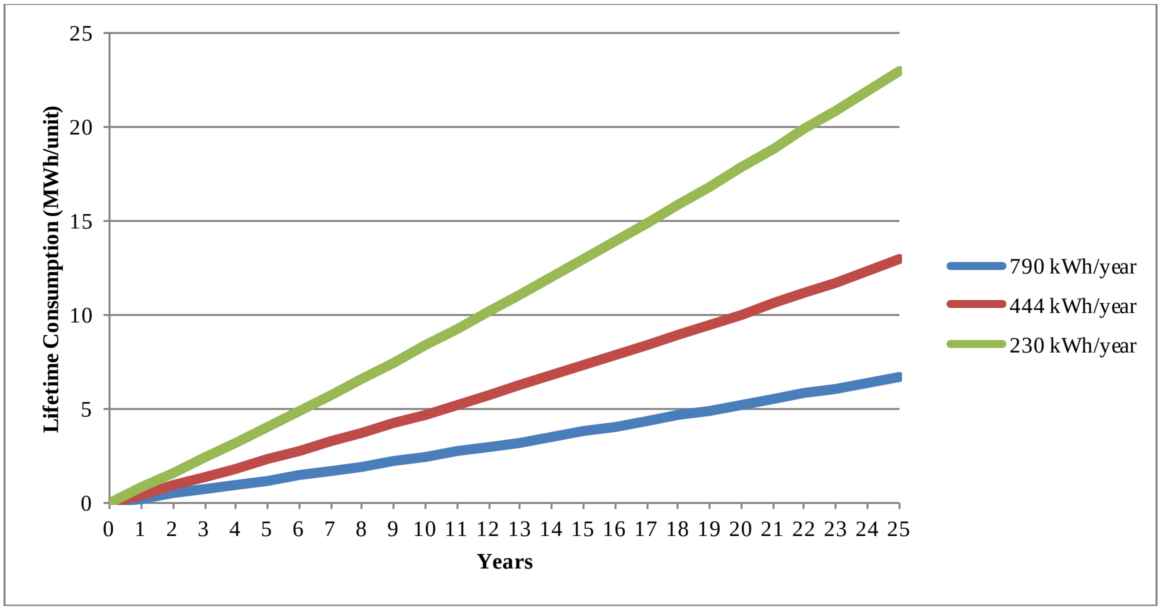

Figure 3-4. Lifetime energy consumption for a single freezer unit sold in 2002 at the high, median, and low consumption estimates with a 1.25% annual degradation rate in energy consumption over an uncertain lifetime between 1 and 25 years.

8. 11. EIO-LCA Use Phase Values for Refrigerators and Freezers

The BEA estimate of national industrial output for the *household refrigerator and home freezer manufacturing* sector in 2002 was \$5.5 billion [48]. Dividing the sum of our point estimates of 84 TWh for refrigerators and 18 TWh for freezers by this industrial output yields 18.7 GWh or 67.2 TJ per million dollars of industrial output. It should be reminded that this number is developed externally to the EIO-LCA model and thus avoids any double counting issues that may otherwise arise.

Since these are all electricity grid purchases, each must be multiplied by a source-to-site ratio to estimate the true energy requirements to run this fleet of appliances over the course of the appliances' lifetimes. In this case, the ratio was 3.336 in 2002 [36]. Applying this ratio yields lifetime energy consumption of the fleet of residential refrigerators and freezers sold in 2002 to be 224 TJ per million dollars of industrial output. Generally the appropriate value here for analysis is the primary energy consumption, as it will reflect the true environmental impacts of the use of a device, however site energy is also important for determining information for energy bills and comparing appliances energy use to one another.

8. 12. Comparison to Manufacturing Data for Refrigerators and Freezers.

Running the EIO-LCA model for $1 million (producer price) in the *Household refrigerator and home freezer manufacturing* sector estimates that there is a total cradle to gate energy consumption of 11.8 TJ [1] (relative standard error of +/- 18% (9.7 TJ – 13.9 TJ) [49]) for the manufacturing of residential refrigerators and freezers. This is 18% of the lifecycle energy estimate given 67.2 TJ of site use energy that is consumed in the use phase by $1 million of household refrigerators and home freezers as predicted above. This is also only 5% of the lifecycle given 224 TJ of source energy that is consumed in the use phase by $1 million of household refrigerators and home freezers. By adding use phase energy to the model it expands its utility and becomes applicable for decision support for how to reduce energy consumption. A graphical comparison of manufacturing versus site and source energy use over the life cycle for various life cycle stages is shown in Figure 3-5. This modeling suggests that approaches that reduce the use phase energy for refrigerators, such as the ENERGY STAR program, are well aimed while approaches to reduce supply chain manufacturing efficiency are less relevant.

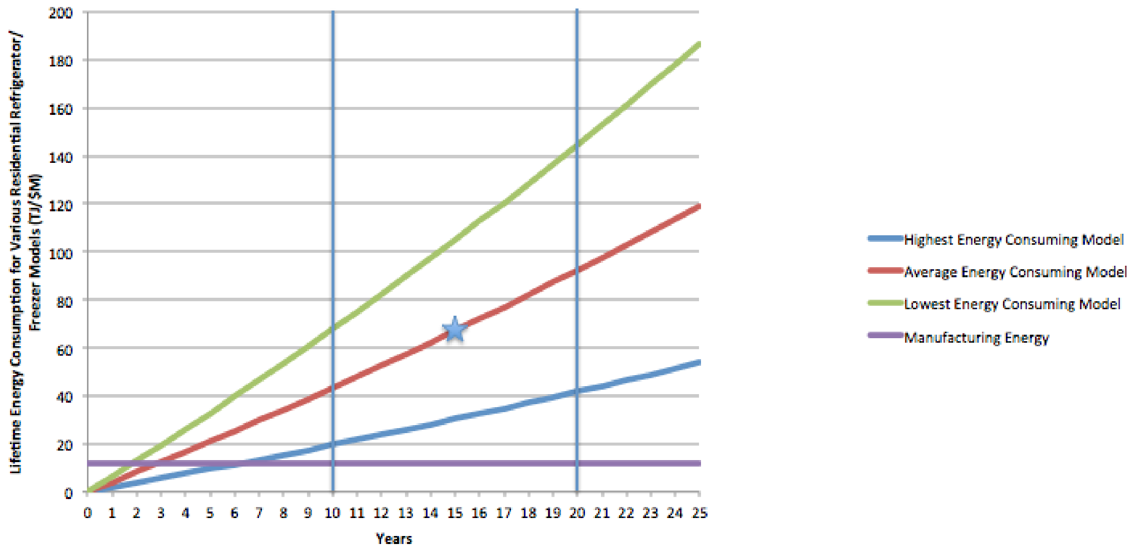

Figure 3-5. Comparison of manufacturing energy (purple line) and lifetime **site** use phase energy for various refrigerator and freezer models (blue, red, and green lines) over various lifetimes. Vertical lines represent the range of expected lifetimes and the star represents the point estimate lifetime site use phase energy for residential refrigerators and freezers per million dollars of industrial output.

As seen in Figure 3-5, the amount of time it takes the appliance use-phase energy to equal that of the manufacturing energy, in terms of site-energy use is between 1.5 years and 6 years depending on whether the lowest energy consuming appliances are chosen or is the highest energy consuming appliances are used. On average, the use phase site energy requirements exceed manufacturing energy requirements in about three years. If we look at source energy use in Figure 3-6, the time is drastically reduced to less than a year (1.5 years for the lowest consuming equipment).

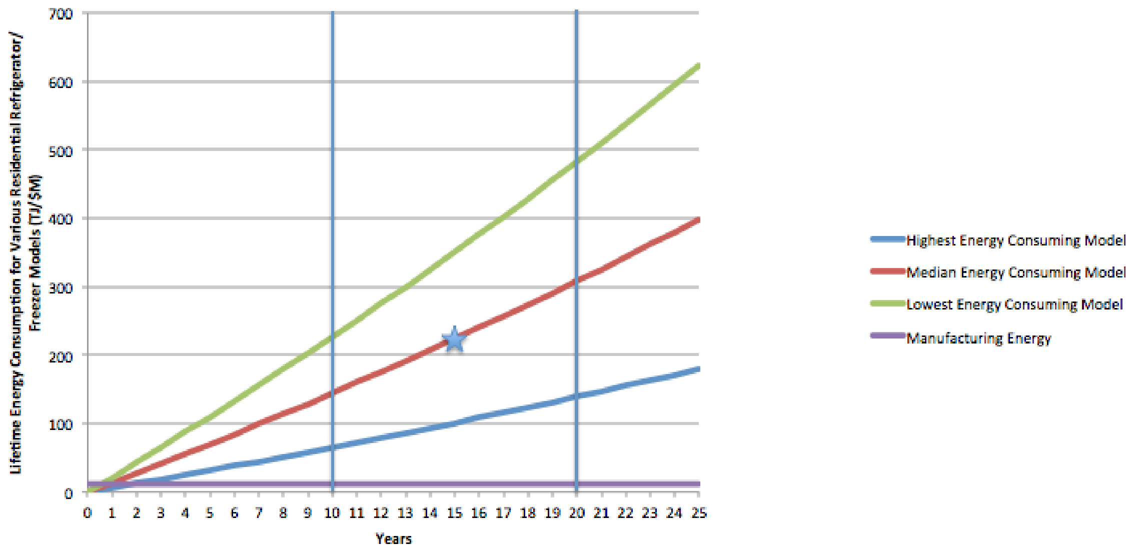

Figure 3-6. Comparison of manufacturing energy (purple line) and lifetime **source** use phase energy for various refrigerator and freezer models (other lines) over various lifetimes. Vertical lines represent the range of expected lifetimes and the star represents the point estimate lifetime site use phase energy for residential refrigerators and freezers per million dollars of industrial output.

From Figures 3-5 and 3-6 we see that our point estimate is 224 TJ of source energy per million dollars of industrial output (star on the figures), however we can also see in Figure 3-7 that these estimates can be as low as 66 TJ per million dollars (lowest energy consuming model at ten years) and as high as 482 TJ per million dollars (highest energy consuming model at 20 years). Even in the lowest use phase energy consumption scenario and the highest possible manufacturing energy scenario given uncertainty in annual appliance consumption, the use phase still consumes nearly ten times more energy than the manufacturing phase of the lifecycle. The bar graph shown here for refrigerators and freezers and the bar graphs for other appliances throughout the appendix can be used to emphasize how much greater the use phase energy for a product can be than its manufacturing energy requirements.

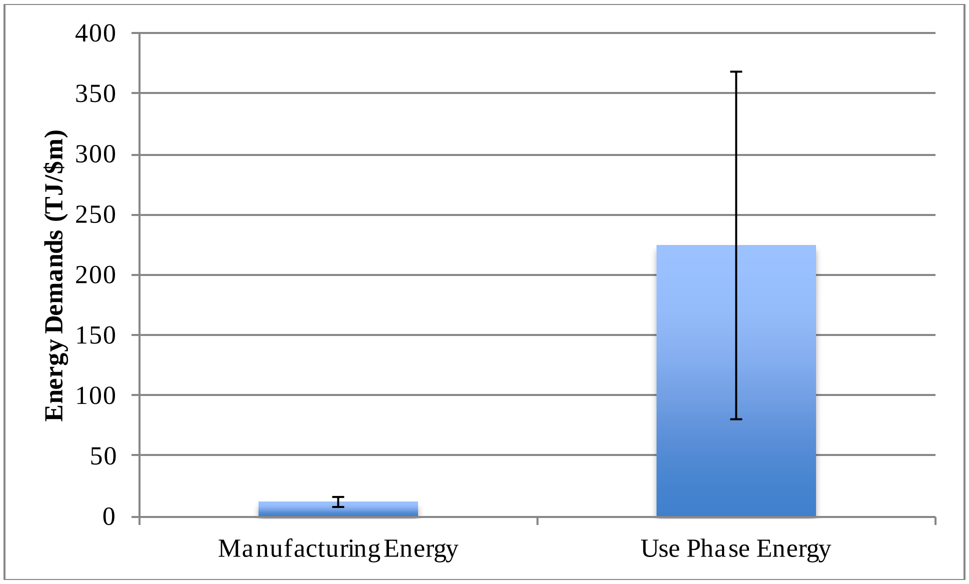

Figure 3-7. Manufacturing vs. lifecycle residential use phase energy for *Household Refrigerator and Home Freezer Manufacturing*.

9. Other Use Phase Energy Consuming Sectors

Similar methods are used to calculate the use phase energy per dollar, with uncertainty ranges, for the remaining residential appliance and personal transportation sectors that consume energy in the use phase. These calculations and related figures can be found in the Appendix to Chapter 2.

10. Validation

This model relies heavily on the assumption that the residential energy use in 2002 for devices and appliances with gaps in the available data is approximately equal to the residential lifetime energy use by all devices sold in 2002. This assumption necessitates that the appliance or device turnover rate is approximately equal to the manufacture rate, or if the manufacture rate is greater than the retirement rate, that the efficiency of new devices is improving at a rate that holds the energy consumption rate fairly stable. This assumption is generally found to be true at the device level as energy requirements generally were not found to be increasing dramatically, and also at the residential energy consumption level for the entire U.S. as the increase in residential site energy consumption is increasing between 2000 and 2006 at about 1.8% [50]. This is further supported by EIA's Annual Energy Outlook (2011) which has residential energy use declining slightly currently but increasing at about 0.2% annually over the next 30 years [51]. The 2002 EIA Annual Energy Outlook also has residential energy use sitting fairly constant with a growth rate of 1% [52]. Given the assumption that energy use in 2002 is approximately equal to the energy use of all devices sold in 2002, the 11.25 quads of site energy use in this model is only 0.4% less than the 11.30 quads consumed in 2002 [53]. Each of these estimates excludes transportation energy. The 21.50 quads of primary residential energy use in the model is also only 2.8% higher than the 20.91 quads that are estimated by the Buildings and Energy Data Book. Looking only at site electricity, this model contains 4.27 quads of electricity use, which is 4 percent higher than the Buildings and Energy Data Book estimate of 2002 consumption. This estimate is also 9 percent higher than the 2001 RECS End-Use data, which is reasonable given the year difference between the two values and that the 2002 Energy and Buildings value is 9.8% higher and the 2001 Energy and Buildings value is 5.4% higher than the 2001 RECS value [22] [50].

The results of this work (including all other sectors detailed in the Appendix) are shown in Table 3-6. This table shows the source energy consumption for the manufacturing sectors whose products have associated use phase energy consumption. Table 3-7 reallocates electricity use into component fuels that are consistent with the fuels used in the EIO-LCA model (coal, petroleum, natural gas, biomass and waste, and other non-fossil electricity sources).

Table 3-6. Total site energy in terajoules (TJ) broken down into component fuels.

IO Sector	Sector Name	Total Electricity	Natural Gas	Fuel Oil	LPG	Other	Renewables	Kerosene	Coal
333414	Heating equipment (except warm air furnaces) manufacturing	147,707	1,118,359	242,663	94,955		126,607	184,635	26,376
333415	Air conditioning, refrigeration, and warm air heating equipment manufacturing	1,192,213	2,616,539	569,730	221,562		295,416	55,390	7,913
333991	Power-driven handtool manufacturing	7,200							
334111	Electronic computer manufacturing	69,840							
33411A	Computer terminals and other computer peripheral equipment manufacturing	72,000							
334210	Telephone apparatus manufacturing	15,840							
334220	Broadcast and wireless communications equipment	7,200							
334290	Other communications equipment manufacturing	3,600							
334300	Audio and video equipment manufacturing	190,800							
335120	Lighting fixture manufacturing	812,393							
335210	Small electrical appliance manufacturing	393,120							
335221	Household cooking appliance manufacturing	232,112	221,562		21,101				
335222	Household refrigerator and home freezer manufacturing	367,200							
335224	Household laundry equipment manufacturing	262,800	137,157						
335228	Other major household appliance manufacturing	460,293	1,213,314	126,607	52,753		21,101		

Table 3-7. Source energy per million dollars (2002) broken down into component fuels. Ranges for each of the total energy point estimates can be found in the Appendix.

IO Sector Number	IO Sector	Sector Name	Total Energy TJ/\$m	Coal TJ/\$m	NatGas TJ/\$m	Petrol TJ/\$m	Bio/Waste TJ/\$m	NonFossElec TJ/\$m
214	333414	Heating equipment (except warm air furnaces) manufacturing	634	74	341	146	36	37
215	333415	Air conditioning, refrigeration, and warm air heating equipment manufacturing	339	86	149	41	15	47
229	333991	Power-driven handtool manufacturing	6.9	3.5	1.3	0.2	0.1	1.9
234	334111	Electronic computer manufacturing	5.1	2.6	0.9	0.1	0.07	1.4
236	33411A	Computer terminals and other computer peripheral equipment manufacturing	17	8.4	3.0	0.4	0.2	4.6
237	334210	Telephone apparatus manufacturing	2.1	1.0	0.4	0.05	0.03	0.6
238	334220	Broadcast and wireless communications equipment	0.8	0.4	0.1	0.02	0.01	0.2
239	334290	Other communications equipment manufacturing	2.3	1.2	0.4	0.06	0.03	0.6
240	334300	Audio and video equipment manufacturing	76	38	14	1.9	1.1	21
260	335120	Lighting fixture manufacturing	293	148	54	7.2	4.1	81
261	335210	Small electrical appliance manufacturing	299	150	55	7.4	4.2	83
262	335221	Household cooking appliance manufacturing	241	91	88	9.5	2.5	50
263	335222	Household refrigerator and home freezer manufacturing	224	113	41	5.5	3.1	62
264	335224	Household laundry equipment manufacturing	290	125	86	6.1	3.5	69
265	335228	Other major household appliance manufacturing	874	224	451	64	12	123

Figures 3-8 shows the manufacturing energy (blue bars) and the use phase energy (red bars) for all of the sectors that have use phase energy associated with them.

11. Comparison of EIO-LCA Results to Open IO Model Results

Table 3-8 is included to compare results between Open IO and the EIO-LCA model. Results are not expected to be exactly the same given the degree to which the bottom up approach is taken in the Open IO model, the use of different data sources, different scopes (residential energy only in EIO-LCA), different allocations (for instance lighting energy is included both in bulbs and lighting fixtures in Open IO while it is only allocated to the fixtures in EIO-LCA). The two models are however reasonably consistent when it comes to use phase energy, especially for sectors that consume a large total use phase energy such as heating equipment, air conditioners, refrigerators, laundry equipment, and cooking appliances.

Table 3-8 Comparison of Use Phase Energy Results Between EIO-LCA and Open IO.

IO Sector	Sector Name	Use Phase Percentage of Lifecycle Energy (Open IO)	Use Phase Percentage of Lifecycle Energy (EIO-LCA)
333414	Heating equipment (except warm air furnaces) manufacturing	95%	99%
333415	Air conditioning, refrigeration, and warm air heating equipment manufacturing	94%	98%
333991	Power-driven handtool manufacturing	41%	44%
334111	Electronic computer manufacturing	56%	54%
33411A	Computer terminals and other computer peripheral equipment manufacturing	59%	76%
334210	Telephone apparatus manufacturing	53%	30%
334220	Broadcast and wireless communications equipment	66%	29%
334290	Other communications equipment manufacturing	57%	31%
334300	Audio and video equipment manufacturing	42%	90%
335120	Lighting fixture manufacturing	66%	97%
335210	Small electrical appliance manufacturing	56%	97%
335221	Household cooking appliance manufacturing	87%	95%
335222	Household refrigerator and home freezer manufacturing	90%	95%
335224	Household laundry equipment manufacturing	95%	97%
335228	Other major household appliance manufacturing	85%	99%

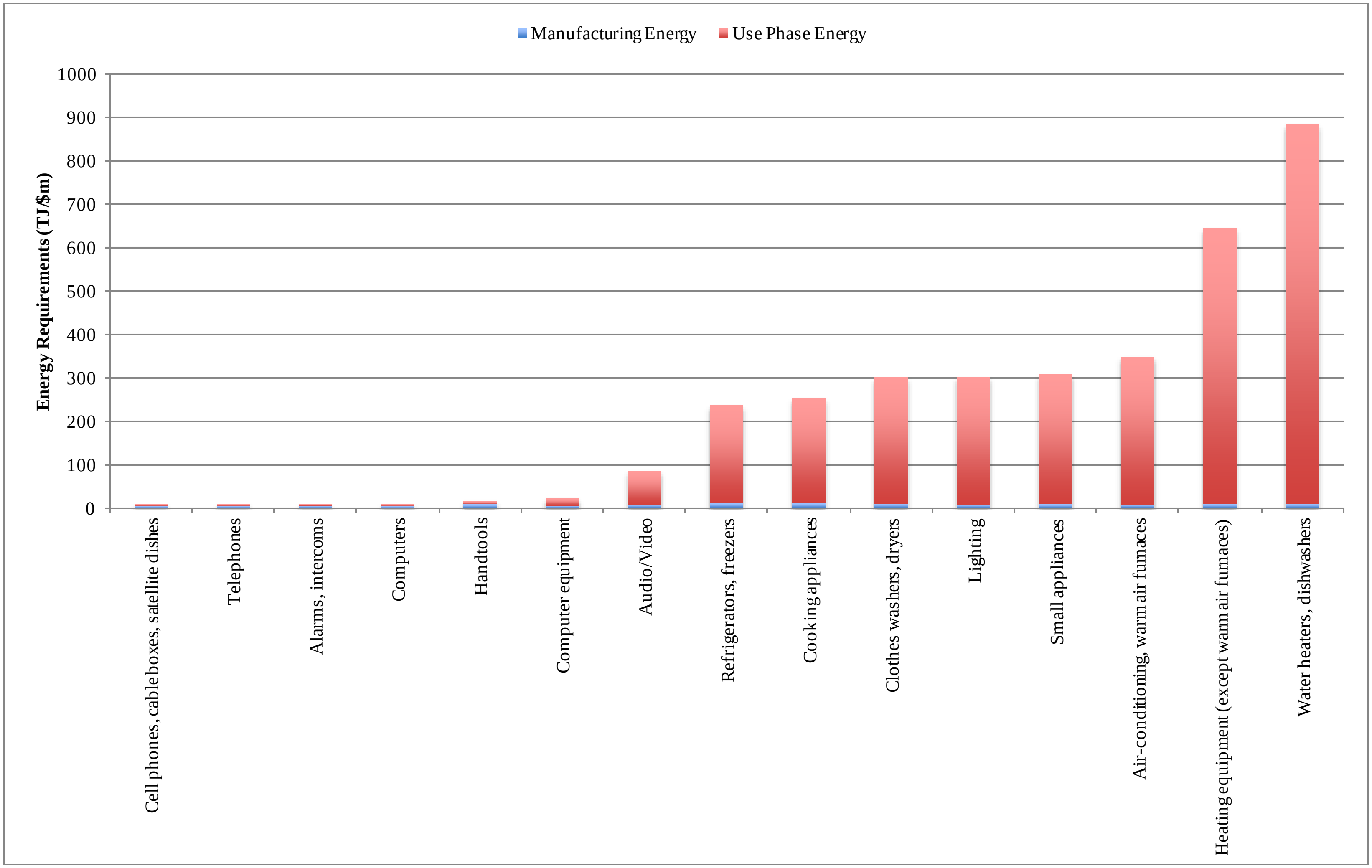

Figure 3-8. Manufacturing vs. use phase energy for the sectors with residential use phase energy.

12. Summary of Residential Transportation Results

The results of the residential transportation work are shown in Table 3-9. This table allocates electricity use into component fuels that are consistent with the fuels used in the EIO-LCA model (coal, petroleum, natural gas, biomass and waste, and other non-fossil electricity sources) Table 3-9 is similar to Table 3-7 but for personal transportation. Figure 3-9 compares use phase energy to manufacturing energy for personal transportation sectors. A complete description of the personal transportation sectors can be found in the Appendix.

Table 3-9. Source energy per million dollars (2002) broken down into component fuels.

IO Sector	Sector Name	Total Energy TJ/$m	Coal TJ/$m	NatGas TJ/$m	Petrol TJ/$m	Bio/Waste TJ/$m	NonFossElec TJ/$m
333112	Lawn and garden equipment manufacturing	18	1.3	0.5	16	0	0.7
336111	Automobile Manufacturing	173	0	0	170	2	0
336612	Boat building	31	0	0	30.5	0.4	0
336991	Motorcycle, bicycle, and parts manufacturing	7.1	0	0	7.0	0.1	0

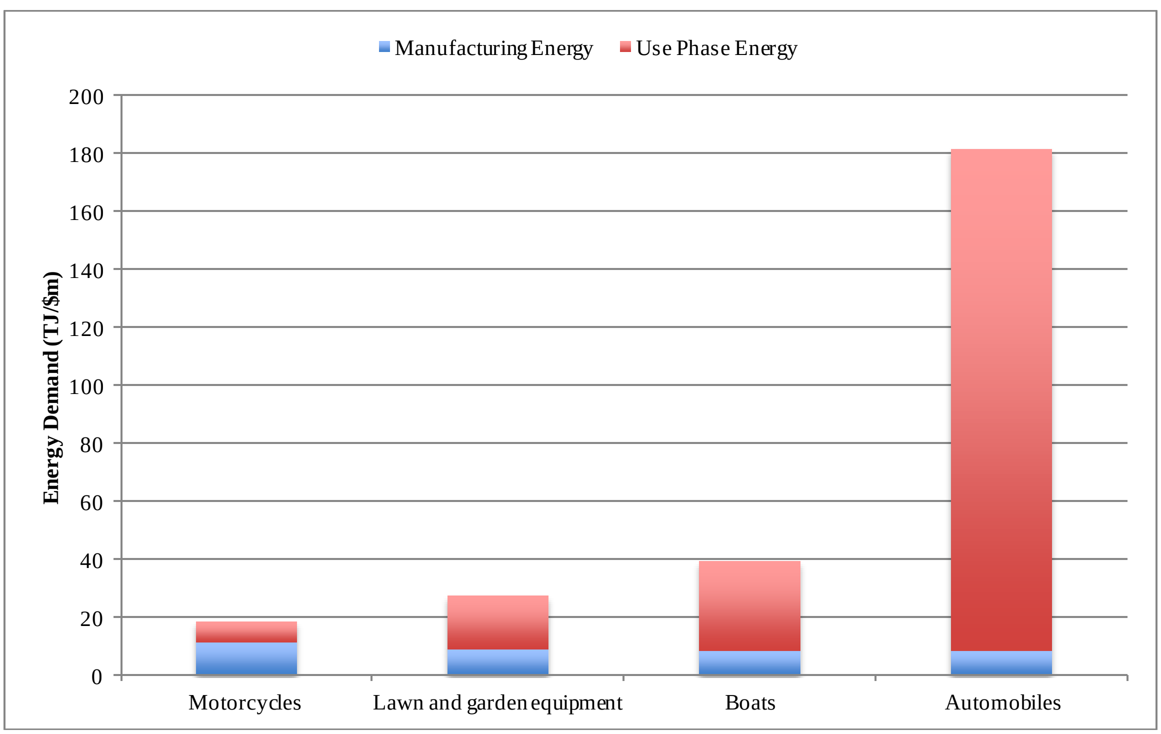

Figure 3-9. Manufacturing vs. source use phase energy for personal transportation sectors.

