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In

Environmental Design and Planning

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This research proposes to simplify the energy consumption assessment for residential homes while building the foundation towards the development of prediction tools that can achieve a credible level of accuracy for confident decision making. The energy consumption assessment is based on simplified energy consumption models. The energy consumption analysis uses a reduced number of energy model equations utilizing a critical, limited set of parameters. The results of the analysis are used to develop the minimum set of consumption influence parameters with predicted effects for each energy consumption domain.

During this research study, multiple modeling approaches and occupancy scenarios were utilized according to climate conditions in Blacksburg, Virginia. As a part of the analysis process, a parameter study was conducted to: develop a comprehensive set of energy consumption influence parameters, identify the inter-relationships among parameters, determine the impact of energy consumption influence parameters in energy consumption models, and classify energy consumption influence parameters under identified energy consumption domains.

Based on the results of the parameter study, a minimum set of parameters and energy consumption influence matrices were developed. This research suggests the minimum set of parameters with predicted effects to be used during the development of the simplified baseline energy consumption model.
Dedication

This dissertation is dedicated to my father, Ergun Durak, who would have been very proud.
Acknowledgment

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1 Executive Summary

The U.S. annual energy demand and service costs for oil, electricity and natural gas are projected to steadily increase in the next decade regardless of the increase in domestic production. Residential energy consumption, which is a significant contributor to overall energy consumption, is also projected to rise due to the increased demand. Subsequently, greenhouse gas emissions are predicted to increase as well despite of global and national legislation and policies implemented in recent years.

Currently, there are various products, applications, and decision making tools available for use in the realm of building energy efficiency in order to address the growing energy demand and its repercussions on a national and global level. However, most of the comprehensive energy efficiency tools target the industrial and commercial sectors. Some of the applications allow for examination of various aspects of energy efficiency options for residential construction through sophisticated energy models. However, these tools usually do not address the capabilities and technical understanding of typical homeowners when it comes to responding to solicited input accurately. Other tools that utilize a reduced and simplified input process are mostly modifications of the previously mentioned comprehensive tools. They utilize the same simulation models, which were originally designed for commercial or industrial applications, by setting many of the input variables to default values. Consequently, no tool has achieved energy performance modeling with a credible accuracy and confidence level, which ultimately should provide energy consumption and energy saving predictions that can be used for reliable retrofit decision-making in residential homes.

This research attempts to reduce the number of total model equations utilizing a critical, limited set of parameters. This set of parameters and equations only consists of those that significantly affect residential energy consumption instead of using comprehensive energy models, such as the DOE-2 building simulation engine, which then needs to set thousands of parameters to default values for simplification, which in turn can blur the overall accuracy of results.

The credible level of accuracy and confidence for simulation results of energy consumption predictions in residences is defined as an error margin of 25% for 70% of homes and 50% for 90% of the homes when compared to actual consumption (EAI and CSG 2009). The tangible outcome from this research is a comprehensive understanding of influence parameters and their...
predicted effects for each residential energy consumption group. Furthermore this research presents an analysis towards a reduced set of influence parameters and modeling equations. Ultimately, this will build the foundation for the development of tools that will allow for energy consumption assessment and predictions with credible levels of accuracy and confidence for retrofit decision-making.
2 Background

2.1 Introduction

According to Annual Energy Outlook 2009 published by Energy Information Administration (EIA), the annual energy service costs for oil, electricity and natural gas are projected to increase by 67% by the year 2030 in U.S. alone (EIA 2009a). The same projections estimate that approximately 19% of the U.S. energy consumption by the year 2030 will be due to residential sector demands, which is an increase of 10%.

Greenhouse gas emissions (GHG) and the negative impact on the environment is another implication of energy production and consumption to satisfy human needs. Carbon Dioxide (CO2) and Methane (CH4) gas emissions during commercial, residential and industrial sector operations make up for the majority of GHG emissions (EIA 2008b). Regardless of policies and restrictions imposed globally, the CO2 emissions are still expected to increase at a rate of 0.3% per year as a result of the increase in primary energy consumption (EIA 2008c). The residential sector is also projected to be the third largest energy consuming sector and contribute to GHG emissions significantly by the year 2030 (EIA 2009a).

Over the course of the past 20 years, many studies have examined different aspects of residential energy efficiency in order to address the growing energy demands for the sector. While some studies dealt with pure model development, other studies explored various types of implications resulting from residential energy efficiency retrofit projects on local and national levels. Subsequent studies have explored the homeowner component in the diffusion of residential energy efficiency strategies, as well as the decision-making component for energy efficiency through evaluations such as multi-criteria analyses. As a result, these research findings have meanwhile been utilized to develop several products, applications, and decision-making tools that are currently in use. Applications like Best Practice House (Energy Saving Trust 2009), Home Advisor (Energy-Star 2009a), Microsoft Hohm Beta (Microsoft-Corporation 2009), and Home Energy Saver (LBNL 2009) have examined various aspects of energy efficiency options for residential construction through sophisticated energy models. However, no tool has yet provided energy performance modeling with a credible level of accuracy and confidence, which ultimately provides accurate energy use and saving predictions for retrofit decision-making in
residential homes (Mills 2004, EAI and CSG 2009). The following question emerges: Is it possible to utilize a simplified energy model for residential home energy consumption assessment that will achieve credible levels of accuracy and confidence towards retrofit decision-making?

### 2.2 Utility Prices and Natural Resource Implications

Increasing energy prices, depleting natural resources, and their national level implications and effects on residential sector have always been the main driving forces behind the research in the field of energy efficiency for residential construction in U.S.

On a national level, the annual energy consumption and the related costs have been steadily increasing over the past decades and the increase is estimated to continue. In the most recent Annual Energy Outlook report published by EIA, the U.S. annual energy service costs for oil, electricity and natural gas were a sum of $1.2 trillion in 2007 and were forecasted to increase to $2 trillion by the year 2030 due to a multitude of global and socioeconomic factors (EIA 2008a, EIA 2008d, EIA 2009a, EIA 2009b, EIA 2009c).

Along with crude and heating oil, the national demand and cost for natural gas is projected to increase as well. Despite lifting of the Presidential ban on offshore drilling in portions of the Outer Continental Shelf on July 2008, the demand for natural gas is expected to increase by 10% while the price of natural gas is still expected to increase by 25% by the year 2030 (EIA 2009a).

Besides oil and natural gas, electricity accounts for the remainder of energy service costs (ibid). Electric power generation in U.S. mainly relies on domestic power plants, the majority of which utilizes fossil fuels that are affected by depleting natural resources and increasing energy prices (EIA 2008). In addition, rising construction costs and weakening economic conditions result in a projected decrease of overall demand and a related increase of 35% in electricity costs (CERA 2008, EIA 2009a).

The residential sector energy consumption and cost projections follow trends similar to those for the national level. In the most recent Annual Energy Outlook report published by EIA, it is estimated that approximately 19% of the U.S. energy consumption by 2030 will be due to residential sector demands, which is estimated to increase by 0.5% per year (2009a).
Similar to other sectors, the three sources of U.S. residential energy consumption are electricity, natural gas and heating oil (EIA 2005). Residential electricity usage has increased by 23% in the past decade due to increased air-conditioning usage as a result of warmer weather conditions and the increased energy demands for new home electronics and other applications (EIA 2009d). Despite the implementation of the best available energy efficient technologies, only a reduction of 1.8% of delivered energy intensity and 1% of residential consumption is predicted (ibid.). The residential sector natural gas consumption is also predicted to increase especially for the Midwest part of U.S., which was estimated to cause a 1.8% rate increase during 2009 alone (EIA 2008f). However, due to a significant decline in consumption over the past decades, the number of U.S. households that use heating oil as the primary source is negligible (EIA 2001).

2.3 Green House Gas Emissions by Residential Sector

Greenhouse gas emissions (GHG) and the negative impact on the environment resulting from energy production and consumption are other driving forces behind the development and implementation of energy efficiency in general and residential energy efficient technologies in particular.

In the U.S. alone, the overall GHG emission of CO2 increased at a rate of 14% and CH4 increased at a rate of 2.3% over a year (EIA 2008f). Over the course of past decades, various international and domestic policies and restrictions have been implemented to control and reduce these emissions. Some of the recent enactments include national and statewide emission limits, the Clean Air Act and its amendments as regulated by the Environmental Protection Agency and the recent federal and state legislations (Carlson and Metcalf 2008). Despite rising energy prices and new incentives outlined in the Emergency Economic Stabilization Act of 2008 and the subsequent Energy Improvement and Extension Act of 2008, the primary energy consumption is predicted to increase by 0.5% per year and CO2 emissions are predicted to increase by 0.3% per year until 2030 (EIA 2009a).

In a recent study, residential sector GHG emissions were identified to account for 18% of the total GHG emissions in U.S in 2007 (EIA 2008c). In 2008, the total GHG emissions for the residential sector were found to have decreased by 1.1% compared to 2007 levels. This can be attributed to an 8.7% decrease in cooling degree-days while observing only a 5.6% increase in
heating degree days over this period (EIA 2008e). However, the total GHG emissions for the residential sector were found to have increased by 27.5% between the years 1990 and 2008 (ibid.). It was also forecasted that if no stringent measures were implemented for utilizing renewable energy sources and energy efficient technologies, the demand for residential and industrial end-user sector electricity will increase and the GHG emitted by the traditional coal operated power plants will increase by 53% by the year 2030 (Johnston et al. 2007). In addition, even though natural gas emits considerably less CO2 compared to fossil fuels, due to the projected increase in consumption, the contribution is projected to be significant (EIA 1998).

2.4 Residential Energy Efficiency

Over the course of the past 20 years, many studies have examined different aspects of residential energy efficiency in order to address the growing energy demands for the residential building sector. The initial studies focused on residential energy efficiency, which provided the foundation for retrofit decision-making tools. The different research areas within the residential energy efficiency domain can be grouped as impact studies, research regarding the homeowner component, and research regarding the decision making component. The breadth of representative studies under each group is provided as follows:

2.4.1 Impact Studies

Earlier studies have explored the following different implications of residential energy efficiency retrofit projects:

a) Academic Research:

Most of the earlier academic research in the residential sector concentrated on energy use during the lifecycle of single family dwellings. Adalberth (1997) and Keoleian et al. (2001) utilized lifecycle analysis to investigate the effects of building envelope and its thermal characteristics while Shah et al. (2008) conducted the analysis to investigate the effects of heating and cooling systems. Utilizing residential Photovoltaic (PV) systems to supply power to a residential dwelling has also been investigated by many studies. Alkamis and Sherif (1997) and Kato et al. (1998) explored the financial aspect of these systems by analyzing Return on Investment (ROI) and the energy payback time. Celik (2006), Celik et al. (2008) and Tripanagnostopoulos et al. (2006) have examined the efficiency and feasibility of these
modules and other more advanced versions. Simonson (2005) has conducted studies on ventilation efficiency of sustainable, low-energy houses in order to reduce the energy consumption demands in the severe weather conditions. Sartori and Hestnes (2007) explored the differences between solar, passive and conventional houses in terms of reduction in energy consumption across multiple countries.

b) Local and National Level:
The concepts of energy efficiency and retrofit decision-making have been explored for varying social constructs and contexts. Mulder (2007) examined the family component in order to determine the behavioral implications of family and society context on residential housing choice. Zavadskas et al. (2008) explored frameworks utilized in order to determine the significance of residential retrofit decision-making based on energy savings and increased market value of the property in city districts. On a national level, Balaras et al. (2007) examined the most effective energy conservation measures in Hellenic residential buildings in order to reduce the GHG emissions through a national action plan and Mills and Rosenfeld (1996) identified the non-energy benefits of energy efficient technologies with a direct impact on the national economy. On a larger scale, Mahlia et al. (2003) tried to predict the energy savings associated with implementing energy efficiency standards for refrigerator-freezer appliances for the residential sector in Europe. The influence and effect of government involvement has also been studied by many researchers. The government energy efficiency incentive programs and energy performance requirements were explored by Srinivasan (2007) and Pinkse and Domisse (2008). Al-Hammad and Said (1992, 1993) have explored electrical energy conservation through energy efficient designs by utilizing government supported applied research efforts in order to reduce government subsidy energy costs.

c) Industrial Sector:
The effect of residential energy efficiency on construction industry is another research area that has been evaluated by researchers. Srinivasan (2007) has explored the effects of the increase in residential applications through higher module efficiencies and rate of return on investments on the world-wide solar-powered heating and cooling industry market share growth. Pinkse and Domissile (2008) on the other hand analyzed the barriers that prevented
the full market integration and effective diffusion of residential energy efficient technologies in the construction industry.

2.4.2 Research regarding the homeowner component

The homeowner component as a part in the diffusion process of residential energy efficiency has been studied in many research projects. In an earlier study, Mills and Rosenfeld (1996) explored non-energy benefits of energy efficient technologies as a residential homeowner motivation tool. The Energy Efficiency Team of Purdue University (EETPU) has developed models to analyze standard Habitat for Humanity dwelling units against different energy efficiency options and determine energy and cost savings in order to make the unit affordable for low-income homeowners (EETPU 2000). More recently, Lopes et al. (2005) analyzed dwellings with a focus on occupant behavior as it relates to electrical appliance use and Ouyang and Hokao (2009) explored the effects of energy-saving education in improving occupant behavior in order to evaluate the energy-savings potential and the related decrease in electricity consumption.

2.4.3 Research regarding the decision-making component

The decision-making component in the form of evaluations and multi-criteria analyses has been another significant aspect of the energy efficiency research area. Unfortunately, most of the studies in the field of decision-making have been geared towards industrial applications, which have subsequently been adapted for residential applications. Earlier studies in the research field consisted of testing the efficacy of multi-criteria analysis as a decision-making tool from an administrative side. Tonn and Martin (1999) evaluated a multi-criteria analysis model in order to test the industrial influence of energy efficiency programs implemented by the government. More recently, these tools have been used by researchers such as Afgan and Carvalho (2002), Pilavachi et al. (2006) and Wang et al. (2009) during the evaluation of industrial combined heat and power (CHP) system options that enable decision makers to obtain accurate results out of a set of weighted and non-numerical indicators. Most recently, the effectiveness of multi-criteria analysis on energy options has been analyzed by applied social science studies as well. Kowalski et al. (2009) utilized five renewable energy options for Austria 2020 in order to examine the efficiency of participatory multi-criteria analysis (PMCA) utilized along with scenario building.
2.5 Energy Efficiency / Retrofit Decision-Making Tools

The evolution of energy efficiency / retrofit decision-making tools as illustrated by Figure 1 have followed the natural progression of the research and its findings in the field of residential energy efficiency in order to address the growing energy demands for the sector. Earlier studies have explored the industrial, academic research, and local and national implications of residential energy efficiency retrofit projects. Subsequent studies have explored the decision-making component for energy efficiency by evaluation and multi-criteria analysis and homeowner component in the diffusion of residential energy efficiency. As a result the research findings have been utilized in order to develop the many products, application and decision-making tools in-use currently.
Figure 1  The evolution of energy efficiency / retrofit decision-making tools
Many findings of the research studies outlined in the previous sections have provided the foundation for the development and implementation of energy efficiency and retrofit decision-making tools by researchers, government entities and corporations. Most of the initial studies and comprehensive product development efforts have targeted industrial applications, which subsequently branched off to and were adopted as residential tools. Table 1 provides some of the examples of the commonly used tools, which are described in more detail in Appendix A.

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<th>Primary Purpose</th>
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<td>Pacific Northwest Laboratory (PNL)</td>
<td>Industrial</td>
<td>Building Facility Management</td>
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<tr>
<td>Best Practice House</td>
<td>Energy Saving Trust (EST)</td>
<td>Residential</td>
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Table 1  Examples of the commonly used decision-making tools

2.5.1 Analysis of Energy-Efficiency / Retrofit Decision Making Tools for Residential Homes

In order to further examine energy-efficiency / retrofit decision-making tools, only those applications that were developed for residential homes have been selected for further analysis. In this analysis, Energy Savers developed by DOE (DOE 2009d), Microsoft Hohm Beta developed by Microsoft Corporation (Microsoft-Corporation 2009), Energy Aide developed by Energy New England (ENE) (ENE 2009), Home Energy Tune-Up developed by CMC Energy Services (CMC) (CMC 2009) and Energy Efficient Rehab Advisor developed by Department of Housing
and Urban Development Office of Policy Development and Research (DHUD) (DHUD 2009) are evaluated in addition to some of the applications discussed in the previous section. Analysis parameters of those applications listed within DOE’s Building Energy Software Tools Directory have been utilized to analyze the capabilities of each tool (DOE 2009c). A summary of results are shown in Table 2 and Table 3. The full results of the analysis are provided in Appendix B.

<table>
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</thead>
<tbody>
<tr>
<td>Models Used</td>
<td>Energy Savings Calculator Under Construction</td>
<td>Information Not Available</td>
<td>Information Not Available</td>
<td>Information Not Available</td>
<td>Information Not Available</td>
<td>Information Not Available</td>
</tr>
<tr>
<td>Accuracy Results</td>
<td>Information Not Available</td>
<td>Information Not Available</td>
<td>No Verification Provided</td>
<td>No Verification Provided</td>
<td>No Verification Provided</td>
<td>No Verification Provided</td>
</tr>
<tr>
<td>Tool Capabilities</td>
<td>Interactive simulation for components and energy efficient technologies</td>
<td>Basic search engine, utilized to provide a list of contractors in the immediate vicinity</td>
<td>Energy use costs as related to parameters; report with periodic estimates</td>
<td>Provides recommendations for systems, and a do-it-yourself document</td>
<td>Provides comparison of national energy use, GHG emission and a yardstick score</td>
<td>Information on audits, remodeling options, assistance programs</td>
</tr>
<tr>
<td>Expertise Required</td>
<td>Intermediate level of system and code knowledge</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>Decision-Making Complexity</td>
<td>Information Not Available</td>
<td>Information Not Available</td>
<td>Inputs include pre-determined costs/unit to calculate total</td>
<td>No decision-making component</td>
<td>Pre-determined local &amp; national averages and yardstick score</td>
<td>Information Not Available</td>
</tr>
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</table>

Table 2 Residential decision-making tool analysis Part I
Table 3  Residential decision-making tool analysis Part II

In addition, Mills (2004) has analyzed 50 web-based and 15 disk-based residential energy analysis tools. Many of them were found not to provide an analysis of energy saving options. In addition, based on inaccurate consumption predictions, they were found to be incapable of evaluating significant building energy issues and efficiency features. The tools provided a wide range of whole-house energy bills inaccurately as a result of many programming and algorithm errors. The overall results of the study are as follows:

- The input choices are often very confusing to the end-users
- Web-based tools appeared to offer a broader end-use coverage compared to disk-based tools
- Many of the underlying calculations and simulation techniques were found to be inaccurate
• Saving calculations were found to be inaccurate even though baseline calculations were accurate in some instances
• Changes to inputs were found to provide inaccurate changes in predicted energy use
• User-specifiable options were found to be incomplete and bad representative values of the actual building
• Many of the design questions were found to bias the accuracy of the results due to input errors and incorrect house descriptions
• Many of the tools were found to produce inaccurate results in different climate conditions
• The sum of all the factors discussed above was found to accumulate and thus result in even more inaccurate predictions.

The study also made the following conclusions necessary for developing an accurate and effective tool to be utilized by the end-users:

• The residential energy analysis tools should incorporate many social science guidelines and principles as well as engineering principles in order to better suit the needs and capabilities of end-users
• The tools need to be carefully designed in order to address the diverse end-user needs and to support the decision-making process and usability.
• The tools need to incorporate estimates of potential energy savings, substantial decision-support content, recent building science research, a wide range of geographic conditions, technical accuracy, modeling for occupant effects that provide open-ended energy calculations with uncertainties embodied in the results and quality control measures in order to reduce programming, design and calculation errors.

More recently, Earth Advantage Institute (EAI) and Conservation Services Group (CSG) has conducted a further analysis of residential energy analysis tools with their Energy Performance Score (EPS) 2008 study (EAI and CSG 2009). EPS 2008 was the primary study conducted to develop standards and guidelines in order to achieve a common miles per gallon type metric applied to home energy use prediction. EPS 2008 study was supported by Energy Trust of Oregon, which is a non-profit organization, and CSG, which is a not-for-profit organization. Although the fieldwork was conducted by EIA and their Home Energy Rating System (HERS) certified auditors, who followed the Residential Energy Services Network (RESNET) rating
protocol, supervision was provided by all the stakeholders and all final reports were peer reviewed. In this study, over 100 energy efficiency option tools were surveyed including those recommended by energy modeling experts, those listed on the DOE’s Building Energy Software Tools Directory (DOE 2009) as well as those analyzed at LBNL by Mills (2004). Fifteen of the tools were reviewed in greater detail to determine the level of prediction accuracy. As a result, two versions (mid-level and complete versions) of Home Energy Saver developed by LBNL, REM/Rate, which is an accredited and widely used Home Energy Rating System software, and SIMPLE, which is a simplified spreadsheet based modeling program with 32 data points, were selected for more in-depth analysis. The analysis was conducted in order to determine the accuracy of energy use prediction, audit time and ease of use. It was based on a sample of 190 homes in Portland and Bend, Oregon during the fall and winter months of 2008. The accuracy analysis consisted of comparing weather normalized utility billing data for each home to energy predictions provided by the software. The mean percent of error (for both over and under predicting) for energy use prediction was found to be 25.1% for SIMPLE, 33.4% for HES full version, 43.7% for REM/Rate and 96.6% for HES mid-level version. The other evaluated measure was prediction confidence, which was determined by the percentage of homes for which the programs predicted well or poorly. Predicting well was defined in the study to be over-predicting or under-predicting by less than 25%, while predicting poorly was defined to be over-predicting or under-predicting by more than 50%. According to these criteria, SIMPLE had 51.6% well and 7.9% poor, HES full version had 53.7% well and 21.6% poor, REM/Rate had 43.2% well and 31.6% poor, and HES mid-level version had 19.5% well and 60.5% poor predictions. SIMPLE software was found to be the easiest to use with the lowest audit time amongst the other applications analyzed. HES full version required 185, REM/Rate required 100, and SIMPLE required 32 data entry points. The required amount of time to complete a home-audit was 1 hour for SIMPLE, while it was 1.5 hours for HES mid-level version, 2 hours for HES full version and 2.5 hours for REM/Rate. Similarly, the estimated time length for data entry by a technician was 14 minutes for SIMPLE, while it was 3 minutes for HES mid-level version, 47 minutes for HES full version and 45 minutes for REM/Rate. Consequently, none of the tools were determined as a comprehensive yet accurate and easy to use option. In addition, the credible level of accuracy for future tools was determined to provide energy use predictions within an error margin of 25% for 70% of homes and 50% for 90% of the homes when compared to actual use. This determination was made as a suggestion:
a. based on software tool analysis, literature search, programs, metrics, and interviews, focus groups and survey findings from a pool of 525 homeowner, realtor, builder, contactor, and green building professional participants.

b. in order to establish a starting point for an EPS software standard, which is deviation from the RESNET accreditation requirements of comparing software predictions to predictions of other software results.

Overall, the results of the EAI study, the previously discussed study by Mills (2004), and the preliminary tool analysis all concluded that none of the currently available tools captured all of the essential characteristics of a residential energy efficiency / retrofit decision-making tool listed below:

a. Credible level of accuracy and confidence for home energy consumption assessment
b. Limited amount of parameters in order to avoid user confusion and inaccurate input
c. Limited level of technical content in order to suit the needs and capabilities of the homeowner

Currently, most of the comprehensive energy efficiency decision-making systems target the industrial and commercial sectors (PNL 2009, FIA 2009, DOE 2009a and DOE 2009b). Applications like Best Practice House (EST 2009), Home Advisor (Energy-Star 2009), Hohm Beta Version (Microsoft 2009) and Home Energy Saver (LBNL 2009) have been developed based on extensive studies that examined various aspects of energy efficiency options for residential construction through sophisticated energy models. Yet none of these studies have investigated the capabilities of the novice homeowner as they correspond to soliciting input accurately. More importantly, several tools have utilized complicated simulation programs or models such as DOE-2 Building Energy Simulation Program, which is primarily developed for engineers, energy consultants, and utility staff in order to calculate energy use and cost for all types of buildings (DOE-2 2010). The DOE-2 model in particular is developed mainly to size equipment and analyze different component effects during the building design phase. It utilizes thousands of parameters that are used in multiple sections through a network of script files and associated relationships in order to cover all types of buildings. When adapted to residential construction, the sections that are irrelevant to residential construction compete with the other sections that are relevant due to the input script files and associated relationships between the sections and the input parameters. In addition, some programs such as building design advisor,
which utilizes the DOE-2 model as a core model, are programmed to automatically assign default values to input parameters based on codes, standards and best business practices causing the energy consumption calculations to be grossly inaccurate when applied to residential construction (LNBL 2010). Consequently, considering that most of the tools that are in current use utilize these sophisticated models or their variations, none of them has been able to provide energy performance modeling with a credible accuracy and confidence level for residential buildings, which would ultimately provide accurate energy use and saving predictions for retrofit decision-making in our homes.
3 Research Overview

3.1 Research Goal

The primary goal of this research is to simplify the energy consumption assessment for residential homes while building the foundation towards the development of prediction tools that will achieve a credible level of accuracy for confident decision making. This research strives to provide a reduced set of influence parameters with predicted effects for each energy consumption domain. The effects of each influence parameter on the various consumption domains are investigated, which provides the foundation for future research on simplified energy performance model development for residential homes.

Throughout this research study, certain terms are frequently used to refer to different components. The definitions of the frequently used terminology are provided below. Also, Figure 2 and Figure 3 illustrate the inter-relationships among these terms through examples.

**Figure 2**  Frequently used Research Terminology

**Energy consumption influence parameter:** These parameters are variable characteristics related to the residential dwellings. They can often be broken down to sub-parts. They do not consume energy. However, they influence the load requirements and impact the amount of energy consumed. Some examples of influence parameters are: “number and size of windows”, “total square footage”, and “number of stories”.

![Diagram of influence parameters and consumption categories](image)
**Energy consumption influence parameter group:** Parameter groups are formed by clusters of relevant consumption influence parameters. These groups are used to simplify modeling paths during consumption calculations. They are also used to determine the combined effect on consumption during impact analysis as well. Some examples of parameter groups are: “thermal envelope characteristics”, “thermal envelope size”, and “inside and outside air conditions”.

**Heat Flow Categories:** These categories consist of different types of heat transfer in the form of heat loss or heat gain between the interior and exterior of the dwelling. The heat flow categories are utilized during heating and cooling energy consumption calculations. These categories consist of: transmission heat flow (Qt), ventilation and infiltration losses (Qv/i), solar gains (Qsol), heat gain from appliances and electronics (Qe), heat gain from people (Qp), and system loads (Qsys).

![Energy Consumption Domain](image)

**Figure 3** Frequently used Research Terminology - Cont.

**Energy consumption domain:** Consumption domains are separate analysis scopes for energy consumption. They are used to simplify the energy consumption analysis and more effectively evaluate the impact of influence parameters. They are usually influenced by multiple parameters and can contain one or more of the consumption items. The energy consumption domains are classified as: appliances and electronics, interior lighting, domestic hot water, space heating, and space cooling.

**Energy consumption item:** Consumption items, which include building systems (such as heating system, cooling system, etc.) as well as stand-alone items (such as washer, stereo equipment, etc.), consume energy to meet the load requirements for the duration of use. A list of various energy consumption items categorized by consumption domain is provided in Table 4.
Energy Consumption Domains | Available Energy Consumption Items
--- | ---

**Space Cooling** | Absorption Cooling, Fan, Evaporative Cooler, Air Conditioner, Radiant Cooling

**Domestic Hot Water** | Conventional Storage, Tankless, Indirect System, Heat Pump, Active

**Interior Lighting** | Incandescent light bulb, CFL light bulb, LED light bulb


Table 4  Energy Consumption Items by Consumption Domain

**Components:** These items consist of domain energy consumption and heat flow values. They are mainly used by modeling paths during heating and cooling energy consumption assessment. Some examples of components are: interior lighting energy consumption (Ql), appliances and electronics energy consumption (Qa/e), and system load (Qsys).

### 3.2 Research Question

What is the minimum set of parameters that needs to be utilized, which can achieve a credible level of accuracy and confidence for residential home energy consumption assessment for retrofit decision-making?

This research reduces the underlying energy model equations to use a limited set of parameters. The set of equations and parameters consists only of those that significantly affect energy consumption instead of using highly complex energy models such as the DOE-2 Building Simulation and setting thousands of parameters to default values. During this study, the credible level of accuracy and confidence, which is defined by EAI and CSG (2009) as achieving energy consumption predictions within an error margin of 25% for 70% of homes and 50% for 90% of the homes when compared to actual consumption amount is used. In addition to the justification provided in the previous sections for determining the anticipated accuracy and confidence levels (see Section 2.5.1), the levels mentioned in the study conducted by EAI and CSG (2009) are
justified for this research due to the similarities in climate zones between the location of the cited study and the location of this analysis, which is Blacksburg, Virginia (2009).

3.3 Research Objectives

The overall objectives of the research are represented as follows:

- **Objective # 1:** Provide an extensive list of primary energy consumption items and a comprehensive set of energy consumption influence parameters for residential energy consumption.
- **Objective # 2:** Identify the inter-relationships among residential energy consumption influence parameters and develop a relational map including the associated consumption items.
- **Objective # 3:** Establish energy consumption influence parameter groups and map them to designated energy domains to generate a framework.
- **Objective # 4:** Demonstrate the approach of analyzing the impact of residential energy consumption influence parameters in energy consumption modeling paths using the framework in order to depict their effect on the different energy consumption domains.
- **Objective # 5:** Identify a minimum set of parameters for conducting residential energy consumption assessment based on influence parameter analyses.
- **Objective # 6:** Provide recommendations for the development of a simplified baseline model for residential energy consumption based on framework, which utilizes the minimum set of parameters to achieve confidence for decision-making.