13. Conclusions

This chapter outlines a framework for estimating use phase residential energy and personal transportation energy for IO sectors on a TJ per million dollars industrial output basis. These estimates are combined to create a series of vectors that are used in conjunction with the EIO-LCA model. This addition to the model allows for streamlined residential use phase estimates as a part of EIO modeling. Prior to the creation of these vectors, the use phase had to be modeled externally to the model, which was potentially resource and time intensive.

14. Future Work: Secondary use phase energy and expansion to 2007 benchmark

Future work could expand this model in that it could move beyond primary use-phase energy allocations to secondary use. As it stands, secondary allocations of use phase energy are outside the scope of this work, which is why the residential use phase energy consumption is limited to 15 sectors that directly consume energy.

Future work should also update these energy vectors to match the 2007 benchmark EIO-LCA model, which should be released sometime in 2014. Many data sources contain data for both 2002 and 2007, and new data sources will become available as the model advances. Other older sources like the 2001 End-Use Table from RECS [22] will have to be replaced with newer, more relevant data sources. Regardless, the framework for this modeling is outlined in this chapter.

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Appendix to Chapter 3

16. Clothes Washers and Dryers

The Household Laundry Equipment Manufacturing sector (NAICS 335224) includes household clothes washers and dryers which consume electricity and natural gas in the use phase [26]. It also includes clothes irons and mangles; however portable electric irons are included in NAICS sector 335210 Small Electrical Appliance Manufacturing and thus contribute no energy use to this sector.

16. 1. Clothes Washers Energy Use

According to The Energy Information Administration (EIA), clothes washers consumed 120 kWh per unit each year excluding water heating needs [22]. These values are applicable to all appliances that were used in 2001, numbers that are expected to be somewhat different than lifetime energy use values for appliances sold in 2002. Clothes dryers may also be powered by natural gas, which is not reflected in the EIA electricity table.

A report by the National Resources Defense Council (NRDC) suggests that between 1993 and 2010, new clothes washers reduced energy consumption by 70% [54]. The 70% reduction in energy consumption is reasonably consistent with the AHAM estimate which suggests nearly a 76% decrease in energy use per cycle for new clothes washers between 1993 and 2010 [29].

AHAM estimates the consumption of new washing machines in 2002 to be 2.13 kWh/cycle [29]. The DOE’s Testing Procedure for Residential Clothes Washers is 392 cycles each year. This makes the total average consumption in 2002 for new washing machines to be 835 kWh per unit [55]. Comparatively, using FTC data, the unweighted average of all of the models of washing machines sold in 2003 indicates that the average consumption for a washing machine is 786 kWh per year with a range of 140 kWh per year – 1,298 kWh per year [28]. Given the average decrease in annual electricity consumption of 5%, and the actual decrease of 8% between 2002 and 2003, the expected 2002 consumption would be 825 and 850 kWh respectively [29].

We must consider issues of double counting use phase energy. Given the fact that much of the hot water used to wash clothes is heated by a hot water heater, not the washing machine itself (also taken into consideration by using average electricity figures for the actual washing machine) the use phase estimates that is dedicated to heating is ignored by the household laundry equipment manufacturing sector and will be accounted for in the sector responsible for the manufacture of household hot water heaters. About one tenth (10%) of this energy is used for the mechanical operation of the washing machine while the 90% goes toward the heating, either internal or external to the washing machine [56][57][58]. Applying the 10% to the range of 140-1,298 kWh and the point estimate of 835 kWh gives a range of 14-130 kWh and an estimate of 83.5 kWh in the first year of use per unit sold in 2002. This point estimate of 83.5 kWh is the number that will be used in the model.

16. 2. Clothes Washers Lifetime

According to ENERGY STAR's "Savings Calculator for ENERGY STAR Qualified Appliances (2012)" [57], clothes washers last about 12 years, though the 2008 ENERGY STAR report "Clothes Washer Product Snapshot" estimates the lifetime of clothes washers to be 11 years [59]. "Scenarios for a Clean Energy Future" uses 14 years as the expected lifetime for a new clothes washer in 2000 [60]. Young found empirically that nearly 63% of Canadian clothes washers survived beyond 16 years and that more than a third survived through 21 years [41]. From this range of data we assume that the 14-year lifetime is the most appropriate in terms of age of the study and is therefore the number we use in this model. We use a range of 10 to 20 years for uncertainty analysis.

16. 3. Clothes Washer Shipments in 2002

In 2002, 8.4 million washing machines were shipped from manufacturers including both imports and exports according to AHAM [30]. Appliance Magazine reported that 7.7 million washing machines were shipped, excluding imports in the same year, which is consistent with the AHAM estimate [31]. While import and export data for these appliances in 2002 was not readily available, data from September of 2008 indicates that the difference between imports and exports for these appliances should not be different by more than a million units (13%) [61]. Data for January through September indicated that 320,000 more washers were exported than imported in 2008. Given that these variations in imports and exports are less than 10% of the 2002 estimates for shipments (5% of the shipments during this time), we will assume that the actual shipment values do not need to be further adjusted for imports and exports. The Appliance Magazine estimate of 7.7 million shipments is the value that is used for this model.

16. 4. Clothes Washer 2002 Model Fleet Energy

Multiplying the average annual consumption of the refrigerator by the number of appliances sold in 2002, we can calculate the total electricity consumption associated with clothes washer use for the first year of use for these new appliances (0.64 TWh). Further multiplying this product by the average lifetime of a refrigerator will estimate the total electricity consumption by clothes washers. The final adjustment to this number is for the degradation of clothes washers over their lifetimes. We discuss the degradation of appliance efficiency above. Given the annual average consumption of 83.5 kWh/year and that 7.7 million refrigerators were sold for use in the U.S. market, refrigerators sold in 2002 consumed 0.64 TWh (Eq. 3-9). Applying the 14-year lifetime and an appliance degradation rate of 1.25% per year we calculate an estimate of 9.8 TWh for the fleet of clothes washers sold in 2002 (Eq. 3-10).

$$Annual\ consumption\ = \left(83.5\ \frac{kWh}{unit\ year}\right) * 7.7\ million\ units = 0.64\ \frac{TWh}{year} \qquad \textbf{\textit{Eq. 3-9}}$$

$$LE(0.64\ TWh) = \ 0.64\ TWh * \frac{(1+1.25\%)^{14}-1}{1.25\%} = 9.8\ \text{TWh} \qquad \textbf{\textit{Eq. 3-10}}$$

16. 5. Uncertainty in Clothes Washer Energy Consumption

Several factors impact the uncertainty of the point estimates for lifetime clothes washer energy developed above. There is uncertainty associated with annual degradation rates as discussed in previous sections. Figure 3-10 compares the lifetime site use phase energy consumption given uncertain annual energy consumption (high, median, and low consuming appliances) over an uncertain lifetime between 1 and 25 years to manufacturing energy. Figure 3-11 makes the same comparison but for source use phase energy rather than site energy.

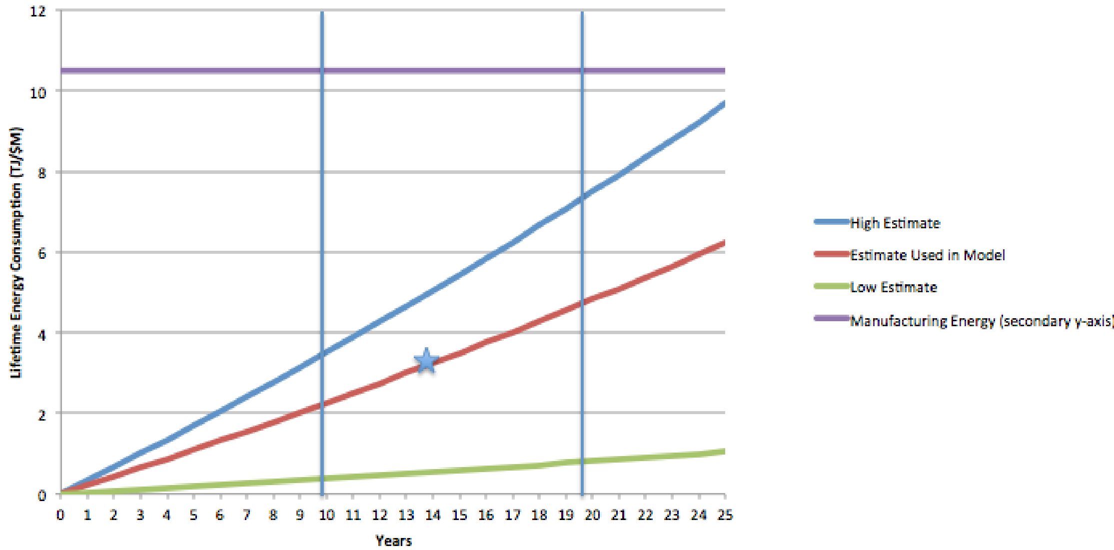

Figure 3-10. Comparison of manufacturing energy (purple line) and lifetime site use phase energy for various appliance models (blue, red, and green lines) over varying lifetimes. Vertical lines represent the range of expected lifetimes (between 10 and 20 years) and the star represents the point estimate lifetime site use phase energy for residential clothes washers per million dollars of industrial output.

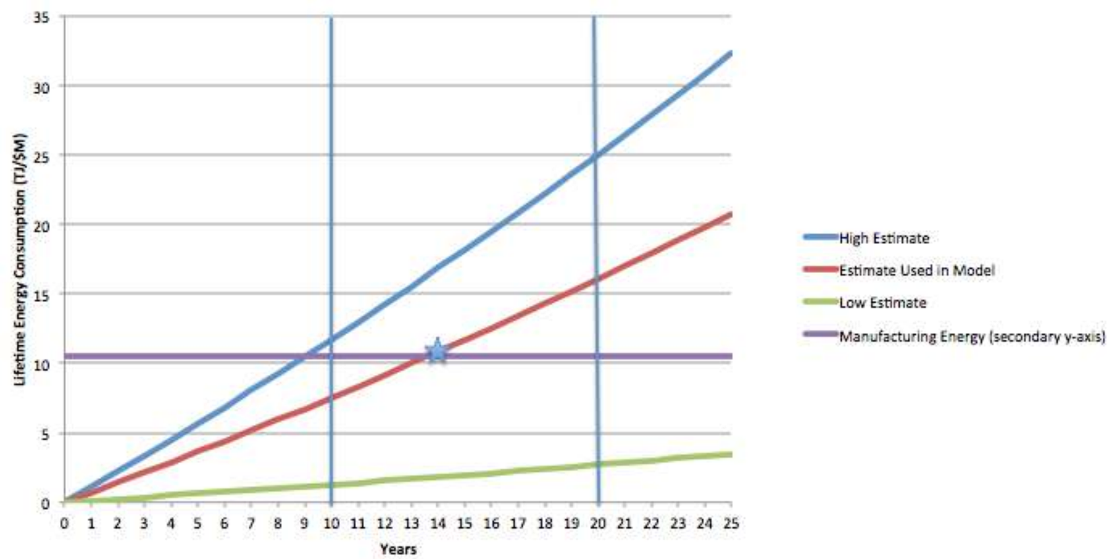

Figure 3-11. Comparison of manufacturing energy (purple line) and lifetime source use phase energy for various appliance models (blue, red, and green lines) over varying lifetimes. Vertical lines represent the range of expected lifetimes (between 10 and 20 years) and the star represents the point estimate lifetime site use phase energy for residential clothes washers per million dollars of industrial output.

As seen in Figure 3-10, the time it takes the appliance use-phase energy to equal that of the manufacturing energy, in terms of site-energy use far exceeds 25 years, however it should be noted that this does not include the energy required to heat the water used by the washing machine. Including energy to heat water (allocated to hot water heaters in this model) this time period much shorter. If we look at source energy use, this time is drastically reduced to be about the same length of time as the expected lifetime of the clothes washer as seen in Figure 3-11. This estimate also excludes energy to heat water for the washing machine.

16. 6. Clothes Dryer Energy Use

Residential electric clothes dryers are estimated to consume 800 kWh annually per appliance, and have not seen significant reductions in energy consumption over the past several decades [22]. One of the reasons that clothes washers may have enjoyed large reductions in energy use while clothes dryers remain relatively stagnant is that ENERGY STAR for clothes washers has been in existence since the late 1990s while no such program for clothes dryers exists [62]. Natural gas clothes dryers are estimated to consume between 0.17 therms/load and 0.28 therms/load [58] and similarly have not undergone significant improvements in efficiency. The NRDC estimates that more than 60 TWh are consumed each year by residential clothes dryers [22][63]. Bendt estimates that 66 TWh are consumed annually by residential clothes dryers [64]. Both of these estimates are reasonably similar to the value we calculate below (63 TWh). He also estimates that despite evidence to the contrary generated in DOE testing procedures, new clothes dryers may be 33% more efficient than their older counterparts. Alternative estimates for electric dryers show that they consume 3.3 kWh/cycle [58][65] and that they consume 684 kWh annually based on 283 cycles annually [66]. 3.3 kWh per cycle for 283 cycles

gives an annual energy consumption of 934 kWh [55]. If the older DOE testing procedure of 416 cycles per year is used [67], the total becomes 1,373 kWh per year.

Gas clothes dryers consume 62.3 therms based on 283 cycles from the DOE testing procedure and the 0.22 therms per load estimate. Using the smallest energy consumption estimate would yield 48.1 therms in the first year of use while the largest consumption rate and the 416 loads per year yields 116.5 therms in the first year of use. We use the middle value of 62.3 therms in this model.

Electric components of gas dryers also need to be considered for the total electricity consumption of clothes dryers. The Multi-housing Laundry Association estimates that the electricity consumption for a gas dryer is 0.5 kWh per cycle [58]. For this model we use the point estimate of 800 kWh per year per electric unit, with a range of 684 kWh per year to 1,373 kWh per year. For the gas dryers we estimate that the electric component consumes 142 kWh annually based on the 283 cycles per year dictated by the DOE testing procedure and this is the estimate we use in the model. If the 416 cycles per year were to be used, the electricity consumed by the average natural gas powered dryer would consume 208 kWh annually.

16. 7. Clothes Dryer Lifetime

ENERGY STAR's "Scoping Report on Residential Clothes Dryers" from November 2011 gives a range of 12-16 years for clothes dryers' lifetimes [66]. The 12 year estimate comes from Appliance Magazine's "Portrait of the U.S. Appliance Industry" [39] while the 16 year estimate comes from the Federal Register [68]. Data from the National Association of Home Builders estimates that an electric clothes dryer has an expected lifetime of 11 years while a gas dryer has an expected lifetime of 10 years [47]. The "Study of Life Expectancy of Home Components" from February 2007 lists 13 years as the expected lifetime for both gas and electric dryers [44]. For this model we will use 13 years, as it seems to be the most reliable and the closest estimate made to the time period of our model. We use 10-20 years as a reasonable expected lifetime for clothes dryers.

16. 8. Clothes Dryer Shipments in 2002

Appliance magazine estimated that there were 5.4 million electric clothes dryer shipments in 2002 [31]. They also estimate that 1.5 million gas dryers were shipped in 2002.

16. 9. Clothes Dryer 2002 Model Fleet Energy

Multiplying the average annual consumption of an electric clothes dryer by the number of appliances sold in 2002, we can calculate the total electricity consumption associated with electric clothes dryer use for a single year. Further multiplying this product by the average lifetime of an electric clothes dryer will give the total electricity consumption by the fleet of electric clothes dryers sold in 2002 in their first year of use. Following the same method for the electric portion of gas clothes dryers and adding it to the electricity use totaled for electric clothes dryers will give the total electricity use for all clothes dryers sold in 2002 in their first year of use. Multiplying the gas use of natural gas heated clothes dryers by the number of gas units sold in 2002 will give the total gas use in the first year for clothes dryers. The final adjustment to this number is for the degradation of clothes dryers over their lifetimes. As discussed above, this degradation is assumed to be 1.25% annually. Given the annual average consumption of 800 kWh/year and that 5.4 million electric clothes dryers were sold for use in the U.S. market, they consumed 4.3 TWh in their first year of use (Eq. 3-11). The electric component of the 1.5 million gas dryers consumed 0.21 TWh in their first year of use (Eq. 3-12). In total, clothes dryers sold in 2002 consumed 4.5 TWh in their first year of use. Multiplying the 62 therms consumed by gas dryers in their first year by the 1.5 million gas dryers sold in 2002 gives a total gas consumption of 93 million therms of natural gas use in the first year of use (Eq. 3-13) Multiplying the annual consumption by the 13-year lifetime and factoring in the 1.25% degradation rate for the appliances gives us a total lifetime consumption of 63 TWh of site electricity (Eq. 3-14) and 1.3 billion therms of site natural gas use (Eq. 3-15) for all of the 6.9 million clothes dryers sold in 2002 in the United States.

$$Annual\ consumption = \left(800\ \frac{kWh}{unit\ year}\right) * 5.4\ million\ units = 4.3\ \frac{TWh}{year} \qquad \textbf{\textit{Eq. 3-11}}$$

$$Annual\ consumption = \left(142\ \frac{kWh}{unit\ year}\right) * 1.5\ million\ units = 0.21\ \frac{TWh}{year} \qquad \textbf{\textit{Eq. 3-12}}$$

$$Annual\ consumption = \left(62\ \frac{therms}{unit\ year}\right) * 1.5\ million\ units = 93\ million\ \frac{therms}{year} \qquad \textbf{\textit{Eq. 3-13}}$$

$$LE(4.5\ TWh) = 4.5\ TWh * \frac{(1+1.25\%)^{13}-1}{1.25\%} = 63\ \text{TWh} \qquad \textbf{\textit{Eq. 3-14}}$$

$$LE(93\ million\ therms) = 93\ million\ \frac{therms}{year} * \frac{(1+1.25\%)^{13}-1}{1.25\%} = 1.3\ \text{billion therms} \qquad \textbf{\textit{Eq. 3-15}}$$

16. 10. Uncertainty in Clothes Dryer Energy Consumption

Several factors impact the uncertainty of the point estimates for lifetime clothes dryer energy developed above. There is uncertainty associated with annual degradation rates as discussed in previous sections. Figure 3-12 compares the lifetime site use phase energy consumption given uncertain annual energy consumption (high, median, and low consuming appliances) over an uncertain lifetime between 1 and 25 years to manufacturing energy. Figure 3-13 makes the same comparison but for source use phase energy rather than site energy.

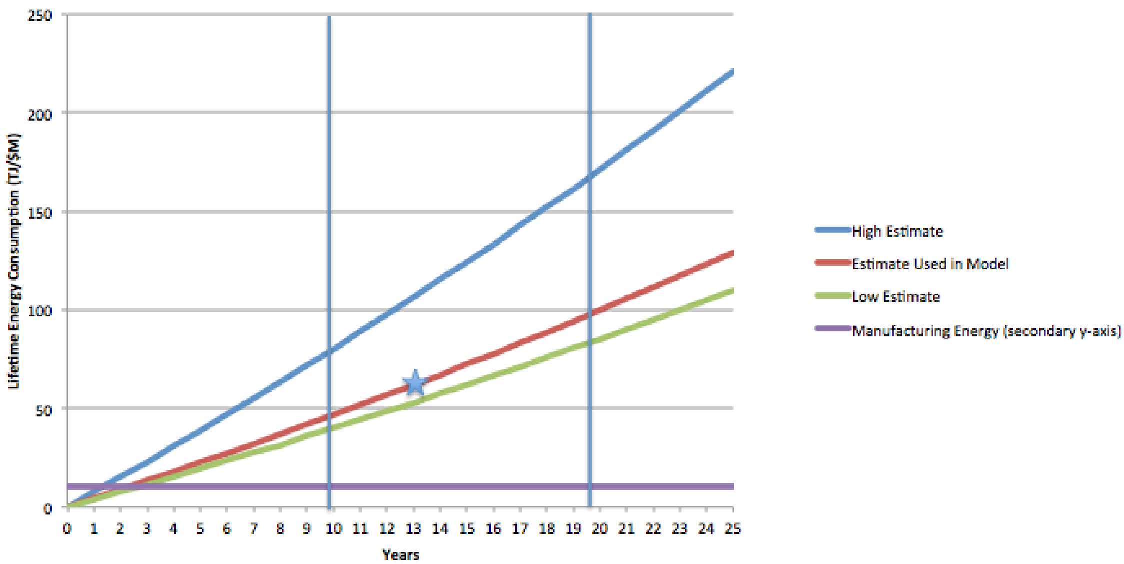

Figure 3-12. Comparison of manufacturing energy (purple line) and lifetime site use phase energy for various appliance models (blue, red, and green lines) over varying lifetimes. Vertical lines represent the range of expected lifetimes (between 10 and 20 years) and the star represents the point estimate lifetime site use phase energy for residential clothes dryers per million dollars of industrial output.

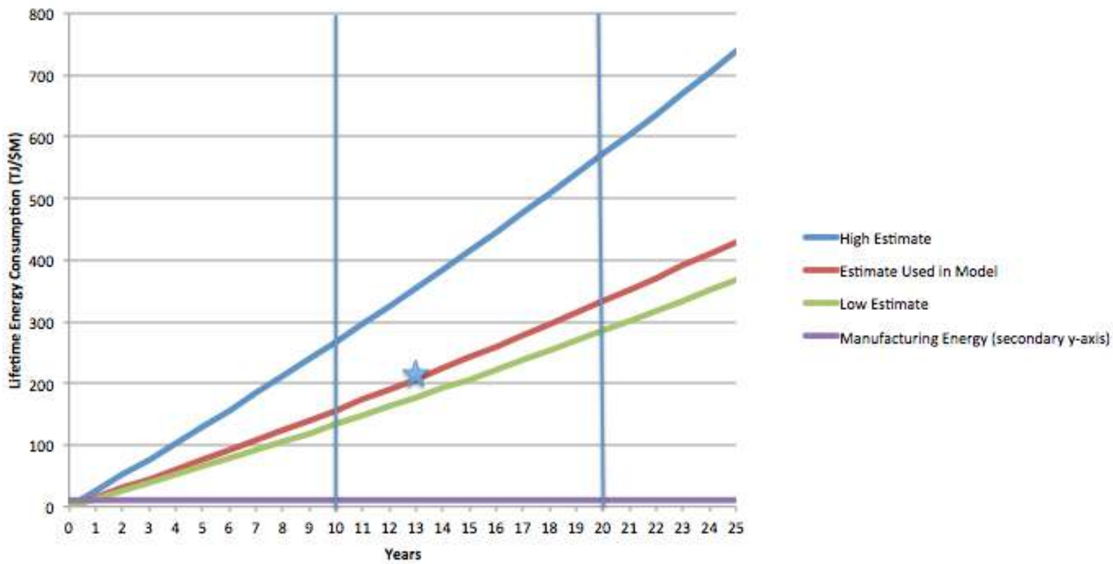

Figure 3-13. Comparison of manufacturing energy (purple line) and lifetime source use phase energy for various appliance models (blue, red, and green lines) over varying lifetimes. Vertical lines represent the range of expected lifetimes (between 10 and 20 years) and the star represents the point estimate lifetime site use phase energy for residential clothes dryers per million dollars of industrial output.

In terms of both site and source energy, the use phase energy consumed by a clothes dryer far exceeds the manufacturing energy required for the lifetime of the appliance. In the most extreme scenario, the site energy use phase energy for the lowest energy consuming dryer exceeds manufacturing energy requirements in less than two years. The majority of clothes washers have use phase energy demands that exceed the manufacturing energy within the first year.

16. 11. EIO-LCA Use Phase Value

The BEA estimate of industrial output for the household laundry equipment manufacturing sector for 2002 was $3.5 billion and the total commodity output was $4.3 billion [48]. Dividing the sum of our electricity point estimates of 9.8 TWh for clothes washers and the 63 TWh for electric components of clothes dryers by this industrial output yields 20.8 GWh or 75.1 TJ per million dollars of industrial output. The commodity output for this sector changes this estimate to 17.0 GWh or 61.1 TJ per million dollars of commodity output. Dividing the natural gas estimate for clothes dryers (1.3 billion therms) by the industrial output ($3.5 billion) gives an estimate of 0.37 million therms or 38.9 TJ per million dollars of industrial output. Dividing the natural gas estimate for clothes dryers (1.3 billion therms) by the commodity output ($4.3 billion) yields an estimate of 0.30 million therms or 31.6 TJ per million dollars of commodity output. Combining the totals of the electricity and natural gas for this sector gives an estimate of 114 TJ per million dollars of industrial output or 92.7 TJ per million dollars of commodity output.

Purchases from the electric grid and natural gas providers must be multiplied by a source-to-site ratio to estimate the true energy requirements to run this fleet of appliances over the course of the appliances' lifetimes. The ratio for electricity purchases was 3.336 in 2002 and the ratio for natural gas use was 1.047 [36]. Applying these ratios yield lifetime use phase electricity consumption of the fleet of residential clothes washers and dryers sold in 2002 to be 251 TJ per million dollars of industrial output and 204 TJ per million dollars of commodity output while the lifetime use phase natural gas consumption was 40.7 TJ per million dollars of industrial output and 33.1 TJ per million dollars of commodity output. The total use phase energy consumption for the sector was 290 TJ per million dollars of industrial output

16. 12. Comparison to Manufacturing Data for Clothes Washers and Dryers

Running the EIO-LCA model for $1 million (producer price) in the *Household Laundry Equipment Manufacturing* sector estimates that there is a total cradle to gate energy consumption of 10.5 TJ [1] (relative standard error of +/- 18% (8.6 TJ – 12.4 TJ) [49]) for the manufacturing of residential clothes washers and dryers. This is much less than the 114 TJ of site use energy that is consumed in the use phase by $1 million of household laundry equipment. This is also much less than the 290 TJ of source energy that is consumed in the use phase by $1 million of household laundry equipment. This means that by not including use-phase energy, the EIO-LCA model does not represent 97% of the lifecycle energy consumption of appliances sold in this sector. These estimates of missed energy by the EIO-LCA model for the *Household Laundry Equipment Manufacturing* sector are potentially even greater depending on the energy consumption associated with the end-of-life phase washing machines and clothes dryers.