3.4 Research Limitations

The purpose of the study is to develop a framework for the energy assessment process rather than a consumption prediction model that can achieve 100% accurate results. Thus, deliberate scope decisions and assumptions are made throughout this study. The framework is developed by utilizing a sample house with fixed geometry in the location of research. The variation in occupancy pattern is captured by two different scenarios that are assumed to depict the different ends of the usage spectrum. Several assumptions are made during the calculations to represent the parameter values for durations of use, system and building characteristics. Therefore, the
results provided by this study cannot necessarily be generalized for other types of buildings in different climate conditions or households with different occupancy patterns. However, the framework developed through this research study and the approach still qualifies for generalizability.

3.5 Research Methodology

This research study is designed to develop a framework for residential energy consumption assessment through a “Parameter Study”. The parameter study consists of systematic research and analyses conducted to investigate consumption influence parameters, determine their impact, and develop a minimum set of consumption influence parameters with predicted effects. The overall approach of the parameter study is based on sequential tasks completed as a part of the iterative process as illustrated in Figure 4.

The following tasks identify the methodology utilized by this research to achieve the research objectives and meet the research goal:

- **Provide a list of consumption items:** A list of primary energy consumption items is derived from multiple sources based on building science fundamentals and previous research. Also, the relation to energy consumption is verified individually for each consumption item.

- **Provide a set of influence parameters:** A comprehensive set of energy consumption influence parameters is derived as a part of this task. The influence parameters are identified through reviewing current tools in use, building science fundamentals, commonly accepted business practices, and previous research. Also, the relation to energy consumption is justified individually for each influence parameter.

- **Establish parameter inter-relationships:** The inter-relationships among the established parameters are investigated and the nature of the relationships is determined. The nature of the relationships is determined by using current software tools in use, previous research, building science fundamentals, commonly accepted business practices. The parameter relationships are classified under primary and secondary relationships. Only primary relationships are justified individually for each parameter.
• **Conduct parameter impact analysis:** The parameter impact analysis is conducted for each energy consumption domain separately. The impact analyses consist of individual sensitivity analysis completed for each applicable parameter to depict its effect on different energy consumption domains. The impact analysis is completed with five distinctive tasks as further explained in Section 4.3.

• **Determine the energy consumption domains:** A comprehensive list of energy consumption domains is determined by expanding the framework provided by Balaras et al. (2000). This expansion is completed to include other relevant consumption domains based on consumption studies such as DOE 2011 as further discussed in Section 4.6.

• **Classify individual influence parameters under domains:** This classification is conducted for all the identified consumption influence parameters. The individual parameters are classified under one or multiple energy consumption domains, depending on their contribution to one or more of the consumption items.

• **Condense the relevant parameter set:** The parameters in the comprehensive list are condensed according to the results of parameter impact and full building analysis. The list of parameters is refined to only include those parameters that are required to complete the simplified energy consumption assessment.

As mentioned earlier, the main focus of this study is to develop a framework for residential energy consumption assessment. Figure 4 illustrates multiple products that are also developed as a part of the iterative process. However, it should be noted that these products are developed based on the sample house, the climate condition of the research location, and the assumptions made throughout this study. Therefore, they cannot necessarily be generalized for other types of buildings in different climate conditions or households with different occupancy patterns.
(*) The results used to develop these products are gathered in Section 4.3. However, the matrices are displayed in Section 4.5

Figure 4  Research Methodology.
3.6 Research Validation

This research study is designed to develop a framework for residential energy consumption assessment. As the main scope of this study is developing the framework rather than producing generalizable energy assessment predictions, the validity of the approach is tested by construct validity. The usual method of testing for construct validity is comparing the obtained measurements with the acceptable measurements of related constructs (Reeves 1992). However, the framework was developed for a sample house in the research location and according to the assumptions made based on design standards, previous research, scenarios, and best information available. Thus, acceptable measurements of related construct are not necessarily acquired during the development of the framework. However, the construct validity is maintained by implementing the following strategies suggested by Robson (2002) as provide below:

- The researcher relies on subject matter expertise and reasonable intuition while selecting appropriate approaches, which are expected to provide appropriate predictions.

- The researcher bias is minimized by investigating and utilizing multiple sources to determine modeling paths, calculation methods, parameter values, and baselines.

The soundness of the research study is also maintained through qualitative validity. The underlying approach of this study meets the four alternative criteria, which are defined as credibility, transferability, dependability, and confirmability by Trochim (2006). Further discussions on these criteria are provided separately for each of the major contribution of this study.

- **Comprehensive set of Influence Parameters for Residential Energy Consumption Assessment:** The comprehensive set of parameters is developed through an extensive review. Throughout this process, explicit and credible sources are utilized. The entire process is clearly stated and systematically documented to allow for confirmability. In other words, the results can be confirmed and corroborated through an audit, which examines of the procedures and the approach for potential bias or distortion.

- **Energy Consumption Influence Parameter Relationship Map:** The parameter relationship map is developed as a result of the parameter relationship analysis. During
the relationship analysis, the parameter relationships are initially classified to limit the scope. These relationships are investigated through a comprehensive review of explicit and credible sources. The entire process is also clearly stated and systematically documented to allow for confirmability. In addition, the results of this qualitative process and the relationship map developed as an outcome can also be articulated by credibility. Throughout this entire process, the feedback of the committee members is used to ensure that the results established through this qualitative process are credible and believable from the perspective of other stakeholders.

- **Parameter Impact Analysis:** The main purpose of this research study is to develop a framework that simplifies the energy consumption assessment process. During the development of the framework, the parameter impact analysis for the sample house is used to demonstrate the process. The process and the decision-making for the impact analysis of this demonstration case is clearly stated and systematically documented. Thus, the thinking can be articulated by confirmability. Also, during the impact analysis, the assumptions are clearly defined; explicit and credible sources are used; data sources are triangulated. The changes that can occur in this demonstration case and how they impact the results are clearly illustrated for the approach used in this study. Therefore, this process can be articulated by dependability.

- **Parameter Classification and Minimum Set of Parameters:** The main contribution of this study is the process used to classify the parameters under energy consumption domains and develop the minimum set of parameters. As mentioned earlier, a demonstration case is used to depict this process, which is articulated by confirmability. Throughout parameter studies, several assumptions are made during the calculations to represent the parameter values for durations of use, system and building characteristics. Therefore, the results provided by this study cannot necessarily be generalized for other types of buildings in different climate conditions or households with different occupancy patterns. However, the framework developed through this research study and the approach still qualifies for generalizability. In addition, the research context and the assumptions that are central to the research are thoroughly described to enhance transferability. As a result, the approach used and the framework developed through this study can allow for transferability.
4 Parameter Study

One of the primary research questions in this dissertation is: “What is the minimum set of parameters to be utilized that can achieve a credible level of accuracy and confidence for residential home energy consumption assessment for retrofit decision-making?” In order to adequately answer this research question, an iterative process that includes the following sequential steps for modeling components is used.

4.1 Energy Consumption Influence Parameters and Consumption Items

The initial task of this parameter study consists of compiling a list of primary energy consumption items and a comprehensive set of energy consumption influence parameters, which in turn meet Research Objective #1: “Provide an extensive list of primary energy consumption items and a comprehensive set of energy consumption influence parameters for residential energy consumption”.

4.1.1 Primary Energy Consumption Items

According to DOE (2011) and Energy-Star (2011), Heating System, Cooling System, Hot Water Heater, Lighting Sources, Electronics, and Appliances are the primary energy consumption items for the residential sector. Thus, the list of energy consumption items is derived from these sources and provided next with their relation to the energy consumption.

- **Heating System:** The heating system consumes energy by increasing the temperature of the interior air during the heating season (Tao and Janis 2001e, ASHRAE 2007a, Szokolay 2004).

- **Cooling System:** The cooling system consumes energy by decreasing the temperature and dehumidifying the interior air during the cooling season (Tao and Janis 2001e, ASHRAE 2007a, Szokolay 2004).

- **Domestic Water Heater:** Domestic water heaters are typically stand-alone systems that consume energy to increase the temperature of water in order for it to be used during household activities such as laundry, dishwashing, showers, and bathing (Tao and Janis 2001e).
• **Lighting Sources:** Lighting sources consist of interior and exterior lighting fixtures that consume energy in order to illuminate a space or its surroundings. These fixtures illuminate the space through different light bulbs and also impact heating and cooling of the space due to the heat energy they emit during these operations (Tao and Janis 2009g).

• **Appliances:** Home appliances (electrical/mechanical machines) consume energy in a dwelling during their regular use as well as through phantom loads, which is when they are not in use but plugged into an outlet (Pearce and Fiori 2009).

• **Electronics:** Household electronic equipment consume energy in a dwelling during their regular use. Some may also consume energy through phantom loads, which is when they are not in use but plugged into an outlet (Pearce and Fiori 2009).

### 4.1.2 Energy Consumption Influence Parameters

The energy consumption influence parameters are identified through reviewing the following sources:

**a) Current tools in use:** As discussed in Section 2.5.1, all of the available energy efficiency assessment tools for residential construction are analyzed. In this comprehensive analysis (see Appendix B for detailed results), individual modeling approaches and parameters used (as accessible), input parameters (for homeowners), tool capability, scenarios used and accuracy of the results are investigated. As a result, parameters used for each tool are established.

**b) Previous research:** Subsequent to the analysis of current tools in use, the findings of the literature review is analyzed to further explore some of the more complicated simulation programs. Mills (2004), EAI and CSG (2009), and LBNL (2010) are some of the scientific studies, which analyzed the models, input parameters and consumption calculation accuracy for these aforementioned simulation programs. The findings of these studies are also used to establish the comprehensive parameter set.

**c) Building science fundamentals:** The third source utilized while building the comprehensive parameter set consists of text books, engineering manuals, design standards and scientific data. Building science textbooks (e.g., Tao and Janis 2001a through g), engineering manuals for energy flow and load calculations (e.g., Lindeburg 2006c), design
standards (e.g., ASHRAE 2007a) and sustainable design principles (e.g., Szokolay 2004, Pearce and Fiori 2009), and scientific data compiled over decades to be utilized in design calculations (e.g., NWS 2010, Wunderground 2010) are some of the other sources utilized to establish the comprehensive parameter set.

d) **Commonly accepted business practices:** Lastly, commonly accepted construction and engineering practices, which are based on minimum code and performance standards (e.g., McVicker 2007, Hodgson 2007, Engineering Toolbox 2010b), are used as the remaining sources in order to compile the comprehensive parameter set.

The aforementioned comprehensive list of energy consumption influence parameters along with the applicable subparts is provided below with a concise justification as to their relationship to the energy consumption:

- **Year Built:** The age of the house affects types of building materials as well as the heating and cooling systems that were available and used at an era. Thus it impacts their performance characteristics, which in turn impacts overall energy consumption. One example for this relationship is the changes in thermal conductance for building envelope components average “U” values and their effect on energy consumption. As illustrated in Appendix C, the average “U” values for exterior walls, roof, windows, and ground slabs show significant changes over the years. As a result, heating and cooling energy consumption amounts show significant changes for houses built in different eras (see Section 4.3.4). Home Energy Suite (Apogee 2009), Home Energy Saver (LBNL 2009), Hohm Beta Version (Microsoft 2009), Home Energy Tune-Up (CMC 2009) and Energy Efficient Rehab Advisor (DHUD 2009) are some of the current tools in use that utilize this consumption influence parameter.

- **Orientation:** Solar gains, which are affected by the orientation of the house, impact the heating and cooling energy consumption amounts (Tao and Janis 2001a). The window size and position on a facade affect sunlight and heat penetrating the space and the related Solar Heat Gain Factor “SHGF”, which is used to calculate solar gains (see Section 4.3.4). The orientation of the house affects the solar gains through this relationship since the number of windows per facade and the position of the windows are different for each side of the house.
- **Total Square Footage:** The total area of the house impacts the heating, cooling and interior lighting energy consumption. When the total square footage of the house increases, space illumination requirements and the related interior lighting energy consumption amount increase. Similarly, as the total square footage increases, the surface areas of the thermal envelope and the interior volume increase. The increase in thermal envelope area causes ventilation losses and gains to increase. The increase in interior volume causes the energy required to change the temperature of the air volume inside the dwelling (due to infiltration losses / gains) to increase (see Section 4.3). As a result, heating and cooling energy consumption amount changes. Home Energy Suite (Apogee 2009), Home Energy Saver (LBNL 2009), Hohm Beta Version (Microsoft 2009), Home Energy Tune-Up (CMC 2009), Energy Efficient Rehab Advisor (DHUD 2009) and Energy Star Yardstick (Energy-Star 2009b) are some of the current tools in use that utilize this consumption influence parameter. Also, Home Energy Saver (LBNL 2009) and Hohm Beta Version (Microsoft 2009) has explored and modeled the effect of individual room square footage on the heating, cooling and lighting consumption in order to account for different uses and illumination and conditioning requirements.

- **Footprint Area:** The building footprint area can be used to determine total square footage, square footage for each level on multi-level dwellings, form factor and the related thermal envelope size. Footprint area affects the interior lighting energy consumption through the relationship with total square footage. Since an increase in footprint increases the total square footage, the illumination requirements and interior lighting energy consumption through interior lighting sources also increases as a result. Footprint area also affects the heating and cooling energy consumption through heating and cooling systems. An increase in footprint area causes the thermal envelope size and interior air volume to increase, which affects the heat gains and losses for the space (see Section 4.3), Home Energy Suite (Apogee 2009), Home Energy Saver (LBNL 2009), Hohm Beta Version (Microsoft 2009), Home Energy Tune-Up (CMC 2009), Energy Efficient Rehab Advisor (DHUD 2009) and Energy Star Yardstick (Energy-Star 2009b) are some of the current tools in use that utilize this consumption influence parameter.

- **Volume:** The volume of the space has a significant influence on the air exchange requirements. The air exchange requirements of the space affect the ventilation gains and
losses, which in turn impacts the heating and cooling energy consumption (Tao and Janis 2001b, McVicker 2007, Hodgson 2007). Ventilation gains and losses affect the total heating and cooling energy consumption due to the need for supplying the energy required to change the temperature of the air volume in the dwelling (see Section 4.3.4).

- **Perimeter Length**: The perimeter length of the house is used to derive the thermal envelope area or the volume of the dwelling and has some effect on infiltration and ventilation air streams, and thus also impacts the heating and cooling energy consumption (see Section 4.3.4). Home Energy Suite (Apogee 2009), Home Energy Saver (LBNL 2009), Hohm Beta Version (Microsoft 2009), Home Energy Tune-Up (CMC 2009) and Energy Efficient Rehab Advisor (DHUD 2009) are some of the current tools in use that utilize this consumption influence parameter.

- **Form Factor**: Similar to the perimeter length, the form factor of the house (as usually depicted by the length and the width) is used to derive the thermal envelope area or the volume of the dwelling. As discussed previously, thermal envelope area and interior volume of the dwelling affect the infiltration and ventilation losses / gains in the space causing an impact on the heating and cooling energy consumption (see Section 4.3.4). Home Energy Suite (Apogee 2009), Home Energy Saver (LBNL 2009), Hohm Beta Version (Microsoft 2009), Home Energy Tune-Up (CMC 2009) and Energy Efficient Rehab Advisor (DHUD 2009) are some of the current tools in use that utilize this consumption influence parameter.

- **Shape of the House**: Shape of the house is used to derive perimeter length or form factor when only total square footage for a dwelling is available. As the shape of the house is used to derive parameters that have direct relationships with thermal envelope area and volume of the dwelling, similar inferences are applicable. Thus, through the relationship with thermal envelope area and interior volume of the dwelling, the shape of the house can influence infiltration and ventilation losses / gains in the space causing an impact on the heating and cooling energy consumption (see Section 4.3.4). Home Energy Saver (LBNL 2009) and Hohm Beta Version (Microsoft 2009) are some of the current tools in use that utilize this consumption influence parameter.

- **Interior Ceiling Height**: The interior ceiling height is used to derive thermal envelope size and the volume of the interior space (see Section 4.3.4). Volume of the space significantly
affects ventilation gains and losses through air exchange requirements. Thermal envelope size impacts infiltration gains and losses. Thus, interior ceiling height has an influence on infiltration and ventilation losses, which in turn impacts the heating and cooling energy consumption (Tao and Janis 2001b, McVicker 2007, Hodgson 2007).

- **Number of Stories:** The number of stories and type of levels (above-ground versus underground) affects the thermal envelope characteristics and the total square footage, which impacts heating and cooling energy consumption. When the total square footage of the house increases, space illumination requirements and the related interior lighting energy consumption amount increase. Similarly, as the total square footage increases, the surface areas of the thermal envelope and the interior volume increase. The increase in thermal envelope area causes ventilation losses and gains to increase. The increase in interior volume causes the energy required to change the temperature of the air volume inside the dwelling (due to infiltration losses / gains) to increase (see Section 4.3.4). As a result, heating and cooling energy consumption amount changes. Home Energy Suite (Apogee 2009), Home Energy Saver (LBNL 2009), Hohm Beta Version (Microsoft 2009), Home Energy Tune-Up (CMC 2009) and Energy Efficient Rehab Advisor (DHUD 2009) are some of the current tools in use that utilize this consumption influence parameter.

- **Number of Rooms:** In addition to the total area of the house, the number and types of rooms can impact the interior lighting energy, appliances and electronics energy consumption. Two houses with the same square footage but different number and type of rooms could potentially have different interior lighting energy consumption due to the differences in illumination requirements and length of use for different types of rooms (e.g., requirements and length of use for kitchen versus bedroom). Similarly, for the same houses, the number and length of use of appliances and electronics could potentially be different for different rooms (see Section 4.3). Home Energy Suite (Apogee 2009), Home Energy Saver (LBNL 2009), Hohm Beta Version (Microsoft 2009), Home Energy Tune-Up (CMC 2009) and Energy Efficient Rehab Advisor (DHUD 2009) are some of the current tools in use that utilize this consumption influence parameter. Also, Home Energy Saver (LBNL 2009) and Hohm Beta Version (Microsoft 2009) has explored and modeled the effect of individual room type on the heating, cooling and lighting consumption in order to account for different uses and illumination and conditioning requirements.
- **Number and Size of Windows:** The number and size of the windows on a façade affect sunlight and heat penetrating the space and the related Solar Heat Gain Factor “SHGF”, which is used to calculate solar gains (see Section 4.3.4). Along with solar gains, the affect window characteristics have on thermal envelope (see Section 4.3.4) impact heating and cooling energy consumption (Tao and Janis 2001a, ASHRAE 2007a, Szokolay 2004, Lindeburg 2006c, Pearce and Fiori 2009). Home Energy Suite (Apogee 2009), Home Energy Saver (LBNL 2009), Hohm Beta Version (Microsoft 2009), Home Energy Tune-Up (CMC 2009) and Energy Efficient Rehab Advisor (DHUD 2009) are some of the current tools in use that utilize this consumption influence parameter.

- **Number and Size of Glass Doors:** The number and size of glass doors on a façade affect sunlight and heat penetrating the space and the related Solar Heat Gain Factor “SHGF”, which is used to calculate solar gains (see Section 4.3.4). Along with solar gains, the affect glass door characteristics have on thermal envelope (see Section 4.3.4) impact heating and cooling energy consumption (Tao and Janis 2001a, ASHRAE 2007a, Szokolay 2004, Lindeburg 2006c). Home Energy Suite (Apogee 2009), Home Energy Saver (LBNL 2009), Hohm Beta Version (Microsoft 2009), Home Energy Tune-Up (CMC 2009) and Energy Efficient Rehab Advisor (DHUD 2009) are some of the current tools in use that utilize this consumption influence parameter.

- **Number and Size of Skylights:** The number and size of the skylights on the roof affect sunlight and heat penetrating the space and the related Solar Heat Gain Factor “SHGF”, which is used to calculate solar gains (see Section 4.3.4). Along with solar gains, the affect skylight characteristics have on thermal envelope of the roof (see Section 4.3.4) impact heating and cooling energy consumption (Tao and Janis 2001a, ASHRAE 2007a, Szokolay 2004, Lindeburg 2006c, Pearce and Fiori 2009). Home Energy Suite (Apogee 2009), Home Energy Saver (LBNL 2009), Hohm Beta Version (Microsoft 2009), Home Energy Tune-Up (CMC 2009) and Energy Efficient Rehab Advisor (DHUD 2009) are some of the current tools in use that utilize this consumption influence parameter.

- **Number of Occupants:** The number of occupants affects the concurrent and/or length of use for interior lighting, appliances, electronics, hot water heating, and space heating and cooling energy consumption (Tao and Janis 2001c, Engineering Toolbox 2010b). The different
modeling approaches and how the number of occupants is utilized during the energy consumption calculations are illustrated in Section 4.3 for different scenarios. Home Energy Suite (Apogee 2009), Home Energy Saver (LBNL 2009), Hohm Beta Version (Microsoft 2009), Home Energy Tune-Up (CMC 2009), Energy Efficient Rehab Advisor (DHUD 2009) and Energy Star Yardstick (Energy-Star 2009b) are some of the current tools in use that utilize this consumption influence parameter.

- **Ages of Occupants:** Along with the number of occupants, the age of occupants can also influence the length of use for interior lighting, appliances, electronics and hot water heating, which impacts the related energy consumption (Tao and Janis 2001c, Engineering Toolbox 2010b). In a recent study, Yohanis et al. (2006) determined age of the occupants along with other occupant attributes to be a significant impact on electricity consumption. Home Energy Saver (LBNL 2009) and Hohm Beta Version (Microsoft 2009) are some of the current tools in use that utilize this consumption influence parameter. These tools include “age of occupants” parameter as a part of the domestic hot water consumption calculation model.

- **Building Thermal Envelope:** Type and characteristics of construction materials and components affect the thermal envelope characteristics, which impacts heating and cooling energy consumption (Tao and Janis 2001d, ASHRAE 2007a, Szokolay 2004, Lindeburg 2006c). One example for this relationship is the changes in construction materials and the related thermal conductance for building envelope component average “U” values. As illustrated in Appendix C, the average “U” values for exterior walls, roof and windows show significant changes for different materials and components. As a result, heating and cooling energy consumption amounts show significant changes for houses built with different construction materials and components (see Section 4.3.4). Home Energy Suite (Apogee 2009), Home Energy Saver (LBNL 2009), Hohm Beta Version (Microsoft 2009), Home Energy Tune-Up (CMC 2009), Energy Efficient Rehab Advisor (DHUD 2009) and Home Advisor (Energy-Star 2009a) are some of the current tools in use that utilize this consumption influence parameter.

- **Space Usage Characteristics:** Space usage characteristics affect the thermal envelope characteristics through insulation, ventilation and conditioning demand, which impacts heating and cooling energy consumption (Tao and Janis 2001d, ASHRAE 2007a, Szokolay
One example for this relationship is the difference between a finished and an unfinished basement. Compared to the unfinished basement, the finished basement could have significant differences in terms of the construction materials and components used (e.g., insulation). The differences in construction materials would provide for different thermal conductance for building envelope component average “U” values (see Appendix C). As a result, heating and cooling energy consumption amounts show significant changes for spaces with different usage characteristics. Home Energy Suite (Apogee 2009), Home Energy Saver (LBNL 2009), Hohm Beta Version (Microsoft 2009), Home Energy Tune-Up (CMC 2009), Energy Efficient Rehab Advisor (DHUD 2009) and Home Advisor (Energy-Star 2009a) are some of the current tools in use that utilize this consumption influence parameter.

- **Infiltration**: Tied to the size of the envelope of the space and the respective thermal characteristics, infiltration significantly affects the air exchange rates in the space and the related infiltration gains and losses (see Section 4.3.4), which in turn impact the heating and cooling energy consumption (Tao and Janis 2001b, ASHRAE 2007a, Szokolay 2004, Lindeburg 2006c). Home Energy Saver (LBNL 2009), Hohm Beta Version (Microsoft 2009), Home Energy Tune-Up (CMC 2009), Energy Efficient Rehab Advisor (DHUD 2009) and Energy Savers (DOE 2009d) are some of the current tools in use that utilize this consumption influence parameter.

- **Ventilation**: The amount of required ventilation used for indoor air quality in the space affects the need for heating and cooling demands and ultimately, the related energy consumption (Tao and Janis 2001b, ASHRAE 2007a, Pearce and Fiori 2009).

- **Zip code**: The geographic location provided through the zip code dictates the applicable regional climate conditions of the house, which determines the outside temperature, the number of heating and cooling days, typical outside air humidity (NWS 2010, Wunderground 2010). All of these variables affect the heating and cooling energy consumption (Tao and Janis 2001d, ASHRAE 2007a, Szokolay 2004, Lindeburg 2006c). Home Energy Suite (Apogee 2009), Home Energy Saver (LBNL 2009), Hohm Beta Version (Microsoft 2009), Home Energy Tune-Up (CMC 2009), Energy Efficient Rehab Advisor (DHUD 2009), Home Advisor (Energy-Star 2009a) are some of the current tools in use that utilize this consumption influence parameter.
Advisor (Energy-Star 2009a) and Energy Star Yardstick (Energy-Star 2009b) are some of the current tools in use that utilize this consumption influence parameter.

- **Local Surroundings:** Landscaping and hardscaping (such as trees, bushes, shrubs, etc.) around the dwelling can affect the infiltration losses as well as solar losses/gains, which impacts heating, cooling and lighting energy consumption (Pearce and Fiori 2009). In one of the many studies in this field, McPherson et al. (1988) determined that outside vegetation in the form of landscaping and hardscaping reduced the cooling loads of buildings in different climate zones by modifying air temperature, solar heat gain, longwave heat gain, and heat loss by convection. In some of the studies, the electrical energy consumed by cooling loads was found to be 20 – 30 % less for some of the landscaping and hardscaping models utilized. Home Energy Saver (LBNL 2009), Hohm Beta Version (Microsoft 2009) and Home Energy Tune-Up (CMC 2009) are some of the current tools in use that utilize this consumption influence parameter.

- **Available Energy Sources:** The different types of energy sources that are available at a lot for building systems affect the hot water heating, appliances, and heating and cooling energy consumption due to difference in capacity, efficiency and power consumption of the different units used (Pearce and Fiori 2009). An example for the effect of different energy sources available is the performance differences for water heaters and dryers. According to California Energy Commission (2011), on average, a water heater fueled by natural gas consumes 272 therms/year compared to a similar model that works on electricity, which consumes 4,875 kWh/year. When these units are compared, the annual consumption cost is determined as 3 times more for the electric model as well as the comparable energy consumed and greenhouse gasses emitted. Similarly, a 1 : 2 ratio is also observed for gas versus electric dryers. Home Energy Suite (Apogee 2009), Home Energy Saver (LBNL 2009), Hohm Beta Version (Microsoft 2009), Home Energy Tune-Up (CMC 2009), Energy Efficient Rehab Advisor (DHUD 2009), and Energy Star Yardstick (Energy-Star 2009b) are some of the current tools in use that utilize this consumption influence parameter.

- **System Characteristics:** The characteristics, specifications and the condition of the building systems, and appliances affect the energy consumed by each consumption item (Tao and Janis 2001a, Tao and Janis 2001e ASHRAE 2007a, McVicker 2007, Pearce and Fiori 2009).
This effect could be better explained with examples for water heaters, cooling systems and appliances. The temperature settings of a central heating and cooling system or a hot water heater can reduce or increase the energy consumption by 10 – 20% (Pearce and Fiori 2009). Appliances that are “Energy Star” rated, in good repair and not too old, properly used, and has the appropriate capacity for the usage demands can also reduce the energy consumption by 25% (ibid). Home Energy Suite (Apogee 2009), Home Energy Saver (LBNL 2009), Hohm Beta Version (Microsoft 2009), Home Energy Tune-Up (CMC 2009), Energy Efficient Rehab Advisor (DHUD 2009), Home Advisor (Energy-Star 2009a) and Energy Savers (DOE 2009d) are some of the current tools in use that utilize this consumption influence parameter. Also, Home Energy Saver (LBNL 2009) Home Energy Tune-Up (CMC 2009), Energy Efficient Rehab Advisor (DHUD 2009) and Hohm Beta Version (Microsoft 2009) has explored and modeled the effect of individual systems, appliances, electronics, and lighting on the heating, cooling and lighting consumption in order to account for these aforementioned differences.

- Occupancy Patterns: The usage pattern for electronics, appliances, indoor lighting sources and hot water heaters are defined by occupancy patterns. Occupancy patterns determine the specific length of use over a period of time, which is used to determine the overall energy consumed for each of the relevant consumption items. (Tao and Janis 2001f, Pearce and Fiori 2009). One example for the occupancy pattern can be given for appliances and electronics consumption items. Even though TVs, computers and gaming systems are all contributors to the energy consumption for the appliances and electronics, the duration of use during a year is different for each of the items. Thus, individual occupancy patterns are determined for each item to calculate the individual energy consumption (see Section 4.3.1). Home Energy Suite (Apogee 2009), Home Energy Saver (LBNL 2009), Hohm Beta Version (Microsoft 2009), Home Energy Tune-Up (CMC 2009), Energy Efficient Rehab Advisor (DHUD 2009) and Energy Star Yardstick (Energy-Star 2009b) are some of the current tools in use that utilize this consumption influence parameter. Also, Home Energy Saver (LBNL 2009) Home Energy Tune-Up (CMC 2009), Energy Efficient Rehab Advisor (DHUD 2009) and Hohm Beta Version (Microsoft 2009) has explored and modeled the effect of occupancy pattern for individual system, equipment and component on the designated energy consumption.
• **Exposure to Elements:** Proximity of other dwellings nearby and the type of community in which the house is located can affect the solar gains, which impacts cooling energy consumption. One of the most predominant examples for this effect can be explained by the “Urban Heat Island Impacts”. “Urban Heat Island” is, as defined by Environmental Protection Agency (EPA), the increase in the landscape temperatures due to the development in urban areas where the open land and vegetation is replaced by infrastructure (EPA 2011). The impact of the “Urban Heat Island” is elevated summertime temperatures in cities with increase in cooling system energy consumption, which is determined as 5 – 10% increase in electricity demands (ibid). Home Energy Saver (LBNL 2009), Hohm Beta Version (Microsoft 2009) and Home Energy Tune-Up (CMC 2009) are some of the current tools in use that utilize this consumption influence parameter.

### 4.2 Energy Consumption Influence Parameter Relationships

In this section, the comprehensive energy consumption influence parameter set (as established during Section 4.1) is further analyzed. This analysis is conducted to determine inter-relationships among parameters and meet **Research Objective # 2:** “Identify the inter-relationships among residential energy consumption influence parameters and develop a relational map including the associated consumption items”. The first two tasks for this research objective consist of investigating the inter-relationships among the established parameters and determining the nature of the relationship. The nature of the relationship is identified by using current software tools in use, previous research, building science fundamentals, and commonly accepted business practices as discussed in Section 4.1 in great detail. Due to the multi-directional nature of these relationships, only a single parameter and its effects on related parameters is analyzed at a time. In order to better understand the nature of these relationships, they are further classified under the following types as listed below:

a. **Primary relationships:** These relationships are considered to be direct effects of one parameter influencing another parameter. A change in the value of the analyzed parameter at hand will cause an immediate change in the value of the affected parameter. These relationship types are illustrated with black lines.
b. **Secondary relationships:** These relationships are considered to have indirect effects. A change in the value of the analyzed parameter at hand can cause a change in the value of another affected parameter. However, this change is usually passed on by a change in the value of a chain of preliminary relationships. Thus, these relationships are not further discussed during this parameter dependency analysis.

The individual energy consumption influence parameters and their inter-relationships are provided with a concise justification and illustration as shown below:

- **Year Built:** The age of the house affects the building type through the materials and systems that were available and used during an era. This effect impacts the performance characteristics of the thermal envelope, which in turn impacts heating and cooling energy consumption through heating and cooling systems. As illustrated in Appendix C, the average “U” values for exterior walls, roof, windows, and ground slab have significantly changed over the years. As a result, heating and cooling energy consumption amounts show significant changes for houses built in different eras (see Section 4.3.4). The age of the house is also found to affect the size of the dwelling through its impact on total square footage. According to a recent study conducted by National Association of Home Builders (2011), the average home size in the U.S. was 2,700 square feet in 2009, up from 1,400 square feet in 1970. The same study expected homes to average 2,152 square feet in 2015, which is 10% smaller than the average size of single-family homes started in the first three quarters of 2010. The results of this study illustrate the different tendencies in residential construction for different eras, which directly affects the total square footage of the dwellings. Thus, both of these parameters are classified as primary relationships and illustrated accordingly in Figure 5. Home Energy Suite (Apogee 2009), Home Energy Saver (LBNL 2009), Hohm Beta Version (Microsoft 2009), Home Energy Tune-Up (CMC 2009) and Energy Efficient Rehab Advisor (DHUD 2009) are some of the current tools in use that utilize this consumption influence parameter.
**Figure 5** Inter-relationships for “Year Built”

- **Orientation:** The orientation of a house in relation to sun exposure can affect the size, number, and the position of windows on a façade. This relationship is due to the role of windows in solar gains, which directly impacts heating and cooling energy consumption through heating and cooling systems. The size, number and position of windows affect the sunlight and heat penetrating the space and the related solar heat gains through the impact on solar heat gain factor (Tao and Janis 2001a). Thus, the size, number and the location of the windows are usually determined according to the orientation of the dwelling. Due to the direct nature of the relationship between orientation and number and size of the windows, it is classified as a primary relationship and illustrated accordingly in Figure 6

**Figure 6** Inter-relationships for “Orientation”

- **Total Square Footage:** The total square footage of the house of the house directly affects footprint area, number of rooms, and volume. The footprint area of a dwelling is simply the outline area of the total area of a lot, which consists of the interior square footage adjusted for multi-level buildings, the outside walls, and other components of the outside façade (ICC 2006a). Therefore, any change in total square footage directly affects footprint area. Similarly, the number of rooms is usually driven the total square footage of a dwelling due to the minimum requirements for habitable spaces (ICC 2006b). Usually, the number of rooms increases with an increase in total square footage. The total square footage is also used with ceiling height of the dwelling derive the interior volume (see Section 4.3.4). As a result, as the total square footage of a dwelling increases so does the interior volume. Due to the direct
nature of these relationships, they are classified as primary relationships and illustrated accordingly in Figure 7. Home Energy Suite (Apogee 2009), Home Energy Saver (LBNL 2009), Hohm Beta Version (Microsoft 2009), Home Energy Tune-Up (CMC 2009), Energy Efficient Rehab Advisor (DHUD 2009) and Energy Star Yardstick (Energy-Star 2009b) are some of the current tools in use that utilize this consumption influence parameter.

**Figure 7** Inter-relationships for “Total Square Footage”

- **Footprint Area:** The building footprint area of a dwelling has direct relationships with total square footage, perimeter length and the form factor. As mentioned previously for total square footage, footprint area and total square footage have a direct impact on one another. Similar to calculations that can be made to derive footprint area from total square footage, footprint area and number of stories can be used to derive total square footage. Footprint area, however, is predominantly used to derive form factor or the perimeter length of the dwelling while determining the thermal envelope size. Although affected by the shape of the house due to the relevant geometric calculations, a change in footprint area directly affects the form factor (the length and width of the dwelling) and perimeter length. These primary relationships are illustrated accordingly in Figure 8. Home Energy Suite (Apogee 2009), Home Energy Saver (LBNL 2009), Hohm Beta Version (Microsoft 2009), Home Energy Tune-Up (CMC 2009), Energy Efficient Rehab Advisor (DHUD 2009) and Energy Star Yardstick (Energy-Star 2009b) are some of the current tools in use that utilize this consumption influence parameter.
• **Volume:** The volume of a dwelling has an impact on ventilation gains and losses through its influence on the air exchange requirements (see Section 4.3.4). Also, total square footage of the space and ceiling height is used to derive the volume of a dwelling. Therefore, a change in total square footage or ceiling height causes a change in the volume of the dwelling and a change in volume also means a change in one of both of these parameters. These primary relationships are illustrated in Figure 9.

**Figure 8** Inter-relationships for “Footprint Area”

- **Perimeter Length:** The perimeter length of a dwelling has direct relationships with the footprint area and form factor. In order to derive parameter length, either form factor or footprint area is used. If form factor is known, the calculation is simple summation since it consists of the dimensions of the property. On the other hand, if footprint area is used, the calculation also requires the use of the shape of the house due to the relevant geometric calculations. These calculations, which are demonstrated in more detail in Section 4.3.4, illustrate the interdependencies and the direct affect each parameter has on the others (Figure 10). Home Energy Suite (Apogee 2009), Home Energy Saver (LBNL 2009), Hohm Beta Version (Microsoft 2009), Home Energy Tune-Up (CMC 2009) and Energy Efficient Rehab
Advisor (DHUD 2009) are some of the current tools in use that utilize this consumption influence parameter.

Figure 10 Inter-relationships for “Perimeter Length”

- **Form Factor:** The form factor of a dwelling has direct relationships with the footprint area and perimeter length. In order to derive parameter length, either form factor or footprint area is used. During either one of these calculations, the shape of the house is also used due to the relevant geometric calculations. These calculations, which are demonstrated in more detail in Section 4.3, illustrate the interdependencies and the direct affect each parameter has on the others (Figure 11). Home Energy Suite (Apogee 2009), Home Energy Saver (LBNL 2009), Hohm Beta Version (Microsoft 2009), Home Energy Tune-Up (CMC 2009) and Energy Efficient Rehab Advisor (DHUD 2009) are some of the current tools in use that utilize this consumption influence parameter.

Figure 11 Inter-relationships for “Perimeter Length”

- **Shape of the House:** The shape of the house directly impacts perimeter length, form factor and footprint area as it is used to derive these parameters. While deriving these parameters through these primary relationships (Figure 12), the shape of the house dictates the type of geometric calculations that should be used through the applicable inter-dependencies (see Section 4.3.4). Home Energy Saver (LBNL 2009) and Hohm Beta Version (Microsoft 2009) are some of the current tools in use that utilize this consumption influence.
- **Interior Ceiling Height:** The ceiling height directly affects the volume parameters through a primary relationship (Figure 13). Along with total square footage, interior ceiling height is used to derive volume of the dwelling (see Section 4.3.4). Home Energy Saver (LBNL 2009) and Hohm Beta Version (Microsoft 2009) are some of the current tools in use that utilize this consumption influence parameter.

- **Number of Stories:** The number of stories and type of levels (above-ground versus underground) directly affects the thermal envelope characteristics and the total square footage. In multi-story buildings, the total square footage of the dwelling is calculated by summing the square footage for each level. Similarly, the exterior wall area for the thermal envelope is calculated according to the total height of the building, which is determined by summing the height of all stories. As a result, a change in number of stories directly impacts both of these parameters through primary relationships (Figure 14). In addition, the type of levels also directly impacts the thermal envelope characteristics for the walls through the types of building materials required in order to meet the minimum code requirements for above versus underground (McVicker 2007, Hodgson 2007). Home Energy Suite (Apogee 2009), Home Energy Saver (LBNL 2009), Hohm Beta Version (Microsoft 2009), Home Energy Tune-Up (CMC 2009) and Energy Efficient Rehab Advisor (DHUD 2009) are some of the current tools in use that utilize this consumption influence parameter.
• **Number of Rooms:** Even though the number of rooms does not have any primary relationships with another energy consumption influence parameter, it has a direct impact on appliances and electronics consumption items. Since this influence parameter directly affects the appliance and electronic equipment needs for the individual space through the number of consumption items available and used within the space, they contribute to the designated energy consumption. Home Energy Suite (Apogee 2009), Home Energy Saver (LBNL 2009), Hohm Beta Version (Microsoft 2009), Home Energy Tune-Up (CMC 2009) and Energy Efficient Rehab Advisor (DHUD 2009) are some of the current tools in use that utilize this consumption influence parameter.

• **Number and Size of Windows:** The number and size of the windows directly affect the building thermal envelope. This primary relationship (Figure 15) is due to the changes in the average thermal conductance “U” values for the walls as a result of the differences between window characteristics compared to other construction materials that are used (see Section 4.3.4). Home Energy Suite (Apogee 2009), Home Energy Saver (LBNL 2009), Hohm Beta Version (Microsoft 2009), Home Energy Tune-Up (CMC 2009) and Energy Efficient Rehab Advisor (DHUD 2009) are some of the current tools in use that utilize this consumption influence parameter.
- **Number and Size of Glass Doors:** The number and size of glass doors directly affect the building thermal envelope. This primary relationship (Figure 16) is due to the changes in the average thermal conductance “U” values for the walls as a result of the differences between glass door characteristics compared to other construction materials that are used (see Section 4.3.4). Home Energy Suite (Apogee 2009), Home Energy Saver (LBNL 2009), Hohm Beta Version (Microsoft 2009), Home Energy Tune-Up (CMC 2009) and Energy Efficient Rehab Advisor (DHUD 2009) are some of the current tools in use that utilize this consumption influence parameter.

- **Number and Size of Skylights:** The number and size of skylights directly affect the building thermal envelope. This primary relationship (Figure 17) is due to the changes in the average thermal conductance “U” values for the roof as a result of the differences between skylight characteristics compared to other construction materials that are used (see Section 4.3.4). Home Energy Suite (Apogee 2009), Home Energy Saver (LBNL 2009), Hohm Beta Version (Microsoft 2009), Home Energy Tune-Up (CMC 2009) and Energy Efficient Rehab Advisor (DHUD 2009) are some of the current tools in use that utilize this consumption influence parameter.
**Figure 17** Inter-relationships for “Number and Size of Skylights”

- **Number of Occupants:** Illustrated in Figure 18 as a primary relationship, the number of occupants has a direct impact on the occupancy patterns. As the number of occupants increases in a dwelling, the number of appliances and electronic equipment as well as their length of use increases. Similarly, the number of occupants causes a direct impact on occupancy patterns for hot water heating and interior lighting as a result of changes in consumption demands (see Section 4.3.4). Home Energy Suite (Apogee 2009), Home Energy Saver (LBNL 2009), Hohm Beta Version (Microsoft 2009), Home Energy Tune-Up (CMC 2009), Energy Efficient Rehab Advisor (DHUD 2009) and Energy Star Yardstick (Energy-Star 2009b) are some of the current tools in use that utilize this consumption influence parameter.

**Figure 18** Inter-relationships for “Number of Occupants”

- **Ages of Occupants:** Along with the number of occupants, age of the occupants also has a direct impact on the occupancy patterns, through a primary relationship (Figure 19). Age is
one of the attributes that is found to have an impact on energy consumption through the different use of consumption items (Yohanis et al. 2006). The change in the age of occupants usually affects the number of appliances and electronic equipment as well as their length of use. Similarly, the ages of occupants causes a direct impact on occupancy patterns for hot water heating and interior lighting as a result of changes in consumption demands (see Section 4.3.4). Home Energy Suite (Apogee 2009), Home Energy Saver (LBNL 2009), Hohm Beta Version (Microsoft 2009), Home Energy Tune-Up (CMC 2009), Energy Efficient Rehab Advisor (DHUD 2009) and Energy Star Yardstick (Energy-Star 2009b) are some of the current tools in use that utilize this consumption influence parameter.

**Figure 19** Inter-relationships for “Ages of Occupants”

- **Building Thermal Envelope:** The size and thermal properties of the building envelope significantly impacts the infiltration (Figure 20) through the air exchange rates in the space and the related infiltration gains and losses (see Section 4.3.4). Home Energy Suite (Apogee 2009), Home Energy Saver (LBNL 2009), Hohm Beta Version (Microsoft 2009), Home Energy Tune-Up (CMC 2009), Energy Efficient Rehab Advisor (DHUD 2009) and Home Advisor (Energy-Star 2009a) are some of the current tools in use that utilize this consumption influence parameter.
Space Usage Characteristics: Space usage characteristics have a direct affect on building thermal envelope and occupancy patterns (Figure 21). The usage of the space can impact thermal envelope characteristics for the surrounding exterior area due to the type of construction materials selected according to the nature of the use. A finished space contains exterior wall insulation and other construction materials selected in order to minimize infiltration losses and gains compared to an unfinished space, which might lack some of these components due to the less frequent nature of occupancy. Similarly, an unfinished space does not have the same occupancy patterns for the consumption items compared to a finished space due to the nature of occupancy. Home Energy Suite (Apogee 2009), Home Energy Saver (LBNL 2009), Hohm Beta Version (Microsoft 2009), Home Energy Tune-Up (CMC 2009), Energy Efficient Rehab Advisor (DHUD 2009) and Home Advisor (Energy-Star 2009a) are some of the current tools in use that utilize this consumption influence.
• **Infiltration:** Even though infiltration does not have any primary relationships with another energy consumption influence parameter, it has a direct impact on heating and cooling systems. This influence parameter directly affects heating and cooling needs for the individual space as a result of the outside air introduced through the thermal envelope (see Section 4.3.4). As a result of the temperature difference and the related losses/gains, infiltration impacts the designated energy consumption (Tao and Janis 2001b, ASHRAE 2007a, Szokolay 2004, Lindeburg 2006c).

• **Ventilation:** Similar to infiltration, ventilation does not have any primary relationships with another energy consumption influence parameter. However, the amount of required ventilation used in the space affects the air flow. As a result, it directly impacts the in-use efficiency of the heating and cooling systems and the related energy consumption (Tao and Janis 2001b, ASHRAE 2007a). The ventilation gains/losses (along with infiltration) and its impact on heating and cooling energy consumption is discussed in more detail in Section 4.3.4.

• **Zip code:** Zip code has a direct impact on orientation and available energy sources influence parameters (Figure 22). The geographic location of the house provided through zip code can dictate the orientation in relation to the sun as well as the available energy sources for consumption items (Tao and Janis 2001b). Examples of this impact are usually provided for rural and urban areas. In a rural setting, there usually is more flexibility in terms of lot sizes compared to urban settings. Thus, there is more latitude to ensure specific orientation of the building in relation to the sun during the construction. Also, some of the energy sources for the consumption items may not be available in rural settings. For example, natural gas is not one of the most commonly available energy sources for appliances such as stoves and clothes dryers in rural settings. On the other hand, these applications are much more common for urban settings due to the availability of this energy source. Energy Suite (Apogee 2009), Home Energy Saver (LBNL 2009), Hohm Beta Version (Microsoft 2009), Home Energy Tune-Up (CMC 2009), Energy Efficient Rehab Advisor (DHUD 2009), Home Advisor (Energy-Star 2009a) and Energy Star Yardstick (Energy-Star 2009b) are some of the current tools in use that utilize this consumption influence parameter.
**Figure 22** Inter-relationships for “Zip code”

- **Local Surroundings:** As illustrated in the local surroundings of a dwelling directly affect the amount of daylighting within the space and the resulting occupancy patterns for indoor lighting source usage (Tao and Janis 2001a). Houses that contain mature landscaping and hardscaping around their perimeter allows less sunlight penetration into the dwelling compared to houses that are in urban settings with minimal vegetation and direct exposure to sunlight. As a result, the occupancy pattern for indoor lighting sources is significantly affected. As discussed previously, local surroundings around a dwelling is also found to directly affect infiltration losses/gains. This impact is found to be due to the modified air temperature and the related modes of heat transfer (see Section 4.1). Home Energy Saver (LBNL 2009), Hohm Beta Version (Microsoft 2009) and Home Energy Tune-Up (CMC 2009) are some of the current tools in use that utilize this consumption influence parameter.

**Figure 23** Inter-relationships for “Local Surroundings”
• **Available Energy Sources:** The different types of energy sources that are available at a lot directly affect the system characteristics (Figure 24). The efficiency, performance rating and power consumption are usually different for similar systems and appliances that utilize different energy sources (see Section 4.3.4) for sample efficiency ratings for heating and cooling systems). Home Energy Suite (Apogee 2009), Home Energy Saver (LBNL 2009), Hohm Beta Version (Microsoft 2009), Home Energy Tune-Up (CMC 2009), Energy Efficient Rehab Advisor (DHUD 2009), and Energy Star Yardstick (Energy-Star 2009b) are some of the current tools in use that utilize this consumption influence parameter.

![Figure 24 Inter-relationships for “Energy Sources Available”](image)

• **System Characteristics:** This influence parameter does not have any primary relationships with another energy consumption influence parameter. However, the characteristics, specifications and the condition of building systems and appliances utilized in a dwelling significantly affects the energy consumption for the individual consumption items. The impact of this parameter on heating, cooling hot water heating and appliances energy consumption is discussed in more detail in Section 4.3.

• **Occupancy Patterns:** This influence parameter does not have any primary relationships with another energy consumption influence parameter. However, the occupancy patterns determine the specific length of use for electronics, appliances, hot water heater, and indoor lighting sources. Since the energy consumed by each consumption item is derived by using the duration of use, this energy influence consumption parameter directly impacts the related energy consumption (see Section 4.3).

• **Exposure to Elements:** This influence parameter does not have any primary relationships with another energy consumption influence parameter. Nonetheless, as discussed in Section
4.1, proximity of other dwellings nearby and the type of community, in which the house is located, can affect the solar gains through affects such as “Urban Heat Island Impacts”. As a result, cooling system energy consumption is found to be impacted (EPA 2011). Home Energy Saver (LBNL 2009), Hohm Beta Version (Microsoft 2009) and Home Energy Tune-Up (CMC 2009) are some of the current tools in use that utilize this consumption influence parameter.

After individual relationships are established as shown during this section, the third task is completed by providing the overall parameter inter-relationship map as illustrated in Figure 25. In this figure, parameter relationship with another parameter is illustrated with black while parameter relationship with a consumption item is illustrated with red lines.
Figure 25  Overall Parameter Relationship Map
4.3 Parameter Impact Analysis in Energy Consumption Models

During this section, Research Objective # 4: “Demonstrate the approach of analyzing the impact of residential energy consumption influence parameters in energy consumption modeling paths using the framework in order to depict their effect on the different energy consumption domains” is met by using five distinctive tasks.

The analysis is conducted separately for each of the 5 consumption domains. These consumption domains are defined as an analysis “lenses” (i.e. scope) and can contain one or more of the primary consumption items identified in Section 4.1. Energy consumption domains and their detailed characterization are further discussed in Section 4.4. The energy consumption for each domain is determined by using modeling approaches and/or equations. Each approach and equation utilizes either individual consumption influence parameters or parameter groups. While determining the values for parameters, different sources of input are used (Figure 26).

![Parameter Impact Analysis Diagram](image)

**Figure 26** Parameter Impact Analysis

- **Task # 1 – Determine Equation(s) & Modeling Path(s):** The first task for each energy consumption item consists of determining the relevant energy flow equations and applicable modeling paths for each consumption item. This study then further groups consumptions items regarding their contribution and impact to different energy consumption domains.
As a part of this task, all relevant energy flow equations and modeling paths are identified for each domain. However, the research study focuses on a simplified approach to analyze energy consumption rather than investigating the whole broad spectrum. For example, while identifying the heating and cooling energy consumption equations, the following assumptions are made to simplify heat transfer (Lindeburg 2006b):

- The heat transfer is a steady state and the area of heat path is constant.
- The heat path only has one dimension. The objects are not infinite in one or more dimensions.
- The construction materials have constant conductivity and thermal resistance.
- The heat path consists of anisotropic materials, which are materials whose heat transfer properties depend on the heat flow direction. Some examples of these materials are plywood and other laminated sheets used for interior finishes.

This simplified approach is also carried out during the selection of the types and number of equations and modeling paths during the impact analysis. For instance, heating and cooling energy consumption equations are simplified by using derivatives of “Equation a” to calculate the heat transfer rate for each building envelope component.

$$Q = U \times A \times (T_1 - T_2) \quad E.a$$

In this simplified equation, all active modes of heat transfer – conduction, convection (both natural and forced), and radiation - are taken into consideration, in order to accurately depict overall energy flow equations (Lindeburg 2006b). Also, the thermal conductance “U” values are used as the overall coefficients of all active modes of heat transfer.

Furthermore, at this point only consumption items that only use electricity are investigated. The analysis for investigating consumption items that use other available energy sources is not included in the scope of this impact analysis.

- **Task # 2 – Identify Parameters:** The second task consists of providing a framework depicting the different equations, modeling paths, and relevant influence parameters that can be used to determine the energy consumption of individual items. After all relevant influence parameters have been identified, they are categorized into Tier-1 and Tier-2 relationships. This categorization is done to simplify the approach by reducing the number of parameter
relationships analyzed during the consumption assessment. Tier-1 relationships refer to dependencies of parameters that have a significant and/or measurable effect on the energy consumption of one or more consumption items. Tier-2 relationships include parameters that are known to have secondary and/or less significant impact on the energy consumption. For example, “Volume” has a Tier-1 relationship with “Ventilation”, which directly impacts the ventilation and infiltration losses “Qv/i” through the inside air. “Interior Ceiling Height”, on the other hand, has a Tier-2 relationship with “Ventilation” through the Tier-1 relationship with “Volume”. Therefore, “Interior Ceiling Height” has an indirect impact on Qv/i through volume.

During this task, only Tier-1 relationships are further analyzed during the impact analysis. This decision is made based on the main focus of this research study, which is to develop a framework that simplifies energy consumption assessment rather than achieve 100% accuracy.

- **Task # 3 – Identify Sources of Input:** For this task, sources for different input parameters or assessment models that are utilized in equations and modeling paths are identified. These sources include:
  - Commonly accepted construction and engineering practices based on code requirements and design standards such as ASHRAE 2007a, ICC 2006a, etc.
  - Building science fundamentals such as Tao and Janis 2001c, BPI 2009, etc.
  - Consumption data based on previous research results such as LBNL 2009, Vine et al. 1987, etc.
  - Weather data based on historic data collected for the research location (Blacksburg, Virginia)
  - Identified data calculation methods based on previous research such as Tribwell and Lerman 1996, Stein et al. 2005b, etc.
  - Scenarios created for occupancy patterns and duration of use
  - Established baseline values
  - Assumptions based on best available information

- **Task # 4 – Establish Baseline Values:** Task four consists of establishing baseline values for the impact analysis. The baseline values are determined individually for each energy consumption domain by using one or more of the following strategies:
Modeling approaches provided by commonly accepted tools are used for calculating parameter values or energy consumption. Calculations and strategies provided by tools such as Home Energy Saver (HES) are utilized for the identified input values during these calculations. The results are then used as a benchmark to make comparisons with the results of simpler calculation methods.

Two plausible scenarios are created to capture the variation in “occupancy pattern”. These scenarios are demonstration cases that are assumed to depict the different ends of the usage spectrum. The “duration of use” values determined through these scenarios are utilized to depict the related minimum and maximum consumption. These values are also used to further analyze the impact of other parameters according to variations in their input values. Scenarios used through this research consist of Scenarios A and B. Scenario A, which is abbreviated as “SA”, refers to single working professional. Scenario B, which is abbreviated as “SB”, refers to a family of 4 with a stay-at-home parent. In this scenario, the age ranges for the children are assumed to be “0-5” and “6 -13” years old.

A sample house with pre-determined parameter values is used as the baseline for some of the construction related parameters during relevant consumption calculations. The sample house selected is assumed to represent a common residential construction type in the research area (Blacksburg, Virginia). The house is wood construction (wood frame and studs) built over ground slab and has vinyl siding. The exterior façade includes a limited amount of masonry stone installed for aesthetic purposes. The dwelling is 60 feet long, 30 feet wide, and approximately 1800 square feet. It is single level and consists of 3 bedrooms, 2 bathrooms, and an attached garage. The individual room properties for this dwelling are provided in Table 5.
<table>
<thead>
<tr>
<th>Space</th>
<th>Quantity</th>
<th>Area Percentage of Individual Space (Based on sqft)</th>
<th>Cumulative Percentage for Room Types (Based on sqft)</th>
<th>Cumulative Sqft for Room Types</th>
</tr>
</thead>
<tbody>
<tr>
<td>Master Bedroom</td>
<td>1</td>
<td>11%</td>
<td>11%</td>
<td>198</td>
</tr>
<tr>
<td>Bedrooms</td>
<td>2</td>
<td>11%</td>
<td>22%</td>
<td>396</td>
</tr>
<tr>
<td>Bathrooms</td>
<td>2</td>
<td>5.5%</td>
<td>11%</td>
<td>198</td>
</tr>
<tr>
<td>Kitchen</td>
<td>1</td>
<td>11%</td>
<td>11%</td>
<td>198</td>
</tr>
<tr>
<td>Dining Room</td>
<td>1</td>
<td>6%</td>
<td>6%</td>
<td>108</td>
</tr>
<tr>
<td>Living Room</td>
<td>1</td>
<td>20%</td>
<td>20%</td>
<td>360</td>
</tr>
<tr>
<td>Garage (2 car)</td>
<td>1</td>
<td>11%</td>
<td>11%</td>
<td>198</td>
</tr>
<tr>
<td>Stairs</td>
<td>1</td>
<td>1%</td>
<td>1%</td>
<td>18</td>
</tr>
<tr>
<td>Misc.</td>
<td>1</td>
<td>7%</td>
<td>7%</td>
<td>126</td>
</tr>
</tbody>
</table>

**Total Sqft = 1800**

Table 5  Individual room properties for sample house

There is an exterior lighting fixture by the front entrance and back deck. Both of these fixtures use a single 60 Watt incandescent light bulb.

The size of the hot water heater tank is 60 gallons. The heating and cooling system is a forced air system with a gas furnace and a split air-conditioning unit.

- In some instances mean values calculated for consumption influence parameters and parameter groups are used as baseline values for the impact analysis. Through the various sources of input, minimum, maximum, and mean values are established for each parameter or parameter group. Minimum values are defined as those numerical parameter values, which provide the lowest amount of energy loss. Maximum values are defined as those numerical parameter values, which provide the highest amount of energy loss. These minimum and maximum parameter values are then compared against the baseline value to better analyze the variation in component values.

- **Task # 5 – Conduct Impact Analysis:** This task consists of carrying out the parameter impact analysis for each energy consumption domain. The impact analysis determines the effect of each parameter and parameter group on the respective energy consumption domain. The ranges of typical input values of each parameter and parameter group are first determined through the established minimum and maximum values. Subsequently, the impact of each parameter and parameter group are determined by comparing the energy consumption calculated for these values to the energy consumption calculated for the previously established baseline values.
Also, where applicable, the impact analysis is conducted to determine the combined total impact of parameter groups on the respective energy domains. The combined total impact of the parameter groups is analyzed by comparing the total minimum and maximum consumption values, which are calculated respectively from utilizing all minimum and all maximum parameter values, to the baseline consumption values.

During heating and cooling energy consumption calculations, the individual impact of influence parameters on the designated consumption domain is analyzed by calculating and comparing individual diverging consumption values to the baseline consumption. The diverging values are calculated by using the maximum value for the analyzed parameter (since the minimum value usually has the same divergence to the mean/baseline value) while holding all other parameters on their baseline values. The individual impact of parameters is only completed for parameters that show a divergence to the established baseline values.