From Figures 3-12 and 3-13 we see that our point estimate is 290 TJ of source energy per million dollars of industrial output (star on the figures), however we can also see in Figure 3-14 that these estimates can be as low as 68.6 TJ per million dollars (lowest energy consuming model at 10 years) and as high as 308 TJ per million dollars (highest energy consuming model at 20 years).

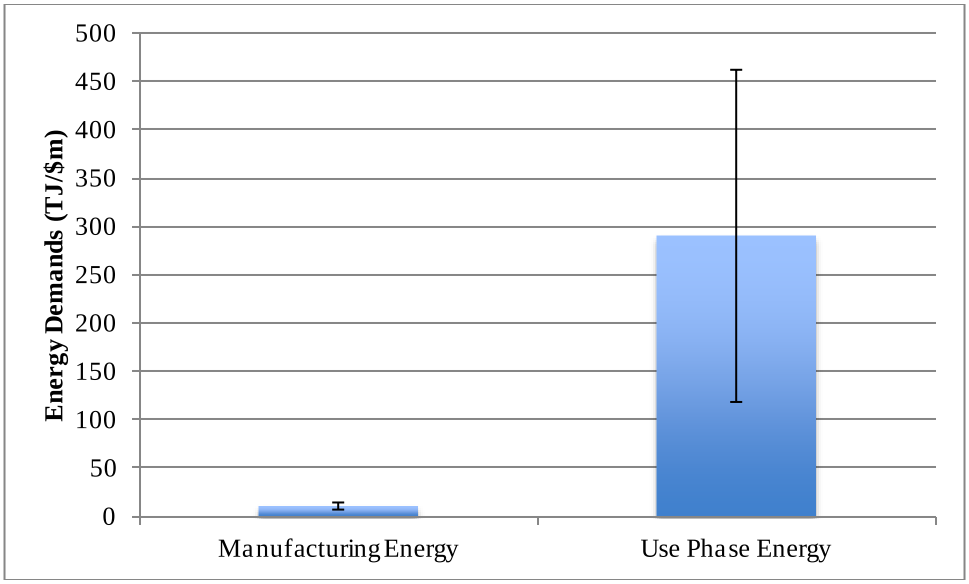

Figure 3-14. Manufacturing vs. lifecycle residential use phase energy for *Household Laundry Equipment Manufacturing*.

17. Other Major Household Appliances

The *Other Major Household Appliance Manufacturing* sector (NAICS 335228) includes major appliances that are not otherwise classified by NAICS such as dishwashers, hot water heaters, garbage disposals, and trash compactors [26]. Similar equipment that is used in a commercial or industrial setting is outside of the scope of this work.

17. 1. Dishwashers Energy Use

According to AHAM, the average dishwasher sold in 2002 consumed 1.84 kWh/cycle [29]. The DOE testing procedure for dishwashers in 2001 indicated that 264 cycles were used per year, though this was down from 315 in the previous standard [69]. The standard was later amended to reflect 215 cycles annually. From the 264 cycles per year estimate in 2002 and energy use of 1.84 kWh/cycle, the average total energy per dishwasher sold in 2002 is 486 kWh/year. Given that as little as 20% of dishwasher energy use is dedicated to actual mechanical energy used by the dishwasher (80% goes to hot water heating), only 97 kWh are consumed annually by the average dishwashers sold in 2002.

17. 2. Dishwasher Lifetime

The average expected lifetime of a dishwasher is 9 years and is the lifetime that is used in the model [44].

17. 3. Dishwasher Shipments in 2002

In 2002, 6.7 million dishwashers were shipped including exports according to AHAM [30]. Appliance Magazine reported that 6.2 million washing machines were shipped, excluding imports in the same year, which is consistent with the AHAM estimate [31]. The Appliance Magazine estimate of 6.2 million shipments is the value that is used for this model as this model is intended to represent the United States and the Appliance Magazine estimate excludes exports.

17. 4. Dishwasher 2002 Model Fleet Energy

Multiplying the average annual consumption of the dishwasher by the number of appliances sold in 2002, we can calculate the total electricity consumption associated with dishwasher use for the first year of use for these new appliances (5.7 TWh). With hot water heating energy, 28.5 TWh are consumed by new dishwashers sold in 2002 in the first year of use. This is reasonably consistent with the 29.0 TWh estimated electricity consumption in 2001 by the entire fleet of dishwashers according to the RECS End-Use Survey. Given that about 20% of dishwasher energy use is dedicated to actual mechanical energy used by the dishwasher and internal heating components (80% goes to hot water heating) [70][71][72][73], only 0.6 TWh in the first year and 5.7 TWh (21,000 TJ) are consumed by dishwashers sold in 2002 as shown in Eq. 3-16 and Eq. 3-17.

$$Annual\ consumption\ =\left(97\ \frac{kWh}{unit\ year}\right)*6.2\ million\ units=0.6\ \frac{TWh}{year} \qquad \textbf{Eq. 3-16}$$

$$LE(0.60\ TWh)=\ 0.60\ TWh*\frac{(1+1.25\%)^{9}-1}{1.25\%}=5.7\ \text{TWh} \qquad \textbf{Eq. 3-17}$$

17. 5. Hot Water Heater Energy Use

Buildings Energy Data Book estimates the 2002 consumption of energy by hot water heaters to be 1.75 quads (1.8 million TJ) of total energy broken down into 1.15 quads (1.2 million TJ) of natural gas use, 0.12 quads (130,000 TJ) of fuel oil, 0.05 quads (50,000 TJ) of LPG, 0.02 quads (20,000 TJ) of renewable energy, and 0.41 quads (430,000 TJ) of site electricity [53]. To make the use phase energy estimation for residential hot water heater use easier, a simplifying assumption that the energy required to run this equipment in a given year is approximately equal to the lifetime energy requirement for all of the devices in the same year. This is supported by the fact that from 1998 to 2008, the energy use for water heating declined by about 4% on average annually [50]. From 2002 to 2005 this energy demand only increased from 1.75 quads to 1.77 quads before falling back to 1.75 quads.

17. 6. Garbage Disposal and Trash Compactor Energy Use

With little information available on garbage disposals and garbage compactors, we assume that their consumption was significantly small in 2001 that it was not reported separately from the "residual" energy consumption in the RECS End-Use of Consumption for 2001 [22]. For this reason we will assume that these do not contribute significantly to the total for "other major appliances" and at most may contribute 1 TWh (3,600 TJ). A simplifying assumption is made that the energy required to run this equipment in a given year is approximately equal to the lifetime energy requirement for all of the devices in the same year.

17. 7. EIO-LCA Use Phase Value

The BEA estimate of industrial output for the *Other Major Household Appliance Manufacturing* sector for 2002 was \$3.4 billion and the total commodity output was \$3.1 billion [26]. Dividing the sum of our energy point estimates of 1.9 million TJ by the industrial output gives an estimate of 544 TJ per million dollars of industrial output. If the commodity output for this sector is used instead we end with 605 TJ per million dollars of commodity output.

Site energy must be multiplied by a source-to-site ratio to estimate the true energy requirements to run this fleet of appliances over the course of the appliances' lifetimes. Applying these ratios yield lifetime use phase electricity consumption of the fleet of other major residential appliances sold in 2002 to be 874 TJ per million dollars of industrial output [36].

17. 8. Comparison to Manufacturing Data for Other Major Household Appliances

Running the EIO-LCA model for $1 million (producer price) in the *Other Major Household Appliance Manufacturing* sector estimates that there is a total cradle to gate energy consumption of 9.9 TJ (relative standard error of +/- 18% [1] (8.1 TJ – 11.7 TJ) [49]) for the manufacturing of other major household appliances. This is much less than the 544 TJ of site use energy that is consumed in the use phase by $1 million of other major household appliances. This is also much less than the 874 TJ of source energy that is consumed in the use phase by $1 million of other major household appliances as seen in Figure 3-15. This means that by not including use-phase energy, the EIO-LCA model is not representing 99% of the lifecycle energy consumption of appliances sold in this sector. These estimates of missed energy by the EIO-LCA model for the *Other Major Household Appliance Manufacturing* sector are potentially even greater depending on the energy consumption associated with the end-of-life phase washing machines and clothes dryers.

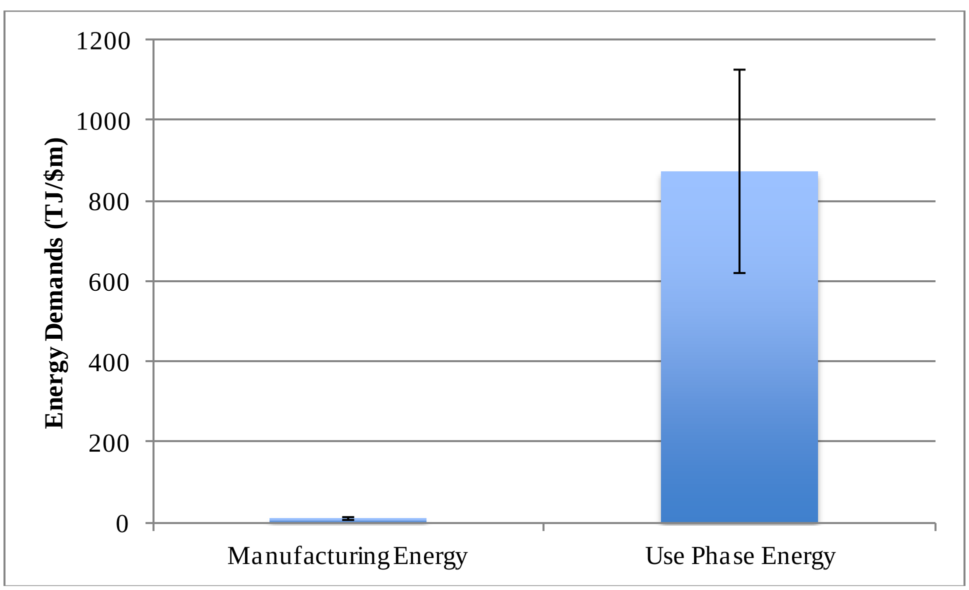

Figure 3-15. Manufacturing vs. lifecycle residential use phase energy for *Other Major Household Appliance Manufacturing*.

18. Heating Equipment

The *Heating Equipment (except Warm Air Furnaces) Manufacturing* sector (NAICS 333414) includes baseboard heating equipment, boilers, burners, fireplaces, furnaces (except forced air), non-portable space heaters, pool heaters, radiators, solar heating systems, and wood stoves [26].

Because there is little data on the average consumption of a home's heating needs given the wide range of housing sizes, climates, heating systems, and fuels and because there is little information on the expected lifetime of the various heating system sold in 2002, a simplifying assumption will be made that this sector's use-phase in 2002 is approximately equal to the lifetime use-phase consumption of all of the air-heating equipment manufactured in 2002 (i.e. that the number of these sold in 2002 is approximately equal to the number of systems retired). Analyzing data from the Buildings Energy Data Book data from 1998 to 2006 indicates that heating energy is increasing slowly at about 1.5% annually [50].

18. 1. Warm Air Furnace Energy Use

Approximately 70% of homes in the United States use forced air (*Air-Conditioning and Warm Air Heating Equipment and Commercial and Industrial Refrigeration Equipment Manufacturing)* to heat their homes [74][75]. For simplicity we will assume that there is not a large difference in fuel use between forced air heating and other types of home heating systems. From the 2004 Building Energy Data Book data on 2002 residential energy use, space heating used 3.54 quads of natural gas, 0.77 quads of fuel oil, 0.30 quads of LPG, 0.08 quads of other fuels, 0.40 quads of renewable energy and

0.48 quads of site electricity [50]. Given that about 70% of homes use forced air, 30% of each of those values should be attributable to the *Heating Equipment (except Warm Air Furnaces) Manufacturing* sector. This means that 1.06 quads (1.1 million TJ) of natural gas, 0.23 quads (240,000 TJ) of fuel oil, 0.09 quads (95,000 TJ) of LPG, 0.02 quads (20,000 TJ) of other fuels, 0.12 quads (130,000 TJ) of renewable resources, and 0.14 quads (150,000 TJ) of electricity are attributable to the use-phase for the residential heating portion of the *Heating Equipment (except Warm Air Furnaces) Manufacturing* sector. Given the 1.5% increase in annual energy consumption by residential heating equipment, the total energy consumed in the use phase by heating equipment is 1.7 quads (1.8 million TJ).

18. 2. EIO-LCA Use Phase Value

The BEA estimate of industrial output for the *Heating Equipment (except Warm Air Furnaces) Manufacturing* sector for 2002 was $3.7 billion and the total commodity output was $3.9 billion [48]. Dividing the sum of our energy point estimates of 1.8 million TJ for heating equipment by this industrial output gives us 524 TJ per million dollars of industrial output.

Site energy use must be multiplied by a source-to-site ratio to estimate the true energy requirements to run this fleet of appliances over the course of the appliances' lifetimes. Applying ENERGY STAR source-to-site ratios to each component fuel that contributes to this sector yields source energy estimates of 2.1 million TJ total, 634 TJ per million dollars of industrial output [36].

18. 3. Comparison to Manufacturing Data for Heating Equipment

Running the EIO-LCA model for $1 million (producer price) in the *Heating Equipment (except Warm Air Furnaces) Manufacturing* sector estimates that there is a total cradle to gate energy consumption of 9.6 TJ [1] (relative standard error of +/- 7% (8.9 TJ – 10.3 TJ) [49]) for the manufacturing of heating equipment. This is much less than the 524 TJ of site use energy that is consumed in the use phase by $1 million of heating equipment. This is also much less than the 634 TJ of source energy that is consumed in the use phase by $1 million of heating equipment as seen in Figure 3-16. This means that by not including use-phase energy, the EIO-LCA model is not representing 99% of the lifecycle energy consumption of appliances sold in this sector. These estimates of missed energy by the EIO-LCA model for the *Heating Equipment (except Warm Air Furnaces) Manufacturing* sector are potentially even greater depending on the energy consumption associated with the end-of-life phase.

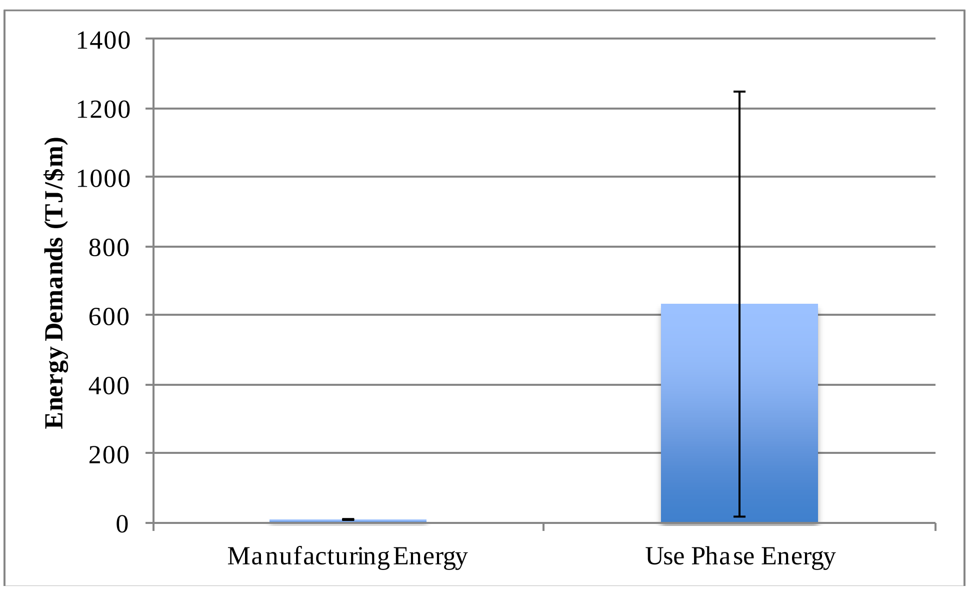

Figure 3-16. Manufacturing vs. lifecycle residential use phase energy for *Heating Equipment (except Warm Air Furnaces) Manufacturing*.

19. Air-Conditioning and Warm Air Heating

The *Air-Conditioning and Warm Air Heating Equipment and Commercial and Industrial Refrigeration Equipment Manufacturing* sector (NAICS 333415) includes household air-conditioners, room air-conditioners, as well as household forced air heating systems. Other types of home heating systems such as heating boilers, heating stoves, floor and wall mount furnaces, and electric wall and baseboard heating units are included in the Heating Equipment (except Warm Air Furnaces) Manufacturing sector [26]. The commercial and industrial refrigeration equipment is irrelevant to residential energy consumption.

Because there is little data on the average consumption of a home's heating and air-conditioning needs given the varying climates, household age, insulation, and floor space and because there is little information on the expected lifetime of various heating systems sold in 2002, a simplifying assumption will be made that this sector's use-phase in 2002 is approximately equal to the lifetime use-phase consumption of all of the air-conditioning and warm air heating systems (i.e. that the number of these sold in 2002 is approximately equal to the number of systems retired). Analyzing data from the Buildings Energy Data Book data from 1998 to 2006 indicates that heating energy is increasing at about 1.5% each year and air-conditioning energy needs are increasing at about 3.3% annually [53].

19. 1. Air Conditioning Energy Use

According to the Buildings Energy Data Book for 2004, the 2002 energy demands for air conditioning were on the order of 0.79 quads of site energy (830,000 TJ), all of which was electricity [50]. Given the annual increase in energy demands for air conditioning of 3.3% [50], the estimate for air conditioning energy use for air conditioners sold in 2002 is 860,000 TJ.

19. 2. Warm Air Furnace Energy Use

Approximately 70% of homes in the United States use forced air to heat their homes [74][75]. For simplicity we will assume that there is not a large difference in fuel use between forced air heating and other types of home heating systems. From the 2004 Building Energy Data Book data on 2002 residential energy use [53], space heating used 3.54 quads of natural gas, 0.77 quads of fuel oil, 0.30 quads of LPG, 0.08 quads of other fuels, 0.40 quads of renewable energy and 0.48 quads of site electricity. Given that about 70% of homes use forced air, 70% of each of those values should be attributable to the *Air-Conditioning and Warm Air Heating Equipment and Commercial and Industrial Refrigeration Equipment Manufacturing* sector. This means that 2.48 quads (2.6 million TJ) of natural gas, 0.54 quads (570,000 TJ) of fuel oil, 0.21 quads (220,000 TJ) of LPG, 0.06 quads (63,000 TJ) of other fuels, 0.28 quads (300,000 TJ) of renewable resources, and 0.34 quads (360,000 TJ) of electricity are attributable to the use-phase for the residential heating portion of the "Air-Conditioning and Warm Air Heating Equipment and Commercial and Industrial Refrigeration Equipment Manufacturing" sector. Given the increase of 1.5% annually in the consumption of energy for heating [50], the total energy used in the use phase is 4.0 quads (4.2 million TJ).

19. 3. EIO-LCA Use Phase Value

The BEA estimate of industrial output for the Air-Conditioning and Warm Air Heating Equipment and Commercial and Industrial Refrigeration Equipment Manufacturing sector for 2002 was $23.2 billion and the total commodity output was $22.3 billion [48]. Dividing the sum of our energy point estimates of 4.1 million TJ for warm air furnaces and the 860,000 TJ for air-conditioners by this industrial output gives us 214 TJ per million dollars of industrial output. If the commodity output for this sector is used instead we end up with 222 TJ per million dollars of commodity output.

Purchases from the electric grid and natural gas providers must be multiplied by a source-to-site ratio to estimate the true energy requirements to run this fleet of appliances over the course of the appliances' lifetimes. Applying ENERGY STAR source-to-site ratios to each component fuel that contributes to this sector yields source energy estimates of 6.9 million TJ total and 339 TJ per million dollars of industrial output [36].

19. 4. Comparison to Manufacturing Data for Air-Conditioning and Warm Air Heating Equipment

Running the EIO-LCA model for $1 million (producer price) in the *Air-Conditioning and Warm Air Heating Equipment and Commercial and Industrial Refrigeration Equipment Manufacturing* sector estimates that there is a total cradle to gate energy consumption of 8.5 TJ [1] (relative standard error of +/- 7% (7.9 TJ – 9.1 TJ) [49] for the manufacturing of air-conditioning and warm air heating equipment. This is much less than the 214 TJ of site use energy that is consumed in the use phase by $1 million of air-conditioning and warm air heating equipment. This is also much less than the 339 TJ of source energy that is consumed in the use phase by $1 million of air-conditioning and warm air heating equipment as seen in Figure 3-17. This means that by not including use-phase energy, the EIO-LCA model is not representing 98% of the lifecycle energy consumption of appliances sold in this sector. These estimates of missed energy by the EIO-LCA model for the *Air-Conditioning and Warm Air Heating Equipment and Commercial and Industrial Refrigeration Equipment Manufacturing* sector are potentially even greater depending on the energy consumption associated with the end-of-life phase.

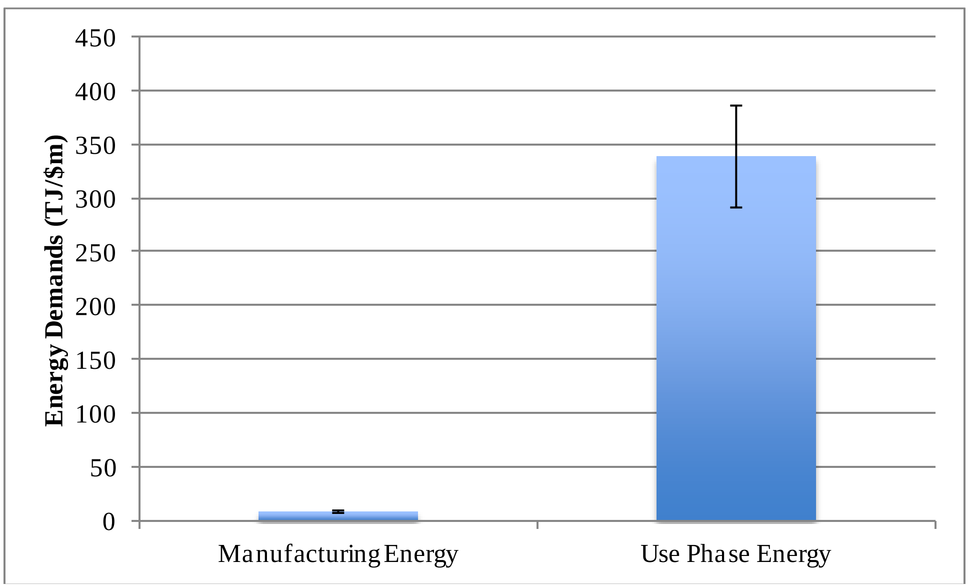

Figure 3-17. Manufacturing vs. lifecycle residential use phase energy for *Air-Conditioning and Warm Air Heating Equipment and Commercial and Industrial Refrigeration Equipment Manufacturing.*

20. Small Electrical Appliances

The *Small Electric Appliance Manufacturing* sector (NAICS 335210) includes appliances such as fans, carpet and floor cleaners, curling irons, electric blankets, portable cooking appliances, portable electric space heaters, portable hair dryers, portable humidifiers and dehumidifiers, and electric scissors [26]. Similar equipment that is used in a commercial or industrial setting is outside of the scope of this work.

To make the use phase energy estimation for residential small electric appliance use easier given the large variety of devices on the market in 2002, the varying use of these devices, as well as the lack of data regarding expected lifetimes and average energy use of each, we make a simplifying assumption that the energy required to run this equipment in a given year is approximately equal to the lifetime energy requirement for all of the devices in the same year. This assumption requires that the retirement rate is approximately equal to the manufacturing rate for small electrical appliances.

20. 1. Small Electrical Appliance Energy Use

RECS makes an estimates for several small household appliances as well as an estimate for residual electricity consumption, which falls into this sector. This includes specific appliances and electronics that have estimates in the 2001 End-Use Consumption of Electricity table produced by RECS such as toaster ovens, coffee makers, ceiling fans, waterbed heaters, aquariums, automobile block, engine, and battery heaters, as well as the RECS residual consumption (includes things like clothes irons, hair dryers, and a myriad of other small electronics that were too small to have their own RECS category) [22]. This accounts for 109.2 TWh of electricity consumption in 2001. Given the assumption that these values are unlikely to change in such a short timeframe, we use the 109.2 TWh (390,000 TJ) value in the model.

20. 2. EIO-LCA Use Phase Value

The BEA estimate of industrial output for the *Small Electrical Appliance Manufacturing* sector for 2002 was \$4.4 billion and the total commodity output was \$4.0 billion [48]. Dividing the energy point estimate of 390,000 TJ for small appliances by this industrial output gives us 90 TJ per million dollars of industrial output. If the commodity output for this sector is used instead we end up with 99 TJ per million dollars of commodity output.

Site energy use must be multiplied by a source-to-site ratio to estimate the true energy requirements to run this fleet of appliances over the course of their lifetimes. Applying ENERGY STAR source-to-site ratio of 3.336 to the electricity that contributes to this sector yields source energy estimates of 300 TJ per million dollars of industrial output [36]. If the commodity output for this sector is used instead we end up with 330 TJ per million dollars of commodity output.

20. 3. Comparison to Manufacturing Data for Small Electrical Appliances

Running the EIO-LCA model for \$1 million (producer price) in *Small Electrical Appliance Manufacturing* sector estimates that there is a total cradle to gate energy consumption of 9.2 TJ [1] (relative standard error of +/- 18% (7.5 TJ – 10.9 TJ) [49]) for the manufacturing of small electrical appliances. This is less than the 90 TJ of site use energy that is consumed in the use phase by \$1 million of small electrical appliances. This is also less than the 290 TJ of source energy that is consumed in the use phase by \$1 million of electronic computers as seen in Figure 3-18. However, by not including use-phase energy, the EIO-LCA model does not represent 97% of the lifecycle energy consumption of the devices sold in this sector. These estimates of missed energy by the EIO-LCA model for the *Small Electrical Appliance Manufacturing* sector are potentially even greater depending on the energy consumption associated with the end-of-life phase.