The energy consumption of heating and cooling systems is analyzed within the same document section due to similarities in the calculations and the dual-purpose nature of most heating and cooling equipment. However, the effects of parameters and components are identified individually for space heating and cooling.

The sequence of the different energy consumption domains discussed in the following impact analysis is chosen based on simplicity of equations rather than on overall impact on the total energy consumption in residential buildings. This approach has been selected to demonstrate the analysis process starting with simpler energy consumption domains (and equations), while gradually advancing to the more complex domains dealing with a variety of subsystems and corresponding equations.

4.3.1 Appliances and Electronics

a) Equations & Modeling Paths

An appliance and electronics energy analysis consists of determining the different types of common household appliances and electronics (e.g., washer, dryer, dishwasher, oven, stove, microwave oven, televisions, home theater system, and computers) and the duration of their use.
Figure 27  Annual Appliances and Electronics Consumption Calculation
Specialty sources, which include equipment such as well pumps, pool pumps, pool heaters, and sump pumps, are not discussed within this research. Since most homes are assumed to not contain these sources, these consumption items are not considered in the modeling discussions. In addition, phantom loads, which are loads consumed by connected electronics, equipment and chargers while not used, are also not accounted for in the modeling discussions.

In Figure 27, A and B illustrate different modeling paths for calculating energy consumption of appliances and electronics. In each path, the consumption data for specific appliance and electronics (e.g., number of items and the designated power consumption per hour) and the durations of use based on occupancy patterns (hrs/year) are determined.

b) Consumption Influence Parameters

As illustrated in Figure 27, Parameter Groups I and II are influenced by various parameters, whereas the parameters “Available Energy Sources”, “System Characteristics”, and “Occupancy Patterns” are identified as Tier-1 relationships.

Influence parameters neglected in the above model and thus categorized as Tier-2 relationships are shown in Figure 28. These parameters are not analyzed in the numerical impact study. However, a brief discussion regarding their influence on appliance and electronics energy consumption is provided below:

![Diagram of Tier-2 Parameter Relationships for Appliances and Electronics](image)

**Figure 28** Tier-2 Parameter Relationships for Appliances and Electronics
• **Year Built:** Houses that are built in different eras can show differences in the number of built-in appliances and electronics. One example of differences is the existence or non-existence of dishwashers. Homes built in 1960s may not contain connections for a dishwasher as opposed to newer homes, most of which includes a dishwasher.

• **Total Square Footage:** The total number of appliances is higher for finished spaces compared to unfinished spaces. Also, attached spaces can potentially increase the total number of appliances for a household. Depending on the nature and duration of the habitation for an attached space, the number of appliances and electronics can be affected. One example for this relationship is attached garages that are used as workshop with stationary power tools. In these instances, refrigerator or stereo system are some of the commonly used additional consumption items.

• **Number of Rooms:** The total number of electronics increases for additional bedrooms, bathrooms, family rooms and living rooms, independent of total square feet area. One example for this relationship is the increase in number of TVs. It is not uncommon to have TVs in bedrooms and family rooms. As the number of these rooms increase so does the number of TVs in the household. This relationship is not necessarily reflected by the total square footage as a larger home can have simply larger rooms rather than a higher number of rooms. Also, the total number of appliances increases depending on the use of the spaces, e.g., for additional kitchens and garages.

• **Number and Occupants:** An increase in the number of occupants in a household generally increases the duration of use for some electronics and appliances and can impact the total number of these consumption items, e.g., multiple TVs to accommodate different user preferences.

• **Ages of Occupants:** Along with the number of occupants, the ages of occupants are found to have an impact on the duration of use for appliances and electronics (Yohanis et al. 2006). Gaming systems, stereos and home theatre systems, and computers are examples of electronics that may be used more frequently by younger occupants compared to older occupants.
c) Parameter Sources

Two different types of sources of input are researched and applied for the modeling path to analyze the impact of relevant influence parameters on appliances and electronics energy consumption. From these types of input, possible values for each influence parameter under Parameter Groups I and II as follows:

- **Consumer Studies:** The duration of use for each consumption item is typically determined by referring to consumer studies conducted in the industry and available consumer utility consumption data for the selected communities as well as national averages provided by government agencies such as DOE and EIA. Specifications and required energy consumption for each item is typically determined by utilizing manufacturer specifications and commonly used typical values (see Table 6).

Five separate sources for regional and national consumer studies are utilized in order to determine energy consumption averages and durations of use for different types of commonly used household appliances and electronics. The compiled data are separated into energy consumption averages per equipment/appliance and duration of use for each item. The data set for energy consumption averages per equipment/appliance for each consumer study is provided by Table 6. The data set for typical durations of use for each equipment/appliance for each consumer study is provided by Table 7. Both data sets provided in Table 6 and Table 7 include adjustments made according to the average number of items in each category per household.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Range / Oven (*)</td>
<td>-</td>
<td>1200 - 3500</td>
<td>1200 - 2400</td>
<td>-</td>
<td>12200</td>
</tr>
<tr>
<td>Dryer (*)</td>
<td>4000</td>
<td>5000</td>
<td>5000</td>
<td>4000</td>
<td>2790</td>
</tr>
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<td>Dishwasher</td>
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<td>1800</td>
<td>1000</td>
<td>1200 – 1500</td>
<td>1201</td>
</tr>
<tr>
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<td>1250</td>
<td>1000 – 1500</td>
<td>800 – 1500</td>
<td>1550</td>
</tr>
<tr>
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<td>1500</td>
<td>1500</td>
<td>600 - 1500</td>
<td>1450</td>
</tr>
<tr>
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<td>1200</td>
<td>1150</td>
<td>1500</td>
<td>1200</td>
<td>1196</td>
</tr>
<tr>
<td>Washer</td>
<td>500</td>
<td>500</td>
<td>1200</td>
<td>500</td>
<td>512</td>
</tr>
<tr>
<td>Refrigerator /</td>
<td>1200 – 1411</td>
<td>300 – 780</td>
<td>383 – 841</td>
<td>500</td>
<td>380 – 800</td>
</tr>
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</table>

64
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Freezer</td>
<td>1080 – 1240</td>
<td>335 – 350</td>
<td>600</td>
<td>440</td>
<td>540 – 700</td>
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<tr>
<td>Vacuum</td>
<td>200 – 700</td>
<td>800 – 1600</td>
<td>800 -1440</td>
<td>200 – 700</td>
<td>630</td>
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<td>900</td>
<td>800</td>
<td>1200</td>
</tr>
<tr>
<td>Iron</td>
<td>1000</td>
<td>-</td>
<td>1100</td>
<td>1000</td>
<td>1100</td>
</tr>
<tr>
<td>Blow-dryer</td>
<td>1000</td>
<td>-</td>
<td>1500</td>
<td>1000</td>
<td>1000</td>
</tr>
<tr>
<td>Dehumidifier / Humidifier</td>
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<td>350</td>
<td>200 – 790</td>
<td>-</td>
<td>177</td>
</tr>
<tr>
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<td>100</td>
<td>100</td>
<td>600</td>
<td>100</td>
<td>-</td>
</tr>
<tr>
<td>Garbage Disposal</td>
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<td>-</td>
<td>-</td>
<td>450</td>
<td>445</td>
</tr>
<tr>
<td>TV</td>
<td>150</td>
<td>125 – 300</td>
<td>130 -375</td>
<td>150</td>
<td>45 – 286</td>
</tr>
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<td>200</td>
<td>180</td>
<td>165</td>
<td>200</td>
<td>177</td>
</tr>
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<td>Laptop</td>
<td>20 – 50</td>
<td>-</td>
<td>75</td>
<td>20 – 50</td>
<td>-</td>
</tr>
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<td>PC</td>
<td>80 – 150</td>
<td>100</td>
<td>270</td>
<td>80 – 150</td>
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<td>75</td>
<td>-</td>
<td>100</td>
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<td>CD / DVD Player</td>
<td>35</td>
<td>40</td>
<td>60</td>
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<td>-</td>
<td>75</td>
<td>10 - 30</td>
<td>-</td>
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<td>30</td>
<td>30</td>
<td>-</td>
<td>30</td>
<td>23</td>
</tr>
</tbody>
</table>

(*) Denotes both natural gas and electricity as potential energy source

Table 6  Average Energy Consumption in Watts - Appliances & Electronics
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Range / Oven</td>
<td>40</td>
<td>200</td>
<td>120</td>
<td>64</td>
</tr>
<tr>
<td>Dryer</td>
<td>24</td>
<td>112</td>
<td>288</td>
<td>323</td>
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<td>Dishwasher</td>
<td>32</td>
<td>160</td>
<td>240</td>
<td>302</td>
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<tr>
<td>Toaster</td>
<td>8</td>
<td>96</td>
<td>300</td>
<td>62</td>
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<tr>
<td>Microwave</td>
<td>20</td>
<td>120</td>
<td>120</td>
<td>130</td>
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<tr>
<td>Frying Pan</td>
<td>40</td>
<td>80</td>
<td>36</td>
<td>83</td>
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<tr>
<td>Washer</td>
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<td>160</td>
<td>192</td>
<td>201</td>
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<td>Refrigerator / Freezer</td>
<td>600</td>
<td>120</td>
<td>8640</td>
<td>3500</td>
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<td>Freezer</td>
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<td>1680</td>
<td>8640</td>
<td>2500</td>
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<td>24</td>
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<td>120</td>
<td>156</td>
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<tr>
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<td>-</td>
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<td>55</td>
</tr>
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<td>Blow-dryer</td>
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<td>-</td>
<td>120</td>
<td>15.6</td>
</tr>
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<td>Dehumidifier / Humidifier</td>
<td>480</td>
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<td>8640</td>
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<td>Printer</td>
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<td></td>
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<td>Garbage Disposal</td>
<td>-</td>
<td>-</td>
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<td>16</td>
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<td>TV</td>
<td>240</td>
<td>1760</td>
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<td>1500</td>
</tr>
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<td>Electric Blanket</td>
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<td>360</td>
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<td>1000</td>
</tr>
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<td>Stereo</td>
<td>-</td>
<td>-</td>
<td>1560</td>
<td>-</td>
</tr>
<tr>
<td>Satellite Receiver</td>
<td>2880</td>
<td>2880</td>
<td>-</td>
<td>2200</td>
</tr>
</tbody>
</table>

**Table 7** Duration of Use in Hours/Year - Appliances & Electronics

- **Consumption data based on previous research (HES):** The typical energy consumption rates are provided by the HES model (LBNL 2009). As shown in Table 8, an annual energy consumption value is provided for every item by this model.
<table>
<thead>
<tr>
<th>Sources</th>
<th>HES Annual Consumption (kWh/Year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range / Oven</td>
<td>604</td>
</tr>
<tr>
<td>Dryer</td>
<td>838</td>
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<td>Dishwasher</td>
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<td>Toaster</td>
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<td>Microwave</td>
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<td>Washer</td>
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<td>Refrigerator / Freezer</td>
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<td>Freezer</td>
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<td>Vacuum</td>
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<td>Coffee Maker</td>
<td>282</td>
</tr>
<tr>
<td>Iron</td>
<td>53</td>
</tr>
<tr>
<td>Blow-dryer</td>
<td>35</td>
</tr>
<tr>
<td>Dehumidifier / Humidifier</td>
<td>100</td>
</tr>
<tr>
<td>Printer</td>
<td>37</td>
</tr>
<tr>
<td>Garbage Disposal</td>
<td>49</td>
</tr>
<tr>
<td>TV</td>
<td>270</td>
</tr>
<tr>
<td>Electric Blanket</td>
<td>122</td>
</tr>
<tr>
<td>Laptop</td>
<td>39</td>
</tr>
<tr>
<td>PC</td>
<td>132</td>
</tr>
<tr>
<td>Sewing Machine</td>
<td>-</td>
</tr>
<tr>
<td>CD / DVD Player</td>
<td>19</td>
</tr>
<tr>
<td>Stereo</td>
<td>46</td>
</tr>
<tr>
<td>Satellite Receiver</td>
<td>27</td>
</tr>
</tbody>
</table>

**Table 8**  Annual appliance consumption according to HES

These values are based on national consumer studies. They are also adjusted according to the average number of items in each category per household. They are used by the HES model as default values when no other parameter input is provided.

*d) Baseline Values and Consumption*

The baseline values for “power consumption” and “duration of use” are established according to median values calculated for the different data sets provided by the consumer studies. The median values are used in order to eliminate the outliers and clean up the data sets. The following steps describe the basic mathematical algorithm used to calculate of median values for the different data sets. This algorithm is selected by the researcher to complete this task. However, it is also stipulated that other approaches can also be used.
• For items with 5 or more values from different consumer studies:
  o List all the values from lowest to the highest
  o Determine the middle value, which is the Median Value (Q3)
  o Identify the lower and higher quartile values on each side of the Median Value (Q2 and Q4)
  o Determine Quartile Range “Qr” by subtracting the lower quartile value from the higher quartile value (Qr = Q4 – Q2)
  o Check for Outliers by validating with “1.5*Qr” intervals. [e.g., Q1 is an outlier if Q1 < Q2 –(1.5 * Qr) and Q5 is an outlier if Q5 > Q4 +(1.5 * Qr)]
  o If there are any outliers, take them out of the data set and follow the same steps to determine the Median Value. If there are no outliers, use Q3 as the Median Value.

• For items with 4 or less values from different consumer studies:
  o List all the values from lowest to the highest
  o If only 3 values are available, the middle value is the Median Value
  o If 4 values are available, the Median Value is equal to (Q2 + Q4)/2
  o If only 2 values are available, the Median Value is equal to (Q1 + Q2)/2

The resulting median values for typical consumption and durations of use per consumption item are provided by Table 9.

<table>
<thead>
<tr>
<th>Sources</th>
<th>Consumer Studies Power Consumption Median Value (W)</th>
<th>Consumer Studies Duration of Use Median Value (Hrs/year)</th>
<th>Consumer Studies Annual Consumption (kWh/Year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range / Oven</td>
<td>2400</td>
<td>92</td>
<td>220.8</td>
</tr>
<tr>
<td>Dryer</td>
<td>4000</td>
<td>200</td>
<td>800</td>
</tr>
<tr>
<td>Dishwasher</td>
<td>1350</td>
<td>240</td>
<td>324</td>
</tr>
<tr>
<td>Toaster</td>
<td>1250</td>
<td>79</td>
<td>98.8</td>
</tr>
<tr>
<td>Microwave</td>
<td>1450</td>
<td>120</td>
<td>174</td>
</tr>
<tr>
<td>Frying Pan</td>
<td>1198</td>
<td>60</td>
<td>71.9</td>
</tr>
<tr>
<td>Washer</td>
<td>500</td>
<td>192</td>
<td>96</td>
</tr>
<tr>
<td>Refrigerator / Freezer</td>
<td>442</td>
<td>600</td>
<td>265.2</td>
</tr>
<tr>
<td>Freezer</td>
<td>490</td>
<td>1680</td>
<td>823.2</td>
</tr>
<tr>
<td>Vacuum</td>
<td>665</td>
<td>50</td>
<td>33.3</td>
</tr>
<tr>
<td>Coffee Maker</td>
<td>850</td>
<td>120</td>
<td>102</td>
</tr>
<tr>
<td>Iron</td>
<td>1050</td>
<td>88</td>
<td>92.4</td>
</tr>
<tr>
<td>Blow-dryer</td>
<td>1250</td>
<td>68</td>
<td>85</td>
</tr>
</tbody>
</table>
The total appliance and electronics baseline energy consumption (AEC Baseline) is then derived by summing up the individual energy requirement for each line item. The individual energy requirement for each consumption item is calculated by multiplying the median power consumption with the median duration of use. For this calculation, it is assumed that one item of all listed appliances exist in the modeled household. The AEC Baseline is calculated as:

\[ \text{AEC Baseline} \Rightarrow \sim 4,000 \text{ kWh/year} \]

e) Impact Analysis

The total appliance and electronics energy consumption (AEC) values are derived by summing up the individual energy requirement for each consumption item. If not known, the individual energy requirement for each consumption item is calculated by multiplying the power consumption (W) and duration of use (hrs/year).

- **Impact of Power Consumption:** Minimum and maximum power consumption values provided by consumer studies are used to analyze the impact of power consumption on the Annual Energy Consumption (AEC) for appliances and electronics. During these calculations, the AEC values are calculated by using the different power consumption and the baseline duration of use values for all the consumption items as provided in Table 10.
<table>
<thead>
<tr>
<th>Sources</th>
<th>Minimum Power Consumption Value (W)</th>
<th>Maximum Power Consumption Value (W)</th>
<th>Median Duration Of Use Value (hrs/year)</th>
<th>Minimum AEC (KWh/year)</th>
<th>Maximum AEC (KWh/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range / Oven</td>
<td>1200</td>
<td>12220</td>
<td>92</td>
<td>110.4</td>
<td>1124.24</td>
</tr>
<tr>
<td>Dryer</td>
<td>2790</td>
<td>5000</td>
<td>200</td>
<td>558</td>
<td>1000</td>
</tr>
<tr>
<td>Dishwasher</td>
<td>1000</td>
<td>1800</td>
<td>240</td>
<td>240</td>
<td>432</td>
</tr>
<tr>
<td>Toaster</td>
<td>800</td>
<td>1550</td>
<td>79</td>
<td>63.2</td>
<td>122.45</td>
</tr>
<tr>
<td>Microwave</td>
<td>600</td>
<td>1500</td>
<td>120</td>
<td>72</td>
<td>180</td>
</tr>
<tr>
<td>Frying Pan</td>
<td>1150</td>
<td>1500</td>
<td>60</td>
<td>69</td>
<td>90</td>
</tr>
<tr>
<td>Washer</td>
<td>500</td>
<td>1200</td>
<td>192</td>
<td>96</td>
<td>230.4</td>
</tr>
<tr>
<td>Refrigerator / Freezer</td>
<td>300</td>
<td>1411</td>
<td>600</td>
<td>180</td>
<td>846.6</td>
</tr>
<tr>
<td>Freezer</td>
<td>335</td>
<td>1240</td>
<td>1680</td>
<td>562.8</td>
<td>2083.2</td>
</tr>
<tr>
<td>Vacuum</td>
<td>200</td>
<td>1600</td>
<td>50</td>
<td>10</td>
<td>80</td>
</tr>
<tr>
<td>Coffee Maker</td>
<td>100</td>
<td>1200</td>
<td>120</td>
<td>12</td>
<td>144</td>
</tr>
<tr>
<td>Iron</td>
<td>1000</td>
<td>1100</td>
<td>88</td>
<td>88</td>
<td>96.8</td>
</tr>
<tr>
<td>Blow-dryer</td>
<td>1000</td>
<td>1500</td>
<td>68</td>
<td>68</td>
<td>102</td>
</tr>
<tr>
<td>Dehumidifier / Humidifier</td>
<td>200</td>
<td>790</td>
<td>921</td>
<td>184.2</td>
<td>727.59</td>
</tr>
<tr>
<td>Printer</td>
<td>100</td>
<td>600</td>
<td>100</td>
<td>10</td>
<td>60</td>
</tr>
<tr>
<td>Garbage Disposal</td>
<td>445</td>
<td>450</td>
<td>68</td>
<td>30.5</td>
<td>49</td>
</tr>
<tr>
<td>TV</td>
<td>125</td>
<td>375</td>
<td>1470</td>
<td>220.5</td>
<td>270</td>
</tr>
<tr>
<td>Electric Blanket</td>
<td>165</td>
<td>200</td>
<td>360</td>
<td>63.7</td>
<td>122</td>
</tr>
<tr>
<td>Laptop</td>
<td>20</td>
<td>75</td>
<td>640</td>
<td>32</td>
<td>39</td>
</tr>
<tr>
<td>PC</td>
<td>80</td>
<td>270</td>
<td>640</td>
<td>96</td>
<td>132</td>
</tr>
<tr>
<td>Sewing Machine</td>
<td>75</td>
<td>100</td>
<td>56</td>
<td>5</td>
<td>-</td>
</tr>
<tr>
<td>CD / DVD Player</td>
<td>35</td>
<td>85</td>
<td>800</td>
<td>34.4</td>
<td>19</td>
</tr>
<tr>
<td>Stereo</td>
<td>10</td>
<td>75</td>
<td>1560</td>
<td>46.8</td>
<td>46</td>
</tr>
<tr>
<td>Satellite Receiver</td>
<td>23</td>
<td>30</td>
<td>2440</td>
<td>65.9</td>
<td>27</td>
</tr>
</tbody>
</table>

**Table 10**  Power Consumption Impact Analysis Data Set

The AEC values are derived by summing up the individual energy requirement for each line item. The individual energy requirement for each consumption item is calculated by multiplying the minimum and maximum power consumption with the median duration of use. The minimum and maximum AEC values are calculated as:
AEC minimum \(\Rightarrow\) \(~ 2,765 \text{kWh/year}\) (compared to \(~ 4,000 \text{kWh/year}\) from BL)

AEC maximum \(\Rightarrow\) \(~ 8,458 \text{kWh/year}\) (compared to \(~ 4,000 \text{kWh/year}\) from BL)

**Figure 29** Impact of Power Consumption on Appliance and Electronics Energy Consumption

<table>
<thead>
<tr>
<th>Sources</th>
<th>Minimum Duration of Use Value (hrs/year)</th>
<th>Maximum Duration of Use Value (hrs/year)</th>
<th>Median Power Consumption Value (W)</th>
<th>Minimum AEC (KWh/year)</th>
<th>Maximum AEC (KWh/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range / Oven</td>
<td>40</td>
<td>200</td>
<td>2400</td>
<td>96</td>
<td>480</td>
</tr>
<tr>
<td>Dryer</td>
<td>24</td>
<td>323</td>
<td>4000</td>
<td>96</td>
<td>1292</td>
</tr>
<tr>
<td>Dishwasher</td>
<td>32</td>
<td>302</td>
<td>1350</td>
<td>43.2</td>
<td>407.7</td>
</tr>
<tr>
<td>Toaster</td>
<td>8</td>
<td>300</td>
<td>1250</td>
<td>10</td>
<td>375</td>
</tr>
</tbody>
</table>

- **Impact of Duration of Use:** Minimum and maximum duration of use values provided by consumer studies are used to analyze the impact of duration of use on the Annual Energy Consumption (AEC) for appliances and electronics. During these calculations, the AEC values are calculated by using the different durations of use and the baseline power consumption values for all the consumption items as provided in Table 11.
<table>
<thead>
<tr>
<th>Sources</th>
<th>Minimum Duration of Use Value (hrs/year)</th>
<th>Maximum Duration of Use Value (hrs/year)</th>
<th>Median Power Consumption Value (W)</th>
<th>Minimum AEC (KWh/year)</th>
<th>Maximum AEC (KWh/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microwave</td>
<td>20</td>
<td>130</td>
<td>1450</td>
<td>29</td>
<td>188.5</td>
</tr>
<tr>
<td>Frying Pan</td>
<td>36</td>
<td>83</td>
<td>1198</td>
<td>43.128</td>
<td>99.434</td>
</tr>
<tr>
<td>Washer</td>
<td>28</td>
<td>201</td>
<td>500</td>
<td>14</td>
<td>100.5</td>
</tr>
<tr>
<td>Refrigerator / Freezer</td>
<td>120</td>
<td>8640</td>
<td>442</td>
<td>53.04</td>
<td>3818.88</td>
</tr>
<tr>
<td>Freezer</td>
<td>720</td>
<td>8640</td>
<td>490</td>
<td>352.8</td>
<td>4233.6</td>
</tr>
<tr>
<td>Vacuum</td>
<td>8</td>
<td>120</td>
<td>665</td>
<td>5.32</td>
<td>79.8</td>
</tr>
<tr>
<td>Coffee Maker</td>
<td>16</td>
<td>156</td>
<td>850</td>
<td>13.6</td>
<td>132.6</td>
</tr>
<tr>
<td>Iron</td>
<td>55</td>
<td>120</td>
<td>1050</td>
<td>57.75</td>
<td>126</td>
</tr>
<tr>
<td>Blow-dryer</td>
<td>15.6</td>
<td>120</td>
<td>1250</td>
<td>19.5</td>
<td>150</td>
</tr>
<tr>
<td>Dehumidifier / Humidifier</td>
<td>480</td>
<td>8640</td>
<td>200</td>
<td>96</td>
<td>1728</td>
</tr>
<tr>
<td>Humidifier</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Printer</td>
<td>36</td>
<td>640</td>
<td>350</td>
<td>12.6</td>
<td>224</td>
</tr>
<tr>
<td>Garbage Disposal</td>
<td>16</td>
<td>120</td>
<td>448</td>
<td>7.168</td>
<td>53.76</td>
</tr>
<tr>
<td>TV</td>
<td>240</td>
<td>1760</td>
<td>150</td>
<td>36</td>
<td>264</td>
</tr>
<tr>
<td>Electric Blanket</td>
<td>120</td>
<td>2880</td>
<td>177</td>
<td>21.24</td>
<td>509.76</td>
</tr>
<tr>
<td>Laptop</td>
<td>100</td>
<td>1080</td>
<td>50</td>
<td>5</td>
<td>54</td>
</tr>
<tr>
<td>PC</td>
<td>100</td>
<td>5200</td>
<td>150</td>
<td>15</td>
<td>780</td>
</tr>
<tr>
<td>Sewing Machine</td>
<td>75</td>
<td>100</td>
<td>88</td>
<td>1.408</td>
<td>12.936</td>
</tr>
<tr>
<td>CD / DVD Player</td>
<td>35</td>
<td>85</td>
<td>43</td>
<td>8.6</td>
<td>61.92</td>
</tr>
<tr>
<td>Stereo</td>
<td>10</td>
<td>75</td>
<td>30</td>
<td>46.8</td>
<td>46.8</td>
</tr>
<tr>
<td>Satellite Receiver</td>
<td>23</td>
<td>30</td>
<td>27</td>
<td>59.4</td>
<td>77.76</td>
</tr>
</tbody>
</table>

Table 11  Duration of Use Impact Analysis Data Set

The AEC values are derived by summing up the individual energy requirement for each line item. The individual energy requirement for each consumption item is calculated by multiplying the minimum and maximum durations of use with the median power consumption. The minimum and maximum AEC values are calculated as:

- AEC minimum $\Rightarrow \sim 1,143 \text{ kWh/year}$ (compared to 4,000 kWh/year from BL)
- AEC maximum $\Rightarrow \sim 15,297 \text{ kWh/year}$ (compared to 4,000 kWh/year from BL)
The total appliance and electronics energy consumption (AEC) is also calculated for input values from HES model and is then compared against the previously determined baseline consumption from consumer studies. The AEC value for HES is derived by summing up the individual annual energy consumption amount for each consumption item provided in Table 8. The AEC value is calculated as:

HES: \[ \text{AEC} \Rightarrow \sim 4,480 \text{ kWh/year} \text{ (compared to 4,000 kWh/year from BL)} \]

**Figure 30** Impact of Duration of Use on Appliance and Electronics Energy Consumption

<table>
<thead>
<tr>
<th>Overall Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>- 71% ← Baseline → +282%</td>
</tr>
</tbody>
</table>

- **Total Consumption Comparison**: The total appliance and electronics energy consumption (AEC) is also calculated for input values from HES model and is then compared against the previously determined baseline consumption from consumer studies.

The AEC value for HES is derived by summing up the individual annual energy consumption amount for each consumption item provided in Table 8. The AEC value is calculated as:

HES: \[ \text{AEC} \Rightarrow \sim 4,480 \text{ kWh/year} \text{ (compared to 4,000 kWh/year from BL)} \]

**Conclusion**

As illustrated in Figure 29 and Figure 30, the AEC values calculated during “Duration of Use” impact analysis show more deviation from the baseline AEC compared to AEC values calculated for “Power Consumption”. Thus, it can be concluded that the occupancy pattern as a consumption influence parameter has more impact on the appliances and electronics energy consumption than the variation of power consumption.

As shown with the HES Annual Energy Consumption value provided above, the baseline consumer studies model provides a value that is 90% of what is assumed by the HES model.
Therefore, a simplified model using consumer studies seems to be practical for calculating appliances and electronics energy consumption due to its simplicity.

4.3.2 Artificial Lighting

Artificial lighting energy analysis consists of determining the different types of common household lighting options for interior and exterior location (e.g., lamps, outdoor, recess and night lighting) and the duration of their use.

4.3.2.1 Interior Lighting

a) Equations & Modeling Paths

Figure 31 Annual Interior Lighting Energy Consumption Calculation
In Figure 31, A, B and C illustrate different modeling paths for calculating energy consumption of interior lighting. In each modeling path, illumination requirements and the duration of use based on occupancy patterns (hrs/year) are determined.

![Diagram of Annual Consumption for Interior Lighting](image)

- **Number of Stories - Below Ground:** The decrease in the number and the size of windows in most basements can impact the amount of daylighting provided within the space. This potential impact on daylighting can affect the duration of use for interior lighting and the related energy consumption.

- **Space Usage Characteristics:** The activities conducted in each space can impact the illumination requirements and the duration of use. For example, a bedroom used as an office can require more illumination for office work and less duration of use compared to a bedroom used for just sleeping. Similarly, a garage used for parking cars can have different illumination requirements and duration of use for interior lighting compared to a garage used as a woodworking shop.

---

**Figure 32** Tier-2 Parameter Relationships for Interior Lighting
- **Number and Size of Skylights:** Skylights can impact the amount of sunlight and daylight that penetrates through the space. The potential impact on day lighting can affect the duration of use for interior lighting and the related energy consumption.

- **Number & Size of Glass Doors:** Glass doors can impact the amount of sunlight and daylight that penetrates through the space. The potential impact on day lighting can affect the duration of use for interior lighting and the related energy consumption.

- **Number and Size of Windows:** Windows impact the amount of sunlight and daylight that penetrates through the space. The impact on day lighting can affect the duration of use for interior lighting and the related energy consumption.

- **Orientation:** The orientation of the house can impact the amount of daylighting provided within a dwelling since the number of windows per façade and the position of the windows are different for each side of the house. The potential impact on the daylighting can also affect the duration of use for interior lighting and the related energy consumption.

- **Local Surroundings:** Landscaping and hardscaping surrounding a home can impact the natural sunlight and daylight coming into the house through, windows, glass doors and skylights. This impact can influence the duration of use for interior lighting and the related energy consumption.

  \[b\) Parameter Sources\]

Five sources of input are researched and applied for the modeling paths A and B to analyze the impact of relevant influence parameters on interior lighting energy consumption. The utilized sources of input include:

- Two separate assumptions based on best information available (ASHRAE/IESNA Standard 90.1).
- Consumption data and calculation methods provided by an engineering reference manual (Stein et al. 2005b)
- Consumption data and calculation methods provided by HES (LBNL 2009)
- Consumption data provided by the results of a utility study (Tribwell and Lerman 1996)
Also, two occupancy scenarios are applied for the modeling paths to analyze the impact of “duration of use” on interior lighting energy consumption. The scenarios are identified as Scenario A “SA” and Scenario B “SB” as discussed in Section 4.3.

c) Baseline Values and Consumption
The spatial baseline values are referred to the 1,800 sqft sample house as defined in Section 4.3.

The baseline values for “duration of use” are established according to the findings of utility research study conducted by Tribwell and Lerman (1996). The findings of this study provide average durations of use values for each individual space as provided in Table 12. The total “duration of use” value is then calculated by summing up individual weighted durations of use, which are calculated by multiplying average duration of use for each space and area percentages of the spaces as illustrated in Table 12. Area percentages of individual spaces are percentage values compared to the entire dwelling size (see Section 4.3).

<table>
<thead>
<tr>
<th>Space</th>
<th>Area Percentage of Individual Space</th>
<th>Average Duration of Use for Interior Lighting Use (hrs / day)</th>
<th>Individual Weighted Duration of Use for Interior Lighting (hrs/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Master Bedroom</td>
<td>11%</td>
<td>1.3</td>
<td>0.143</td>
</tr>
<tr>
<td>Bedrooms</td>
<td>22%</td>
<td>1.2</td>
<td>0.264</td>
</tr>
<tr>
<td>Bathrooms</td>
<td>11%</td>
<td>1.7</td>
<td>0.187</td>
</tr>
<tr>
<td>Kitchen &amp; Dining Room</td>
<td>17%</td>
<td>3.9</td>
<td>0.663</td>
</tr>
<tr>
<td>Living Room</td>
<td>20%</td>
<td>3.1</td>
<td>0.620</td>
</tr>
<tr>
<td>Rest of the House</td>
<td>12%</td>
<td>1.6</td>
<td>0.192</td>
</tr>
</tbody>
</table>

Table 12 Total Duration of Use – Baseline Level during Impact of Illumination Requirement

The annual “duration of use” is calculated by multiplying the total “duration of use” value of 2.069 hours/day (see Table 12) and 365 days. As a result, the baseline annual duration of use is 755.2 hours/year.

Currently, there are no designated illumination requirements per footage for residential construction. The illumination requirements for different occupancy types are provided by
ASHRAE/IESNA Standard 90.1 – “Energy Standard for Buildings except Low-Rise Residential Buildings” and range from 0.7 to 2.3 W/sqft. Based on this standard, the illumination requirement for the dwelling can be assumed to be 1.0 W/sqft. The baseline illumination load is thus established as $1,800\ W$ for the sample building.

The baseline AEC is then established as follows:

$$\text{AEC} \Rightarrow 1,800\ W \times 755.2\ \text{hrs/year} = 1,361,000\ \text{Wh} = 1,361\ \text{kWh/year}$$

\textit{d) Impact Analysis}

The AEC of lighting is calculated by multiplying the illumination requirement (in W/sqft) with the size of the dwelling (in sqft) and the annual duration of use (in hrs/year).

- **Impact of Illumination Requirement:** Five different input sources are used to analyze the impact of different illumination requirements on the Annual Energy Consumption (AEC) for interior lighting. During these calculations, the different illumination requirements are determined from the different sources and the AEC is calculated using baseline values for all other parameters as provided above.

\textbf{Source # 1 – ASHRAE/IESNA Standard 90.1 – Minimum acceptable level assumption:}

This source is referred as the base illumination load (ASHRAE 2007a) and thus results in an AEC as follows:

$$\text{AEC} \Rightarrow 1,800\ W \times 755.2\ \text{hrs/year} = 1,361,000\ \text{Wh} = 1,361\ \text{kWh/year}$$

\textbf{Source # 2 – ASHRAE/IESNA Standard 90.1 - Maximum level assumption:}

Similar to the baseline assumption there is no designated maximum illumination value based on square footage for residential construction. Based on values provided by ASHRAE/IESNA Standard 90.1 (ASHRAE 2007a), the maximum illumination requirement for a dwelling can be assumed to be 1.25 W/sqft. The illumination requirement is multiplied with the sample house size of 1800 sqft (see Section 4.3). The illumination load of 2,250 W is then used to calculate AEC as follows:

$$\text{AEC} \Rightarrow 2,250\ W \times 755.2\ \text{hrs/year} = 1,701,000\ \text{Wh} = 1,701\ \text{kWh/year}$$
**Source # 3 – Engineering Reference Manual:**

Stein et al. (2005b) provides illumination requirements separately for each room as provided by Table 13. Thus, the total average illumination load is calculated by summing up individual weighted illumination requirements, which are calculated by multiplying illumination requirements for each space and area percentages of the spaces as illustrated in Table 13. Area percentages of individual spaces are percentage values compared to the entire dwelling size (see Section 4.3).

<table>
<thead>
<tr>
<th>Space</th>
<th>Sqft Percentage of Individual Space</th>
<th>Illumination Requirement (W/sqft)</th>
<th>Individual Weighted Illumination (W/sqft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bedrooms</td>
<td>33%</td>
<td>1.3</td>
<td>0.43</td>
</tr>
<tr>
<td>Bathrooms</td>
<td>11%</td>
<td>0.8</td>
<td>0.09</td>
</tr>
<tr>
<td>Kitchen</td>
<td>11%</td>
<td>1.2</td>
<td>0.132</td>
</tr>
<tr>
<td>Dining Room</td>
<td>6%</td>
<td>1.2</td>
<td>0.07</td>
</tr>
<tr>
<td>Living Room</td>
<td>20%</td>
<td>1.4</td>
<td>0.28</td>
</tr>
<tr>
<td>Garage</td>
<td>11%</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Stairs</td>
<td>1%</td>
<td>0.01</td>
<td>0.001</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td>~ 1.0</td>
<td></td>
</tr>
</tbody>
</table>

Table 13  Total Average Illumination Requirement – Source # 3

The total average illumination requirement for the sample dwelling according to Stein et al. (2005b) results in a value of 1 W/sqft, which multiplied with the size of the dwelling again results in an illumination load of 1,800 W. Thus the AEC follows as:

\[
AEC \Rightarrow 1,800 \text{ W} \times 755.2 \text{ hrs/yr} = 1,361,000 \text{ Wh} = 1,361 \text{ kWh/yr}
\]

**Source # 4 – Home Energy Saver (HES):**

LBNL (2009) utilizes a predetermined data set for interior lighting annual consumption per each identified space as provided by Table 14. These values are based on national consumer studies. They are also adjusted according to the average square footage of residential dwellings in the U.S. The numbers of rooms is determined for each category from the sample dwelling used (see Section 4.3).
<table>
<thead>
<tr>
<th>Space</th>
<th>Quantity</th>
<th>Interior Lighting Annual Consumption (kWh)</th>
<th>Cumulative Annual Interior Lighting Consumption (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Master Bedroom</td>
<td>1</td>
<td>81</td>
<td>81</td>
</tr>
<tr>
<td>Bedrooms</td>
<td>2</td>
<td>73</td>
<td>146</td>
</tr>
<tr>
<td>Bathrooms</td>
<td>2</td>
<td>192</td>
<td>384</td>
</tr>
<tr>
<td>Kitchen</td>
<td>1</td>
<td>218</td>
<td>218</td>
</tr>
<tr>
<td>Dining Room</td>
<td>1</td>
<td>136</td>
<td>136</td>
</tr>
<tr>
<td>Living Room</td>
<td>1</td>
<td>109</td>
<td>109</td>
</tr>
<tr>
<td>Garage (2 car)</td>
<td>1</td>
<td>142</td>
<td>142</td>
</tr>
<tr>
<td>Stairs</td>
<td>1</td>
<td>98</td>
<td>98</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>1314</strong></td>
<td><strong>1314</strong></td>
</tr>
</tbody>
</table>

**Table 14**  Interior Lighting Annual Consumption – Source # 4

The AEC value is calculated by summing up the cumulative annual interior lighting consumption amounts, which are calculated by multiplying interior lighting annual consumption for each space and the number of the spaces as illustrated in Table 14. The total AEC for this source results with:

\[
\text{AEC} \rightarrow 1,314 \text{ kWh/year}
\]

**Source # 5 - Utility Study:**

The results of a study conducted by Tribwell and Lerman (1996) are used to determine the AEC value. The results of this study determined that AEC value for an average household size of 2,500 sqft is approximately 1,818 kWh for residential dwellings in the U.S. In order to make a better comparison among the different sources, the AEC determined by this study is adjusted according to the baseline value established for the household total square footage (see Section 4.3) as follows:

\[
\text{AEC} \rightarrow (1,818 \text{ kWh / 2,500 sqft}) \times 1,800 \text{ sqft} = 1,309 \text{ kWh/year}
\]

The annual interior lighting energy consumption amounts comparing the four alternatives with the baseline consumption are illustrated in Figure 33.
As illustrated in Figure 33, the AEC values for Input Sources 1, 3, 4, and 5 show similar results. The AC value provided by Source # 2 is significantly higher compared to the rest of the AEC values. However this is due to the assumption made based on maximum illumination value.

- **Impact of Lighting Duration of Use:** Two occupancy scenarios are used as input sources to calculate Annual Energy Consumption (AEC) for interior lighting. During these calculations, durations of use are determined separately by each occupancy scenario according to the sample house parameter values as provided in Section 4.3. The illumination requirement is kept consistent by using the established baseline values. The AEC values for Scenarios A and B are
calculated by multiplying the baseline illumination load of $1,800 \text{ W}$ and annual durations of use as follow:

**Scenario A – Consumption patterns for single working professional:**

The average daily uses of each individual space are assumed for the sample house for Scenario A as provided with Table 15.

<table>
<thead>
<tr>
<th>Space</th>
<th>Mon (hrs)</th>
<th>Tues (hrs)</th>
<th>Wed (hrs)</th>
<th>Thur (hrs)</th>
<th>Fri (hrs)</th>
<th>Sat (hrs)</th>
<th>Sun (hrs)</th>
<th>Daily Average (hrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Master Bedroom</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1.43</td>
</tr>
<tr>
<td>Bedrooms</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>3</td>
<td>0</td>
<td>0.86</td>
</tr>
<tr>
<td>Bathrooms</td>
<td>1.2</td>
<td>1.2</td>
<td>1.2</td>
<td>1.2</td>
<td>1.2</td>
<td>1.2</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>Kitchen &amp; Dining Room</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1.7</td>
</tr>
<tr>
<td>Living Room</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Rest of the House</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1.5</td>
<td>1.5</td>
<td>0.43</td>
<td>0.43</td>
</tr>
</tbody>
</table>

* Effects of stairs are considered negligible

**Table 15** Average Daily Use for Individual Spaces – Scenario A

The total average duration of use is determined by summing up individual weighted durations of use for interior lighting, which is determined by multiplying average durations of use for interior lighting and area percentages of individual spaces (see Table 16). Area percentages of individual spaces are percentage values compared to the entire dwelling size (see Section 4.3).

<table>
<thead>
<tr>
<th>Space</th>
<th>Area Percentage of Individual Space</th>
<th>Average Duration of Use for Interior Lighting (hrs / day)</th>
<th>Individual Weighted Duration of Use for Interior Lighting (hrs/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Master Bedroom</td>
<td>11%</td>
<td>1.43</td>
<td>0.157</td>
</tr>
<tr>
<td>Bedrooms</td>
<td>22%</td>
<td>0.86</td>
<td>0.189</td>
</tr>
<tr>
<td>Bathrooms</td>
<td>11%</td>
<td>1.2</td>
<td>0.132</td>
</tr>
<tr>
<td>Kitchen &amp; Dining Room</td>
<td>17%</td>
<td>1.7</td>
<td>0.289</td>
</tr>
<tr>
<td>Living Room</td>
<td>20%</td>
<td>3.0</td>
<td>0.60</td>
</tr>
<tr>
<td>Rest of the House</td>
<td>12%</td>
<td>0.43</td>
<td>0.05</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>~ 1.417</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 16** Weighted Duration of Use for Interior Lighting – Scenario A
The annual duration of use is then calculated by multiplying the total average duration of use value of 1.417 hours/day (see Table 16) by 365 days. As a result, the annual duration of use value of 517.2 hours/year is determined and used to calculate the Annual Energy Consumption (AEC) values by input sources as follows:

AEC ➔ 1,800 W * 517.2 hrs/year = 931 kWh/year

**Scenario B – Consumption patterns for family of 4 with stay-at-home-parent:**

The average daily uses of each individual space are assumed for the sample house for Scenario B as provided with Table 17.

<table>
<thead>
<tr>
<th>Space</th>
<th>Mon (hrs)</th>
<th>Tues (hrs)</th>
<th>Wed (hrs)</th>
<th>Thur (hrs)</th>
<th>Fri (hrs)</th>
<th>Sat (hrs)</th>
<th>Sun (hrs)</th>
<th>Daily Average (hrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Master Bedroom</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Bedrooms</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Bathrooms</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Kitchen &amp; Dining Room</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Living Room</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>5.43</td>
</tr>
<tr>
<td>Rest of the House</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

* Effects of stairs are considered negligible

**Table 17**  Average Daily Use for Individual Spaces – Scenario B

The total average duration of use is determined by summing up individual weighted durations of use for interior lighting, which is determined by multiplying average durations of use for interior lighting and area percentages of individual spaces (see Table 18). Area percentages of individual spaces are percentage values compared to the entire dwelling size (see Section 4.3).

<table>
<thead>
<tr>
<th>Space</th>
<th>Sqft Percentage of Individual Space</th>
<th>Average Length of Interior Lighting Use (hrs / day)</th>
<th>Individual Weighted Length of Interior Lighting (hrs/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Master Bedroom</td>
<td>11%</td>
<td>2</td>
<td>0.22</td>
</tr>
<tr>
<td>Bedrooms</td>
<td>22%</td>
<td>4</td>
<td>0.88</td>
</tr>
<tr>
<td>Bathrooms</td>
<td>11%</td>
<td>3</td>
<td>0.33</td>
</tr>
<tr>
<td>Kitchen &amp; Dining Room</td>
<td>17%</td>
<td>6</td>
<td>1.02</td>
</tr>
<tr>
<td>Living Room</td>
<td>20%</td>
<td>5.43</td>
<td>1.09</td>
</tr>
<tr>
<td>Rest of the House</td>
<td>12%</td>
<td>2</td>
<td>0.24</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td>~ 3.78</td>
</tr>
</tbody>
</table>

**Table 18**  Length of Use for Interior Lighting – Scenario B
The annual duration of use is then calculated by multiplying the total average duration of use value of \(3.78\) hours/day (see Table 18) by 365 days. As a result, the annual duration of use value of \(1380\) hours/year is determined and used to calculate the Annual Energy Consumption (AEC) values by input sources as follows:

\[
\text{AEC} \rightarrow 1800 \text{ W} \times 1380 \text{ hrs/year} = 2484 \text{ kWh/year}
\]

**Figure 34** Annual Interior Lighting Energy Consumption for Consistent Illumination

<table>
<thead>
<tr>
<th>Impact of Lighting Duration Assumptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
</tr>
<tr>
<td>Scenario A</td>
</tr>
<tr>
<td>Scenario B</td>
</tr>
<tr>
<td>Baseline</td>
</tr>
<tr>
<td>Single Adult</td>
</tr>
<tr>
<td>Family of 4 with Stay-at-Home Parent</td>
</tr>
<tr>
<td>Annual Indoor Lighting Consumption (kWh/year)</td>
</tr>
<tr>
<td>0 500 1000 1500 2000 2500</td>
</tr>
<tr>
<td>1361</td>
</tr>
<tr>
<td>931</td>
</tr>
<tr>
<td>2484</td>
</tr>
<tr>
<td>Overall Range - 32% Baseline + 82%</td>
</tr>
</tbody>
</table>

**e) Conclusions**

As illustrated in Figure 34, the AEC values for Scenarios A and B differ significantly from the baseline AEC. Thus, it can be concluded that the occupancy pattern as a consumption influence
parameter has more impact on the overall interior lighting energy consumption than the variation of illumination requirements.

Due to its impact, it is recommended that “occupancy pattern” related influence parameters are provided through homeowner input to more accurately calculate interior lighting energy consumption. In addition, it is recommended that the effect of incandescent vs. fluorescent light bulbs is included as a possible adjustment due to differences in energy consumption (which was not compared in this analysis). CFL light bulbs consume less power (typically 1/6th) compared to incandescent light bulbs giving the same amount of visible light (The Engineering Toolbox 2010a). The difference in the amount of light bulbs can be captured from a homeowner response to a sample question provided below:

- **What proportion of your household light fixtures contains fluorescent light fixtures?**
  a. None (less than 5%)
  b. Some (5% - 25%)
  c. Many (25% - 50%)
  d. Most (more than 50%)

Subsequently, the annual interior lighting energy consumption amount can be corrected by the multiplying with the designated adjustment factor calculated separately for each response as shown:

a. Adjustment Factor_1 = (1/6kWh) * (0.05) + (1) * (0.95) = 0.96
b. Adjustment Factor_2 = (1/6kWh) * (0.25) + (1) * (0.75) = 0.79
c. Adjustment Factor_3 = (1/6kWh) * (0.50) + (1) * (0.50) = 0.58
d. Adjustment Factor_4 = (1/6kWh) * (0.75) + (1) * (0.25) = 0.38

### 4.3.2.2 Exterior Lighting

Exterior lighting energy consumption is analyzed by using the framework defined in Section 4.3. Through this analysis, contribution of exterior lighting to overall artificial lighting energy consumption is determined.
a) Equations & Modeling Paths
The modeling path used for calculating energy consumption of exterior lighting is similar to modeling path C as illustrated in Figure 31. The exterior lighting energy consumption is determined by number of fixtures, type and capacity of the light bulbs and the duration of use based on occupancy patterns (hrs/year).

b) Consumption Influence Parameters
The consumption influence parameters for exterior lighting are similar to those illustrated in Figure 31, and can be split into two parameter groups: “Specific Illumination Consumption”, consisting of number of luminaires and their individual consumption values, and “Usage Patterns”, consisting of hours used per day or similar duration values.

c) Parameter Sources
Two sources of input are researched and applied for the modeling path to analyze the influence on annual energy consumption. The utilized sources include:

- The values retrieved for the sample house as defined in Section 4.3.
- Consumption data and calculation methods provided by HES (LBNL 2009)

d) Baseline Values and Consumption
The exterior lighting energy consumption of the sample house is established as the baseline for the impact analysis. As discussed in Section 4.3, the sample house has two exterior light fixtures with a single 60 Watt light bulb each.

For the baseline calculation it is assumed that they are used at average 0.5 hr/day. The baseline AEC is then established as follows:

\[
\text{AEC} \rightarrow 60 \text{ W} \times 2 \times 0.5 \text{ hr/day} \times 365 \text{ days} = 22 \text{kWh/year}
\]

e) Impact Analysis
During the impact analysis, the exterior lighting energy consumption is calculated for the consumption input value from HES and is then compared against the previously determined baseline consumption of the sample house.
According to the default value (based on consumer studies) provided by LBNL (2009), the light bulb(s) used in each fixture consumes 103 Watts on average. As discussed above, the baseline duration of use for each exterior lighting fixture is assumed with an average of 0.5 hr/day. As a result, the AEC value is calculated as follows:

\[
\text{AEC} \quad \Rightarrow \quad 103 \text{ W} \times 2 \times 0.5 \text{ hr/day} \times 365 \text{ days} = 38 \text{ kWh/year}
\]

\(f\) Conclusions

As shown with the Annual Energy Consumption values provided above, exterior lighting energy consumes approximately 1-2% of the overall artificial lighting energy consumption. Even with doubling the duration of use, exterior lighting energy consumption would still account for no more than 2-3% of the overall artificial lighting energy consumption. Thus, the impact of duration of use is not analyzed explicitly. In general, if no special lighting system (e.g., landscape lighting) is in place, the exterior lighting energy consumption can be neglected or simply addressed as a single 1-2% correction factor.

4.3.3 Domestic Hot Water

\(a\) Equations & Modeling Paths

In Figure 35, A and B illustrate different modeling paths for calculating domestic hot water energy consumption. In each modeling path, occupant demographics are determined first. According to the occupant demographics, the total hot water consumption (gals/day) is then calculated. The total hot water consumption is used to calculate the total energy required to condition the water mass (kWh/year). This calculation is based on system parameters and ambient conditions.
Figure 35  Annual Domestic Hot Water Heating Consumption Calculation
b) Consumption Influence Parameters

As illustrated in Figure 35, Parameter Groups I, II, and III are influenced by various parameters, whereas the parameters “System Characteristics”, “Occupancy Patterns”, “Number of Occupants”, and “Ages of Occupants” are identified as Tier-1 relationships.

Influence parameters neglected in the above model and thus categorized as Tier-2 relationships are shown in Figure 36. These parameters are not analyzed in the numerical impact study. However, a brief discussion regarding their influence on domestic hot water energy consumption is provided below:

- **Year Built**: If not replaced, the original hot water heaters present in older homes are not as efficient as their newer counterparts. Thus, they consume more energy to produce the same hot water consumption demand. The age of the house also affects the type of building materials used during construction, which includes the insulation for building systems and piping. The differences in insulation for systems and piping can impact the amount of heat lost during the transfer of hot water throughout the dwelling. As a result, the amount of energy required to provide the same hot water demand can be impacted (see Equations 2 and 4). In addition, without proper maintenance, calcification build up in the heating unit can result in a decrease in efficiency.

---

**Figure 36** Tier-2 Parameter Relationships for Annual Domestic Hot Water Heating
• **Space Usage Characteristics:** Similar to the impact of insulation, the amount of heat lost during the transportation of hot water inside the dwelling through a conditioned space versus and un-conditioned space can be different (see Equations 2 and 4). As a result, the amount of energy required to provide the same hot water demand can be impacted in homes where the water pipes go through conditioned spaces versus unconditioned.

• **Zip code:** Although it is not common, if the hot water heater is housed in an unconditioned space, the external climate becomes an influence through the ambient temperature (see Equations 2 and 4). As a result, the amount of energy required to provide the same hot water demand is increased due to a possibly higher temperature differential.

• **Available Energy Sources:** The availability of different energy sources can determine the system type of hot water heaters used in the dwelling. Electric hot water heaters and gas furnaces are examples of water heater types that differ only slightly in efficiency. If heat pumps are facilitated for hot water generation the differences become more relevant; however, these applications are not common in residential buildings at this time.

• **Number of Rooms:** The number of bathrooms and kitchens can potentially increase the use of hot water, especially for homes with mother-in-law suites, guest quarters or pool / club houses.

• **Type of Heating System:** Hydronic heating systems such as boilers not only increase the temperature of the interior air during the heating season but they can also provide domestic hot water (DOE 2011) and thus can impact hot water consumption in a dwelling.

  **c) Parameter Sources**

The average water usage can be determined through evaluation of utility bills, local government water consumption data, and national averages provided by government agencies such as DOE and EIA. Along with average water consumption per occupant, manufacturer’s specifications for the individual water heater (e.g., efficiency, service factor, tank size, required power and output capacity), commonly used typical values for the individual system/equipment, and other available tabular weather data are used to determine the required energy. Depending on the available data type, equations similar to Equations 2 and 4 are often utilized to calculate the energy and the related domestic hot water energy consumption.
Four different types of sources of input are identified and applied for the modeling path B to analyze the impact of relevant influence parameters on domestic hot water energy consumption. The utilized sources of input include:

- Consumption data and calculation methods provided by HES (LBNL 2009)
- Consumption data and calculation methods provided by the results of research studies (DeOreo and Mayer 2000, Vine et al. 1987)
- System parameters based on default values provided by research studies (provided as referenced numerical values adjacent to the component descriptions).
- System parameters for the sample house (see Section 4.3).

Also, two occupancy scenarios are applied for the modeling path to analyze the impact of “occupancy patterns” on domestic hot water. The scenarios are identified as Scenario A “SA” and Scenario B “SB” as discussed in Section 4.3.

d) **Baseline Values and Consumption**

The consumption calculation methods provided by HES model (LBNL 2009) are used to establish the baseline values for the impact analysis through Equations 1 and 2. The methodology based on this model, which utilized data from national consumer studies conducted in the U.S, is used to establish separate baseline values for hot water consumption and energy consumption. While establishing the hot water and energy consumption baseline, the following system parameter values (provided as referenced numerical values adjacent to the component descriptions) are assumed for the baseline configuration:

\[
\begin{align*}
T_t & = \text{Water heater thermostat set point temperature (°F)} \\
& \quad (\text{used as } 135°F – \text{Stein 2005a}) \\
\text{Tank\_size} & = \text{Rated volume of water heater} \\
& \quad (\text{used as 60 gal – based on sample house}) \\
T_{in} & = \text{Inlet water temperature} \\
& \quad (\text{used as } 55°F – \text{based on average temperature value}) \\
T_{average} & = \text{Average annual outdoor air temperature} \\
& \quad (\text{used as } 55°F – \text{Wunderground 2010}) \\
cwGals & = \text{Calculated gallons of hot water used by clothes washer} \\
& \quad (\text{used as 3.6 gallons/day/person - Vine et al. 1987})
\end{align*}
\]
\( dwGals \) = Calculated gallons of hot water used by dishwasher

(used as 15 gallons/day - Vine et al. 1987)

\( RE \) = Recovery efficiency of the water heater

(used as 0.98 - DOE-2 2010)

\( UA \) = Standby heat loss coefficient of water heater

(used as -0.006 BTU/hr-°F - DOE-2 2010)

\( Tamb \) = Annual average air temperature around the water heater (°F)

(used as 67.5°F - DOE-2 2010)

\( Pon \) = Rated input power of the water heater

(used as 4.5 Btu/hr - DOE-2 2010)

\( EF \) = Overall system efficiency

(used as 0.9 - DOE-2 2010)

\( FC \) = Factor of Conversion

\( 3,412.76 \) BTU/kWh

For hot water and energy consumption separate baseline values are established for Scenarios A and B as identified by abbreviations SA and SB below:

**Hot Water Consumption Baseline:** Equation 1 is used to calculate household hot water consumption for each scenario as shown below:

\[
HW_{use} = [-1.78 + 0.9744 \times Occupants + 6.3933 \times Age1 + 10.5178 \times Age2 + 15.3052 \times (Age3 + Age4) -0.1277 \times Tt + 0.1437 \times Tank\_size -0.1794 \times Tin + 0.5115 \times Taverage + 10.2191 \times Adult\_at\_home + cwGals + dwGals] \times 365 \times Senior \times Pay \\
Eq.1
\]

Where,

\( HW_{use} \) = Hot Water Consumption (gallons/year)

\( Occupants \) = Number of persons in the household (sum age group 1 -4)

\( Age1 \) = Number of people in age group 0-5 yrs

\( Age2 \) = Number of people in age group 6-13 yrs

\( Age3 \) = Number of people in age group 14-64 yrs

\( Age4 \) = Number of people in age group 65+ yrs
Adult\_at\_home = 1 if TRUE, 0 if FALSE, adult at home during the day

Senior = 0.379 if only seniors live in household and it is a multifamily residence, otherwise senior =1

Pay = 1.3625 if residents do not pay for energy to make hot water (to reflect less water-conserving behavior), otherwise pay = 1

Baseline – SA:

\[ HW\_use = [-1.78 + 0.9744 - 0.1277 * 135 + 0.1437 * 60 - 0.1794 * 55 + 0.5115 * 55 + 3.6 + 15] * 365 = 18,020.6 \text{ gals/year} \]

Baseline – SB:

\[ HW\_use = [-1.78 + 0.9744 * 4 + 6.3933 + 10.5178 + 15.3052 * 2 - 0.1277 * 135 + 0.1437 * 60 - 0.1794 * 55 + 0.5115 * 55 + 10.2191 + 3.6 * 4 + 15] * 365 = 36,135 \text{ gals/year} \]

Hot Water Energy Consumption Baseline: The energy consumption (AEC) is the amount of energy consumed by the system in order to supply the previously calculated hot water demands. Equation 2 is used to determine the energy needed to condition the water mass. Previously calculated annual water consumption is used for each scenario as follows:

\[
 AEC = \left[ \frac{HW\_use \cdot Dens \cdot Cp \cdot (Tt - Tin)}{RE} \cdot \left[ 1 - \frac{UA \cdot (Tt - Tamb)}{Pon} \right] + 24 \cdot UA \cdot (Tt - Tamb) \right] \cdot EF \hspace{1cm} \text{Eq.2}
\]

Where,

\[ HW\_use = \text{Hot Water Consumption (gallons/year)} \]

\[ Dens = \text{Density of water (8.293752 lb/gallon)} \]

\[ Cp = \text{Specific heat of water (1.000743 Btu/lb-°F)} \]

\[ Ti = \text{Water heater thermostat set point temperature (°F)} \]

\[ Tin = \text{Inlet water temperature} \]

\[ RE = \text{Recovery efficiency of the water heater} \]


\[ UA = \text{Standby heat loss coefficient of water heater} \]

\[ Tamb = \text{Annual average air temperature around the water heater (°F)} \]

\[ Pon = \text{Rated input power of the water heater} \]

\[ EF = \text{Overall system efficiency} \]

\[ FC = \text{Factor of Conversion} \]

**Baseline – SA:**

\[
\begin{align*}
\text{AEC} &= \left[ (18,020.6 \times 8.283752 \times 1.000743 \times 80) / 0.98 \times (1 - (-0.006 \times 67.5) / 4.5) \\
+ 24 \times (-0.006) \times 67.5 \right] \times 0.9 / 3,412.76 = 3930.71 \text{ kWh/year}
\end{align*}
\]

**Baseline – SB:**

\[
\begin{align*}
\text{AEC} &= \left[ (36,135 \times 8.283752 \times 1.000743 \times 80) / 0.98 \times (1 - (-0.006 \times 67.5) / 4.5) + \\
24 \times (-0.006) \times 67.5 \right] \times 0.9 / 3,412.76 = 7881.86 \text{ kWh/year}
\end{align*}
\]

**e) Impact Analysis**

To determine the effect of “occupancy patterns” and “system characteristics” on the energy consumption separately, hot water consumption and energy consumption are evaluated separately for the variation of identified values as follows:

- **Hot Water Consumption:** The hot water consumption per each activity and per household are determined separately for each source of input. The occupancy patterns are determined for Scenarios A and B (see Section 4.3). As a result, different consumption amounts are calculated separately for each source and each scenario.