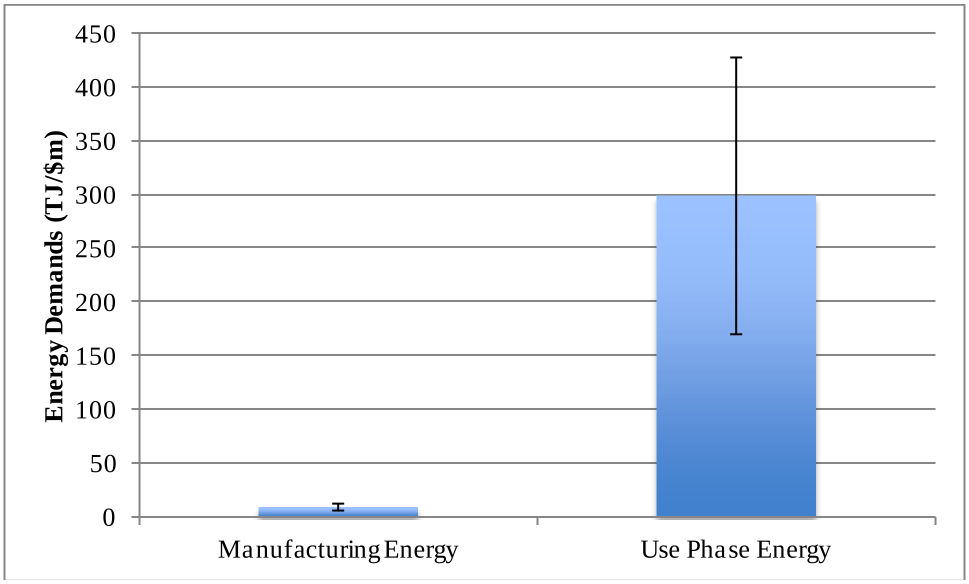

Figure 3-18. Manufacturing vs. lifecycle residential use phase energy for The *Small Electrical Appliance Manufacturing*.

21. Lighting

The *Lighting Fixture Manufacturing* sector (NAICS 335120) includes lighting fixtures, both fixed and portable, for use indoors and outdoors [26]. We will focus on residential lighting demands as commercial and industrial demands are outside the scope of this work and would result in double counting issues as discussed previously.

Because there are so many lighting fixtures inside and outside of each home and there is such a range of fixtures with varying energy demands and lifetimes, we make a simplifying assumption for energy demands by residential lighting fixtures. The simplifying assumption is that given relatively stable energy demands for lighting from year to year, the retirement rate of lighting fixtures is approximately equal to the manufacturing rate. Given this assumption lighting demands in 2002 should be approximately equal to the demands of lighting fixtures manufactured in 2002 over their lifetimes. Analyzing data from the Buildings Energy Data Book data from 2001 to 2006 indicates that heating energy is decreases at about 0.2% annually [50]. There is a clear jump in lighting demands according to the Buildings and Energy Data Book between 2000 and 2001 that more than doubles the demand for lighting from 0.37 quads of electricity to 0.76 quads of electricity. This jump seems unnatural as the data from 1998 to 2000 is all fairly flat (0.39 quads, 0.36 quads, 0.39 quads respectively), and the data from 2001 to 2008 is also relatively flat (varying from 0.74 quads to 0.80 quads). Even given this huge jump in 2001, the average increase from 1998 to 2008 is only 4.5% annually. Given the seemingly unnatural jump and the relatively constant consumption between 2001 and 2006, we assume that there is not a large annual growth in the residential energy demand for lighting. The amount of energy consumed in 2002 for residential lighting purposes should be approximately equal to the lifetime energy demands of lighting fixtures manufactured in 2002.

21. 1. Residential Lighting Energy Use

From the 2004 Building Energy Data Book data on 2002 residential energy use, residential electricity demands for lighting were 0.77 quads (810,000 TJ) [53]. Given the 0.2% decrease in annual energy consumption by residential lighting equipment [50], the total energy consumed in the use phase by heating equipment remains 0.77 quads (810,000 TJ).

21. 2. EIO-LCA Use Phase Value

The BEA estimate of industrial output for the *Lighting Fixture Manufacturing* sector for 2002 was $9.2 billion and the total commodity output was $9.5 billion [48]. Dividing the energy point estimate of 810,000 million TJ for heating equipment by this industrial output gives us 88 TJ per million dollars of industrial output. If the commodity output for this sector is used instead we end up with 85 TJ per million dollars of commodity output.

Site energy use must be multiplied by a source-to-site ratio to estimate the true energy requirements to run this fleet of appliances over the course of the appliances' lifetimes. Applying ENERGY STAR source-to-site ratio of 3.336 to the electricity that contributes to this sector yields source energy estimates of 293 TJ per million dollars of industrial output [36]. If the commodity output for this sector is used instead we end up with 284 TJ per million dollars of commodity output.

21. 3. Comparison to Manufacturing Data for Clothes Washers and Dryers

Running the EIO-LCA model for $1 million (producer price) in the *Lighting Fixture Manufacturing* sector estimates that there is a total cradle to gate energy consumption of 8.5 TJ [1] (relative standard error of +/- 18% (7.0 TJ – 10.0 TJ) [49]) for the manufacturing of lighting equipment. This is much less than the 88 TJ of site use energy that is consumed in the use phase by $1 million of lighting fixtures. This is also much less than the 293 TJ of source energy that is consumed in the use phase by $1 million of lighting fixtures as seen in Figure 3-19. This means that by not including use-phase energy, the EIO-LCA model is not representing 97% of the lifecycle energy consumption of appliances sold in this sector. These estimates of missed energy by the EIO-LCA model for the *Lighting Fixture Manufacturing* sector are potentially even greater depending on the energy consumption associated with the end-of-life phase.

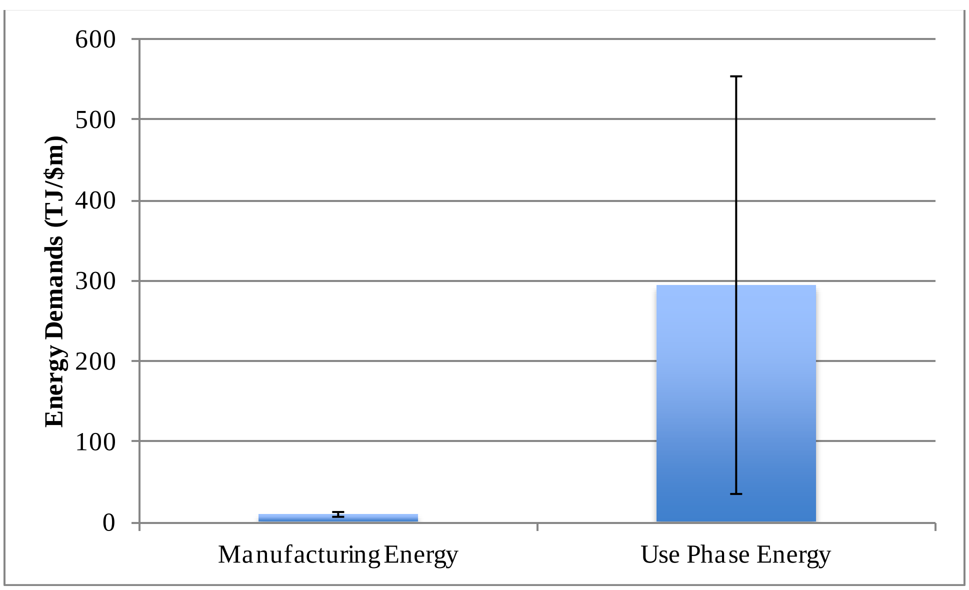

Figure 3-19. Manufacturing vs. lifecycle residential use phase energy for *Lighting Fixture Manufacturing*.

22. Audio and Video

The *Audio and Video Equipment Manufacturing* sector (NAICS 334310) includes video cassette recorders, televisions, stereo equipment, speaker systems, household-type video cameras, jukeboxes, and amplifiers for musical instruments and public address systems [26].

With little readily available data on the average energy consumption of audio/video equipment, usage of equipment, sales of each of these types of equipment, and lifetime expectancy of each device, we make a simplifying assumption that the energy required to run this equipment in a given year is approximately equal to the lifetime energy requirement for all of the devices in the same year.

22. 1. Audio and Video Equipment Energy Use

Audio and video equipment consumed around 53 TWh (190,000 TJ) according to the 2001 RECS End-Use Survey [22]. This is split into color televisions, VCR/DVD players, compact stereo systems, component stereo systems, portable stereos, and other stereo systems. If we make similar assumptions that the audio and video sector is not significantly changing from year to year, we can assume that the amount of electricity consumed in 2001 by all audio and video equipment is approximately equal to the amount of electricity consumed by all audio and video equipment sold in 2002.

22. 2. EIO-LCA Use Phase Value

The BEA estimate of industrial output for the *Audio and Video Equipment Manufacturing* sector for 2002 was \$8.3 billion and the total commodity output was \$9.6

billion [48]. Dividing the energy point estimate of 190,000 TJ for audio and video equipment by this industrial output yields 22.8 TJ per million dollars of industrial output. If the commodity output for this sector is used instead we end up with 19.8 TJ per million dollars of commodity output.

Site energy use must be multiplied by a source-to-site ratio to estimate the true energy requirements to run this fleet of appliances over the course of the appliances' lifetimes. Applying ENERGY STAR source-to-site ratio of 3.336 to the electricity that contributes to this sector yields source energy estimates of 76.1 TJ per million dollars of industrial output [36]. If the commodity output for this sector is used instead we end up with 66.1 TJ per million dollars of commodity output.

22. 3. Comparison to Manufacturing Data for Audio and Video Equipment

Running the EIO-LCA model for $1 million (producer price) in *Audio and Video Equipment Manufacturing* sector estimates that there is a total cradle to gate energy consumption of 8.4 TJ [1] (relative standard error of +/- 11% (7.5 TJ – 9.3 TJ) [49]) for the manufacturing of audio and video equipment. This is much less than the 22.8 TJ of site use energy that is consumed in the use phase by $1 million of residential audio and videos equipment. This is also much less than the 76.1 TJ of source energy that is consumed in the use phase by $1 million of audio and video equipment as seen in Figure 3-20. This means that by not including use-phase energy, the EIO-LCA model is not representing 90% of the lifecycle energy consumption of appliances sold in this sector. These estimates of missed energy by the EIO-LCA model for the *Audio and Video Equipment Manufacturing* sector are potentially even greater depending on the energy consumption associated with the end-of-life phase.

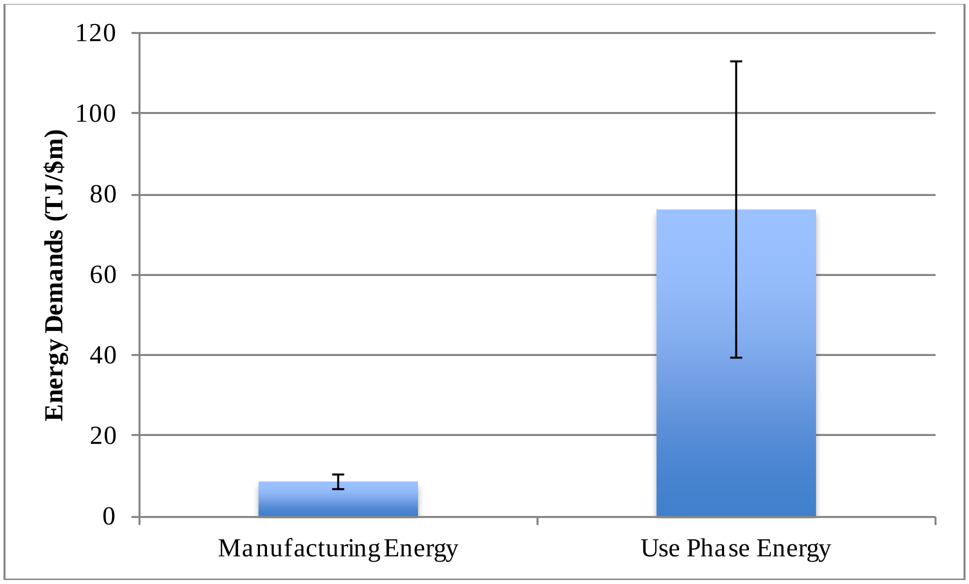

Figure 3-20. Manufacturing vs. lifecycle residential use phase energy for *Audio and Video Manufacturing*.

23. Household Cooking

The *Household Cooking Appliance Manufacturing* sector (NAICS 335221) includes barbecues, braziers, convection ovens, ranges, microwave ovens, and ovens [48]. Many portable cooking devices such as electric skillets, hot plates, griddles, toasters, and percolators are classified in *Small Electrical Appliance Manufacturing*. Commercial cooking appliances are also classified elsewhere and fall outside the scope of this work.

To make the use phase energy estimation for cooking appliance use easier given the large variety of devices on the market in 2002, the varying use of these devices, as well as the lack of data regarding expected lifetimes and average energy use of each, we make a simplifying assumption that the energy required to run this equipment in a given year is approximately equal to the lifetime energy requirement for all of the devices in the same year.

23. 1. Cooking Energy Use

Buildings Energy Data Book estimates the 2002 consumption of cooking appliances to be 0.46 quads (490,000 TJ) of total energy broken down into 0.21 quads (220,000 TJ) of natural gas use, 0.02 quads (20,000 TJ) of LPG, and 0.22 quads (230,000 TJ) of site electricity [53]. To make the use phase energy estimation for residential cooking appliance use easier, a simplifying assumption that the energy required to run this equipment in a given year is approximately equal to the lifetime energy requirement for all of the devices in the same year. This is supported by the fact that from 1998 to 2008, the energy use for cooking increased by about 0.6% on average annually [50]. The total increase over the ten-year period is from 0.43 quads to 0.48 quads.

23. 2. EIO-LCA Use Phase Value

The BEA estimate of industrial output for the *Household Cooking Appliance Manufacturing* sector for 2002 was $4.3 billion and the total commodity output was $4.2 billion [48]. Dividing the energy point estimate of 490,000 TJ for residential cooking by this industrial output gives us 111 TJ per million dollars of industrial output.

Site energy use must be multiplied by a source-to-site ratio to estimate the true energy requirements to run this fleet of devices over the course of the their lifetimes. Applying ENERGY STAR source-to-site ratios yields source energy estimates of 990,000 TJ total and 241 per million dollars of industrial output [36].

23. 3. Comparison to Manufacturing Data for Cooking Equipment

Running the EIO-LCA model for $1 million (producer price) in *Household Cooking Appliance Manufacturing* sector estimates that there is a total cradle to gate energy consumption of 11.6 TJ [1] (relative standard error of +/- 18% (9.5 TJ – 13.2 TJ) [49]) for the manufacturing of cooking equipment. This is much less than the 111 TJ of site use energy that is consumed in the use phase by $1 million of cooking appliances. This is also more than the 241 TJ of source energy that is consumed in the use phase by $1 million of cooking appliances as seen in Figure 3-21. However, by not including use-phase energy, the EIO-LCA model is not representing 95% of the lifecycle energy consumption of the devices sold in this sector. These estimates of missed energy by the EIO-LCA model for the *Household Cooking Appliance Manufacturing* sector are potentially even greater depending on the energy consumption associated with the end-of-life phase.

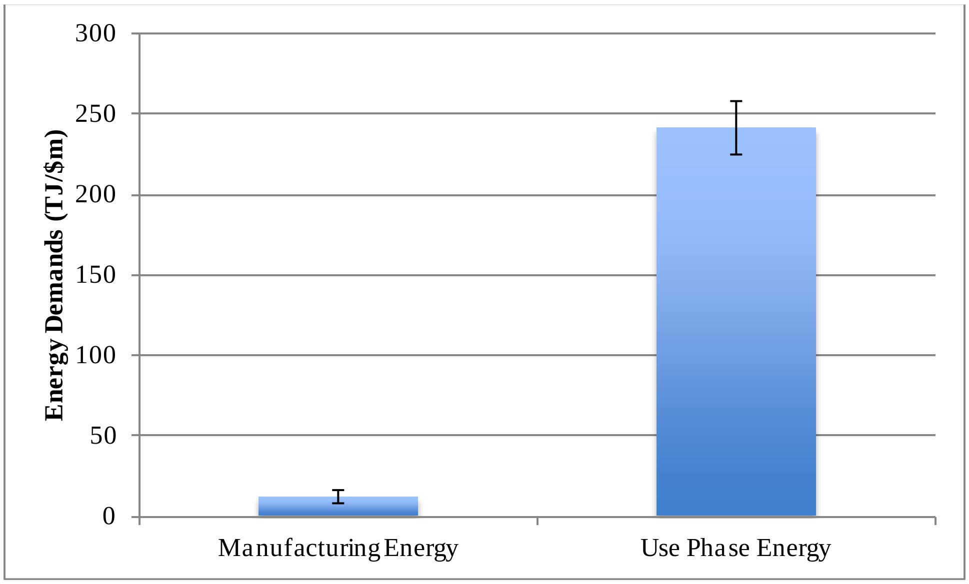

Figure 3-21. Manufacturing vs. lifecycle residential use phase energy for *Household Cooking Appliance Manufacturing*.

24. Computers

The *Electronic Computer Manufacturing* sector (NAICS 334111) includes desktop and laptop computers [26]. To make the use phase energy estimation for residential computer use easier given various computers on the market in 2002 and the varying use of these computers we make a simplifying assumption that the energy required to run this equipment in a given year is approximately equal to the lifetime energy requirement for all of the devices in the same year. We only explore the residential computer usage and do not include commercial and industrial computer use as to avoid double-counting issues as discussed previously.

24. 1. Electronic Computer Energy Use

RECS estimates desktop computer use in 2001 totaled 17.2 TWh for 65.8 million units [22]. The same source estimates laptop consumption was 1.3 TWh by 16.6 million units. The increase in computer ownership between 1997 and 2001 was about 19% and the increase in computer ownership between 2001 and 2005 was about 10% [27]. Based on this we assume a 2.5% growth between 2001 and 2002 [27]. Accounting for the 2.5% increase annually we should expect that the fleet of computers in 2002 to consume 19.0 TWh and computers sold in 2002 to consume 19.4 TWh (70,000 TJ)

24. 2. EIO-LCA Use Phase Value

The BEA estimate of industrial output for the *Electronic Computer Manufacturing* sector for 2002 was $45.7 billion and the total commodity output was $41.3 billion [26]. Dividing the energy point estimate of 70,000 TJ for computers by this industrial output yields 1.5 TJ per million dollars of industrial output. If the commodity output for this sector is used instead the result is 1.7 TJ per million dollars of commodity output.

Site energy use must be multiplied by a source-to-site ratio to estimate the true energy requirements to run this fleet of computers over the course of their lifetimes. Applying ENERGY STAR source-to-site ratio of 3.336 to the electricity that contributes to this sector yields source energy estimates of 5.1 TJ per million dollars of industrial output [36]. If the commodity output for this sector is used instead we end up with 5.6 TJ per million dollars of commodity output.

24. 3. Comparison to Manufacturing Data for Electronic Computers

Running the EIO-LCA model for $1 million (producer price) in *Electronic Computer Manufacturing* sector estimates that there is a total cradle to gate energy consumption of 4.3 TJ [1] (relative standard error of +/- 11% (3.8 TJ – 4.8 TJ) [49]) for the manufacturing of computers. This is greater than the 1.5 TJ of site use energy that is consumed in the use phase by $1 million of computers. This is however, less than the 5.1 TJ of source energy that is consumed in the use phase by $1 million of electronic computers as seen in Figure 3-22. This means that by not including use-phase energy, the EIO-LCA model does not represent 54% of the lifecycle energy consumption of computers sold in this sector. These estimates of missed energy by the EIO-LCA model for the *Electronic Computer Manufacturing* sector are potentially even greater depending on the energy consumption associated with the end-of-life phase.

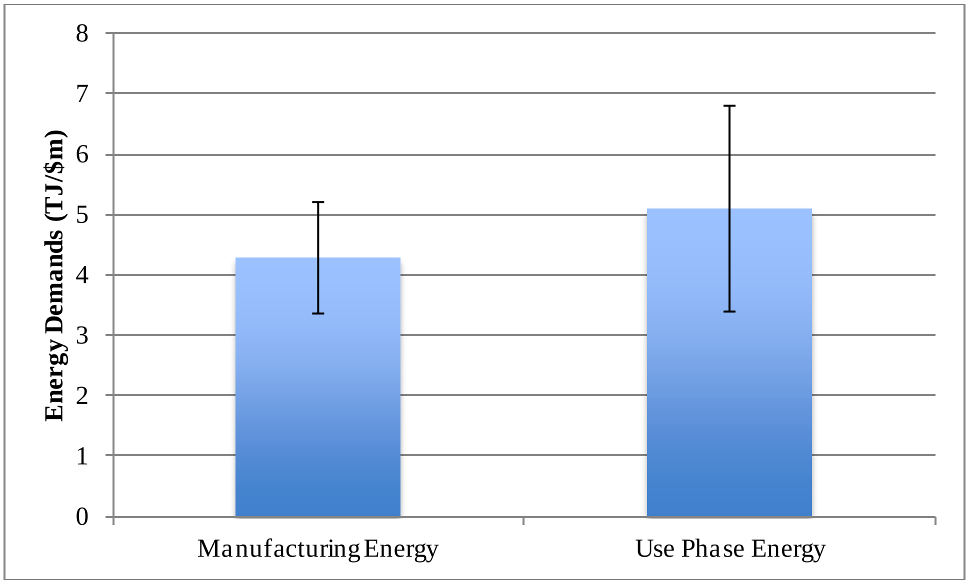

Figure 3-22. Manufacturing vs. lifecycle residential use phase energy for *Electronic Computer Manufacturing*.

25. Computer Monitors, Scanners, Printers, and Similar Devices

The *Computer Terminal and Other Computer Peripheral Equipment Manufacturing* sector (NAICS 334118) includes various computer equipment such as keyboards, mice, monitors, plotters, scanners, and printers [26]. The sector includes other devices such as automatic teller machines (ATMs) that are outside the scope of this work.

To make the use phase energy estimation for residential computer terminals and peripherals use easier given various computer equipment on the market in 2002 and the varying use of this computer equipment we make a simplifying assumption that the energy required to run this equipment in a given year is approximately equal to the lifetime energy requirement for all of the devices in the same year. We only explore the residential computer usage as to avoid double-counting issues as discussed previously.

25. 1. Computer Terminal and Peripheral Energy Use

ENERGY STAR estimates total energy use for computers and related peripheral equipment to be between 70 and 90 TWh in 2001 [76]. Some of this energy use is dedicated to commercial computer use and some is consumed by computers in the home. 48% of computer product sales are residential versus commercial computer product sales which account for the remaining 52% according to an analysis of IDC PC sales data between 1992 and 2004 [77]. If we assume that 20 TWh are consumed by computers in the home, and about the same amount of energy is consumed by commercial computers, we are left with between 30 and 50 TWh. If these values are also split equally between commercial and residential uses, we can assume that between 15 and 25 TWh are consumed by computer terminal and other computer peripheral equipment in 2002. We will assume the middle value of 20 TWh (72,000 TJ) for the model.

25. 2. EIO-LCA Use Phase Value

The BEA estimate of industrial output for the *Computer Terminal and Other Computer Peripheral Equipment Manufacturing* sector for 2002 was $14.4 billion and the total commodity output was $18.0 billion [48]. Dividing the energy point estimate of 72,000 million TJ for computer peripherals by this industrial output yields 5.0 TJ per million dollars of industrial output. Using the commodity output for this sector is used instead yields 4.0 TJ per million dollars of commodity output.

Site energy use must be multiplied by a source-to-site ratio to estimate the true energy requirements to run this fleet of appliances over the course of the appliances' lifetimes. Applying ENERGY STAR source-to-site ratio of 3.336 to the electricity that contributes to this sector yields source energy estimates of 16.7 TJ per million dollars of industrial output [36].

25. 3. Comparison to Manufacturing Data for Computer Terminals and Peripherals

Running the EIO-LCA model for $1 million (producer price) in *Computer Terminal and Other Computer Peripheral Equipment Manufacturing* sector estimates that there is a total cradle to gate energy consumption of 5.4 TJ [1] (relative standard error of +/- 11% (4.8 TJ – 6.0 TJ) [49]) for the manufacturing of computer peripherals. This is greater than the 5.0 TJ of site use energy that is consumed in the use phase by $1 million of computer peripherals. This is however, less than the 16.7 TJ of source energy that is consumed in the use phase by $1 million of electronic computers as seen in Figure 3-23. This means that by not including use-phase energy, the EIO-LCA model does not represent 76% of the lifecycle energy consumption of appliances sold in this sector. These estimates of missed energy by the EIO-LCA model for the *Computer Terminal and Other Computer Peripheral Equipment Manufacturing* sector are potentially even greater depending on the energy consumption associated with the end-of-life phase.

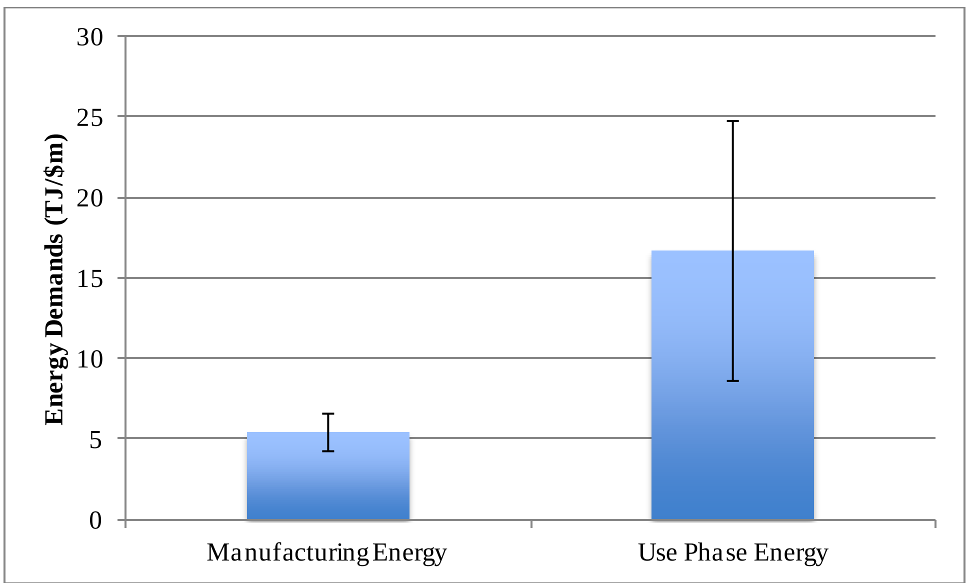

Figure 3-23. Manufacturing vs. lifecycle residential use phase energy for *Computer Terminal and Other Computer Peripheral Equipment Manufacturing*.

26. Power-Driven Handtools

The *Power-Driven Handtool Manufacturing* sector (NAICS 333991) includes tools such as drills, screwguns, circular saws, chain saws, staplers, and nailers used in a residential setting [26]. Similar equipment that is used in a commercial or industrial setting is outside of the scope of this work.

To make the use phase energy estimation for residential power-driven handtool use easier given the large variety of devices on the market in 2002, the varying use of these devices, as well as the lack of data regarding expected lifetimes and average energy use of each, we make a simplifying assumption that the energy required to run this equipment in a given year is approximately equal to the lifetime energy requirement for all of the devices in the same year.

26. 1. Power-driven Handtool Energy Use

The RECS End-Use Consumption Survey for 2001 estimates that 2.1 TWh are consumed by the power driven hand tool sector [22]. The energy use difference between 2001 and 2002 is likely insignificant given the short time frame and the relatively small electricity consumption compared to the size of the unit of measurement. Given the assumption that these values are unlikely to change, we use the 2.1 TWh (7,600 TJ) value in the model. This assumption indicates that the retirement rate is approximately equal to the manufacturing rate for power-driven handtools.

26. 2. EIO-LCA Use Phase Value

The BEA estimate of industrial output for the *Power-Driven Handtool*

Manufacturing sector for 2002 was \$3.5 billion and the total commodity output was \$3.5 billion [48]. Dividing the energy point estimate of 19,000 million TJ for power-driven handtools by this industrial output yields 2.1 TJ per million dollars of industrial output. If the commodity output for this sector is used instead we end up with 2.1 TJ per million dollars of commodity output.

Site energy use must be multiplied by a source-to-site ratio to estimate the true energy requirements to run this fleet of devices over the course of the their lifetimes. Applying ENERGY STAR source-to-site ratio of 3.336 to the electricity that contributes to this sector yields source energy estimates of 6.9 TJ per million dollars of industrial output [36].

26. 3. Comparison to Manufacturing Data for Communications Equipment

Running the EIO-LCA model for \$1 million (producer price) in *Power-Driven Handtool Manufacturing* sector estimates that there is a total cradle to gate energy consumption of 8.7 TJ [1] (relative standard error of +/- 7% (8.1 TJ – 9.3 TJ) [49]) for the manufacturing of power-driven handtools. This is greater than the 2.1 TJ of site use energy that is consumed in the use phase by \$1 million of power-driven handtools. This is also more than the 6.9 TJ of source energy that is consumed in the use phase by \$1 million of electronic computers as seen in Figure 3-24. However, by not including use-phase energy, the EIO-LCA model is not representing 44% of the lifecycle energy consumption of the devices sold in this sector. These estimates of missed energy by the EIO-LCA model for the *Power-Driven Handtool Manufacturing* sector are potentially even greater depending on the energy consumption associated with the end-of-life phase.

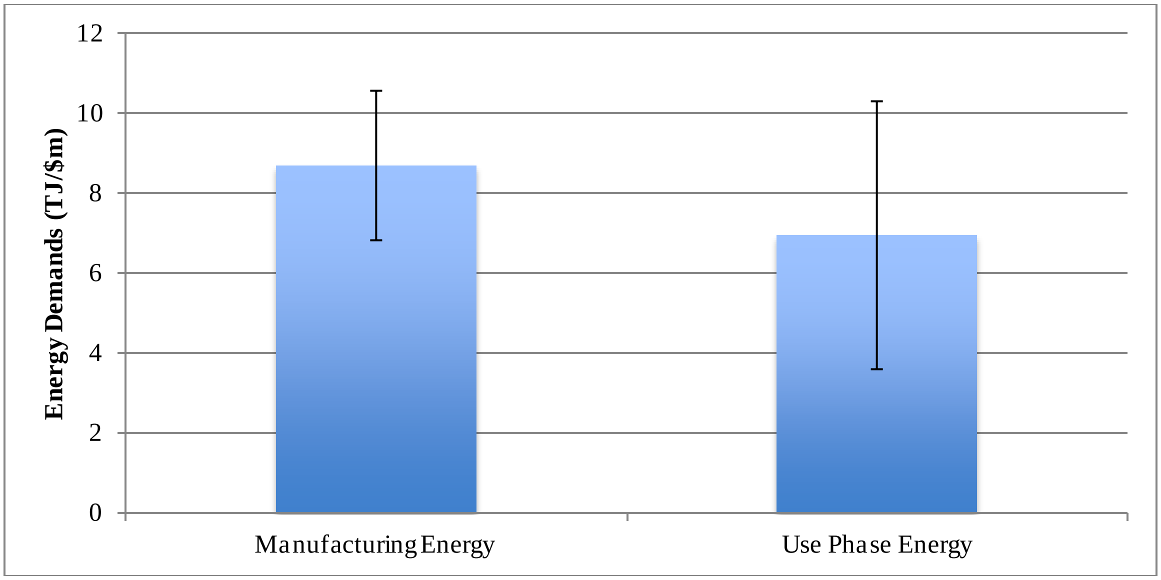

Figure 3-24. Manufacturing vs. lifecycle residential use phase energy for The *Power-Driven Handtool Manufacturing*.

27. Alarms and Intercoms

Other Communications Equipment Manufacturing sector (NAICS 334290) includes household fire alarms and intercom systems in residential settings [26].

27. 1. Other Communications Energy Use

With little information available on these devices, we assume that their consumption was significantly small in 2001 that it was not reported separately from the "residual" energy consumption in the RECS End-Use of Consumption for 2001 [22]. For this reason we will assume that these do not contribute significantly to the total for other communication equipment and at most may contribute 1 TWh (3,600 TJ). A simplifying assumption that the energy required to run this equipment in a given year is approximately equal to the lifetime energy requirement for all of the devices in the same year.

27. 2. EIO-LCA Use Phase Value

The BEA estimate of industrial output for the *Other Communications Equipment Manufacturing* sector for 2002 was $5.2 billion and the total commodity output was $5.2 billion. Dividing the sum of our energy point estimate of 3,600 TJ by the industrial output gives an estimate of 0.7 TJ per million dollars of industrial output. If the commodity output for this sector is used instead we end with 0.7 TJ per million dollars of commodity output.

Site energy must be multiplied by a source-to-site ratio to estimate the true energy requirements to run this fleet of appliances over the course of the appliances' lifetimes.

Applying these ratios yield lifetime use phase electricity consumption of the fleet of other communications equipment sold in 2002 to be 2.3 TJ per million dollars of industrial output and 2.3 TJ per million dollars of commodity output [36].

27. 3. Comparison to Manufacturing Data for Alarm Systems and Intercoms

Running the EIO-LCA model for $1 million (producer price) in the *Other Communications Equipment Manufacturing* sector estimates that there is a total cradle to gate energy consumption of 5.3 TJ [1] (relative standard error of +/- 11% (4.7 TJ – 5.9 TJ) [49]) for the manufacturing of communications equipment. This is more than the 0.7 TJ of site use energy that is consumed in the use phase by $1 million of communications equipment. This is also more than the 2.3 TJ of source energy that is consumed in the use phase by $1 million of other communications equipment as seen in Figure 3-25. This means that by not including use-phase energy, the EIO-LCA model is not representing 30% of the lifecycle energy consumption of appliances sold in this sector. These estimates of missed energy by the EIO-LCA model for the *Other Communications Equipment Manufacturing* sector are potentially even greater depending on the energy consumption associated with the end-of-life phase.

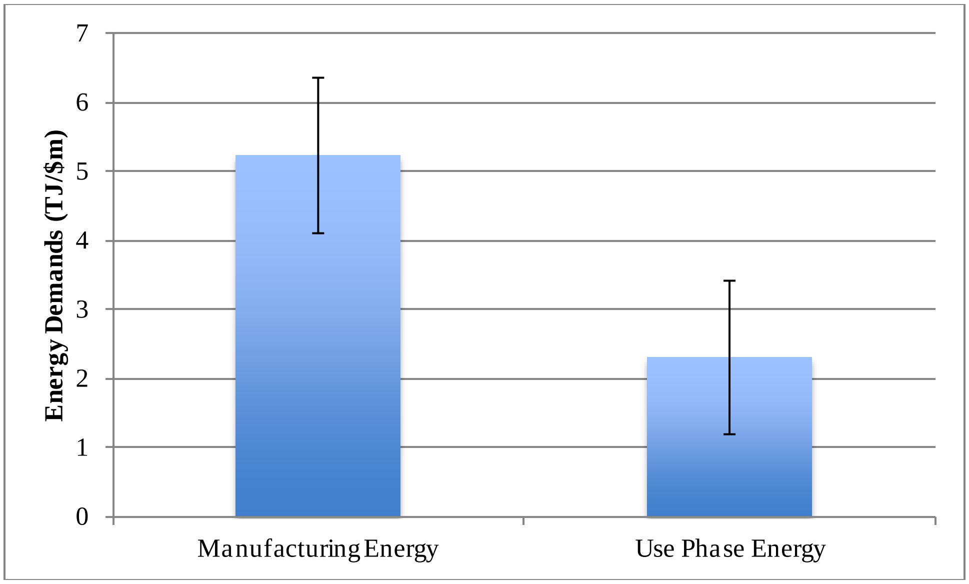

Figure 3-25. Manufacturing vs. lifecycle residential use phase energy for *Other Communications Equipment Manufacturing*.

28. Telephones

The *Telephone Apparatus Manufacturing* sector (NAICS 334210) includes telephones, caller identification devices, and answering machines [26]. It does not include the electricity that is used to power corded telephones, as the telephone company supplies this.

To make the use phase energy estimation for residential telephone electricity use easier given various telephones on the market in 2002, the varying use of these telephones, as well as the lack of data regarding expected lifetimes and average energy use, we make a simplifying assumption that the energy required to run this equipment in a given year is approximately equal to the lifetime energy requirement for all of the devices in the same year. We only explore the residential telephone usage as to avoid double-counting issues as discussed previously.

28. 1. Telephone Energy Use

The 2001 RECS End-Use Survey estimates cordless telephones consumed 2.1 TWh in 2001 [22]. The energy use difference between 2001 and 2002 is likely insignificant given the short time frame and the relatively small electricity consumption compared to the size of the unit of measurement. The 2001 RECS End-Use Survey also estimates answering machines consumed 2.3 TWh in 2001. Given the assumption that these values are unlikely to change between 2001 and 2002, we use the 4.4 TWh (16,000 TJ) value in the model. This assumption indicates that the retirement rate is approximately equal to the manufacturing rate for telephone apparatus.

28. 2. EIO-LCA Use Phase Value

The BEA estimate of industrial output for the *Telephone Apparatus Manufacturing* sector for 2002 was $25.5 billion and the total commodity output was $25.4 billion [48]. Dividing the energy point estimate of 16,000 million TJ for telephone equipment by this industrial output gives us 0.6 TJ per million dollars of industrial output. If the commodity output for this sector is used instead we end up with 0.6 TJ per million dollars of commodity output.

Site energy use must be multiplied by a source-to-site ratio to estimate the true energy requirements to run this fleet of telephones over the course of the appliances' lifetimes. Applying ENERGY STAR source-to-site ratio of 3.336 to the electricity that contributes to this sector yields source energy estimates of 2.1 TJ per million dollars of industrial output [36]. If the commodity output for this sector is used instead we end up with 2.1 TJ per million dollars of commodity output.

28. 3. Comparison to Manufacturing Data for Telephones

Running the EIO-LCA model for $1 million (producer price) in *Telephone Apparatus Manufacturing* sector estimates that there is a total cradle to gate energy consumption of 4.7 TJ [1] (relative standard error of +/- 11% (4.2 TJ – 5.2 TJ) [49]) for the manufacturing of telephones. This is greater than the 0.6 TJ of site use energy that is consumed in the use phase by $1 million of telephones. This is also more than the 2.1 TJ of source energy that is consumed in the use phase by $1 million of electronic computers as seen in Figure 3-26. However, by not including use-phase energy, the EIO-LCA model is not representing 31% of the lifecycle energy consumption of telephones sold in this sector. These estimates of missed energy by the EIO-LCA model for the *Telephone Apparatus Manufacturing* sector are potentially even greater depending on the energy consumption associated with the end-of-life phase.

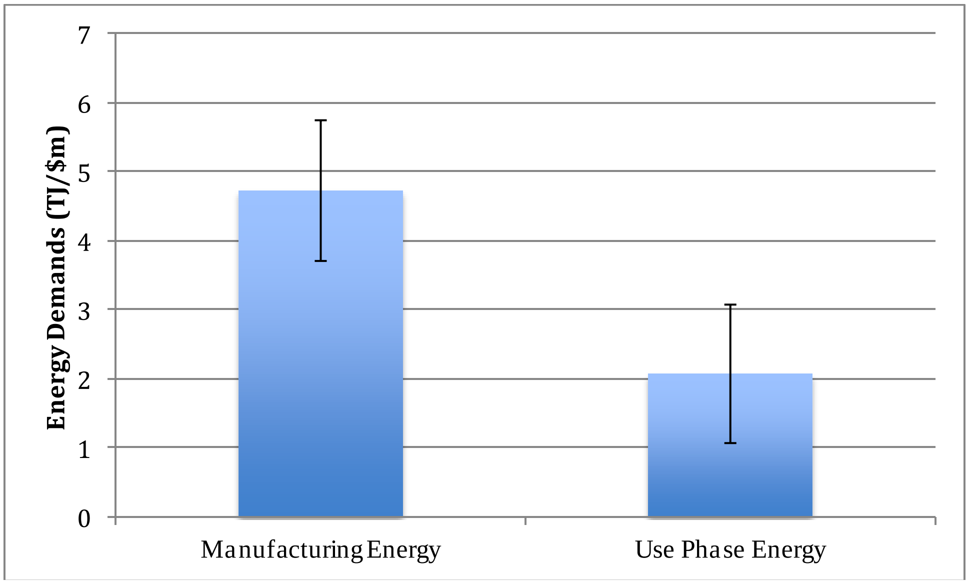

Figure 3-26. Manufacturing vs. lifecycle residential use phase energy for *Telephone Apparatus Manufacturing*.

29. Cell Phones, Cable Boxes, and Satellite Dishes

The *Radio and Television Broadcasting and Wireless Communications Equipment Manufacturing* sector (NAICS 334220) includes, cellular telephones, cable boxes, satellite dishes, pagers, GPS devices, and many other pieces of equipment that are outside of the scope of this work [26]. The only devices that contribute to residential energy consumption are cellular telephones, cable boxes, and satellite dishes.

To make the use phase energy estimation for residential telephone electricity use easier given various devices on the market in 2002, the varying use of these devices, as well as the lack of data regarding expected lifetimes and average energy use, we make a simplifying assumption that the energy required to run this equipment in a given year is approximately equal to the lifetime energy requirement for all of the devices in the same year. We only explore the residential usage of this equipment as to avoid double-counting issues as discussed previously.

29. 1. Communications Energy Use

Cellular telephones consume approximately 3 kWh/year per unit for recharging in 2001 [22]. The energy use difference between 2001 and 2002 is likely insignificant given the short time frame and the relatively small electricity consumption compared to the size of the unit of measurement. Given that there were about 140 million cell phones in the US in 2002, the average cell phone lasts about 2 years, and that the number of cell phones was increasing by nearly 24 million every year, there were roughly 80 million cell phone shipments in 2002 [78]. Those 80 million cell phones consumed 0.5 TWh over their lifetimes. The 2001 RECS End-Use Survey also estimates 24.4 million cable boxes consumed 2.9 TWh and 13.9 million satellite dishes consumed 1.8 TWh in 2001 [22]. These are likely not significantly different than the values in 2002 given the short time frame and the relatively small values compared to the size of the unit of measurement. Given the assumption that these values are unlikely to change between 2001 and 2002, we use the 5.2 TWh (19,000 TJ) value in the model. This assumption indicates that the retirement rate is approximately equal to the manufacturing rate for telephone apparatus.

29. 2. EIO-LCA Use Phase Value

The BEA estimate of industrial output for the *Radio and Television Broadcasting and Wireless Communications Equipment Manufacturing* sector for 2002 was $31.7 billion and the total commodity output was $31.0 billion [48]. Dividing the energy point estimate of 19,000 million TJ for communications equipment by this industrial output gives us 0.6 TJ per million dollars of industrial output. If the commodity output for this sector is used instead we end up with 0.6 TJ per million dollars of commodity output.

Site energy use must be multiplied by a source-to-site ratio to estimate the true energy requirements to run this fleet of appliances over the course of the appliances' lifetimes. Applying ENERGY STAR source-to-site ratio of 3.336 to the electricity that contributes to this sector yields source energy estimates of 2.0 TJ per million dollars of industrial output [36]. If the commodity output for this sector is used instead we end up with 2.1 TJ per million dollars of commodity output.

29. 3. Comparison to Manufacturing Data for Communications Equipment

Running the EIO-LCA model for $1 million (producer price) in *Radio and*

Television Broadcasting and Wireless Communications Equipment Manufacturing sector estimates that there is a total cradle to gate energy consumption of 4.8 TJ [1] (relative standard error of +/- 11% (4.3 TJ – 5.3 TJ) [49]) for the manufacturing of communications equipment. This is greater than the 0.6 TJ of site use energy that is consumed in the use phase by $1 million of residential communications equipment. This is also more than the 2.0 TJ of source energy that is consumed in the use phase by $1 million of electronic computers as seen in Figure 3-27. However, by not including use-phase energy, the EIO-LCA model is not representing 29% of the lifecycle energy consumption of the devices sold in this sector. These estimates of missed energy by the EIO-LCA model for the *Radio and Television Broadcasting and Wireless Communications Equipment Manufacturing* sector are potentially even greater depending on the energy consumption associated with the end-of-life phase.

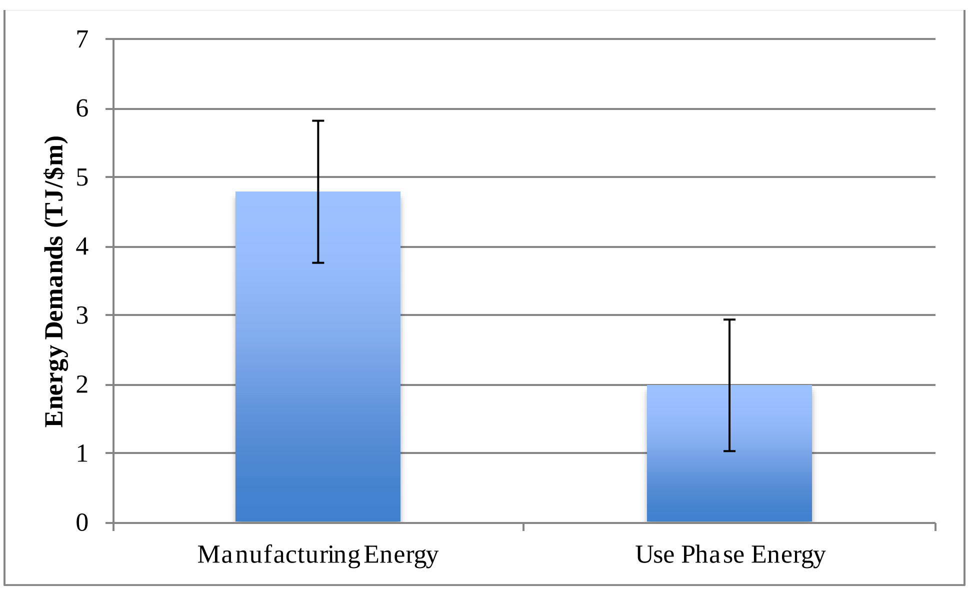

Figure 3-27. Manufacturing vs. lifecycle residential use phase energy for The *Radio and Television Broadcasting and Wireless Communications Equipment Manufacturing*.

30. **Personal Transportation**

IO-LCA models include transportation upstream of the consumer purchase and thus should not be double counted in this model. Purchaser price models also include transportation to get goods and services delivered to the consumer. Missing from the model are use phase energy requirements for personal transportation (e.g. driving to and from work), personal lawn and gardening equipment, recreational boating, motorcycles, and similar equipment. A vast majority of the energy requirements for these sectors are fulfilled by petroleum and therefore included in transportation energy estimates and not residential energy estimates. Nevertheless, this energy is unaccounted for in the EIO-LCA model and therefore is included in the use phase energy vectors.

31. Automobile Manufacturing

The *Automobile Manufacturing* sector (NAICS 336111) is the sector responsible for the manufacturing of complete automobiles and automobile chassis [26]. To make the use phase energy estimation for automobile use easier given the large variety of vehicles on the market in 2002, the varying use of these vehicles, we make a simplifying assumption that the energy required to run these automobiles in a given year is approximately equal to the lifetime energy requirement for all of the automobiles sold in the same year.

31. 1. Residential Vehicle Energy Use

According to the US Energy Information Administration's data on alternative fuels, alternative fuel vehicles (fuels other than gasoline and diesel fuel) only constituted about 0.2% of total transportation energy use [79]. About half of the alternative fuel energy was supplied by natural gas, a quarter by propane, and a quarter supplied by ethanol (E85 vehicles). Electricity supplied about 1.5% and hydrogen supplied a nearly negligible amount of alternative fuel energy (0.03%). According to the EIA's Residential Transportation Energy Consumption Survey, vehicles in 2001 consumed 113.1 billion gallons of gasoline equivalent [38]. Between 1987 and 2001 transportation grew by 1.4% annually, which brings the total consumption in 2002 to 114.7 billion gallons of gasoline equivalent (15.1 million TJ). Ethanol demands in 2002 were 2.085 billion gallons (200,000 TJ) or 1.3% of market share of gasoline. The growth rate for the number of vehicles is about 3.69 million vehicles annually [80] and the fleet of US passenger vehicles consisted of 230 million in 2002.

31. 2. EIO-LCA Use Phase Value

The BEA estimate of industrial output for the *Automobile Manufacturing* sector for 2002 was $87.6 billion and the total commodity output was $86.1 billion [48]. Dividing the energy point estimate of 15.1 million TJ for automobiles by this industrial output gives us 173 TJ per million dollars of industrial output.

Site energy use does not need to be multiplied by a source-to-site ratio to estimate the true energy requirements to run this fleet of devices over the course of the their lifetimes as the energy to transport fuels to pumping stations is accounted for in the commercial and industrial sectors for most fuels. Applying ENERGY STAR source-to-site ratio of 3.336 to the electricity that contributes to this sector is necessary, though nearly negligible as electricity only contributes 0.001 TJ of source energy per million dollars of industrial output [36].

31. 3. Comparison to Manufacturing Data for Automobiles

Running the EIO-LCA model for $1 million (producer price) in *Automobile Manufacturing* sector estimates that there is a total cradle to gate energy consumption of 8.3 TJ [1] (relative standard error of +/- 4% (8.0 TJ – 8.7 TJ) [49]) for the manufacturing of communications equipment. This is much less than the 173 TJ of site use energy that is consumed in the use phase by $1 million of automobiles. This is also much less than the 172 TJ of source energy that is consumed in the use phase by $1 million of automobiles as seen in Figure 3-28. However, by not including use-phase energy, the EIO-LCA model is not representing 95% of the lifecycle energy consumption of the vehicles sold in this sector. These estimates of missed energy by the EIO-LCA model for the *Automobile Manufacturing* sector are potentially even greater depending on the energy consumption associated with the end-of-life phase.

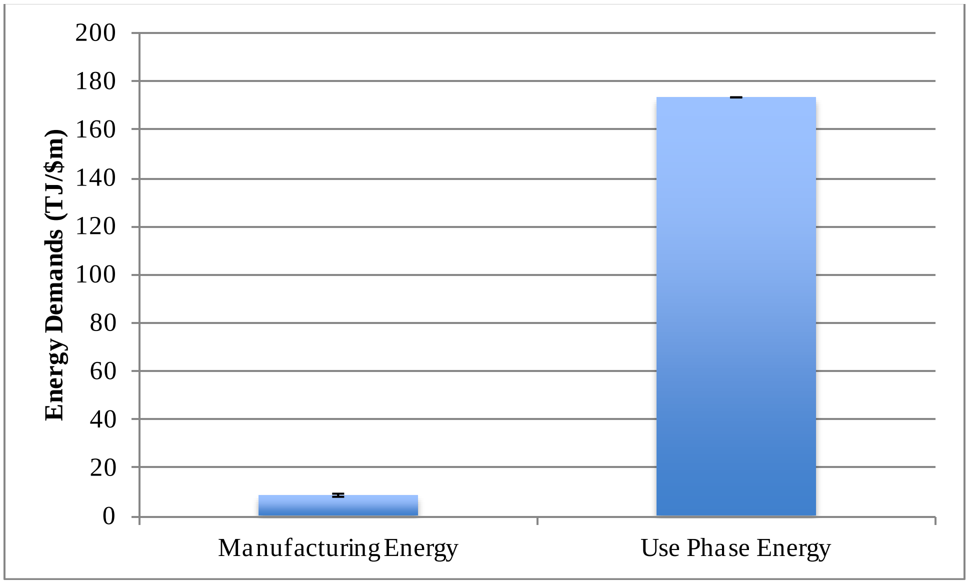

Figure 3-28. Manufacturing vs. lifecycle residential use phase energy for *Automobile Manufacturing*.

32. Boats

The *Boat Building* sector (NAICS 336612) is the sector responsible for the building of boats as the name suggests [26]. To make the use phase energy estimation for boat use easier given the large variety of vehicles on the market in 2002 and the varying use of these vehicles, we make a simplifying assumption that the energy required to run these boats in a given year is approximately equal to the lifetime energy requirement for all of the boats sold in the same year.

32. 1. Recreational Boat Energy Use

According to the US Energy Information Administration's 2013 Annual Energy Outlook, recreational boats consumed 0.25 quads of energy in 2010 [81]. Recreational boat use was holding fairly steady in 2010, growing by 0.6% annually, which brings the total consumption in 2002 down to 0.24 quads (250,000 TJ) [52]. For simplicity we assume that alternative fuels for recreational boating are negligible and that recreational boats utilize petroleum fuels.

32. 2. EIO-LCA Use Phase Value

The BEA estimate of industrial output for the *Boat Building* sector for 2002 was $8.1 billion and the total commodity output was $8.0 billion [48]. Dividing the energy point estimate of 250,000 TJ for automobiles by this industrial output yields 31 TJ per million dollars of industrial output.

Site energy use does not need to be multiplied by a source-to-site ratio to estimate the true energy requirements to run this fleet of devices over the course of the their lifetimes as the energy to transport petroleum fuels to pumping stations is accounted for in the commercial and industrial sectors.

32. 3. Comparison to Manufacturing Data for Boats

Running the EIO-LCA model for $1 million (producer price) in the *Boat Building* sector estimates that there is a total cradle to gate energy consumption of 8.3 TJ [1] (relative standard error of +/- 4% (8.0 TJ – 8.7 TJ) [49]) for the manufacturing of boating. This is less than the 31 TJ of site use energy that is consumed in the use phase by $1 million of boats. This is also more than the 31 TJ of source energy that is consumed in the use phase by $1 million of boats as seen in Figure 3-29. However, by not including use-phase energy, the EIO-LCA model is not representing 2% of the lifecycle energy consumption of the vehicles sold in this sector. These estimates of missed energy by the EIO-LCA model for the *Automobile Manufacturing* sector are potentially even greater depending on the energy consumption associated with the end-of-life phase.