**Source # 1 – Flow Trace Analysis:**

DeOreo and Mayer (2000) utilize predetermined data for household hot water consumption as provided by Table 19. These values are based on local consumer studies and are provided individually for each consumption activity. The total consumption per occupant is calculated by summing up the water consumption for all the activities. The total household water consumption is calculated by multiplying the total water consumption per occupant and the number of occupants in the household for each scenario.
Table 19  Water use per Occupant – Source # 1

Source # 1 – SA: Hot Water Consumption  $$\Rightarrow 25.1 \text{ gals/day} \times 365 \text{ days/year} = 9,162 \text{ gals/year}$$

Source # 2 – SB: Hot Water Consumption  $$\Rightarrow 25.1 \text{ gals/day} \times 4 \text{ People} \times 365 \text{ days/year}$$

$$\Rightarrow = 36,648 \text{ gals/year}$$

Source # 2 – Consumption Study by Vine et al.:

Vine et al. (1987) utilize Equation 3 to calculate household hot water consumption. In this equation, the hot water consumption is determined separately for each activity based on duration and frequency. The duration and frequency of hot water consumption for each activity are assumed separately for Scenarios A and B and provided with Table 19 and Table 20 respectively. The total hot water consumption is calculated by summing up the individual consumption per activity.

<table>
<thead>
<tr>
<th>Category</th>
<th>Water Use per Occupant (Gal/Day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bath</td>
<td>4.2</td>
</tr>
<tr>
<td>Clothes Washer</td>
<td>3.9</td>
</tr>
<tr>
<td>Dishwasher</td>
<td>0.9</td>
</tr>
<tr>
<td>Faucet</td>
<td>8.6</td>
</tr>
<tr>
<td>Potential Pipe Leak</td>
<td>1.2</td>
</tr>
<tr>
<td>Shower</td>
<td>6.3</td>
</tr>
<tr>
<td>Toilet</td>
<td>0.0</td>
</tr>
<tr>
<td>Other</td>
<td>0.01</td>
</tr>
<tr>
<td>Total</td>
<td>~ 25.1</td>
</tr>
</tbody>
</table>

**Table 20**  Water use per Occupant for Scenario A– Consumption Study

<table>
<thead>
<tr>
<th>Category</th>
<th>Duration</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shower</td>
<td>10 Minutes</td>
<td>1.5 showers / day</td>
</tr>
<tr>
<td>Bath</td>
<td></td>
<td>0.5 baths / week</td>
</tr>
<tr>
<td>Clothes Washer</td>
<td></td>
<td>1 load / week</td>
</tr>
</tbody>
</table>

**Table 21**  Water use per Occupant for Scenario B – Consumption Study

<table>
<thead>
<tr>
<th>Category</th>
<th>Duration</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shower</td>
<td>10 Minutes</td>
<td>0.8 showers/ person/day</td>
</tr>
<tr>
<td>Bath</td>
<td></td>
<td>1 bath / week</td>
</tr>
<tr>
<td>Clothes Washer</td>
<td></td>
<td>4 load / week</td>
</tr>
</tbody>
</table>

Total Water Consumption  $$= \text{Shower} + \text{Bath} + \text{Sink} + \text{Washer} + \text{Dishwasher}$$  \text{Eq.3}
Shower = (2.5 gals/min)*(min/shower)*(shower/day)
Bath = (12.5 gals/bath)*(bath/day)
Sink = (3 gals/person/day)
C. Washer = (25 gals/load)*(loads/day)
Dishwasher = (15 gals/day)

Source # 2 – SA:
Shower = 37.5 gals/day  Bath = 0.9 gals/day  Sink = 3 gal/day
Clothes Washing = 3.6 gals/day  Dishwasher = 15 gals/day
Total = ~ 60 gals/day  =>  = ~ 21,900 gals/year

Source # 2 – SB:
Shower = 80 gals/day  Bath = 1.8 gals/day  Sink = 12 gal/day
Clothes Washing = 14 gals/day  Dishwasher = 15 gals/day
Total = ~ 122.8 gals/day  =>  = ~ 44,822 gals/year

Figure 37 and Figure 38 illustrate the different hot water consumptions for Scenarios A and B calculated individually for the sources of input. Figure 39, on the other hand, provides a side by side illustration of hot water consumption calculated for each source of input for Scenario A and normalized equivalent values derived from Scenario B. These normalized equivalents (denoted by ‘’) are calculated from the results of Scenario B by dividing the consumption amounts by the total number of occupants (4).
Figure 37  Annual Hot Water Consumption for Scenario A

Figure 38  Annual Hot Water Consumption for Scenario B
If the hot water energy consumption baseline assumptions are applied to the hot water consumption calculated for Sources #1 and #2, energy consumption for each source and scenario can be determined as illustrated in Figure 40 and Figure 41.

**Figure 39** Annual Hot Water Consumption with Normalized Comparison

**Figure 40** Annual Hot Energy Consumption for Scenario A – Baseline Assumptions
Figure 41  Annual Hot Energy Consumption for Scenario B – Baseline Assumptions

- **Energy Consumption:** While calculating the energy consumption for each source separately, the effect of system parameters is analyzed by using simplified equations. Equation 4 follows from Equation 2 based on the following assumptions:

\[
RE = 1 \quad (\text{Recovery efficiency of the water heater is neglected, i.e. set to be 100\%})
\]

\[
UA = 0 \quad (\text{The tank losses through the insulation are assumed to be negligible})
\]

\[
AEC = [HW\_use \times Dens \times Cp \times (Tt-Tin)] \times EF \times FC
\]  \hspace{1cm} Eq.4

Where,

- \(HW\_use\) = Hot Water Consumption (gallons/year)
- \(Dens\) = Density of water (8.293752 lb/gallon)
- \(Cp\) = Specific heat of water (1.000743 Btu/lb-\(^\circ\)F)
- \(Tt\) = Water heater thermostat set point temperature (\(^\circ\)F)
- \(Tin\) = Inlet water temperature
- \(EF\) = Overall system efficiency
- \(FC\) = Factor of Conversion
Source # 1 – Flow Trace Analysis:

Source # 1 – SA: AEC = (9,162 * 8.283752) * (1.000743) * (135 – 55) *0.9 / (3,412.76)
= 1,602.34 kWh/year

Source # 1 – SB: AEC = (36,646 * 8.283752) * (1.000743) * (135 – 55)*0.9 / (3,412.76)
= 6,409.1 kWh/year

Source # 2 – Consumption Study by Vine et al.:

Source # 2 – SA: AEC = (21,900 * 8.283752) * (1.000743) * (135 – 55) *0.9 / (3,412.76)
= 3838.2 kWh/year

Source # 2 – SB: AEC = (44,822 * 8.283752) * (1.000743) * (135 – 55) *0.9 / (3,412.76)
= 7839.2 kWh/year

Figure 42 and Figure 43 illustrate the different energy consumptions for Scenarios A and B calculated individually for the sources of input. Figure 44, on the other hand, provides a side by side illustration of energy consumption calculated for each source of input for Scenario A and normalized equivalent values derived from Scenario B. These normalized equivalents (denoted by ‘’) are calculated from the results of Scenario B by dividing the consumption amounts by the total number of occupants (4).
Figure 42  Annual Hot Water Heating Electricity Consumption for Scenario A

Figure 43  Annual Hot Water Heating Electricity Consumption for Scenario B
**Figure 44** Annual Hot Water Heating Electricity Consumption with Normalized Comparison

### f) Conclusions

<table>
<thead>
<tr>
<th>Source</th>
<th>Annual Electricity Consumption (kWh/year)</th>
<th>Range of Fluctuation from the Baseline (B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source #1</td>
<td>1602.34</td>
<td>- 49% $\Rightarrow$ B $\Rightarrow$ + 22% (AEC based on water consumption)</td>
</tr>
<tr>
<td>Source #2</td>
<td>3,838.20</td>
<td>- 59% $\Rightarrow$ B $\Rightarrow$ + 0% (AEC based on system parameters)</td>
</tr>
<tr>
<td>Source #2'</td>
<td>1,959.80</td>
<td>- 0% $\Rightarrow$ B $\Rightarrow$ + 24% (AEC based on water consumption)</td>
</tr>
<tr>
<td>Baseline</td>
<td>3,930.71</td>
<td>- 18% $\Rightarrow$ B $\Rightarrow$ + 0% (AEC based on system parameters)</td>
</tr>
<tr>
<td>Baseline'</td>
<td>1,970.47</td>
<td></td>
</tr>
</tbody>
</table>

As illustrated in Figure 44, the AEC values for Scenarios A and B differ significantly from the baseline AEC. Thus, it can be concluded that the occupancy pattern as a consumption influence parameter has more impact on the domestic hot water energy consumption than the variation of
system parameters. Due to this impact, it is recommended that “occupancy pattern” and the related influence parameters are provided through homeowner input to more accurately calculate domestic hot water energy consumption.

Similar AEC values are calculated through Source # 2 and the Baseline. Consumer study (Source # 2) provides values that are 98% of what are assumed by the Baseline HES model. The energy consumption values calculated by both Sources # 2 and the Baseline Level also show a ratio of ½ between the two scenarios. Therefore, a simplified model using consumer studies and the ratio to account for variation in number of occupants seems to be practical for calculating domestic hot water energy consumption due to its simplicity.

4.3.4 Space Heating and Space Cooling

The analysis process investigates a common residential single level house, which consists of four walls, a roof, and the ground slab. The house is considered as a closed, non-reacting system and thermal equilibrium is calculated by a simple application of the first law of Thermodynamics. As defined by Mechanical Engineering Reference Manual (MERM), thermal equilibrium is reached at the point where the temperature of all parts is the same (Lindeburg 2006a). As the thermal equilibrium occurs spontaneously between the heating and cooling masses, external work term is “0” in the first law equation. The total energy exchange is due to the heat coming off the cooling masses, as depicted with the subscripts “loss”, and the energy stored by the increasing temperature of the warmed masses, as depicted with the subscripts “gain”. Since the total energy exchanges for the closed systems are equal, the net energy change is be “0”, as depicted with Equation 6.

\[ Q_{\text{net}} = \sum Q_{\text{gains}} - \sum Q_{\text{losses}} = 0 \]

\[ \text{Eq.6} \]

During this analysis, all active modes of heat transfer – conduction, convection (both natural and forced), and radiation - are taken into consideration, in order to accurately depict overall energy flow equations (Lindeburg 2006b). Thus, the heat flow between the interior and exterior is calculated with the Equation 7.

\[ Q_t + Q_{v/i} + Q_{\text{sol}} + Q_e + Q_{p} + Q_{sys} = 0 \]

\[ \text{Eq.7} \]
In Equation 7, “Qt” is the total transmission heat flow, “Qv/i” are the ventilation and infiltration losses, “Qsol” are the solar losses/gains, “Qe” is the heat gain from equipment (i.e. interior lighting, systems and appliances), “Qp” is the heat gain from people (i.e. occupants), and “Qsys” is the thermal system load (heating/cooling) that needs to be provided to reach equilibrium with the exterior climate. After all heat flow components are calculated and “Qsys” is determined, the total energy consumption “Qtotal” of the heating/cooling system can be calculated through Equation 8.

\[ Q_{\text{total}} = \frac{(Q_{\text{sys}} \times N_a)}{SE} \quad \text{Eq.8} \]

“Na” represents the adjusted total degree days, which are adjusted for the temperature difference and “SE” is the system efficiency for the heating and cooling equipment used.

The parameter analysis is done separately for all heat flow components provided in Equation 7 and the total energy consumption is provided through Equation 8. The analyses for space heating and cooling are conducted individually for all heat flow components as provided below:

4.3.4.1 **Total Transmission Heat Flow (Qt)**

**a) Equations & Modeling Paths**

The total transmission heat flow consists of laminar transmission losses (e.g., through wall components), as well as linear and singular point losses (i.e. thermal bridges) and is calculated by utilizing Equation 9.

\[
Qt = \left\{ \begin{align*}
& (\sum U_w \times A_w) \times (TETD) + (\sum U_r \times A_r) \times (TETD) + (\sum U_f \times A_f) \times (T_i - T_o) \\
& + (\sum U_{gr} \times A_{gr}) \times (T_i - T_{gr}) \\
& + [(\sum F_w \times L_w) \times (T_i - T_o) + (\sum F_f \times L_f) \times (T_i - T_o)] + (\sum F_{gr} \times L_p) \times (T_i - T_{gr}) \\
& + (\sum X_i \times n) \times (T_i - T_o)
\end{align*} \right\} \quad \text{Eq.9}
\]

In Equation 9, the nomenclatures used are identified as follows: “w” stands for walls, “r” for roof, “f” for fenestrations (windows), “gr” for ground and slab, “p” for the perimeter of the dwelling, “Ti” is the inside air temperature, “To” is the outside air temperature, “Tgr” is the temperature of
the ground, and “TETD” is the total equivalent temperature differential facilitated in calculating the cooling load. When calculating heating loads, TETD is replaced by the direct temperature differential (Ti – To). Equation 9 consists of three subsets of losses as identified by Boxes 1, 2, and 3.

Box 1 in Equation 9 illustrates the two-dimensional transmission losses that are caused by heat losses through walls, fenestrations, ground slab and the roof. While calculating these losses, effects of solar radiation, chimneys, un-insulated attic spaces, doors and windows are accounted for by calculating an individual overall U-value for the entire building envelope provided through the four walls and the ceiling roof (Szokolay 2004). In these calculations, “U” represents the thermal conductance for a building envelope element and “A” represents the respective area for the building envelope element.

Box 2 in Equation 9 illustrates the linear transmission losses that are caused by additional heat lost along boundaries of two-dimensional envelope components, such as the perimeter around ground slabs through the face and the other exposed edges such as window sills. These additional losses result from thermal bridges along these edges (Lindeburg 2006c). No linear losses are calculated during this analysis as they are accounted for by using the exterior dimensions for determining the size of the building envelope. This approach causes the other two-dimensional losses to be slightly overstated. As a result, it compensates for the linear losses due to thermal bridges. Even though there are modeling approaches in the literature such as “ISO 13370 – a simplified method to assess the annual heating energy use in buildings”, the linear losses caused by heat loss from the ground slab edge are not calculated during this analysis (Medved and Cerne 2002). These losses depend on and become more critical with improved thermal performance of the adjacent two-dimensional elements along with the other linear heat losses. For the assessment of the existing building stock in the U.S. those are assumed to not have any significant effect on the total transmission losses.

Box 3 in Equation 9 illustrates the singular point transmission losses (e.g., thermal bridges at the intersection of three planes and envelope intersections with columns, or envelope penetrations such as roof drains), which are considered to be negligible for residential construction. Thus, they are not calculated during this analysis.
As a result, the total transmission heat flow equation can be simplified as shown in Equation 10.

\[
Qt = \left[ (\sum Uw \times Aw)(TETD) + (\sum Ur \times Ar)(TETD) + (\sum Uf \times Af)(T_i - T_o)
+ (\sum Ugr \times Agr)(T_i - Tgr) \right] \tag{Eq. 10}
\]

Figure 45 illustrates the modeling path for calculating the total transmission heat flow. In this modeling path, first the thermal envelope characteristics are determined in form of U values; then the area values for each component are calculated; and finally the inside and outside air conditions are determined. It should also be noted that different parameter combinations can be used to calculate the required area values. Depending on the selected combination, not all of the listed parameters are utilized.
As illustrated in Figure 45, Parameter Groups I, II, and III are influenced by various parameters, whereas the parameters “Building Thermal Envelope”, “Space Usage Characteristics”, “Number and Size of Windows”, “Year Built”, “Footprint Area”, “Perimeter Length”, “Shape of the House”, “Total Square Footage”, “Form Factor”, “Interior Ceiling Height”, and “Zip code” are identified as Tier-1 relationships.

**Figure 45** Total Transmission Heat Flow Calculation

**b) Consumption Influence Parameters**
Influence parameters neglected in the above model and thus categorized as Tier-2 relationships are shown in Figure 46. These parameters are not analyzed in the numerical impact study. However, a brief discussion regarding their influence on total transmission heat flow is provided below:

![Diagram of Total Transmission Heat Flow](image)

**Figure 46** Tier-2 Parameter Relationships for Total Transmission Heat Flow

- **Number and Size of Glass Doors:** The number and size of glass doors on a façade affect sunlight and heat penetrating the space and the related Solar Heat Gain Factor “SHGF”, which is used to calculate solar gains (see Section 4.3.4.3). Along with solar gains, the effect glass door characteristics can have on thermal envelope (similar to the effects of windows) impact heating and cooling energy consumption (ASHRAE 2007a and Szokolay 2004). However, as the size of glass doors is normally negligible compared to the size of the thermal envelope, the impact of this influence parameter on thermal envelope characteristics is also assumed to be negligible.

- **Number and Size of Skylights:** The number and size of skylights on a façade affect sunlight and heat penetrating the space and the related Solar Heat Gain Factor “SHGF”, which is used to calculate solar gains (see Section 4.3.4.3). Along with solar gains, the affect skylight characteristics can have on thermal envelope (similar to the effects of windows) impact heating and cooling energy consumption (ASHRAE 2007a and Szokolay 2004).

**c) Parameter Sources:**
Five different types of sources of input are identified and applied for the modeling path to analyze the impact of relevant influence parameters on space heating and cooling energy consumption. The different types of sources of input include (detailed references are provided during the discussion of each influence parameter and parameter group):

- Commonly accepted values obtained from codes and design standards
• Building science fundamentals (e.g., Tao and Janis 2001c)
• Weather data based on historic data collected for the research location obtained through online databases
• Identified data calculation methods based on previous research
• Assumptions based on best available information from design standards and previous research

From the different types of sources identified above, possible values for each influence parameter under Parameter Groups I, II, and III are determined individually. As a result, minimum, maximum, and mean values are established for each parameter under the parameter groups as provided below:

• **Parameter Group I - Thermal Envelope Characteristics ("U" values):** The thermal conductance of the different building envelope components ("U" values) are investigated separately. Following the nomenclature established previously, "Uw" represents the thermal conductance of the exterior walls, "Ur" represents the thermal conductance of the roof, "Uf" represents the thermal conductance of the window (fenestrations), and "Ugr" represents the thermal conductance of the ground slab. During this analysis, individual component “U” values are obtained from online sources such as Do-It-Yourself Network (DIY), and research organizations and authorities such as Sustainable Energy Authority of Ireland (SEAI), Federation of Authorized Energy Rating Organizations (FAERO) and Energy Saving Trust. These values are grouped according to material type and year available for each reference source and provided as a full data set in Appendix C. During this analysis, a minimum, maximum, and a mean value are established for each of the building envelope component (Table 22). The mean value is as baseline used to determine the rate of variation of minimum and maximum component values as shown for each component in Table 22.
Table 22  Summary Table for Parameter Thermal Conductance Values

- **Parameter Group II - Thermal Envelope Size (“A” values):** Similar to the thermal conductance values, the range and methods to derive area values for the different building envelope components are investigated separately. Following the nomenclature established previously, “Aw” represents the area of the exterior walls, “Ar” represents the area of the roof, “Af” represents the area of the windows (fenestrations), and “Agr” represents the area of the ground slab.

- **Area of the exterior walls “Aw”:** The exterior length and width dimensions (or perimeter length) of the building is multiplied by the interior floor-to-floor height for each wall section in order to determine the aggregate wall area. This aggregated area is, then, adjusted by subtracting the area covered by the windows, which provides the net area amount to be used. If the exterior dimensions of the dwelling are not given the perimeter length can be calculated.
by utilizing a form factor and the footprint area (Option # 1 in Figure 47). Total square footage and number of stories can also be utilized to determine footprint of the house.

As most of the aforementioned consumption influence parameters utilized during this calculation are consistent, interior ceiling height, shape of the house, and number of stories are the only parameters that are further elaborated due to potential changes.

The most common interior ceiling height is determined as 8 feet due to the minimum height requirement imposed by applicable building codes (McVicker.com 2007) and most of the construction materials being provided correspond to 8 feet ceiling height (e.g., drywall, insulation, studs, etc.) (Hodgson 2007). Many of the simulation tools such as HES and Hohm

Figure 47  Net Wall Area “Aw” Calculation
Beta Version also have the default ceiling height value set up for 8 feet ceiling heights (LBNL 2009, Microsoft 2009).

In order to illustrate the effect of the shape of the house, three houses with different shapes and same square footage are explored. For all the houses, the ceiling height is 8 feet and the total square footage is 1200. The first house has a square shape. The second house has a rectangular shape with a length to width ratio of 1/2. The third house also has a rectangular shape with a length to width ratio of 1/3. The rest of the calculations for these houses are provided in Table 23.

<table>
<thead>
<tr>
<th>Area of Exterior Walls (sqft)</th>
<th>Percentage of Area Increase Compared to House # 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Side A (ft)</td>
<td>Side B (ft)</td>
</tr>
<tr>
<td>House # 1 (Square)</td>
<td>34.6</td>
</tr>
<tr>
<td>House # 2 (Rectangular – 1/2)</td>
<td>24.5</td>
</tr>
<tr>
<td>House # 3 (Rectangular – 1/3)</td>
<td>20</td>
</tr>
</tbody>
</table>

**Table 23** Effect of Shape of the House on Exterior Wall Area

As displayed in Table 23, change in shape of the house causes a change in the area of exterior walls. Houses that are closer to a cubic form have less exterior wall area.

In order to illustrate the effect of number of stories, two houses with the same shape and square footage are explored. For both of the houses, the shape is a square and the total square footage is 1200. The first house is a single level ranch-style home. The second house is a colonial-style home with two above ground levels. The rest of the calculations for these houses are provided in Table 24.
As displayed in Table 24, change in number of stories causes a significant change in the area of exterior walls for the same total floor space. However, due to the change in the dimensions of the footprint area, this change also impacts the area of the roof. For the sample houses selected for the illustration, the wall area increases by 42% while the roof area decreases by 50% for House # 2.

Although the increase in the roof pitch angle causes an additional increase in the overall wall area due to the exposed sides for houses with cathedral ceilings that do not have attics, the effect of the pitch angle on wall area is investigated during the roof area calculations.

- **Area of the roof “Ar”:** The roof area is determined through the footprint area, either by directly multiplying the exterior length and width dimensions if available or through dividing the total square feet of the building by the number of stories. This represents the projected size of the roof and needs to be adjusted according to the pitch angle of the roof. For rectangular buildings, the exterior roof dimensions (length and width) can also be calculated by utilizing form factor and footprint area (Options # 2 and Option # 3 in Figure 48). The footprint size is directly utilized as approximation for houses with non-rectangular shapes (Option # 1 in Figure 48). The impact of shape of the house is influential for exterior wall area calculations but not for the roof area, which is based on the footprint area. The only impact the shape factor has is its influence on size of gable walls for pitched roofs. Thus the two effects investigated during this impact analysis are the pitch of the roof on roof area and the shape factor combined with the pitch on gable wall sizes. The pitch of the roof can vary greatly for each region and state as a result of the local minimum requirements enforced by the applicable mandates driven by the climate conditions (APB Pole Barns 2009).
Two differently shaped houses are explored for roof pitch angles of 0°, 15°, 25°, 35° and 45°. Both houses are 1250 square feet. The first house has a square footprint and each side is 35.355 feet. The second house has a rectangular footprint (with 2/1 ratio for the sides). The longer side, which is the front and the back side of the house, is 50 feet. The shorter side is 25 feet. The related calculations and the contribution of different angles towards the increase are provided in Table 25.

**Figure 48** Net Roof Area “Ar” Calculation
### Table 25  Roof area increase due to different pitch angles

The results in Table 25 show that the increase in roof area can be up to 41% higher for steep sloped roofs and is less significant for roofs with smaller pitch angles.

For houses with cathedral ceilings that do not have an attic, the increase in the roof pitch angle causes an increase in the overall wall area due to the exposed sides. As shown by the calculations provided in Table 26 and Table 27, the impact of the form factor increases the wall areas twice as much for House # 1 compared to House # 2.

### Table 26  Project Wall Area Increase for Pitch Angles for Cathedral Ceilings – House # 1

---

---
<table>
<thead>
<tr>
<th>Perimeter (ft)</th>
<th>Ceiling Height (ft)</th>
<th>Wall Area (sqft)</th>
<th>0°</th>
<th>15°</th>
<th>25°</th>
<th>35°</th>
<th>45°</th>
</tr>
</thead>
<tbody>
<tr>
<td>House # 2 (Rectangular)</td>
<td>150 8 1200</td>
<td></td>
<td>0</td>
<td>84</td>
<td>145</td>
<td>218</td>
<td>312.5</td>
</tr>
<tr>
<td>Percentage of Projected Roof Area</td>
<td>0% 7% 12% 18% 26%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 27**  
Project Wall Area Increase for Pitch Angles for Cathedral Ceilings – House # 2

- **Area of the fenestrations “Af”**: The calculations for fenestration (window) area are based on the total square footage and derive a minimum and maximum allowable fenestration area depending on the thermal conductance values (Uf) of windows used in the building.

For determining the maximum fenestration area, the design standards established by Energy Conservation Code (IECE) are used. These standards are developed by the International Code Council (ICC) and adopted for use in the Commonwealth of Virginia. In the latest edition of IECE standards, 2006 edition, the maximum allowable fenestration area is required to be less than 15% of the floor area for habitable spaces for Uf values more than 2.56 W/ m²K and 20% of the floor area for habitable spaces for Uf values less than 2.1 W/ m²K (ICC 2006c, AACounty 2011). According to the Uf values set for the sample building (see Table 22), 15% of the floor area for habitable space is used for the maximum allowable fenestration area.

For determining the minimum fenestration area, an adaptation of the minimum fenestration requirements for habitable spaces established by International Residential Code (IRC) is used due to no other existing standards that are currently in effect. According to IRC, all habitable rooms should have a fenestration area not less than 8% of the floor area to allow for adequate natural light provided into the space (ICC 2006b). Thus, a minimum of 8% of the floor area for habitable spaces is used for the minimum allowable fenestration area.

- **Area of the ground slab “Agr”**: The ground slab area is calculated same as projected roof area with no pitch. The ground slab area is determined through the footprint area, either by directly multiplying the exterior length and width dimensions if available or through dividing the total square feet of the building by the number of stories. For rectangular buildings, the
exterior dimensions (length and width) can be calculated by utilizing form factor and footprint area (Options # 2 and Option # 3 in Figure 48). The footprint size is directly utilized as approximation for houses with non-rectangular shapes (Option # 1 in Figure 48).

- **Parameter Group III – Inside and Outside Air Conditions (“ΔT” / “TETD” values):** Temperature difference components are either obtained by subtracting outside temperature “To” or ground temperature “Tgr” values from the inside temperature “Ti” value. To compensate for transient-short-term effects of solar impact (thermal mass, surface color), total equivalent temperature difference value can be utilized. A separate discussion on each of these values is provided below:

- **Inside Air Temperature (Ti):** For determining the inside air temperature, most modeling approaches use default values. In the following, the three most commonly used temperature settings are described:

  **Setting #1:** This setting establishes 70°F as the average internal temperature. This is the minimum acceptable temperature a room 3 ft above the floor in all habitable rooms according to most design standards (McVicker.com 2007).

  **Setting #2:** This setting, which is utilized by Home Energy Saver (HES), consists of pre-established schedules for thermostat setting as presented with Table 28 and Table 29 (LBNL 2009).

<table>
<thead>
<tr>
<th>Temperature (°F)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Day</strong></td>
<td><strong>Night</strong></td>
</tr>
<tr>
<td>8:00 AM</td>
<td>68</td>
</tr>
<tr>
<td>5:00 PM</td>
<td>64</td>
</tr>
</tbody>
</table>

**Table 28** Temperature Schedule for Standard Thermostat

<table>
<thead>
<tr>
<th>Temperature (°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Wake</strong></td>
</tr>
<tr>
<td>7:00 AM</td>
</tr>
<tr>
<td>9:00 AM</td>
</tr>
<tr>
<td>7:00 PM</td>
</tr>
<tr>
<td>11:00 PM</td>
</tr>
</tbody>
</table>

**Table 29** Temperature Schedule for Programmable Thermostat
Setting #3: This setting is the construction industry standard temperature schedule for energy efficient design of low-rise buildings as provided with Table 30 (ASHRAE 2007a).

<table>
<thead>
<tr>
<th>Time Period</th>
<th>Single Zone</th>
<th>Multiple Zone</th>
<th>Temperature (°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Heat</td>
<td>Cool</td>
<td>Zone 1 – Living</td>
</tr>
<tr>
<td>0600 – 0900</td>
<td>68</td>
<td>78</td>
<td>68</td>
</tr>
<tr>
<td>0900 – 1700</td>
<td>68</td>
<td>78</td>
<td>68</td>
</tr>
<tr>
<td>1700 – 2300</td>
<td>68</td>
<td>78</td>
<td>68</td>
</tr>
<tr>
<td>2300 – 0600</td>
<td>60</td>
<td>78</td>
<td>60</td>
</tr>
</tbody>
</table>

Table 30 Temperature Schedule for ANSI/ASHRAE 90.2

Minimum and maximum Ti values are used separately for heating and cooling calculations. For heating calculations, Ti minimum value is determined as 64 °F and Ti maximum value is determined as 76°F. For cooling calculations, Ti maximum value is determined as 78 °F and Ti minimum value is determined as 81°F. However, both of the values are adjusted to account for the fluctuation introduced by the occupant. Therefore, for heating, Ti minimum value is adjusted to 68°F and Ti maximum value is adjusted to 80°F. For cooling, Ti minimum value is adjusted to 75°F and Ti maximum value is adjusted to 65°F. Ti mean is also determined as 74°F for heating and as 70 °F for cooling.

- **Outside Air Temperature (To):** For determining outside air temperatures, either historic data for the research location or default values used by different modeling approaches are utilized. The three most commonly used settings are defined as follows:

Setting #1: In this setting, either monthly (Table 31) or separate annual mean temperatures for the heating and cooling seasons are used. For the heating season at the research location (Blacksburg, Virginia), which is considered to be October through April, a mean temperature of 41.5°F is used. For the cooling season, which is considered to be May through September, mean temperature of 71.6°F is used. Both of these values are mean outdoor dry bulb temperatures (°F) recorded during the calendar year of 2009 in Roanoke, Virginia (Wunderground 2010).
Table 31 Monthly Outdoor Temperature for Roanoke, Virginia for Calendar Year 2009

Setting #2: In this setting, a mean temperature of 40°F is used for the heating season, which is considered to be October through April. A mean temperature of 70°F is used for the cooling season, which is considered to be May through September. These values represent the mean annual outdoor dry bulb temperature for Zone 4. The values for Zone 4 are calculated from normalized data over 42 years and cover the entire state of Virginia (ASHRAE 2006).

Default setting #3: In this setting, mean temperature of 41.4°F is used for the heating season, which is considered to be October through April. Mean temperature of 71.4°F is used for the cooling season, which is considered to be May through September. These values represent the mean annual outdoor dry bulb temperature. They are calculated by National Weather Service (NWS) from normalized data over 30 years and cover the entire state of Virginia (NWS 2010).

As the data provided by all three settings are within 2-3% of each other, only a single “To” value is selected for heating and cooling. “To” value of 40°F and 71°F is used for heating and cooling energy consumption respectively.

- Temperature of the ground (Tgr): For determining the temperature of the ground, historic data for the research location, Blacksburg, Virginia, or default design values are utilized. Two different settings that can be utilized are defined as follows:

Setting #1: In this setting, either monthly (Table 32) or annual mean temperature of 60°F is used. Both of the values are mean ground surface temperatures (°F), which were recorded during a Virginia Tech research study in the Commonwealth of Virginia (Geo4VA 2011).

Table 32 Monthly Ground Surface Temperature for Virginia
Setting #2: In this setting, an annual ground surface temperature of 59°F is used. This value represents the mean ground surface temperature in the Commonwealth of Virginia, which is established for geothermal heat pump design calculations (McQuay International 2010).

- **Total equivalent temperature differential (TETD):** While determining the cooling consumption, using only the temperature difference between inside and outside temperature does not account for the solar heat influences as the outside surface of the wall or the roof usually is much warmer than the surrounding air (Tao and Janis 2001a). Therefore, a TETD is utilized to account for orientation, time of day, absorption property of the surface, and thermal mass of the assembly (and the associated time lag). The TETD value is usually calculated by utilizing available tabulations, which depend on the type of construction, geographical location, time of the day, and wall orientation (Tao and Janis 2001a). Engineering reference manuals and design standards such as ISO Standard 13790 – “Energy Performance of Buildings, Calculation of Energy Use for Space Heating and Cooling” can also be utilized to determine TETD values.

In order to determine the effect of using inside and outside temperature difference versus TETD, the southern exposure walls of a sample house is utilized. The sample house is assumed to be in Blacksburg, Virginia. The exposure walls are south facing north latitude walls. The inside temperature is estimated to be 75°F and maximum outdoor temperature is 95°F with an outdoor daily range of 21°F (ASHRAE 2007a).

To maintain consistency with the common construction type in the location of the dwelling, Group A and B construction types are selected from the available tabulations. The design data and the related tabulations for these construction types are provided below:

**Group A:**
- 1” stucco + 4” light weight concrete block + air space (U value: 0.267)
- 1” stucco + air space + 2” insulation (U value: 0.106)

**Group B:**
- 1” stucco + 4” common brick (U value: 0.393)
- 1” stucco + 4” heavy weight concrete block (U value: 0.481)
TETD values are calculated by utilizing the tabulations specified by Tao and Janis (2001a) for the sample house (Table 33).

<table>
<thead>
<tr>
<th>Group</th>
<th>Wall Color Type</th>
<th>TETD*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group A</td>
<td>Light Exterior Wall Color</td>
<td>15.6</td>
</tr>
<tr>
<td></td>
<td>Dark Exterior Wall Color</td>
<td>22.6</td>
</tr>
<tr>
<td>Group B</td>
<td>Light Exterior Wall Color</td>
<td>16.4</td>
</tr>
<tr>
<td></td>
<td>Dark Exterior Wall Color</td>
<td>24.1</td>
</tr>
<tr>
<td>Average (Group A &amp; B)</td>
<td>Light Exterior Wall Color (TETDl)</td>
<td>16.0**</td>
</tr>
<tr>
<td></td>
<td>Dark Exterior Wall Color (TETDd)</td>
<td>23.4**</td>
</tr>
</tbody>
</table>

*Mean TETD values of all of the periodic data presented for each group & wall color type
**Overall Mean TETD values for each wall color type across both groups

Table 33  TETD Values for Dwelling Scenario in Roanoke

The temperature difference for the sample house is calculated as follows:

Average Outdoor annual temperature for Roanoke (To)  ➔  55°F
Average Inside temperature for dwelling (Ti)  ➔  75°F

Temperature difference ($\Delta T = Ti – To$)  ➔  20°F

The comparison between inside and outside air temperature difference and TETD yields the following results:

**Increase** in temperature difference for dark exterior wall color

$$\frac{(TETDd – \Delta T)}{\Delta T} = \frac{(23.4 – 20)}{20} \Rightarrow +17\%$$

**Decrease** in temperature difference for light exterior wall color

$$\frac{(\Delta T – TETDl)}{\Delta T} = \frac{(16 -20)}{20} \Rightarrow -20\%$$

The minimum and maximum TETD values are determined by utilizing the results provided above. TETD for dark exterior color is considered to be TETD maximum and TETD for light exterior is considered to be TETD minimum values. The temperature difference value for houses with dark exterior wall color is increased by 17% to derive the TETD maximum value.
The temperature difference value for houses with light exterior wall color is decreased by 20% to derive the TETD minimum value. For minimum $\Delta T$ of 0K, TETD minimum value is determined as 0K. For maximum $\Delta T$ of 6K, TETD minimum value is determined as 7K. The mean TETD is also determined as 3.5K.

**d) Baseline Values and Consumption**

In this section the baseline values are established for each relevant influence parameter and utilized to calculate baseline values for $Q_t$, separately for heating energy consumption and for cooling energy consumption. In most cases mean values are calculated as baseline values for consumption influence parameters and are used for the impact analysis.

- **Parameter Group I - Thermal Conductance Baseline:** Thermal conductance mean values are used as the baseline. As shown in Table 22, the baseline values are as follows:

  \[
  U_w = 0.62 \text{ W/ m}^2\text{K} \quad Ur = 0.70 \text{ W/ m}^2\text{K} \quad U_f = 3.32 \text{ W/ m}^2\text{K} \quad U_{gr} = 0.78 \text{ W/ m}^2\text{K}
  \]

- **Parameter Group II - Spatial Baseline Parameters:** The spatial baseline values are referred to the 1,800 sqft sample house as defined in Section 4.3. For the sample house with the dimensions as provided below, (see Section 4.3), the thermal envelope area values are calculated as follows:

  - **Interior Ceiling Height:** 2.44 meters (8 feet)
  - **Building Length:** 18.3 meters (60 feet)
  - **Building Width:** 9.1 meters (30 feet)
  - **Shape of the House:** Rectangular
  - **Number of Stories:** 1 Story
  - **Habitable Space:** 50% of the total floor area

The Wall Area “$A_w$” for the sample house is calculated as follows (as the sample house spatial values are used as the baseline, only a single value is calculated for “$A_w$”):

\[
A_w = [(2.44 * 18.3) + (2.44 * 9.1)] * 2 = 133 \text{ m}^2 \quad \Leftarrow \text{Baseline}
\]

The Roof Area “$A_r$” for the sample house is calculated for 0° (minimum value) and 45° pitch (maximum value) as follows:

\[
A_r (\text{min}) = (18.3 * 9.1) * 1 = 166.53 \text{ m}^2
\]
Ar (max) = (18.3 * 9.1) * 1.414 = 235.47 m²
Ar (mean) = (166.53 + 235.47) / 2 = 201 m²  ⇐ Baseline

The Area of fenestrations “Af” for the sample house is calculated for 8% (minimum value) and 15% (maximum value) of the floor area as follows:
Af (min) = (18.3 * 9.1) * 0.5 * 0.08 = 6.6 m²
Af (max) = (18.3 * 9.1) * 0.5 * 0.15 = 12.4 m²
Af (mean) = (6.6 + 12.4) / 2 = 9.5 m²  ⇐ Baseline

The Ground Slab Area “Agr” for the sample house is calculated as follows (as the sample house spatial values are used as the baseline, only a single value is calculated for “Agr”):
Agr = (18.3 * 9.1) = 166.53 m²  ⇐ Baseline

- **Parameter Group III - Air Temperature Baseline:** Separate baseline values are established for “Ti”, “To”, “Tgr”, and “TETD” according to the parameter sources as provided below:

  **Ti:** The baseline is established as 74°F for heating and as 75 °F for cooling energy consumption.

  **To:** The baseline is established as 40°F for heating and as 71°F for cooling energy consumption.

  **Tgr:** The baseline is established as 59.5°F, which is the mean of the two values provided under parameter sources.

  **TETD:** The baseline is established as 3.5K for cooling energy consumption.

Minimum, maximum and baseline values for the influence parameters under parameter groups are summarized in Table 34.
Table 34 Minimum, maximum, and baseline parameter values for calculating Qt

<table>
<thead>
<tr>
<th>Group</th>
<th>Parameter</th>
<th>Minimum Value</th>
<th>Maximum Value</th>
<th>Baseline (Mean) Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Uw</td>
<td>0.25 W/ m²K</td>
<td>1.6 W/ m²K</td>
<td>0.62 W/ m²K</td>
</tr>
<tr>
<td></td>
<td>Ur</td>
<td>0.16 W/ m²K</td>
<td>1.6 W/ m²K</td>
<td>0.70 W/ m²K</td>
</tr>
<tr>
<td></td>
<td>Uf</td>
<td>2.0 W/ m²K</td>
<td>5.8 W/ m²K</td>
<td>3.32 W/ m²K</td>
</tr>
<tr>
<td></td>
<td>Ugr</td>
<td>0.25 W/ m²K</td>
<td>1.2 W/ m²K</td>
<td>0.78 W/ m²K</td>
</tr>
<tr>
<td>II</td>
<td>Aw</td>
<td>133 m²</td>
<td>133 m²</td>
<td>133 m²</td>
</tr>
<tr>
<td></td>
<td>Ar</td>
<td>166.53 m²</td>
<td>235.47 m²</td>
<td>201 m²</td>
</tr>
<tr>
<td></td>
<td>Af</td>
<td>6.6 m²</td>
<td>12.4 m²</td>
<td>9.5 m²</td>
</tr>
<tr>
<td></td>
<td>Agr</td>
<td>166.53 m²</td>
<td>166.53 m²</td>
<td>166.53 m²</td>
</tr>
<tr>
<td>III</td>
<td>Ti</td>
<td>290K (68°F) (H)</td>
<td>300 K (80°F) (H)</td>
<td>296 K (74°F) (H)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>297 K (75°F) (C)</td>
<td>291 K (65°F) (C)</td>
<td>293 K (70°F) (C)</td>
</tr>
<tr>
<td></td>
<td>To</td>
<td>277 K (40°F) (H)</td>
<td>277 K (40°F) (H)</td>
<td>277 K (40°F) (H)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>294.8 K (71°F) (C)</td>
<td>294.8 K (71°F) (C)</td>
<td>294.8 K (71°F) (C)</td>
</tr>
<tr>
<td></td>
<td>Tgr</td>
<td>288.6 K (59.5°F)</td>
<td>288.6 K (59.5°F)</td>
<td>288.6 K (59.5°F)</td>
</tr>
<tr>
<td></td>
<td>TETD</td>
<td>0K</td>
<td>7K</td>
<td>3.5K</td>
</tr>
</tbody>
</table>

• **Qt Baseline for Heating Energy Consumption:** Since heating energy consumption is considered steady state energy flow (Tao and Janis 2001d), the TETD as illustrated in Equation 11 is replaced with temperature difference “ΔT” (“Ti – To” in Equation 12) value. As a result, the total transmission heat flow “Qt” equation for heating energy consumption becomes:

\[
Qt = [( \sum Uw \times Aw) \times (Ti - To) + ( \sum Ur \times Ar) \times (Ti - To) + ( \sum Uf \times Af) \times (Ti - To) + ( \sum Ugr \times Agr) \times (Ti - Tgr)]
\]

\[Eq. 11\]

For the baseline parameter values, the baseline total transmission heat flow is calculated as:

\[Qt \text{ (baseline)} = 5.88 kWh/h\]

• **Qt Baseline for Cooling Energy Consumption:** Since cooling energy consumption is considered a transient energy flow equation with time lag accounted for the thermal masses (Tao and Janis 2001d), the TETD parameters are utilized as illustrated in Equation 12.
Qt = \[(\sum Uw \times Aw) \times (TETD) + (\sum Ur \times Ar) \times (TETD) + (\sum Uf \times Af) \times (To - Ti) + (\sum Ugr \times Agr) \times (Ti - Tgr)\]  

Eq. 12

For the baseline parameter values, the baseline total transmission heat flow is calculated as:

Qt (baseline) = 0.13 kWh/h

e) Impact Analysis

The individual impact of influence parameters on Qt is analyzed by calculating and comparing individual Diverging Qt values to the baseline consumption. The Diverging Qt values are calculated by using the maximum value for the analyzed parameter (since the minimum value usually has the same divergence to the mean/baseline value) while holding all other parameters on their baseline values. The individual impact of parameters is only completed for parameters that show a divergence to the established baseline values.

The combined total impact of the various parameter groups on Qt is analyzed by comparing a total Qt (min) and total Qt (max), which are calculated respectively from utilizing all minimum and all maximum parameter values, to the Qt baseline values.

- **Individual Parameter Impact on “Qt” during Heating Energy Consumption:** The Diverging Qt value is calculated for each parameter separately by using Equation 11. The impact of each parameter is then determined by using the Diverging Qt values in Equation 13 and completing the calculations for each parameter.

Parameter effect = \[\frac{\text{Diverging Qt} - \text{Qt (baseline)}}{\text{Qt (baseline)}}\]  

Eq. 13

The results of the calculations and the impact analysis for all parameters are provided by Table 35 and further illustrated in Figure 49.
Table 35  Individual parameter impact on “Qt” – Heating Energy Consumption

<table>
<thead>
<tr>
<th>Group</th>
<th>Parameter</th>
<th>Baseline</th>
<th>Diverging Qt Value</th>
<th>Impact on Qt</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Uw</td>
<td>0.62 W/ m²K</td>
<td>8.4 kWh/h</td>
<td>42% (Increase)</td>
</tr>
<tr>
<td></td>
<td>Ur</td>
<td>0.70 W/ m²K</td>
<td>9.3 kWh/h</td>
<td>58% (Increase)</td>
</tr>
<tr>
<td></td>
<td>Uf</td>
<td>3.32 W/ m²K</td>
<td>6.3 kWh/h</td>
<td>7% (Increase)</td>
</tr>
<tr>
<td></td>
<td>Ugr</td>
<td>0.78 W/ m²K</td>
<td>6.4 kWh/h</td>
<td>8% (Increase)</td>
</tr>
<tr>
<td>II</td>
<td>Ar</td>
<td>201 m²</td>
<td>6.3 kWh/h</td>
<td>7% (Increase)</td>
</tr>
<tr>
<td></td>
<td>Af</td>
<td>9.5 m²</td>
<td>6.1 kWh/h</td>
<td>4% (Increase)</td>
</tr>
<tr>
<td>III</td>
<td>Ti</td>
<td>296 K (74°F)</td>
<td>7.4 kWh/h</td>
<td>26% (Increase)</td>
</tr>
</tbody>
</table>

Figure 49  Individual parameter impact on “Qt” – Heating Energy Consumption

- **Combined Impact of Parameter Groups on “Qt” during Heating Energy Consumption:** For parameter minimum and maximum values, Qt values are calculated by Equation 11 as follows:

  \[
  Qt \text{ (min)} = 1.03 \text{ kWh/h} \quad Qt \text{ (baseline)} = 5.88 \text{ kWh/h} \quad Qt \text{ (max)} = 17.61 \text{ kWh/h}
  \]

  The joint impact of minimum and maximum parameter values on the total transmission heat flow is evaluated with Equations 14 and 15 as follows:

  \[
  Qt \text{ min effect (H)} = \frac{Qt \text{ (min)} - Qt \text{ (base)}}{Qt \text{ (base)}} = -82\% \text{ (decrease)} \quad Eq.14
  \]

  \[
  Qt \text{ max effect (H)} = \frac{Qt \text{ (max)} - Qt \text{ (base)}}{Qt \text{ (base)}} = +200\% \text{ (increase)} \quad Eq.15
  \]
• **Individual Parameter Impact on “Qt” during Cooling Energy Consumption:** The Diverging Qt value is calculated for each parameter separately by using Equation 11. The impact of each parameter is then determined by using the Diverging Qt values in Equation 13 and completing the calculations for each parameter.

The results of the calculations and the impact analysis for all parameters are provided by Table 36 and further illustrated in Figure 50.

<table>
<thead>
<tr>
<th>Group</th>
<th>Parameters</th>
<th>Baseline</th>
<th>Diverging Qt Value</th>
<th>Impact on Qt</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Uw</td>
<td>0.62 W/ m²K</td>
<td>0.58 kWh/h</td>
<td>346% (Increase)</td>
</tr>
<tr>
<td></td>
<td>Ur</td>
<td>0.70 W/ m²K</td>
<td>0.76 kWh/h</td>
<td>484% (Increase)</td>
</tr>
<tr>
<td></td>
<td>Uf</td>
<td>3.32 W/ m²K</td>
<td>0.13 kWh/h</td>
<td>No Change</td>
</tr>
<tr>
<td></td>
<td>Ugr</td>
<td>0.78 W/ m²K</td>
<td>-0.23 kWh/h (No Cooling)</td>
<td>277% (Decrease)</td>
</tr>
<tr>
<td>II</td>
<td>Ar</td>
<td>201 m²</td>
<td>0.21 kWh/h</td>
<td>62% (Increase)</td>
</tr>
<tr>
<td></td>
<td>Af</td>
<td>9.5 m²</td>
<td>0.13 kWh/h</td>
<td>No Change</td>
</tr>
<tr>
<td>III</td>
<td>Ti</td>
<td>293 K (70°F)</td>
<td>0.52 kWh/h</td>
<td>300% (Increase)</td>
</tr>
<tr>
<td></td>
<td>TETD</td>
<td>3.5 K</td>
<td>0.91 kWh/h</td>
<td>600% (Increase)</td>
</tr>
</tbody>
</table>

Table 36  Individual parameter impact on “Qt” – Cooling Energy Consumption

**Figure 50**  Individual parameter impact on “Qt” – Cooling Energy Consumption

• **Combined Impact of Parameter Groups on “Qt” during Cooling Energy Consumption:** For parameter minimum and maximum values, Qt values are calculated by Equation 12 as follows:
Qt (min) = -0.21 kWh/h (no cooling)  Qt (baseline) = 0.13 kWh/h  Qt (max) = 3.66 kWh/h

The joint impact of minimum and maximum parameter values on the total transmission heat flow is evaluated with Equations 16 and 17 as follows:

\[ Qt \text{ min effect (H)} = \frac{Qt (\text{min}) - Qt (\text{base})}{Qt (\text{base})} = -261\% \text{ (decrease)} \quad \text{Eq.16} \]

\[ Qt \text{ max effect (H)} = \frac{Qt (\text{max}) - Qt (\text{base})}{Qt (\text{base})} = +2715\% \text{ (increase)} \quad \text{Eq.17} \]

f) Conclusions

The Qt values calculated for heating differ significantly from the Qt values calculated for cooling. This difference can be attributed to the different temperature difference values and the impact of ground slab on cooling. As illustrated in the calculations, TETD values, which are only used during cooling calculations, differ significantly from the temperature difference values used during heating calculations. The temperature difference between inside and outside air is also significantly larger for heating compared to cooling. In addition, the heat flow through the ground slab is a heat loss, which reduces the cooling load and increases the heating load for the dwelling.

As illustrated in Figure 49 and Figure 50, compared to the other parameter groups, the Diverging Qt values for Parameter Groups I and III differ significantly from the Qt baseline for both heating and cooling energy consumption. Also, the following conclusions can be drawn from the differences in parameter Diverging Qt values:

- “Thermal Envelope Characteristics” parameter group has more impact on the Qt than “Inside and Outside Air Conditions” parameter group for heating energy consumption. The thermal conductance of the walls and the roof of the dwelling mainly contribute to this impact.

- “Inside and Outside Air Conditions” parameter group has more impact on the Qt than “Thermal Envelope Characteristics” parameter group for cooling energy consumption. The inside air temperature, which is affected by occupant behavior, and the solar heat influence (for TETD) causes this impact. Also, in addition to the thermal conductance of the walls and the roof, the thermal conductance of ground slab also contributes to the impact of thermal envelope characteristics parameter group on Qt for cooling.
4.3.4.2   **Ventilation and Infiltration Loses (Qv/i)**

  a) **Equations and Modeling Paths**

The heat transfer losses from sensible and latent loads due to ventilation and infiltration effects are usually calculated separately (Tao and Janis 2001b). Theoretically, only sensible load is calculated for heating, while both sensible and latent losses are calculated for cooling in order to account for the energy used for dehumidification. However, during this analysis, the effect of the latent load is assumed to be non-relevant since residential cooling systems are typically not driven by relative humidity but rather indoor temperature. Thus, only the losses related to sensible load are analyzed. The ventilation and infiltration losses are calculated through Equation 18.

\[ Q_{v/i} = 1.1 \times \text{CFM} \times (T_i - T_o) \]  

*Eq. 18*

In Equation 18, “CFM” is air exchange in cubic feet/minute. It represents the amount of outside air introduced through ventilation systems, and/or the air leakage (infiltration) through the envelope. As already defined in the previous section, “T_i” is the inside temperature, while “T_o” is the outside temperature.

Figure 51 illustrates the modeling approach for calculating ventilation and infiltration losses. In this modeling path, first the “Air Changes per Hour” (ACH) value is determined from indoor air quality (i.e. ventilation) requirements and from thermal envelope characteristics; then the ACH value is converted to CFM by utilizing “Volume” consumption influence parameter. If volume of the space is not known, it can be calculated by multiplying “Total Square Footage” and “Interior Ceiling Height” parameters. Finally, for any given inside and outside air temperatures values the ventilation and infiltration losses are calculated by using Equation 18.
As illustrated in Figure 51, Parameter Groups I and II are compromised by various parameters, wherein “Building Thermal Envelope”, “Space Usage Characteristics”, “Year Built”, “Infiltration”, “Volume”, “Total Square Footage”, “Interior Ceiling Height”, and “Zip code” are identified as Tier-1 relationships.

Influence parameters neglected in the above model and thus categorized as Tier-2 relationships are shown in Figure 52. These parameters are not analyzed in the numerical impact study.

**Figure 51**  Ventilation and Infiltration Loss Calculation

**b) Consumption Influence Parameters**

As illustrated in Figure 51, Parameter Groups I and II are compromised by various parameters, wherein “Building Thermal Envelope”, “Space Usage Characteristics”, “Year Built”, “Infiltration”, “Volume”, “Total Square Footage”, “Interior Ceiling Height”, and “Zip code” are identified as Tier-1 relationships.

Influence parameters neglected in the above model and thus categorized as Tier-2 relationships are shown in Figure 52. These parameters are not analyzed in the numerical impact study.
However, a brief discussion regarding their influence on ventilation and infiltration losses is provided below:

**Figure 52** Tier-2 Parameter Relationships for Ventilation and Infiltration Losses

- **Local Surroundings:** Outside vegetation in the form of landscaping and hardscaping around the dwelling can potentially affect the infiltration losses. The conditions of the surrounding air around the exterior walls can show differences for homes where landscaping and hardscaping provides a physical perimeter. As a result, the amount of air infiltration can be impacted (McPherson et al. 1988).

- **Exposure to Elements:** Similar to landscaping and hardscaping, proximity of other dwellings nearby the dwelling can potentially affect the infiltration losses. Exposure to severe weather conditions can be altered by the nearby structures. As a result, the conditions of the surrounding air around the exterior walls can show differences and the amount of air infiltration can be impacted.

  \[c)\] **Parameter Sources:**

The different types of input sources identified for Qt (see Section 4.3.4.1c) are researched and applied for the single modeling path to analyze the impact of relevant influence parameters on ventilation and infiltration losses.

From these different types of sources, possible values for each influence parameter under Parameter Groups I and II are determined individually. As a result, minimum, maximum, and mean values are established for each parameter under the parameter groups as provided below:

- **Parameter Group I - Air Flow Requirements (“CFM” values):** Air Change per Hour (ACH) values for different house thermal envelope and weather conditions are determined from tabulations based on empirical studies as provided in Table 37 (Chan et al. 1996).
As required by many design standards such as ASHRAE Standard 62.2 – 2007, the minimum acceptable air exchange rate in a residential dwelling is 0.35 ACH (BPI 2009). Houses with tighter thermal envelope are required to implement mechanical means to maintain this ACH value. Therefore, during this analysis, 0.35 ACH is established as the minimum acceptable level and the two lower levels listed on Table 37 (0.2 and 0.3) are not further considered. As a result, the total minimum and maximum ACH rates (infiltration + ventilation) can be assumed at 0.35 and 1.6 respectively.

These ACH values are now converted into CFM by utilizing the Equation 19.

\[
CFM = \frac{ACH \times \text{Volume of the Dwelling}}{60} \quad \text{Eq.19}
\]

When the minimum and maximum ACH values are used in Equation 19, CFM minimum and maximum values are calculated as a function of volume as shown below:

\[
\begin{align*}
\text{CFM (min)} &= \frac{0.35 \times \text{Volume}}{60} = 0.0058 \text{ V/min} \\
\text{CFM (max)} &= \frac{1.60 \times \text{Volume}}{60} = 0.0267 \text{ V/min}
\end{align*}
\]

The mean CFM value is also calculated from the minimum and maximum values as shown below:

\[
\text{CFM (mean)} = \frac{[(0.35 + 0.5 + 1 + 1.6) / 4] \times \text{Volume}}{60} = 0.0144 \text{ V/min}
\]

During the CFM conversion, the “Volume” influence parameter can be used directly if available, or can be obtained by multiplying the square footage of the dwelling with the interior floor-to-floor height.
• **Parameter Group II – Inside and Outside Air Conditions (“ΔT” / “TETD” values):** The same inside and outside air temperature values are utilized as determined in Section 4.3.4.1c) in this impact analysis.

  **d) Baseline Values and Consumption**

In this section the baseline values are established for each relevant influence parameter and utilized to calculate baseline values for Qv/i, separately for heating energy consumption and for cooling energy consumption. In most cases mean values are calculated as baseline values for consumption influence parameters and are used for the impact analysis.