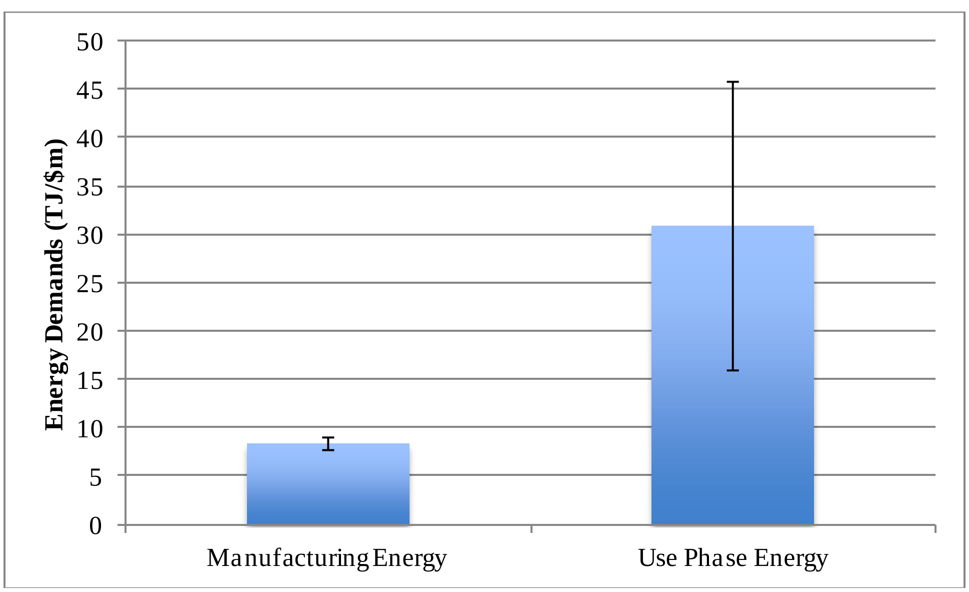

Figure 3-29. Manufacturing vs. lifecycle residential use phase energy for *Boat Building*.

33. Motorcycles

The *Motorcycle, Bicycle, and Parts Manufacturing* sector (NAICS 336991) is the sector responsible for the building of motorcycles. To make the use phase energy estimation for motorcycle use easier given the large variety of vehicles on the market in 2002, the varying use of these vehicles, we make a simplifying assumption that the energy required to run these motorcycles in a given year is approximately equal to the lifetime energy requirement for all of the motorcycles sold in the same year.

33. 1. Motorcycle Energy Use

Motorcycles consumed about 240 million gallons of gasoline in 2001 according to *US Department of Transportation, Bureau of Transportation Statistics* (31,600 TJ) [82]. For simplicity this model assumes that petroleum fuels supply all of this energy.

33. 2. EIO-LCA Use Phase Value

The BEA estimate of industrial output for the *Motorcycle, Bicycle, and Parts Manufacturing* sector for 2002 was \$4.4 billion and the total commodity output was \$4.2 billion [48]. Dividing the energy point estimate of 31,600 TJ for automobiles by this industrial output gives us 7.1 TJ per million dollars of industrial output.

Site energy use does not need to be multiplied by a source-to-site ratio to estimate the true energy requirements to run this fleet of devices over the course of the their lifetimes as the energy to transport petroleum fuels to pumping stations is accounted for in the commercial and industrial sectors.

33. 3. Comparison to Manufacturing Data for Communications Equipment

Running the EIO-LCA model for $1 million (producer price) in the *Motorcycle, Bicycle, and Parts Manufacturing* sector estimates that there is a total cradle to gate energy consumption of 11.3 TJ [1] (relative standard error of +/- 4% (10.8 TJ – 11.8 TJ) [49]) for the manufacturing of motorcycles. This is more than the 7.1 TJ of site use energy that is consumed in the use phase by $1 million of motorcycles. This is also more than the 7.1 TJ of source energy that is consumed in the use phase by $1 million of motorcycles as seen in Figure 3-30. However, by not including use-phase energy, the EIO-LCA model is not representing 39% of the lifecycle energy consumption of the motorcycles sold in this sector. These estimates of missed energy by the EIO-LCA model for the *Motorcycle, Bicycle, and Parts Manufacturing* sector are potentially even greater depending on the energy consumption associated with the end-of-life phase.

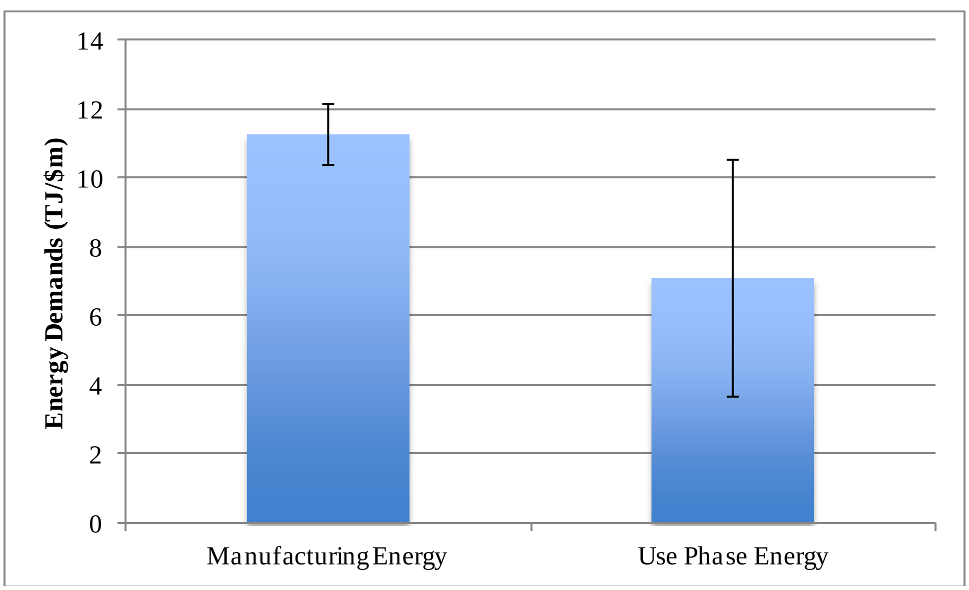

Figure 3-30. Manufacturing vs. lifecycle residential use phase energy for *Motorcycle, Bicycle, and Parts Manufacturing*.

34. Lawn and Garden Equipment

The *Lawn and Garden Tractor and Home Lawn and Garden Equipment Manufacturing* sector (NAICS 333112) is the sector responsible for the manufacturing of lawn and garden equipment [26]. To make the use phase energy estimation for this equipment use easier given the large variety of lawn and garden equipment on the market in 2002, the varying use of this equipment, we make a simplifying assumption that the energy required to run this equipment in a given year is approximately equal to the lifetime energy requirement for all of the equipment sold in the same year.

34. 1. Lawn and Garden Equipment Energy Use

According to the DOE lawn equipment consumes 1.2 billion gallons of gasoline annually [83]. 35% of this consumption is for commercial law care equipment; the rest of this is used in the residential sector (103,000 TJ). Electric powered mowers sold about 300,000 units in 2007 compared to 6 million gasoline powered mowers [84]. Assuming that the two types of lawn equipment consume energy at about the same efficiency and that the lawn care equipment sector is not rapidly changing, electric lawn care equipment consumed about 5,000 TJ of electricity in 2008. This brings the total consumption to 108,000 TJ for the lawn care equipment sector.

34. 2. EIO-LCA Use Phase Value

The BEA estimate of industrial output for the *Lawn and Garden Tractor and Home Lawn and Garden Equipment Manufacturing* sector for 2002 was $6.5 billion and the total commodity output was $6.4 billion [48]. Dividing the energy point estimate of

108,000 TJ for lawn equipment by this industrial output yields 16.5 TJ per million dollars of industrial output.

Site energy use for petroleum fuels does not need to be multiplied by a source-to-site ratio to estimate the true energy requirements to run this fleet of devices over the course of the their lifetimes as the energy to transport fuels to pumping stations is accounted for in the commercial and industrial sectors. Applying ENERGY STAR source-to-site ratio of 3.336 to the electricity that contributes to this sector is necessary and results in a total primary consumption of 18.4 per million dollars of industrial output [36].

34. 3. Comparison to Manufacturing Data for Communications Equipment

Running the EIO-LCA model for $1 million (producer price) in *Lawn and Garden Tractor and Home Lawn and Garden Equipment Manufacturing* sector estimates that there is a total cradle to gate energy consumption of 8.9 TJ [1] (relative standard error of +/- 7% (8.3 TJ – 9.5 TJ) [49]) for the manufacturing of lawn and garden equipment. This is less than the 16.5 TJ of site use energy that is consumed in the use phase by $1 million of lawn and garden equipment. This is also much less than the 18.4 TJ of source energy that is consumed in the use phase by $1 million of lawn care equipment as seen in Figure 3-31. However, by not including use-phase energy, the EIO-LCA model is not representing 67% of the lifecycle energy consumption of the equipment sold in this sector. These estimates of missed energy by the EIO-LCA model for the *Lawn and Garden Tractor and Home Lawn and Garden Equipment Manufacturing* sector are potentially even greater depending on the energy consumption associated with the end-of-life phase.

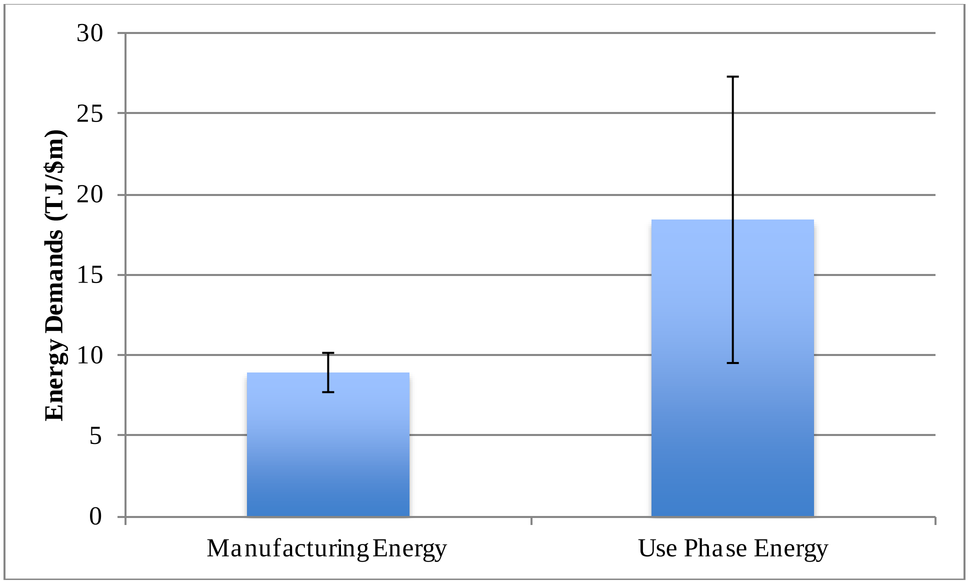

Figure 3-31. Manufacturing vs. lifecycle residential use phase energy for the *Lawn and Garden Tractor and Home Lawn and Garden Equipment Manufacturing*.

Chapter 4. Maximum Reasonable Expectations for Short-Term Energy Reductions in the Residential Sector Using EIO-LCA with Residential Energy Use Phase Vectors

As discussed in Chapter 2, energy management in the home is important for consumers to save money and reduce energy-environmental footprints, and for governmental agencies to comply with greenhouse gas policies and to ensure energy security. Policies like the US Department of Energy's ENERGY STAR program seek to improve the efficiency of residential and commercial appliances to reduce energy demands in a household, thereby reducing impacts on the environment. One such method for reducing energy consumption is by reducing lifecycle energy use for residential retail products. There is a desire amongst consumers and policymakers to reduce residential environmental footprints though both parties often are unaware of effective ways to reduce these impacts, hindering investment in energy efficient products [1][2][3][4][5][6]. This research builds on Chapter 3 and explores where energy is consumed over the lifecycle for various products as well as examines and compares the potential opportunities for retail products to reduce both embedded and use phase consumer energy demands for various products consumed in the residential sector in the United States. Such opportunities include activities such as state or federal efficiency programming, or an energy labeling like program to reduce energy if implemented with a realistic efficiency.

This research focuses on potential reductions in energy consumption of retail products in the residential sector given that 22 percent of US energy use (21.48 quads) comes from the residential sector [7]. The average consumer unit had total expenditures of nearly $50,000 in 2011 (BLS Consumer Expenditure Survey) for a total of $6 trillion. This makes for a large potential reduction in use phase energy (direct consumption by the residential sector) and embedded energy demands for the products and services purchased by these expenditures (via indirect consumption by consumers allocated to the industrial sector, which consumed 32 percent of all source energy demands in 2011) [7]. Retail products purchased in the residential sector are also the focus of this work because the lifecycle energy use of these products is a relatively untapped source of energy reductions with the exception of major appliances through the Department of Energy's ENERGY STAR program which does not preclude further use phase energy reductions and does not address embedded energy [8].

To analyze the potential national level energy reductions that could result, we analyze the current manufacturing and use phase energy demands for twenty retail products in the residential energy sector through use of Carnegie Mellon University's Economic Input-Output Life-Cycle Assessment (EIO-LCA) tool in conjunction with the use phase energy data that were developed in Chapter 3. We next explore the potential to reduce lifecycle energy demands by running this expanded model using the manufacturing practices with the lowest energy demands and the lowest potential use-phase energy demands as calculated in other related works [9]. Finally we explore realistic potentials for energy reduction by accounting for realistic adoption rates for durable retail purchases such as appliances and electronics. Varying potentials for supply chain, manufacturing, and use phase energy reductions are explored to show how each may potentially affect lifecycle energy and which lifecycle stage offers the most robust reduction potentials. This work shows how behavior, which is represented by the variability in the scenarios, affects the total lifecycle energy of a product. This work also provides insight into where in the lifecycle of a given product the largest potential or energy reductions likely lie as well as whether uncertainty in manufacturing efficiency or variability in use phase energy demands may have a larger potential effect on energy reductions.

1. Related Work

A study funded by the California Air Resources Board (CARB) and the California Environmental Protection Agency (EPA) in 2011 explored the potential for carbon footprint labels to reduce GHG emissions both within California and in the United States using a Multi-Regional Input Output (MRIO) LCA model that was developed at Carnegie Mellon University by this author and detailed industry-specific efficiency curves to estimate cradle to gate manufacturing energy and GHG emission reductions for 22 consumer products [9]. The process of developing use phase estimates was similar to the approach taken in Chapter 3 but using bottom up methods for a small number of specific products with specific California expenditures. The CARB report used estimates for lifetime, use, unit prices, producer to purchaser conversions, and mass per unit to calculate use phase estimates for lifetime as well as transportation and end of life impacts. The inclusion of the use phase energy vectors created in Chapter 3 to the EIO-LCA model allows for a consistent method of estimating use phase impacts for many sectors, which allows for similar analysis in a more streamlined fashion.

While the 2011 CARB/California EPA study (referred to as the 'CARB report' in the rest of this Chapter) was organized around the potential for reductions via energy labels, the results are generic in that current and potential life cycle energy use values were estimated, with the assumption that policies such as energy labels could motivate manufacturers and consumers to drive market performance for efficient products. Energy labels would not be required for such reductions; other activities such as focused state-level efficiency programming could achieve similar results. Nonetheless, the CARB report found that "significant life-cycle GHG emissions reductions might be achievable via product carbon labels and/or life-cycle standards". The report also found that certain products offered larger GHG emissions reductions than others such as "energy-using devices and animal-based food items". The CARB report estimated the potential for lifecycle GHG emissions reductions for the 22 products in the study to be a total of 29 Tg CO2e over the period 2011-2015.

The CARB report is limited in the number of products that were explored due to time and resource constraints as identified in the conclusions. The report is also based on a Multi-Regional Input-Output (MRIO) LCA model that utilizes specific California manufacturing facility data from the CARB GHG Emissions Inventory and thus is not necessarily applicable to the U.S. as a whole. The work in this chapter is necessary to perform a similar analysis as the CARB report that is based on energy use and applicable to the U.S. This work is also important as it demonstrates the ability for the EIO-LCA use phase energy vectors to effectively perform more streamlined analyses of retail products in the U.S. in a significantly shorter, less resource intensive, time period than using the methods of studies like the CARB report.

While not all GHGs result directly from energy production, and not all energy produces GHGs, there is a strong correlation between energy use and GHG emissions in the US. The US Environmental Protection Agency (EPA) indicates that "the largest source of greenhouse gas emissions from human activities in the United States is from burning fossil fuels for electricity, heat, and transportation." Because there is a direct relationship between energy use and GHG emission we expect that similar results could be achieved in a state or national efficiency program as the theoretical carbon labeling program in California.

In theory, an energy footprint-labeling program could put pressure on manufacturers to reduce embedded energy in consumer products as consumers may wish to make environmentally responsible decisions in regards to the products that they consume. As consumers purchase products with low embedded energy and smaller use phase requirements, manufacturers will face market forces that necessitate the adoption of lower energy intensive manufacturing processes and the production of products that minimize lifetime use phase energy consumption. Carbon labels have been proposed and even implemented by governments, nongovernmental organizations, and companies in many regions of the world. California has proposed AB 19 sponsored by Rep. Ira Ruskin [10]. Carbon Trust, an independent carbon footprinting organization, has developed and standardized the first carbon label that is becoming increasingly popular for producers who wish to demonstrate environmental impacts to consumers [11]. Lack of third party oversight is a contributing factor to uncertainty in carbon footprinting and must be standardized [12][13] for comparable carbon footprints. The same is true for a hypothetical energy footprint label.

The vast majority of energy use in a home comes from energy using products that are purchased such as refrigerators, hot water heaters, heating equipment, and electronics.

Because of this, much of the energy consumption in a home is directly tied to purchase decisions of the homeowner or resident, and may be reduced with alternate purchases. These decisions tend to lock consumers into efficient or inefficient energy paths for relatively long periods of time. Weber and Matthews estimated that about a third of GHG emissions associated with the residential sector come from personal transportation while a third comes from residential energy use [14]. The remaining third comes from the production and disposal of purchased goods and services in a home, sometimes known as embedded emissions. This means that nearly two thirds of residential GHG emissions (and by extension the associated energy consumption) may come from retail goods and services, demonstrating again a large potential untapped source of energy reductions.

2. Products

The products chosen for this study intentionally match the products from the CARB report, with the exceptions of restaurants and hard disk drives, which have been removed from our list of products. Restaurants are part of the commercial sector and therefore outside of the scope of this work, despite being tied to consumer decisions. Many hard disk drives will be accounted for in the production and use of personal computers, which is consistent with the use phase energy mapping found in Chapter 3 of this document. These products represent a wide spectrum of industries that consumers purchase from which also offer insights into differing supply chain characteristics and manufacturing processes. The products selected in the CARB report and subsequently this study also had high-quality data available regarding energy use and consumption.

The products selected are mapped into IO sectors for use in Carnegie Mellon University's EIO-LCA model. This mapping can be found in Table 4-1 [15].

Table 4-1. Mapping of retail products into IO sectors.

Industry	Product	IO Sector	Sector Name
Apparel	Men's dress shirt	315220	Men's and boys' cut and sew apparel manufacturing
Appliances	CFL	335110	Electric lamp bulb and part manufacturing
	Refrigerator	335222	Household refrigerator and home freezer manufacturing
	Water heater	335228	Other major household appliance manufacturing
Beverages	Beer	312120	Breweries
	Soft drink	312110	Soft drink and ice manufacturing
	Wine	312130	Wineries
Chemicals	Paint	325510	Paint and coating manufacturing
Electronics	Flat panel TV	334300	Audio and video equipment manufacturing
	Personal computer	334111	Electronic computer manufacturing
Food	Beef	1121A0	Cattle ranching and farming
	Bread	311810	Bread and bakery product manufacturing
	Canned tomatoes	311420	Fruit and vegetable canning, pickling and drying
	Cheese	311513	Cheese manufacturing
	Milk	31151A	Fluid milk and butter manufacturing
	Chicken	112300	Poultry and egg production
	Tortillas	311830	Tortilla manufacturing
Forestry	Paper towels	322120	Paper mills
	Wooden cabinet	337110	Wood kitchen cabinet and countertop manufacturing
Minerals	Masonry cement	327310	Cement manufacturing

3. Methods

3. 1. Base Case

To estimate the baseline manufacturing and transportation energy for the cradle-to-consumer energy impacts for the 20 selected products, the 2002 EIO-LCA purchaser price model is employed [15]. The purchaser price model is a comprehensive scoping tool that provides national average data for the environmental impacts based on purchaser priced economic activity in the United States. This model includes transportation impacts to get goods and services from factory gate to consumer as well as overhead from wholesale and retail activities. The model provides data on the energy requirements for the total economic activity for each of the 20 selected products.

Use phase energy estimates will come from the energy vectors developed in Chapter 3 as an add on to the EIO-LCA model. The same economic input (final demand) data is used to generate the use phase energy estimates as is used to generate manufacturing and transportation energy demands. This step is done separately because as of now the use phase data has not been fully incorporated into the existing EIO-LCA model (but is expected to be in the future).

End of life energy estimates are outside of the scope of the EIO-LCA model and also outside of the scope of this work. For future work to estimate these impacts, assumptions about the unit price of retail products and services must be made as well as assumptions about the unit mass of retail products. From these assumptions one could develop mass per expenditures estimates for each of the 20 products. Without a streamlined end-of-life series of vectors for the EIO-LCA model, end-of-life energy demands would have to be independently developed for each product. Future work to develop an end of life add on to the EIO-LCA model would be useful for such analysis. The overall scope of this work is shown in Figure 4-1 as it relates to the lifecycle of a product.

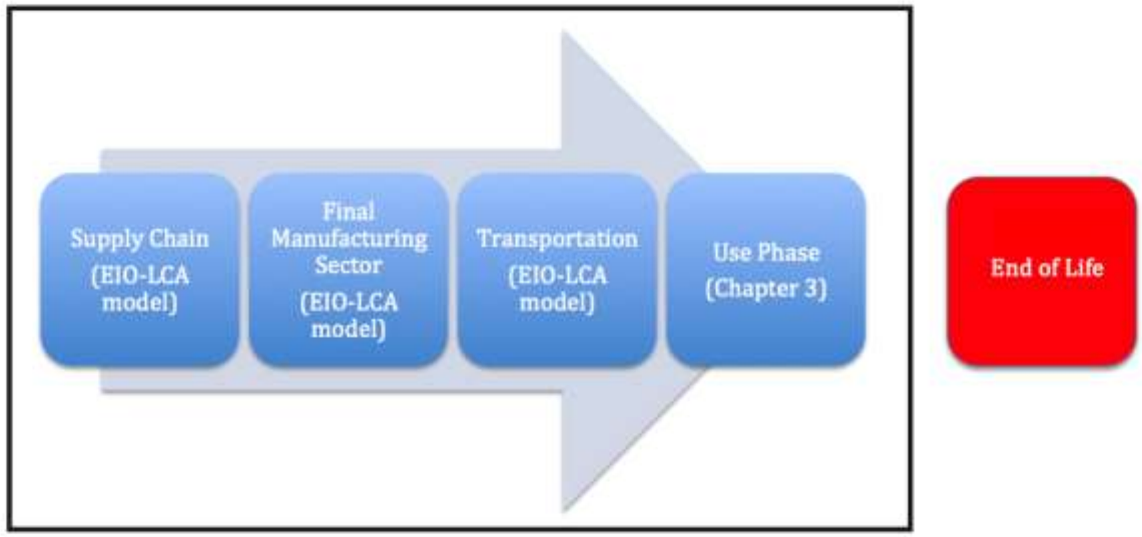

Figure 4-1. Overall Scope of Work. Note the scope of the model as it relates to the lifecycle of a product is shown in the black box.

The price inputs for the model were developed in the CARB report for California annual expenditures for 2011 in 2002 dollars to match the 2002 EIO-LCA model. The consumer expenditures in California were adjusted to US level spending using a gross domestic product (GDP) ratio as described below. The consumer expenditures are used as inputs into the EIO-LCA model to derive manufacturing, transportation, and use phase energy estimates for each product in this study. The result of this initial modeling leads to the base case energy consumption for this work.

3. 2. Product Energy Reduction Potential Scenarios

Five manufacturing energy reduction scenarios are developed and compared to the base case for manufacturing energy requirements. Similarly, two use phase energy reduction scenarios are developed and compared to the potential reductions of the other scenarios and base case use phase energy.

The lifecycle reductions for this analysis can come from improvements in energy efficiency in the supply chain and transportation, improvement in the final manufacturing energy (energy consumed by the manufacturing sector responsible for the production of a product), and reductions in the efficiency of products' use phase energy requirements. Other reductions may come about as a result of improvements in end of life energy demands; however these are outside the scope of this work. Each of the scenarios is briefly motivated below, followed by comparative results.

3. 3. Scenarios 1-3: Improvements to the supply chain

Improvements to the supply chain are reductions to the energy vectors for each sector in the supply chain for a given product by a given percentage, which represents a reduction in energy needs over a given industrial output. Improvements in the supply chain for analysis were estimated using the methodology developed by Masanet et. al. known as the Supply Chain Technology Potentials Model for Energy Emissions, and the Environment (eSTEP) [16]. These reductions represent readily available technology improvements in the manufacturing sector that offer short-term payback in three years or less. Significantly more savings potentially could be available if medium and long-term savings in the manufacturing sectors were leveraged as well, however these lay outside the scope of this work. The summary of IO sectors and fuels that are covered in the eSTEP model are provided in Table 4-2. For simplicity in this work, three standard efficiency improvements in the supply chain, of 5% (scenario 1), 10% (scenario 2), and 15% (scenario 3) are assumed. The 15% improvement in supply chain sectors (scenario 3) is considered to be a bounding case for supply chain improvements and that further improvements beyond 15% are unlikely. This is based on a generalization of eSTEP supply chain improvements that predicts potential improvements for motor systems, HVAC, refrigeration, and lighting for sectors at the three-digit NAICS level. The unweighted average for all of the potential reductions in energy is between 14 and 15%.

Table 4-2. IO Sectors and fuels covered in eSTEP [9].

Manufacturing (electricity, natural gas, coal, and petroleum)	
Conventional Boiler Use	Facility HVAC
CHP and/or Cogeneration Process	Facility Lighting
Process Heating	Onsite Transportation
Process Cooling and Refrigeration	Conventional Electricity Generation
Machine Drive	Other
Electro-Chemical Processes	
Commercial (electricity)	
Space Heating	Cooking
Cooling	Refrigeration
Ventilation	Office Equipment
Water Heating	Computers
Lighting	Other
Commercial (natural gas)	
Space Heating	Cooking
Water Heating	Other
Agriculture (electricity, natural gas, petroleum)	
Motors	Machinery
Lighting	Other
Onsite Transport	
Water Treatment (electricity)	
Pumping Systems	
Mining (petroleum, electricity)	
Mining Vehicles	Conveyors
Pumps	

3. 4. Scenario 4 & 5: Improvements to final manufacturing sectors

Improvements in the final manufacturing energy, or energy consumed by the manufacturing sector responsible for the production of a product, are estimated in the CARB report and are applicable to both manufacturing in California and the United States as a whole [9]. The improvements stem from a host of manufacturing improvements including increased use of recycled materials, packaging redesign, and other similar product improvements which are estimated in another CARB report on the eSTEP model [16]. These improvements are all readily available improvements to the manufacturing sector that offer payback periods of three years or less. Significantly more reductions are potentially available if the investments in new technology were extended to those with payback expectations in the medium and long-term future. The resulting energy reductions can be found in Table 4-3. Use phase energy reductions were estimated from the best available ENERGY STAR appliance or device when available. The estimated percentage reduction in use phase energy can be found in Table 4-4. This is an assessment for the maximum reasonable short-term energy reductions given easy to implement improvements to final manufacturing sectors that have a payback period of three years or less.

Table 4-3. Final manufacturing energy efficiency improvements [9].

Industry	**Product**	**Electricity Reduction**	**Fuel Reduction**
Apparel	Men's dress shirt	30%	25%
Appliances	CFL	25%	20%
	Refrigerator	25%	20%
	Water heater	25%	20%
Beverages	Beer	15%	25%
	Soft drink	15%	20%
	Wine	25%	25%
Chemicals	Paint	20%	20%
Electronics	Flat panel TV	25%	20%
	Personal computer	25%	20%
Food	Beef	20%	30%
	Bread	20%	30%
	Canned tomatoes	30%	35%
	Cheese	25%	20%
	Milk	30%	30%
	Chicken	20%	30%
	Tortillas	20%	30%
Forestry	Paper towels	15%	20%
	Wooden cabinet	15%	20%
Minerals	Masonry cement	30%	5%

Table 4-4. Use Phase Energy Reductions [9].

Industry	Product	Estimated Reduction in Use Phase Energy
Appliances	CFL	20%
	Refrigerator	30%
	Water Heater	15%
Electronics	Flat Panel TV	30%
	Personal Computer	35%

Scenario 4 assumes that all of the products on the market would switch to efficient manufacturing techniques overnight. In reality, products, especially ones with long lifetimes, will only be replaced at the rate at which they need to be replaced and consumers are unlikely to purchase the most efficient products in all cases. It would be unrealistic, for example, to expect that all of the refrigerators in the U.S. would be replaced overnight and that those refrigerators would all adopt the models with the least embedded and use phase energy. Likewise, due to brand loyalty, aesthetics, and other preferences, it is unlikely that consumers would purchase products like men's dress shirts based on the lowest embedded energy. After more than 20 years, ENERGY STAR qualified products only make up 44% of the possible ENERGY STAR qualified products. ENERGY STAR, is arguably the best marketing campaign to reduce energy demands for products with use phase energy demands, and will be used as the upper bound for adoption of appliances and electronics in this analysis. The market shares for the ENERGY STAR products in this study are shown in Table 4-5. For Scenario 5, we will assume that the appliances and electronics in this study will have the same adoption rates as ENERGY STAR products (e.g., 20% of CFLs).

Table 4-5. ENERGY STAR market shares for products in this study.

Industry/sector	**Product**	**ENERGY STAR product market share**
Appliances	CFL	20%
	Refrigerator	50%
	Water heater	12%
Electronics	Flat panel television	77%
	Personal computer	47%
ENERGY STAR (all products)	Average	44%

4. Retail Product Expenditures

The CARB report outlines consumer expenditures in California for the 20 items outlined in this work in terms of California consumer prices. Given the economic basis of the core IO-LCA model used, we employ a Gross State Product (GSP) to Gross Domestic Product (GDP) ratio for California to the US and use this as a proxy for US equivalent expenditures. Population was also explored as the basis for this ratio and the two numbers were very similar. California GDP was about 13% of the US GDP in 2012

[17]. The California population was about 12% of the total US population in 2012 [18]. Consumer expenditures can be found in Table 4-6. Two adjustments were made and one note should be taken regarding Table 4-6. First, the expenditures on televisions far exceeded the 2002 IO industrial output, likely as a result of a rapidly growing audio and video industry. In 2012, $26 billion in televisions were sold [19] which makes it reasonable that the retail consumer estimate for US expenditures is nearly double the IO industrial output from ten years prior. Secondly, expenditures on tortillas for the US were nearly double the 2002 IO industrial output. This is likely due to the doubly higher percentage of Hispanic population in California relative to the US (38.2% in California compared to 16.9% nationwide [20], As a result, the US expenditure is adjusted to the 2002 IO output estimate plus 10% for a growing population. The U.S. expenditures for the products in this study in year 2002 producer price dollars, to maintain consistency with the EIO-LCA model data, are listed in Table 4-6 along with the California producer price expenditures from the CARB report for comparison as they were the basis for the U.S. estimates used in this model.

Producer prices were converted to purchaser prices using BEA data contained in the MATLAB EIO-LCA model. This was done to accurately model the entire lifecycle of retail purchases up to (but not including) the disposal. This includes transportation, though specific reductions for transportation were not included in this modeling.

Table 4-6. California and US 2011 consumer expenditures in producer prices for retail products.

Product	CA expenditures (2002 $ m)	US expenditures (2002 $m)	2002 IO Industrial Output (2002 $m)
Men's dress shirt	152	1,148	11,010
CFL	8.1	61	2,522
Refrigerator	526	3,973	5,462
Water heater	126	952	3,446
Beer	259	1,956	21,553
Soft drink	345	2,606	32,617
Wine	1,300	9,819	9,821
Paint	61	461	19,193
Flat panel TV	2,200	16,617	8,363
Personal computer	2,900	21,905	45,730
Beef	1,800	13,596	42,259
Bread	201	1,518	36,905
Canned tomatoes	170	1,284	30,155
Cheese	449	3,391	20,098
Milk	953	7,198	23,816
Chicken	671	5,068	21,051
Tortillas	358	1,536	1,397
Paper towels	77	582	46,011
Wooden cabinet	850	6,420	14,446
Masonry cement	56	423	7,294

Each product in this study is modeled separately for each scenario using the 2002 purchaser price EIO-LCA model in MATLAB and the purchaser price inputs shown in Table 4-6. Use phase energy estimates are calculated using the energy vectors created in Chapter 3 in conjunction with the purchaser price model. Supply chain reductions see reductions to the total energy vector for each sector except for the final manufacturing sector responsible for the production of the product being modeled. This assumption means that all of the supply chain sectors with the exception of the final manufacturing sector (sectors can and do make purchases from themselves) see the benefit of these reductions. This is a realistic assumption because it would be unreasonable to assume that the final manufacturing sector would be able to make reductions to its energy impacts only for supply chain purposes but not for final production. Reductions to final manufacturing sectors are also modeled separately, keeping the other 427 sectors of the model constant while reducing the single manufacturing sector. This also creates a bit of energy reduction in the supply chain as purchases made by the final manufacturing sector from itself also enjoy the benefits of this reduction in the model. Again this is assumed to be reasonable as it is unlikely that a sector would be able to reduce energy demands for only final production purposes but not for manufacturing purposes. Use phase energy is modeled in a similar manner. Further explanation of how the EIO-LCA model and the energy vectors work can be found in Chapter 3.

5. Results

The results of the model show total base case energy demands for the US consumption of the 22 retail products of 1.36 million TJ. Reductions in the final manufacturing sector for the 20 retail products in the study have a maximum short-term embedded energy savings of 51 thousand TJ are available compared to the base case assuming only readily implementable improvements to manufacturing techniques as described in the eSTEP model [16]. These potential savings are unevenly distributed amongst the modeled products. It should also be noted that the maximal energy savings could be significantly larger in the long term with significant investment in new manufacturing equipment that has medium and long-term payback periods. The smallest savings modeled are available in the tortilla manufacturing industry, which has the potential to net a savings of only 0.12 TJ (7% of the base manufacturing energy for tortillas). The largest savings are available in the beef manufacturing sector, which offers a potential savings of 24 thousand TJ (9% of the base manufacturing energy requirements for beef production and nearly half of the potential final manufacturing sector reductions in this study). This is not unexpected given the disparity between consumer expenditures on tortillas and beef ($1,518 for tortillas compared to $13,596 for beef) and the difference between energy requirements to produce the two (12.9 TJ/$m for tortillas compared to 18.7 TJ/$m for beef in the base case) [1]. The full savings for all 20 products are shown in Table 4-7.

Table 4-7. Scenario 4 - US Energy Savings with improvements to final manufacturing sectors sorted by base case energy demands (in Thousand TJ).

Product	**Base Case Energy Demand (Thousand TJ)**	**Potential Savings for Scenario 4 (Thousand TJ)**	**Reduction from Base Case (Scenario 4)**
Beef	267	24	9%
Chicken	104	5.8	6%
Paper towels	61	4.3	7%
Masonry cement	33	3.4	10%
Milk	121	3.2	3%
Wine	121	2.3	2%
Cheese	61	1.6	3%
Canned tomatoes	20	1	5%
Flat panel TV	182	0.88	0%
Wooden cabinet	81	0.77	1%
Bread	20	0.71	4%
Beer	32	0.64	2%
Personal computer	146	0.42	0%
Refrigerator	58	0.41	1%
Soft drink	45	0.41	1%
Men's dress shirt	14	0.14	1%
Paint	8.2	0.09	1%
Water heater	15	0.03	0%
CFL	0.61	0.01	1%
Tortillas	0.0031	0.00012	4%

Scenario 5 is constrained by realistic adoption rates (based on ENERGY STAR adoption rates) offers slightly reduced results from the maximum reasonable expected energy savings from affordable and available investments in improvements in the final manufacturing sector with short-term payback periods. The results can be seen in Table 4-8. The results are fairly similar with a difference in potential savings of only 0.4%. The small difference between the scenarios 4 and 5 is indicative of the fact that the final manufacturing energy use for electronics and appliances is only a small portion of the embedded manufacturing energy of a consumer's total expenditures. This is because food items, such as beef, are purchased regularly and have a relatively high manufacturing energy demand per dollar of output while appliances and electronics are purchased less frequently and have a lower manufacturing energy requirement per dollar of output. Adjusting the adoption rates for other products beyond electronics and appliances would likely have a larger effect on the difference between the two scenarios.

Table 4-8. Scenario 5 - US Energy Savings given a adoption rate constrained scenario with improvements to final manufacturing sectors sorted by base case energy demands (in Thousand TJ).

Product	**Base Case Energy Demand (Thousand TJ)**	**Potential Savings for Scenario 5 (Thousand TJ)**	**Reduction from Base Case (Scenario 5)**
Beef	267	24	9%
Chicken	104	5.8	6%
Paper towels	61	4.3	7%
Masonry cement	33	3.4	10%
Milk	121	3.2	3%
Wine	121	2.3	2%
Cheese	61	1.6	3%
Canned tomatoes	20	1	5%
Flat panel TV	182	0.87	0%
Wooden cabinet	81	0.84	1%
Refrigerator	58	0.71	1%
Bread	20	0.71	4%
Beer	32	0.64	2%
Personal computer	146	0.52	0%
Soft drink	45	0.42	1%
Water heater	15	0.22	1%
Men's dress shirt	14	0.12	1%
Paint	8.2	0.09	1%
CFL	0.61	0.03	4%
Tortillas	0.0031	0.00012	4%

The potential for energy savings tends to be increased when manufacturers may be able to leverage energy reductions from their suppliers. Energy reduction results for 5, 10, and 15 percent improvements in supply chain energy requirements (including transportation) are shown in Table 4-9. Relatively large reductions are shown for each product, which indicates that supply chain energy makes up a significant portion of the manufacturing energy demands. Manufacturers that are able to leverage supplier relationships may be able to see significant embedded energy reductions in their products.

Table 4-9. US Potential reductions given improvements to supply chain sectors for Scenarios 1, 2, and 3.

Product	Base Case Energy Demands (Thousand TJ)	Scenario 1 5% Supply Chain Reduction (Thousand TJ)	Scenario 2 10% Supply Chain Reduction (Thousand TJ)	Scenario 3 15% Supply Chain Reduction (Thousand TJ)
Flat panel TV	182	8.9	17.8	27
Beef	267	8.4	16.7	25
Personal computer	146	7.2	14.4	22
Wine	121	5.6	11.2	17
Milk	121	5.5	11.0	17
Chicken	104	3.9	7.8	12
Wooden cabinet	81	3.8	7.6	11
Refrigerator	58	2.8	5.5	8.3
Cheese	61	2.7	5.4	8.1
Soft drink	45	2.1	4.2	6.3
Beer	32	1.4	2.8	4.2
Paper towels	61	1.0	2.0	3.0
Bread	20	0.9	1.7	2.6
Canned tomatoes	20	0.8	1.7	2.5
Water heater	15	0.72	1.4	2.2
Men's dress shirt	14	0.66	1.3	2.0
Paint	8.2	0.39	0.77	1.2
Masonry cement	33	0.37	0.74	1.1
CFL	0.61	0.025	0.050	0.075
Tortillas	0.0031	0.00012	0.00025	0.00037

Figure 4-2 shows the total energy consumption required to manufacture each product in each of the five manufacturing energy reduction scenarios and for the base case. The differences between each bar and the base case bar for each product represent the total manufacturing energy savings. It is obvious from the bar graph that there are large disparities in energy demand between the different products. Figure 4-3 also shows the potential savings for each scenario as compared to base case manufacturing energy requirements. This makes it even clearer that the potential savings that are available are not evenly dispersed. This also shows that the largest savings potentials are available in the supply chain for most sectors and the final manufacturing sector for a select few sectors such as beef, chicken, cement, and paper towels.

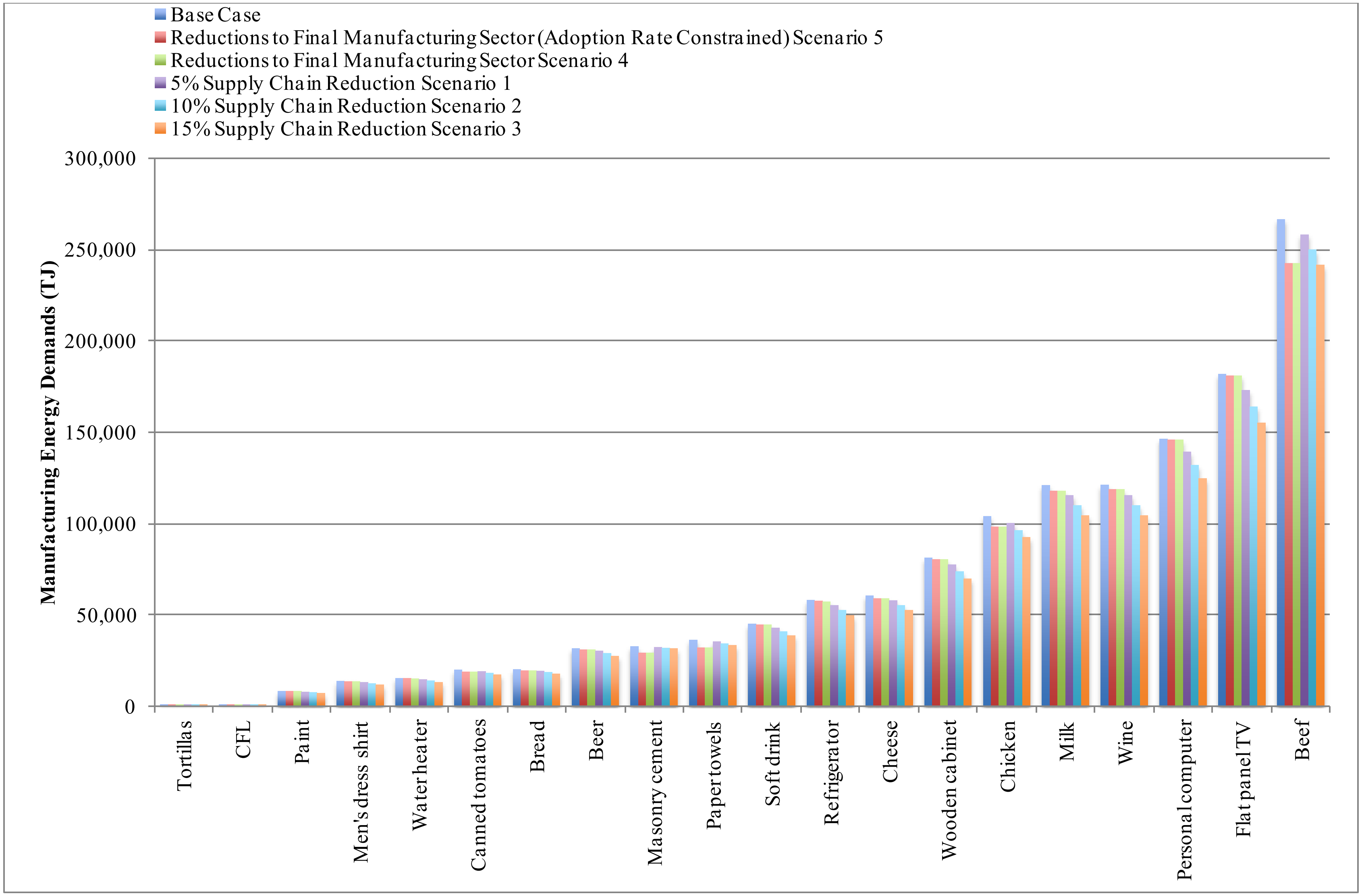

Figure 4-2. Potential manufacturing energy requirements for various scenarios.

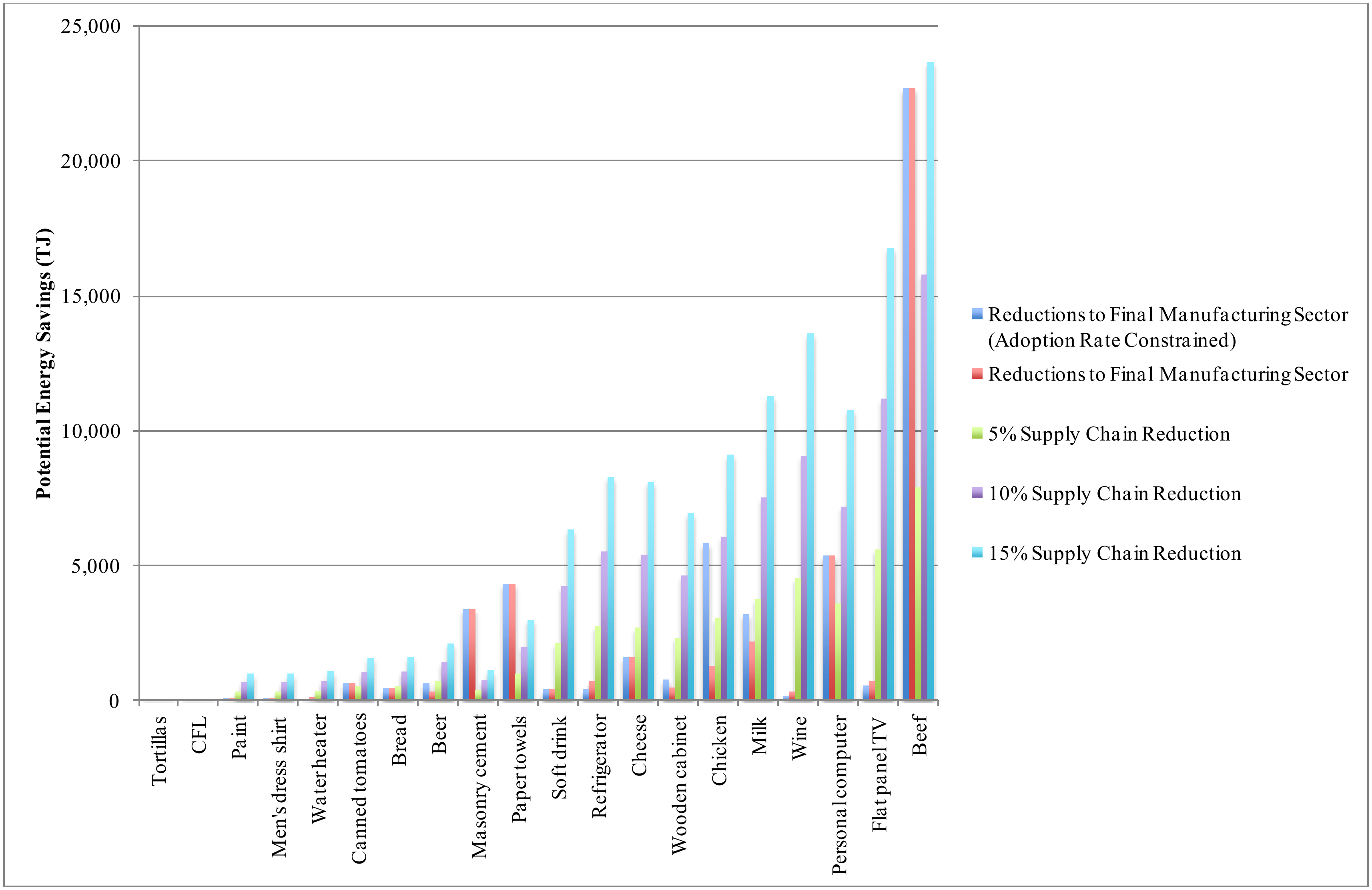

Figure 4-3. Potential manufacturing energy savings for various scenarios over the base case.

Use phase energy reductions for the 20 products in this study are potentially as high as 390,000 TJ in scenario 6 (about the same as the electricity consumption of 9.7 million US homes or 3,500 MJ saved per household), which is more than eight times the potential savings from manufacturing improvements in the final sector, and more than three times greater than the potential savings from the 15% reduction in supply chain manufacturing energy scenario. The adoption rate constrained scenario (scenario 7), which is likely a more realistic scenario, brings the potential savings down significantly to 217,000 TJ (about the same consumption as 5.3 million US homes or 2,000 MJ saved per household) but this is still more than quadruple the adoption-constrained savings offered by the manufacturing improvements to final manufacturing sectors scenario. The scenario offering 15% reductions to supply chain manufacturing sectors offers a little more than half of the potential energy reductions in the manufacturing sector than are available in the use phase indicating that there is still a large potential to reduce embedded energy in the supply chain given enough leveraging ability, though these opportunities are spread amongst many different suppliers. Total use phase energy reductions can be found in Table 4-10. Comparing the potential savings columns to manufacturing savings in Tables 4-8 and 4-9 show how large the use phase energy potential savings are compared to manufacturing savings. The same relationship holds true for use phase demands compared to manufacturing demands.

Table 4-10. US Lifecycle use phase energy demands and potential reductions sorted by reductions.

Product	**Use Phase Energy Demand (Thousand TJ)**	**Potential Savings (Thousand TJ)**	**Potential Savings (Adoption Rate Constrained) (Thousand TJ)**
Flat panel TV	867	255	196
Refrigerator	1,000	251	125
Water heater	790	117	14
Personal computer	162	36	17
CFL	56	6	1

Figure 4-4 shows potential energy reductions for both manufacturing and use phase for the five products that have potential reductions in their use phase energy demands. Potential energy savings split into supply chain reductions, final manufacturing sector reductions, and use phase reductions are shown in Figure 4-5. Four of the five products that have use phases have use phase reductions that exceed manufacturing reductions. Reductions are shown on a logarithmic scale to make manufacturing reductions visible.

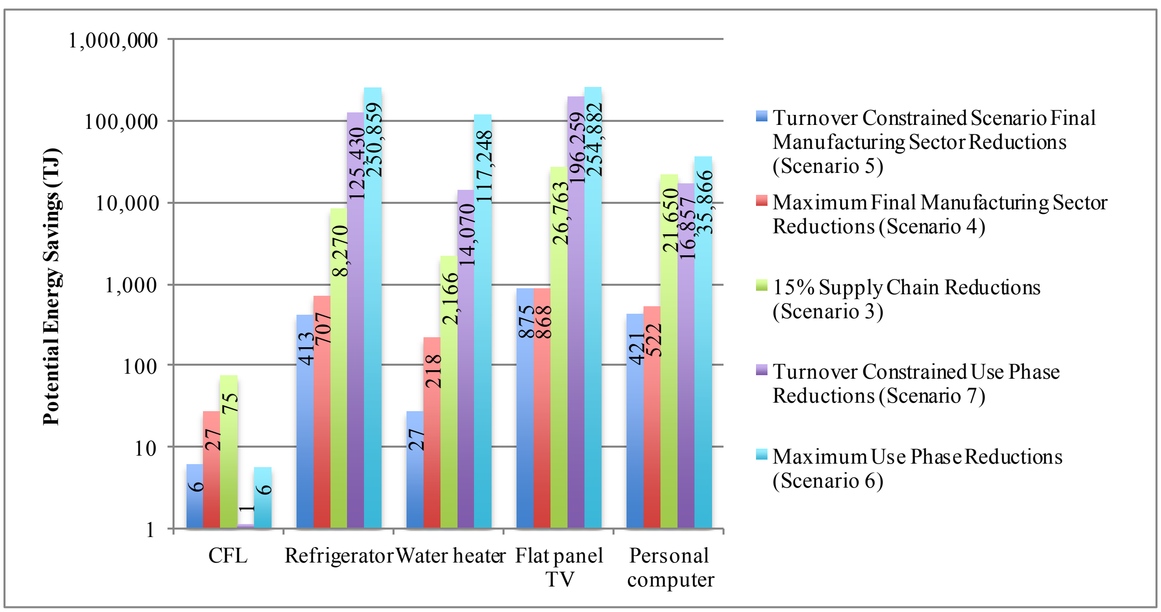

Figure 4-4. Comparison of manufacturing and use phase potential energy savings for selected products.

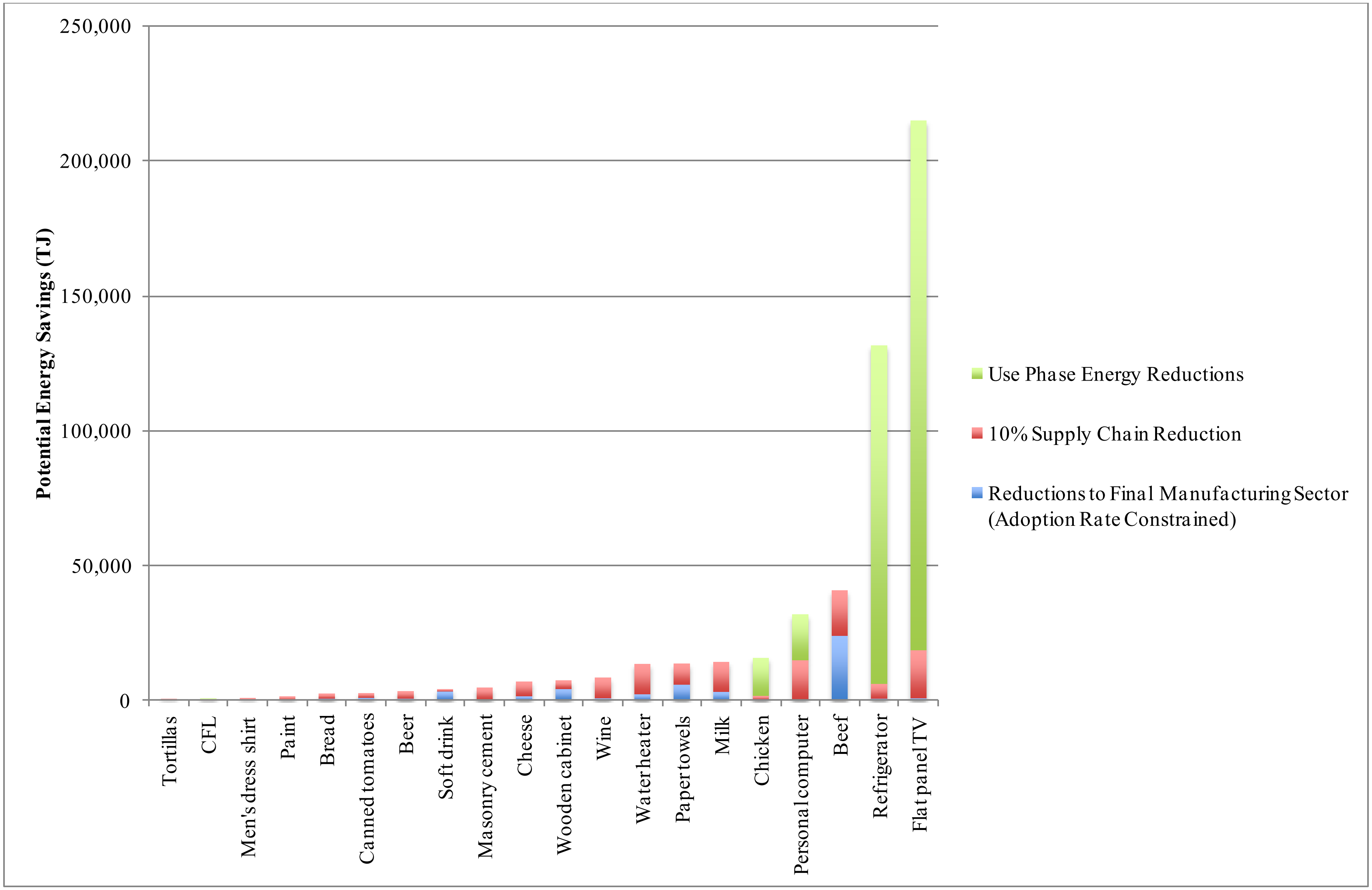

Figure 4-5. Total potential energy savings split into supply chain reductions, final manufacturing sector reductions, and use phase reductions.

6. Conclusions

Modeling of retail products for analysis is streamlined, making an analysis of manufacturing, transportation, and use phase energy quick and easy using the 2002 purchaser price EIO-LCA model with the use phase energy model add-on. The model yields reasonable results that are reasonably consistent with similar analysis done by the CARB report [9]. Differences between the two models are likely due to differences in manufacturing efficiencies in California as compared to the US, differences in potential manufacturing energy reductions modeled, and because the California model considers process GHG emissions which are not the direct result of energy use. Generally results between the two models are fairly similar, however process GHG emissions increase the GHG emissions for animal products. The CARB report employed an MRIO-LCA model which modeled transactions within California at different manufacturing energy intensities than transactions in the rest of the United States based on a CARB GHG Emissions Inventory which is different than that used in the EIO-LCA model. The work in this chapter offers a streamlined approach to this modeling in a different geopolitical boundary from the CARB report using energy instead of GHG emissions.

Use phase energy offers a larger potential for reductions in a fewer number of products. 68% of the available reductions modeled in this analysis are available in the use-phase. The potential to reduce energy by curbing use phase energy consumption through products with a more efficient use phase is larger than nearly every potential reduction through manufacturing improvements with the exception of improving all of the supply chain consumption by 15%. 62% of the available reductions in this model are found in the potential reductions of the use phase in televisions and refrigerators. This suggests that programs aimed at reducing use phase energy consumption without altering behavior, like ENERGY STAR, are well focused and could potentially be expanded for further reductions in energy consumption. These results should be interpreted cautiously, as the list of products in the study, while intended to represent many potential products and manufacturing processes, is not an exhaustive list of relevant retail products. This research could be expanded using something like the Bureau of Labor Statistics Consumer Expenditure Survey [21] to more accurately model the products and services consumed by a consumer unit. Abbreviated results showing results for selected products are displayed in Figure 4-4.

While use phase energy offers a more lucrative reduction than manufacturing energy, reductions are available, though unevenly distributed. Large reductions are available in the production of appliances, electronics, and animal products. This is consistent with the analysis in the CARB report. The results from the CARB report are displayed in Figure 4-6, which shows potential GHG emissions reductions as opposed to the results of this Chapter which are energy reductions. Similar reductions are shown in both analyses; large use phase reductions are available in the use phase of a select few products (refrigerators, hot water heaters, computers, and televisions) and manufacturing reductions are available for animal products. Restaurants have the largest reduction potential in the CARB report but are not modeled in this Chapter as they lie outside the residential sector and thus are outside of the scope of this work. Despite small differences between the two analyses and the fact that they are measured in terms of different metrics, the results are similar in that the top six sectors consistent of the appliances and electronics (not CFLs), and two animal products. While the order is not exactly the same, the broad take-home message is the same in terms of large use phase reduction potentials and smaller, but non-negligible manufacturing reductions for animal products.

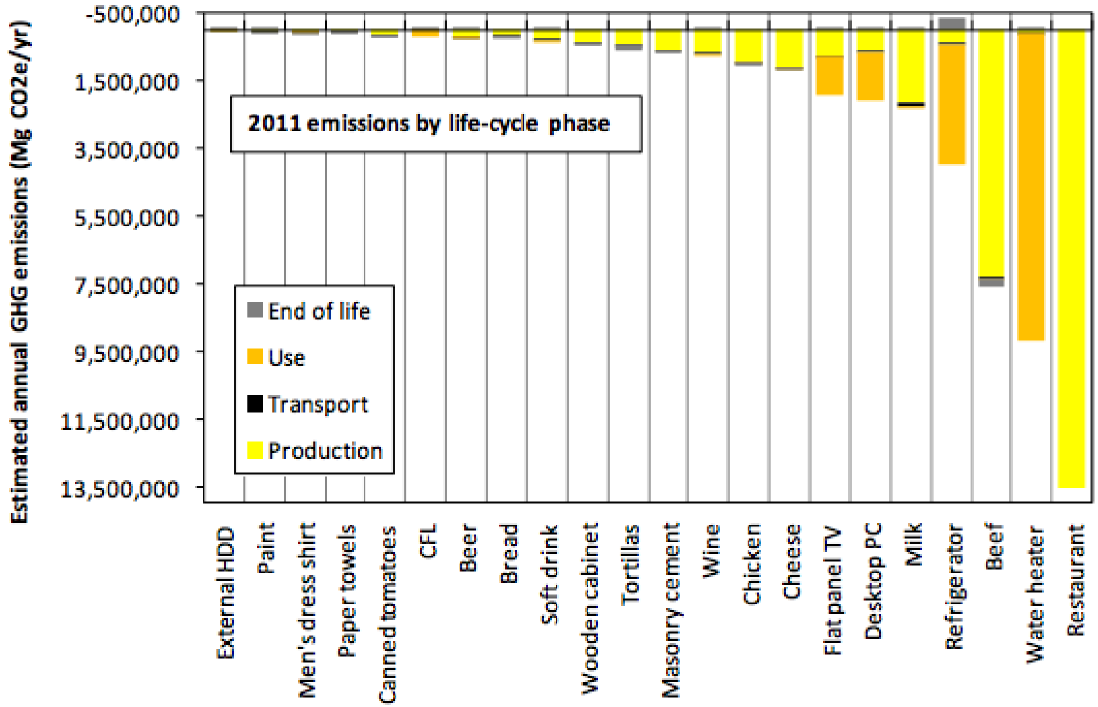

Figure 4-6. Results from the CARB report showing potential reductions in GHG emissions for 22 products that are modeled in the report [9].

Comparing Table 4-10 to Tables 4-8 and 4-9 shows that use phase energy demands far exceed the supply chain and final manufacturing energy demands for the products in the study that have a use phase with the exception of CFLs (televisions, computers, water heaters, and refrigerators) and also have a greater potential for energy reductions than manufacturing reductions. Large manufacturing reductions are also available for a few specific products such as beef production, which has larger reductions potentials than some of the use phase potentials of other products. 90% of the total reductions available in this work are available in only five of 15 sectors (televisions, refrigerators, beef, computers, and chicken).

Given these findings, money that is allocated to reducing residential energy consumption should be dedicated first to programs aimed at reducing use phase energy consumption through technology change and through behavioral changes, then to programs aimed at the manufacturing of certain products like electronics, appliances, and food products from animals, and finally to programs aimed at reducing other manufacturing energy. Regardless of this analysis, actual energy reductions will only be realized if consumers use this better information to make different choices for products than they otherwise would. Altering consumer behavior before an actual purchase is made is important, especially for the purchase of appliances and electronics, which will lock consumers into an energy consumption pathway for several years. Allocating funds in this manner could potentially maximize the energy reductions in residential energy consumption or reduce the cost per energy unit reduced of programs.

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Chapter 5. Conclusions, Contributions, and Future Work

Improved knowledge on energy use in the home is important for consumers to save money and reduce environmental footprints, utilities in order to comply with energy and greenhouse gas policies and mandates, and governmental agencies to comply with intergovernmental greenhouse gas policies and to ensure energy security. This thesis explores the idea that improved information on residential energy consumption can be used by consumers, governments, and companies to enable residential energy reductions. Evidence exists that residential consumers desire to reduce consumption but lack the knowledge and other resources to do so [1][2][3][4][5]. Better information, models, and analysis of retail energy consumption is needed to both enable more effective energy reductions and for a more accurate accounting of programs to reduce energy consumption. This research closes some of this knowledge gap in residential energy consumption.

This Chapter provides conclusions of this research that fall in line with the original research questions presented in Chapter 1 as well as to briefly expand on the contributions of this research. The rest of this chapter will use the original research questions to guide the conclusions of this work.

How can we use aggregated data such as the RECS to predict the quantity and which appliances are likely to be present in a specific household? (Chapter 2)

Understanding the difference between average residential electricity consumption and actual residential consumption is very important when looking at common data like the RECS microdata and the RECS End Use Table [6]. A party interested in systems to monitor household consumption should not make policy or decisions based on the RECS average data, which would overestimate the number of contributing appliances to a household electric load. Likewise, policy makers and other parties interested in energy reductions should use caution when using household or appliance level data when crafting policy at a level that is higher than the household. Using RECS, a model was created that is able to predict the quantity and which appliances are likely to be present in a household based on a number of metrics including household size, household income, census region, and total electricity consumption.

How can we predict differences in appliance ownership and use based on various factors including geography, socioeconomic status, housing size, or total energy consumption? (Chapter 2)

Estimating the number of appliances that contribute to a home's electricity consumption is a difficult, complex problem that many parties are interested in, including national, state, and local policy makers as well as utilities that wish to perform peak shaving and consumers of electricity who may wish to reduce consumption for economical and environmental concerns. Electricity consumption in a household is spread widely amongst many appliances and electronics, but in reality the number of appliances that consume significant electricity in a home is much lower than the average home that is depicted by RECS. Our results suggest it generally requires only 8 appliances to reach 80% of a household's total electricity consumption but this number varies significantly depending on the appliance ownership and usage. To hit the 50%

threshold, generally only the four biggest appliances need to be monitored, but this number drops as low as 2 in the West South Central where central air conditioners typically constitute 40% of a household electric bill. Simply using data from RECS to discover the number of appliances and types of appliances one might expect to find in a home is not sufficient as in the average scenario we see that it takes 12 appliances to reach the 80% threshold. We find that there is not a big difference in the number of appliances to reach the 50% and 80% thresholds for the typical, natural gas, and electric scenarios with the electric scenario requiring 3 appliances to reach 50% and 8 appliances to reach 80% of the household electricity consumption. The natural gas house requires three appliances to reach 50%, but only 7 to reach the 80% threshold. All three of these scenarios require significantly fewer appliances than the average scenario depicts suggesting that using aggregate, national data is inaccurate for decisions at the household level without manipulating the data.

What data sources are available to create use-phase energy vectors that are applicable to EIO-LCA models and where are the significant gaps in the data? (Chapter 3)

Economic Input-Output Life Cycle Assessment (EIO-LCA) is a valuable tool that predicts environmental impacts of economic activity [7]. Despite its value and popularity as a scoping tool, the EIO-LCA model, like most other IO-LCA models, does not include residential use phase energy in the model and as a result includes about 69.5 quads of about 97.7 quads of energy consumed in the United States in 2002, the year of the model [8]. Free, publically available data sources exist from government agencies, nongovernment organizations and companies regarding the consumption of residential energy, lifetime of appliances, degradation of appliances over time, and personal transportation energy use, as well as on annual expenditures for each sector. Little data exists on the expected lifetime energy consumption for all of the devices sold in a given year in a given sector but data is manipulated to estimate this value. From these estimates, energy vectors can be created for each sector of IO models on an energy use per dollar estimate.

Including 21.5 quads of residential energy consumption and 14.7 quads of personal transportation energy brings the total energy consumption to 105.7 quads of energy use in 2002, the year of the EIO-LCA model. Given that the residential energy consumption estimate is about 2.8% higher than the Buildings Energy Data Book estimate for 2002, residential transportation accounts for most of the difference between the EIA total energy estimate and the estimate in the EIO-LCA model. The documentation for the EIO-LCA model confirms that 15.3 quads of transportation energy is intentionally left out of the model for personal transportation which makes the 14.7 quads estimate about 4% lower than we would otherwise expect from the EIO-LCA documentation [9]. Gaps in the data on lifetime consumption for certain appliances and devices are filled with annual energy use estimates that are available under the assumption that the turnover rate is approximately equal to the production rate for these products.

What is the uncertainty associated with use phase energy data and how does it compare across sectors and energy impacts in the EIO-LCA model? (Chapter 3)

Despite having a total energy consumption of about 8% more than the energy consumption in 2002, the EIO-LCA model is much more complete with use phase energy vectors. Without residential use phase energy, the model was missing about 29% of the total energy consumed in 2002. It is also reasonable that this model contains more energy in 2002 than was consumed in 2002 as use phase energy represents total energy over the lifecycle of the goods and services sold in 2002 rather than the total energy consumption in 2002. This is possible because of positive growth rates for the energy demands in the U.S [10].

Uncertainty in use phase energy stems from various components in each calculation in the model including the expected lifetime, number of shipments, energy use per model, behavioral use of each device, and degradation of the devices. Each parameter is discussed in Chapter 3 and the Appendix to provide the best point estimate as well as uncertainty ranges. Even with uncertainty ranges, residential use phase energy always exceeds manufacturing energy for 10 of the 15 sectors that are expected to have use phase energy impacts. An eleventh sector (computers) can be added to this list in most cases except for the highest estimate for manufacturing energy and the lowest use phase energy case. The four remaining sectors have use phase energy estimates that make up between 29 percent and 45 percent of the lifecycle energy consumption. Of these four sectors (handtools, cell phones and cable boxes, alarm systems and intercoms, and telephones), only one sector (handtools) can potentially have a use phase that exceeds manufacturing energy. This means that with the uncertainties in the data, the use phase energy will always exceed manufacturing energy in ten sectors, manufacturing will always exceed use phase energy in three sectors, and two sectors are ambiguous as to which sector may be greater.

What is the maximum reasonable expectation for short-term energy reductions if consumers are given better information regarding retail goods and services to enable consumers to reduce energy? (Chapter 4)

Modeling of retail products for analysis is streamlined in Chapter 4 making an analysis of manufacturing, transportation, and use phase energy quick and easy using the 2002 purchaser price EIO-LCA model with the use phase energy model add-on. The analysis finds that use phase energy offers a larger potential for reductions in a fewer number of products than manufacturing energy. The potential to reduce energy by curbing use phase energy consumption through products with a more efficient use phase is larger than nearly every potential reduction through manufacturing improvements with the exception of improving all of the supply chain consumption by 15%. More than 50% of the available reductions in this model are found in the potential reductions of the use phase in televisions and refrigerators. This suggests that programs aimed at reducing use phase energy consumption through technology without altering behavior, like ENERGY STAR, are well focused and could potentially be expanded for further reductions in energy consumption. This work can be expanded to show the large potential reductions in lifecycle energy that are available in a relatively few number of retail products, namely anything with a use phase component to its lifecycle energy demands. Other sectors in this study that did not have use phase energy demands offered varying degrees of smaller savings. Large supply chain energy reductions are available in the manufacture of electronics and appliances while final manufacturing sector reductions are available in the production of animal products.

What are the particular sets of goods or services that are particularly well suited for better consumer awareness to reduce lifecycle energy on the basis of variation in manufacturing and use phase energy? (Chapter 4)

While use phase energy offers a more lucrative reduction than manufacturing energy, reductions are available, though unevenly distributed. Large reductions are available in the production of appliances, electronics, and animal products. This is consistent with the analysis in the CARB/ California EPA report.

Given these findings, money that is allocated to reducing residential energy consumption should be dedicated first to programs aimed at reducing use phase energy consumption, then to programs aimed at the manufacturing of certain products like electronics, appliances, and food products from animals, and finally to programs aimed at reducing other manufacturing energy. Large total manufacturing reductions are available in these sectors, especially the final manufacturing sector of animal products, and the supply chain sectors of electronics and appliances. While other sectors may offer large relative reductions to their total manufacturing energy, the total consumer expenditures for these sectors keep these potential savings low. Allocating funds in the manner depicted above could potentially maximize the energy reductions in residential energy consumption or reduce the cost per energy unit reduced of programs.

1. Contributions

This work makes several important contributions to the understanding of residential energy consumption in the United States. These contributions potentially can enable people, companies, and governments to reduce this use phase energy in the residential sector.

The first contribution that this thesis makes is a model and analysis that predicts which appliances and how many are expected contribute to a household's electricity consumption given varying characteristics of that home (Chapter 2). This already published work provides a tool that can provide valuable information about which appliances may significantly contribute to residential consumers' electricity consumption thereby enabling reductions of energy consumption through behavioral or technological changes.

The second contribution comes in the form of residential use phase energy data for use in the 2002 EIO-LCA model that predict lifetime use phase contributions of a sector given an economic input. These vectors bring the model closer to modeling the total energy use for all of the purchases in the United States (though end of life energy is still missing from the model). These vectors also increase the breadth of the EIO-LCA model, enabling it to provide scoping analysis that includes residential energy consumption. The ultimate intent of this work is to add these energy vectors to the eiolca.net website for public use to help with disseminating results. Consideration for how to present uncertainty with these additional energy vectors in the model is a necessity.

The final contribution of this work is an analysis of the maximum reasonable potential energy reductions expected as a result of reductions in manufacturing energy from improved consumer knowledge of the lifecycle energy demands for retail products and services given available manufacturing reductions with short payback periods of three years or less. This modeling utilizes the energy vectors created in Chapter 3 to analyze potential energy reductions in both the use phase and manufacturing sectors for many retail products. The work offers streamlined analysis that suggests that the largest potential reductions stem from the use phase energy of a few products, followed by manufacturing energy in the supply chain of certain types of products including animal products, electronics, and appliances.

2. Future Work

While this work improves knowledge of residential energy consumption at the sectoral and product levels, it also identifies areas that could be expanded upon to further these improvements.

First, upon the complete release of 2009 RECS microdata, the analysis and model created in Chapter 2 could be updated [11]. The 2009 microdata offers about three times the number of samples in its survey as well as state specific data for 16 states as opposed to the four states identified in the 2005 microdata [12]. This data would improve the model and analysis by bringing the data closer to the present, offering a larger and more accurate sample, and providing more ways to identify a household. With a larger sample size and more identifying characteristics, multiple metrics could potentially be utilized simultaneously to more accurately predict the characteristics of electricity consumption in a home. For example, rather than separately exploring likely appliances found in a given census region and likely appliances found in a home with a certain income level, the two metrics could be combined to model a specific income level and a given census region. The improved data could also be used to create ranges of energy consumption for the use phase energy vectors discussed in Chapter 3.

The work in Chapter 2 could also be further expanded to include or separately model consumption of natural gas and other fuels, and other appliances. Electricity was selected as it is the largest component of primary energy consumption in the residential sector and because it is so spread amongst various end-uses. Natural gas is also a large consumer of energy in the home, though it tends to spread amongst fewer appliances and end uses. Other fuels could also be included, though like natural gas appliances, are spread amongst fewer appliances, primarily for heating purposes (hot water heaters, clothes dryers, space heating, etc.) which could be useful for efficiency programs and cost-effectiveness studies. Adding natural gas and other fueled appliances could enable users with improved understanding of energy consumption to reduce it beyond electricity reductions through behavioral or technological based approaches.

Improved modeling may be possible in the future as smart appliances that monitor their own energy consumption and communicate with control systems in a home become increasingly popular. These improved appliances will offer insight into both the consumption within the homes that they reside which is incredibly valuable to homeowners, but also for modeling at a higher level such as local or regional levels. With real, empirical data, regression models to predict energy consumption in homes will be unnecessary and data about residential energy consumption will be more reliable with less uncertainty. This data could replace RECS data to strengthen the predictive capabilities of the model described in Chapter 2.

In the future, the work in this thesis should be expanded beyond the scope of individual appliances to include household systems level changes to explore the potential energy reduction capabilities of such a system across all of the energy consumption in a home. An example of this would be something like adding direct current (DC) storage and DC compatible circuitry in the home for the addition of renewable energy systems. Large systems changes of this magnitude that have the potential to affect many appliances are not modeled in this work but should be explored in the future, especially with the increasing popularity of solar panels, storage batteries, and other alternative energy sources at the household level. Comparisons of large systems changes could be compared to the individual product modeling that was performed in Chapter 4. These additions could also work well with the addition of residential use phase greenhouse gas emissions vectors to the EIO-LCA model as discussed above.

The work could further be expanded by combining the works of Chapter 2 and 4 to predict individual consumer purchases to model and predict how energy is consumed in a home. This combination could also predict ways in which energy demands may be reduced given certain characteristics of that home such as location, total electricity, household income, or total floor space; and how that home is expected to consume electricity and, more broadly, energy including manufacturing or embedded energy in the products it likely consumes. For example, if policy makers were interested in where large potentials existed to save energy in the residential sector in New England, they might find a different set of efficiency measures than policy makers interested in the same reduction potentials in the East South Central Census Division.

The RECS dataset and summary reports rely on relatively few data points. Hopefully the RECS will continue to grow in sample size and improve in data quality as it moves from the 2005 survey to the 2009 survey and beyond. Regardless of improvements that may be made to the RECS dataset, it is vital that stakeholders are able to distinguish between the average home and what an actual home may consume in terms of electricity in order to better facilitate reductions in electricity consumption. Careful analysis of RECS, the most comprehensive national survey regarding energy consumption, reveals important details about which appliances we expect will be significant consumers in households. This information can be used to further develop disaggregation techniques such as nonintrusive load monitoring (NILM) as it potentially could reduce the number of appliances that need to be included in such a tool. This, in turn, will help stakeholders make informed decisions in regards to energy use. This analysis of which appliances are expected to significantly contribute to a household based on certain household characteristics may also be used to further improve the next iteration of RECS and other top-down energy models, thereby continuing the symbiotic improvement of both top-down and bottom-up residential energy models.

The class of use phase energy vectors for IO-LCA models created in Chapter 3 can be expanded to create greenhouse gas (GHG) emission vectors based on national average emissions factors for the use phase energy vectors. Leaks and wasted primary energy is accounted for in the totals, which makes this future work relatively easy. GHG vectors would be useful as interest in curbing GHG emissions increases with the ever-present threat of climate change. These vectors would directly connect the energy use in the vectors to GHG emissions and enable similar analysis on a GHG basis rather than on the basis of energy consumption alone.

The use phase energy (and potentially GHG emissions) vectors created could be developed regionally, using methods shown in Chapter 2, to help show variations in energy and GHG emissions regionally, adding a dimension not shown in the current work.

Future work could further expand the EIO-LCA model in that it could move beyond primary use-phase energy allocations to secondary use. This is best explained through an example like a refrigerator. A primary use phase energy allocation would assign all of the energy use to run a refrigerator over its lifetime to the IO sector 335222 Household Refrigerator and Home Freezer Manufacturing. However there are very few running refrigerators that do not contain goods that need to be refrigerated. These products are what drive the demand for the refrigeration. A secondary use-phase allocation may take the energy that is consumed by the refrigerator and reallocate a portion of it to the goods that the refrigerator is cooling. Maintaining a primary use phase vector without double counting is possible if we were to set up an allocation factor that can be adjusted between 0 and 100% that would allow the user to select what portion of the use-phase energy and impacts should be allocated to the primary use (the refrigerator), and how much should be allocated to the products in the refrigerator. Alternatively, the model could track both primary and secondary use phase energy but leave the secondary use-phase energy out of the totals, thus avoiding any double counting issues that would otherwise arise. The most difficult part of the development of a secondary use-phase energy vector would be deciding where to draw the boundaries. All energy use can be associated to another product or service to some degree. For example, the energy use required to run a home vacuum cleaner could be allocated to the carpets that are being cleaned. The energy used that is allocated to the carpet could further be allocated to wool or nylon manufacturers and color dye producers, and so on ad infinitum. As it stands, secondary allocations of use phase energy are outside the scope of this work, which is why the residential use phase energy consumption is limited to 15 sectors that directly consume energy. The application of this secondary source reallocation would be to allow use phase energy to be associated with the life cycles of more products/sectors than currently modeled, such as food products.

Providing information on products to reduce energy consumption could potentially be expanded to commercial goods and services such as hotels and restaurants which have large purchasing power and the ability to reduce energy consumption at all points in the supply chain by providing information on embedded and use phase emissions to managers and owners of these commercial entities as well as consumers. Consumers, if provided information on energy consumption of the goods and services, could pressure commercial operations to improve energy demands for goods and services. Incentivizing commercial sectors to reduce their energy consumption both in the use phase and in the manufacturing sectors of the goods and services that they provide could potentially have an equally profound or larger effect as the residential consumer program identified in Chapter 4.

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