• **Parameter Group I – CFM Baseline:** The spatial baseline values are referred to the 1,800 sqft sample house as defined in Section 4.3. For the sample house with the dimensions as provided below, (see Section 4.3), the volume of the dwelling is calculated as follows:

  Interior Ceiling Height: 8 feet (2.44 meters)
  Total Squarefeet: 1800 sqft
  Building Width: 30 feet (9.1 meters)
  Shape of the House: Rectangular

\[ V = (8 \times 1800) = 14,400 \text{ ft}^3 \]

CFM minimum, maximum, and mean values, which are derived in the previous section as a function of volume, are calculated as shown below:

CFM (min) = 0.0058 V/min = (0.0058 * 14,400 ft³/min) = 83.52 ft³/min

CFM (max) = 0.0267 V/min = (0.0267 * 14,400 ft³/min) = 384.5 ft³/min

CFM (mean) = 0.0144 V/min = (0.0144 * 14,400 ft³/min) = 207 ft³/min ➡ Baseline

• **Parameter Group II – Air Temperature Baseline:** Separate baseline values are established for “Ti” and “To” according to the parameter sources as provided below:

  **Ti:** The baseline is established as 74°F for heating and as 71.8 °F for cooling energy consumption.
To: The baseline is established as 40°F for heating and as 71.8°F for cooling energy consumption.

Minimum, maximum and baseline values for the influence parameters are summarized in Table 38.

<table>
<thead>
<tr>
<th>Group</th>
<th>Parameter</th>
<th>Minimum Value</th>
<th>Maximum Value</th>
<th>Baseline Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>CFM</td>
<td>83.52 ft³/ min</td>
<td>384.5 ft³/ min</td>
<td>207 ft³/ min</td>
</tr>
<tr>
<td>II</td>
<td>Ti</td>
<td>290K (68°F) (H) 297 K (75°F) (C)</td>
<td>300 K (80°F) (H) 291 K (65°F) (C)</td>
<td>296 K (74°F) (H) 294K (70°F) (C)</td>
</tr>
<tr>
<td></td>
<td>To</td>
<td>277 K (40°F) (H) 294.8 K (71°F) (C)</td>
<td>277 K (40°F) (H) 294.8 K (71°F) (C)</td>
<td>277 K (40°F) (H) 294.8 K (71°F) (C)</td>
</tr>
</tbody>
</table>

Table 38 Baseline and Parameter Values for Qv/i

- **Qv/i Baseline for Heating Energy Consumption:** For the baseline values (for heating), the baseline ventilation and infiltration losses is calculated by Equation 18 as:

  \[ Qv/i \text{ (baseline)} = 7,286.4 \text{ Btu/h (2.14 kWh/h)} \]

- **Qv/i Baseline for Cooling Energy Consumption:** For the baseline values (for cooling), the baseline ventilation and infiltration losses is calculated by Equation 18 as:

  \[ Qv/i \text{ (baseline)} = -182 \text{ Btu/h (-0.05 kWh/h)} \]

**e) Impact Analysis**

The analysis conducted for Qt in Section 4.3.4.1e) is utilized during the Qv/i impact analysis. The individual impacts of influence parameters for Qv/i are analyzed by calculating and comparing individual Diverging Qv/i values to the baseline consumption. The individual impact of parameters is only pursued further for parameters that actually show a divergence to the established baseline values.

The combined total impact of the various parameter groups on Qv/i is analyzed by comparing a total Qv/i (min) and total Qv/i (max), to the Qv/i baseline values.

- **Individual Parameter Impact on “Qv/i” during Heating Energy Consumption:** The Diverging Qv/i value is calculated for each parameter separately by using Equation 18. The
impact of each parameter is then determined by using the Diverging Qv/i values in Equation 20 and completing the calculations for each parameter.

Parameter effect = \[\text{Diverging Qv/i – Qv/i (baseline)} / \text{Qv/i (baseline)}\] 

Eq. 20

The results of the calculations and the impact analysis for all parameters are provided by Table 39 and further illustrated in Figure 53.

<table>
<thead>
<tr>
<th>Group</th>
<th>Parameter</th>
<th>Baseline</th>
<th>Diverging Qv/i Value</th>
<th>Impact on Qv/i</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>CFM</td>
<td>207 ft³/min</td>
<td>13,478 Btu/h (3.95 kWh/h)</td>
<td>85% (increase)</td>
</tr>
<tr>
<td>II</td>
<td>Ti</td>
<td>296 K (74°F)</td>
<td>8,223 Btu/h (2.41 kWh/h)</td>
<td>+ 12.5% (increase)</td>
</tr>
</tbody>
</table>

Table 39  Individual parameter impact on “Qv/i” – Heating Energy Consumption

![Qv/i Parameter Impact Analysis - Heating Energy Consumption](image)

Figure 53  Individual parameter impact on “Qv/i” – Heating Energy Consumption

- **Combined Impact of Parameter Groups on “Qv/i” during Heating Energy Consumption:**
  
  For parameter minimum and maximum values, Qv/i values are calculated by Equation 18 as follows:

  \[
  \text{Qv/i (min)} = 2,572.4 \text{ Btu/h (0.754 kWh/h)} \quad \text{Qv/i (baseline)} = 7,286.4 \text{ Btu/h (2.14 kWh/h)}
  \]

  \[
  \text{Qv/i (max)} = 15,226 \text{ Btu/h (4.46 kWh/h)}
  \]
The joint impact of minimum and maximum parameter values on the infiltration and ventilation losses is evaluated with Equations 21 and 22 as follows:

\[
Qv/i \text{ min effect (H)} = \frac{[Qv/i \text{ (min)} - Qv/i \text{ (base)}]}{Qv/i \text{ (base)}} = -65\% \text{ (decrease)} \quad Eq.21
\]

\[
Qv/i \text{ max effect (H)} = \frac{[Qv/i \text{ (max)} - Qv/i \text{ (base)}]}{Qv/i \text{ (base)}} = +108\% \text{ (increase)} \quad Eq.22
\]

- **Individual Parameter Impact on “Qv/i” during Cooling Energy Consumption:** The Diverging Qv/i value is calculated for each parameter separately by using Equation 18. The impact of each parameter is then determined by using the Diverging Qv/i values in Equation 20 and completing the calculations for each parameter. The results of the calculations and the impact analysis for all parameters are provided by Table 40 and further illustrated in Figure 54.

<table>
<thead>
<tr>
<th>Group</th>
<th>Parameter</th>
<th>Baseline</th>
<th>Diverging Qv/i Value</th>
<th>Impact on Qv/i</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>CFM</td>
<td>207 ft³/ min</td>
<td>-0.1 kWh/h</td>
<td>100% (Decrease)</td>
</tr>
<tr>
<td>II</td>
<td>Ti</td>
<td>294.8 K (71°F) (°C)</td>
<td>-0.25 kWh/h</td>
<td>400% (Decrease)</td>
</tr>
</tbody>
</table>

**Table 40** Individual parameter impact on “Qv/i” – Cooling Energy Consumption

![Qv/i Parameter Impact Analysis - Cooling Energy Consumption](image)

**Figure 54** Individual parameter impact on “Qv/i” – Cooling Energy Consumption

- **Combined Impact of Parameter Groups on “Qv/i” during Cooling Energy Consumption:** For parameter minimum and maximum values, Qv/i values are calculated by Equation 18 as follows:
The joint impact of minimum and maximum parameter values on the infiltration and ventilation losses is evaluated with Equations 23 and 24 as follows:

\[
Q_{v/i} \text{ min effect (C)} = \frac{[Q_{v/i} \text{ (min)} - Q_{v/i} \text{ (base)}]}{Q_{v/i} \text{ (base)}} = +840\% \text{ (decrease)} \quad \text{Eq.23}
\]

\[
Q_{v/i} \text{ max effect (C)} = \frac{[Q_{v/i} \text{ (max)} - Q_{v/i} \text{ (base)}]}{Q_{v/i} \text{ (base)}} = -60\% \text{ (increase)} \quad \text{Eq.24}
\]

\(f\) Conclusions

The Qv/i values calculated for heating differ significantly from the Qv/i values calculated for cooling. This difference can be attributed to the different temperature values. The outside temperature values are always significantly lower than inside temperature values during heating energy consumption. Thus, the effect of ventilation is always heat loss during heating energy consumption. However, only the minimum outside temperature is lower than the minimum inside temperature during cooling energy consumption. Thus, the effect of ventilation is heat gain for maximum and baseline values and heat loss for minimum values.

As illustrated in Figure 53, the Diverging Qv/i values for “CFM” differ significantly from the Qv/i baseline for heating energy consumption. Figure 54 shows that the Diverging Qv/i value for “Ti” differs significantly from the Qv/i baseline for cooling energy consumption. Thus, it can be concluded that “the infiltration rate”, which is affected by thermal envelope conditions, has the highest impact on Qv/i for heating energy consumption, while Ti”, which is affected by occupant behavior, has the highest impact on Qv/i for cooling energy consumption.

4.3.4.3 Solar Gains (Qsol)

a) Equations and Modeling Paths

The effects of solar impact are calculated to determine the heat transfer gains through windows, which includes simple conduction and solar transmission gains (Tao and Janis 2001b). The overall heat transfer gains due to solar effects “Qsol” are calculated (in kWh/h) through Equation 25.
Q_{sol} = \sum Af \times SC \times SHGF \quad Eq.25

The effect of solar impact is considered a gain for both heating and cooling calculations. In Equation 25, “Af” is the area of transfer (i.e. the fenestration area), “SC” is the shading coefficient, and “SHGF” is the solar heat gain factor for each window.

Figure 55 illustrates the modeling approach for calculating solar gains. In this modeling path, first the “SC” and “SHGF” values are determined from envelope characteristics; then “Af” is determined from window sizes. As a result, the solar gains are calculated by using Equation 25.

**Figure 55**  Solar Heat Gain Calculation

b) **Consumption Influence Parameters**
As illustrated in Figure 55, Parameter Groups I and II are compromised by the individual parameters “Building Envelope”, “Space Usage Characteristics”, “Number and Size of Windows”, “Year Built”, “Footprint Area”, “Perimeter Length”, “Shape of the House”, “Form
Factor”, “Total Square Footage”, and “Interior Ceiling Height”, all of which are identified as Tier-1 relationships.

The only influence parameter neglected in the above model and thus categorized as Tier-2 relationship is the “Orientation” as shown in Figure 56. This parameter is not analyzed in the numerical impact study. However, a brief discussion regarding its influence on solar gains is provided below:

- **Orientation**: The window size and position on a façade affect sunlight and heat penetrating the space and the related Solar Heat Gain Factor “SHGF”, which is used to calculate solar gains (Equation 25). The orientation of the house can affect the solar gains through this relationship since the number of windows per façade and the position of the windows are different for each side of the house.

**c) Parameter Sources**

The different types of sources of input identified previously for Qt (see Section 4.3.4.1c) are utilized again and applied for the modeling path to analyze the impact of relevant influence parameters on solar gains.

From these different types of sources, possible values for each influence parameter under Parameter Groups I and II are determined individually. As a result, minimum, maximum, and mean values are established for each parameter under the parameter groups as provided below:

- **Parameter Group 1 – Fenestration Characteristics (“SC” / “SHGF” values)**: The “SC” and “SHGF” values for fenestrations are investigated separately. During this analysis, values are obtained from sources such as Tao and Janis (2001a), ARCA (2010), and Stein et al. (2005a). These values are grouped according to type of glass, type of window, and the peak values for the location of the study. Minimum, maximum and mean values established from these sources are provided in Table 41.
**Parameter Group II – Fenestration Size (“Af” values):** The area of fenestration values determined during Section 4.3.4.1c) are utilized during the impact analysis. Minimum, maximum and mean values established for “Af” are also provided in Table 41.

<table>
<thead>
<tr>
<th>Group</th>
<th>Parameter</th>
<th>Minimum Value</th>
<th>Maximum Value</th>
<th>Mean Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Af</td>
<td>6.6 m²</td>
<td>12.4 m²</td>
<td>9.5 m²</td>
</tr>
<tr>
<td>II</td>
<td>SC</td>
<td>0.4</td>
<td>0.7*</td>
<td>0.55</td>
</tr>
<tr>
<td></td>
<td>SHGF</td>
<td>0.23 kW/ m²</td>
<td>0.65 kW/ m²</td>
<td>0.44 kW/ m²</td>
</tr>
</tbody>
</table>

*This value is adjusted to reflect in-use conditions (e.g., dirt, window treatments, etc...)

Table 41 Minimum, Maximum, and Mean Parameter Values used for calculating Qsol

d) *Baseline Values and Consumption*

Baseline values are established for each relevant influence parameter and utilized to calculate baseline value for Qsol. In most cases the mean values as derived above are utilized as baseline values for consumption influence parameters and are used for the impact analysis.

- **Parameter Group I – Fenestration Characteristics Baseline:** The calculated mean values for consumption influence parameters “SC” and “SHGF” (Table 41) are used as baseline values for the impact analysis.

  **SC:** The baseline is established as 0.55;  
  **SHGF:** The baseline is established as 0.44 kW/ m².

- **Parameter Group II – Fenestration Area Baselines:** The calculated mean value for consumption influence parameters “Af” (Table 41) is used as baseline value for the impact analysis.

  **Af:** The baseline for the total fenestration area is established as 9.5 m².

- **Baseline for Energy Consumption Qsol:** The baseline for Qsol is calculated through Equation 25 as:

  \[ Q_{sol} \text{ (baseline)} = 9.5 \text{ m}^2 \times 0.55 \times 0.44 \text{ kW/ m}^2 = 2.30 \text{ kWh/h} \]
e) Impact Analysis

The individual impact of influence parameters on Qsol are analyzed by calculating and comparing individual Diverging Qsol values to the baseline consumption.

The combined total impact of the various parameter groups on Qsol is then analyzed by comparing the total Qsol (min) and total Qsol (max), to Qsol baseline values.

- **Individual Parameter Impact on “Qsol”:** The Diverging Qsol value is calculated for each parameter separately by using Equation 25. The impact of each parameter is then determined by using the Diverging Qsol values in Equation 26 and completing the calculations for each parameter.

Parameter effect = \[
\frac{\text{Diverging Qsol} - \text{Qsol (baseline)}}{\text{Qsol (baseline)}}
\]  

Eq.26

The results of the calculations and the impact analysis for all parameters are provided in Table 42 and further illustrated in Figure 57.

<table>
<thead>
<tr>
<th>Group</th>
<th>Parameter</th>
<th>Baseline</th>
<th>Diverging Qsol Value</th>
<th>Impact on Qsol</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Af</td>
<td>9.5 m²</td>
<td>3.00 kWh/h</td>
<td>31% (increase)</td>
</tr>
<tr>
<td>II</td>
<td>SC</td>
<td>0.55</td>
<td>2.93 kWh/h</td>
<td>27% (increase)</td>
</tr>
<tr>
<td></td>
<td>SHGF</td>
<td>0.44 kW/ m²</td>
<td>3.40 kWh/h</td>
<td>48% (increase)</td>
</tr>
</tbody>
</table>

Table 42  Individual parameter impact on “Qsol”

![Qsol Parameter Impact Analysis](image)

Figure 57  Individual parameter impact on “Qsol”
**Combined Impact of Parameter Groups on “Qsol”:** For parameter minimum and maximum values, Qsol values are calculated by Equation 25 as follows:

\[ Q_{\text{sol (min)}} = 0.60 \text{ kWh/h} \quad Q_{\text{sol (baseline)}} = 2.30 \text{ kWh/h} \quad Q_{\text{sol (max)}} = 5.64 \text{ kWh/h} \]

The joint impact of minimum and maximum parameter values on the solar gains is evaluated with Equations 26 and 27 as follows:

\[ Q_{\text{sol min effect}} = \left[ Q_{\text{sol (min)}} - Q_{\text{sol (base)}} \right] / Q_{\text{sol (base)}} = -74\% \text{ (decrease)} \quad \text{Eq.26} \]

\[ Q_{\text{sol max effect}} = \left[ Q_{\text{sol (max)}} - Q_{\text{sol (base)}} \right] / Q_{\text{sol (base)}} = +145\% \text{ (increase)} \quad \text{Eq.27} \]

**Conclusions**

As illustrated in Figure 57, the Diverging Qsol values for Parameter Groups I and II both differ significantly from the Qsol baseline. Thus, it can be concluded that “Fenestration Characteristics” and “Fenestration Area” both impact Qsol.

4.3.4.4 **Heat Gain from Interior Lighting, Appliances and Electronics (Qe):**

**a) Equations and Modeling Paths**

The power consumption for interior lighting, and appliances and electronics is used to determine the related heat gains introduced to the space. The power consumption for interior lighting, and appliances and electronics is calculated individually as provided in Sections 4.4.2 and 4.4.3 respectively. Subsequently, “Qe” can be derived by assuming that almost all electrical power consumption for interior lighting, and appliances and electronics directly will convert thermal energy in one way or the other:

\[ Q_e = \left( Q_{\text{a/e}} + Q_l \right) \quad \text{Eq.29} \]

In Equation 29, “Qa/e” is the energy consumption for appliances and electronics, while “Ql” is the energy consumption for interior lighting.

**b) Consumption Influence Parameters**

During the impact analysis, only “Ql” and “Qa/e” components are investigated. Thus, “Ql” and “Qa/e” energy consumption are both identified as Tier-1 relationships.
c) Parameter Sources
The minimum and maximum values determined for “Ql” and “Qa/e” in Sections 4.4.2 and 4.4.3 are used during the impact analysis. These values have to be converted to hourly values through dividing by 24. The values established for “Ql” and “Qa/e” components are provided by Table 43.

<table>
<thead>
<tr>
<th>Components</th>
<th>Minimum Value</th>
<th>Maximum Value</th>
<th>Mean Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ql</td>
<td>0.043 kWh/h</td>
<td>0.18 kWh/h</td>
<td>0.11 kWh/h</td>
</tr>
<tr>
<td>Qa/e</td>
<td>0.32 kWh/h</td>
<td>0.96 kWh/h</td>
<td>0.45 kWh/h</td>
</tr>
</tbody>
</table>

Table 43  Parameter Values as Input for calculating Qe

d) Baseline Values and Consumption
Baseline values established for are determined separately for each component and utilized to calculate baseline value for “Qe”. Mean values are calculated as baseline values for components and are used for the impact analysis.

- **Component Baselines:** The lighting and appliance baselines are established as 0.11 kWh/h for “Ql” and 0.45 kWh/h for “Qa/e” respectively.

- **Baseline for Energy Consumption Qe:** The baseline for Qe is calculated through Equation 29 as:

\[ Qe \text{ (baseline)} = (0.45 + 0.11) = 0.56 \text{ kWh/h} \]

e) Impact Analysis
The individual impact of components on Qe is analyzed by calculating and comparing individual Diverging Qe values to the baseline consumption.

The combined total impact of the various parameter groups on Qe is then analyzed by comparing the total Qe (min) and total Qe (max), to the Qe baseline value.

- **Individual Component Impact on “Qe”:** The Diverging Qe value is calculated for each component separately by using Equation 29. The impact of each component is then determined by using the Diverging Qe values in Equation 30 and completing the calculations for each component.
Parameter effect = \[ \frac{\text{Diverging } Q_e - Q_e \text{ (baseline)}}{Q_e \text{ (baseline)}} \] \hspace{1cm} Eq. 30

The results of the calculations and the impact analysis for components are provided by Table 44 and further illustrated in Figure 58.

<table>
<thead>
<tr>
<th>Components</th>
<th>Baseline</th>
<th>Diverging Qe Value</th>
<th>Impact on Qe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ql</td>
<td>0.11 kWh/h</td>
<td>0.63 kWh/h</td>
<td>13% (increase)</td>
</tr>
<tr>
<td>Qa/e</td>
<td>0.45 kWh/h</td>
<td>1.07 kWh/h</td>
<td>91% (increase)</td>
</tr>
</tbody>
</table>

**Table 44**  Individual parameter impact on “Qe”

![Qe Impact Analysis](image)

**Figure 58**  Individual parameter impact on “Qe”

- **Combined Impact of Parameter Groups on “Qe”:** For parameter minimum and maximum values, Qe values are calculated by Equation 29 as follows:

  \[ Q_e (\text{min}) = 0.36 \text{ kWh/h} \quad Q_e \text{ (baseline)} = 0.56 \text{ kWh/h} \quad Q_e \text{ (max)} = 1.14 \text{ kWh/h} \]

  The joint impact of minimum and maximum parameter values on the solar gains is evaluated with Equations 31 and 32 as follows:

  \[ Q_e \text{ min effect} = \frac{[Q_e \text{ (min)} - Q_e \text{ (base)}]}{Q_e \text{ (base)}} = -36\% \text{ (decrease)} \quad Eq. 31 \]

  \[ Q_e \text{ max effect} = \frac{[Q_e \text{ (max)} - Q_e \text{ (base)}]}{Q_e \text{ (base)}} = +104\% \text{ (increase)} \quad Eq. 32 \]
Conclusions
As illustrated in Figure 58, the Diverging Qe values for Qa/e differ significantly more from the Qe baseline than those for Ql. Thus, it can be concluded that heat gains from appliances and electronics impacts Qe more than heat gains from interior lighting.

4.3.4.5 Heat Gain from Occupants (Qp)

a) Equations and Modeling Paths
Figure 59 illustrates the modeling path for calculating heat gains from occupants. In this modeling path, heat gain requirements per activity and occupancy patterns for the dwelling (hrs/day) are determined.

![Figure 59 Heat Gain from Occupants Calculation](image)

b) Consumption Influence Parameters
As illustrated in Figure 60, Parameter Groups I and II influenced by “Number of Occupants” are identified as Tier-1 relationships.
The influence parameter “Ages of Occupants” is neglected in the above model and thus categorized as Tier-2 relationships as shown in Figure 60. This parameter is not analyzed in the numerical impact study. However, a brief discussion regarding its influence on heat gains from occupants is provided below:

**Figure 60** Tier-2 Parameter Relationships for Total Transmission Heat Flow

- **Ages of Occupants:** The ages of the occupants can affect the type, length and the intensity of the activities performed within the household. Each of these factors can impact the amount of heat gain introduced to the space during these activities. As a result, the overall heat gain amount can be affected.

  c) **Parameter Sources**

Four sources of input are researched and applied for the modeling path to analyze the impact of heat gain per activity and occupancy patterns on heat gain from occupants separately.

- **Parameter Group I – Heat Gain per Activity:** The sources of input utilized for heat gain per activity include:
  - Commonly accepted construction and engineering practices (Autodesk 2010)
  - Books on building science fundamentals (Tao and Janis 2001c)
  - Consumption data based on previous research results (Engineering Toolbox 2010b)

No variation in heat gain values is observed for the data provided by the sources. Thus, a single set of values for heat gain per activity is used as provided by Table 45. It should also be noted that the metabolic rates provided by these sources do not include all types of activities performed in a household. These rates are average values that are generally used during cooling load calculations (in cooling climates) to determine the cooling system capacity. These values are used by the researcher as the main focus of this study is a simplified framework for consumption assessment. However, it is also stipulated that other approaches can also be used during to determine heat gain values per activity.
Table 45  Heat Gain per Activity

- **Parameter Group II – Occupancy Patterns:** Two occupancy scenarios are used as input sources and applied for the modeling path to analyze the impact of “occupancy pattern” on heat gains from occupants. The scenarios are identified as Scenario A “SA” and Scenario B “SB” as discussed in Section 4.3.

For each activity, the number of occupants and the number hours spent are assumed separately for the scenarios as provided by Table 46 and Table 47. The total daily heat gain from occupants is calculated by summing up the total heat gain per activity, which is determined by multiplying the designated heat gain, the hours spent per day, and the number of occupants.

<table>
<thead>
<tr>
<th>Activity</th>
<th>Heat Gain (Btu/h)</th>
<th>Number of Occupants</th>
<th>Number of Hours for Activity / Day</th>
<th>Daily Average Heat Gain (Btu/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sleeping</td>
<td>330</td>
<td>1</td>
<td>8</td>
<td>2,639</td>
</tr>
<tr>
<td>Sitting / Reading / Watching TV</td>
<td>400</td>
<td>1</td>
<td>4</td>
<td>1,599</td>
</tr>
<tr>
<td>Eating</td>
<td>450</td>
<td>1</td>
<td>1</td>
<td>448</td>
</tr>
<tr>
<td>Cooking</td>
<td>500</td>
<td>1</td>
<td>0.5</td>
<td>249</td>
</tr>
<tr>
<td>Doing Chores</td>
<td>1000</td>
<td>1</td>
<td>0.5</td>
<td>124</td>
</tr>
<tr>
<td>Cleaning</td>
<td>1350</td>
<td>1</td>
<td>0.25</td>
<td>337</td>
</tr>
<tr>
<td>Working Out</td>
<td>1800</td>
<td>1</td>
<td>1</td>
<td>1,800</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>7,201</strong></td>
<td></td>
<td><strong>(2.11 kWh/day)</strong></td>
<td></td>
</tr>
</tbody>
</table>

Table 46  Daily Heat Gains from Occupants – Scenario A
As provided by Table 46 and Table 47, the Daily Heat Gains from Occupants are calculated for Scenarios A and B as 2.11 kWh/day and 9.33 kWh/day respectively. The Hourly Heat Gain values for Scenarios A and B are 0.09 kWh/h and 0.39 kWh/h respectively, which are determined by dividing the Daily Heat Gain values by 24.

The hourly heat gains calculated for Scenarios A and B are assumed as the minimum and maximum values respectively. The mean value for daily heat gain is determined as 0.24 kWh/h.

\[ d) \text{ Baseline Values and Consumption} \]

Mean values are utilized as baseline values for each influence parameter.

- **Parameter Group I – Heat Gain Baseline:** The baseline is established as provided by Table 48.

![Table 47 Daily Heat Gains from Occupants – Scenario B](image)

![Table 48 Heat Gain Baseline](image)
• **Parameter Group II – Occupancy Pattern Baseline:** The hourly heat gain baseline is established as $0.24 \text{ kWh/h}$.

  
  
  *e) Impact Analysis*
  
  No variation in Parameter Group I (heat gain values) is observed for the data provided by the sources. Thus, this parameter group is not further analyzed.

  The individual impact of occupancy pattern on $Q_p$ is analyzed by calculating and comparing individual Diverging $Q_p$ value to the baseline consumption.

  The combined total impact of the parameter groups on $Q_p$ is then analyzed by comparing the total $Q_p$ (min) and total $Q_p$ (max), to the $Q_p$ baseline value.

  • **Individual Component Impact on “$Q_p$”:** The Diverging $Q_p$ value is calculated for occupancy pattern. The impact is then determined by using the Diverging $Q_p$ value in Equation 33.

  Parameter effect = \[
  \frac{\text{Diverging } Q_p - Q_p \text{ (baseline)}}{Q_p \text{ (baseline)}}
  \] \hspace{1cm} \text{Eq.33}

  The results of the calculations and the impact analysis are provided by Table 49.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Baseline</th>
<th>Diverging $Q_p$ Value</th>
<th>Impact on $Q_p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Occupancy Pattern</td>
<td>$0.24 \text{ kWh/h}$</td>
<td>$0.39 \text{ kWh/h}$</td>
<td>63% (increase)</td>
</tr>
</tbody>
</table>

  
  Table 49  Occupancy pattern impact on “$Q_p$”

  • **Combined Impact of Parameter Groups on “$Q_p$”:** For parameter minimum and maximum values, $Q_p$ values are calculated as follows:

  \[
  Q_p \text{ (min)} = 0.09 \text{ kWh/h} \quad Q_p \text{ (baseline)} = 0.24 \text{ kWh/h} \quad Q_p \text{ (max)} = 0.39 \text{ kWh/h}
  \]

  The joint impact of minimum and maximum parameter values on the heat gains from occupants is evaluated with Equations 34 and 35 as follows:

  \[
  Q_p \text{ min effect} = \frac{Q_p \text{ (min)} - Q_p \text{ (base)}}{Q_p \text{ (base)}} = -63\% \text{ (decrease)} \hspace{1cm} \text{Eq.34}
  \]

  \[
  Q_p \text{ max effect} = \frac{Q_p \text{ (max)} - Q_p \text{ (base)}}{Q_p \text{ (base)}} = +63\% \text{ (increase)} \hspace{1cm} \text{Eq.35}
  \]
\textbf{f) Conclusions}

The parameter impact analysis is only conducted for occupancy patterns due to lack of variation in data for heat gain values. The results of this analysis show that “occupancy patterns” can cause an increase up to 63\% in Qp value.

The Qp values calculated by Scenarios A and B also show a ratio of 1/4.4. Therefore, a simplified model using a factor of 1.1 per occupant to account for variation in number of occupants (for instances with stay-at home parents) seems to be practical for calculating Qp values due to its simplicity.

\textbf{4.3.4.6 System Load (Qsys):}

\textbf{a) Equations and Modeling Paths}

The system load is the amount of energy required to heat or cool the dwelling. It is calculated through Equation 36. This equation is derived from Equation 7 provided in Section 4.4.1.

\[
Q_{sys} = -Q_t - Q_{v/i} - Q_{sol} - Q_e - Q_p \tag{Eq.36}
\]

\textbf{b) Consumption Influence Parameters}

During the impact analysis, the transmission heat flow “Qt”, the ventilation and infiltration losses “Qv/i”, the solar gains “Qsol”, the heat gains from interior lighting, appliances and electronics “Qe”, and heat gain from occupants “Qp” are investigated.

\textbf{c) Parameter Sources}

The minimum, maximum, and mean values for the components listed in Equation 36 have been determined throughout the previous sections and are here used during impact analysis separately for heating and cooling energy consumption. They are provided as negative or positive values to distinguish gains from losses.

\textbf{d) Baseline Values and Consumption}

In this section the baseline values are established for each component and utilized to calculate baseline values for Qsys, separately for heating energy consumption and for cooling energy consumption. In most cases mean values are calculated as baseline values for components and are used for the impact analysis.
• **Load Component Baselines – Heating Energy Consumption:** Heat load component baseline values are established from mean values as calculated in the previous sections and provided in Table 50. For the Qsys heating energy consumption calculations, Qt and Qv/i are considered to be losses as illustrated by negative values; Qsol, Qe and Qp values are considered to be gains as illustrated by positive values.

<table>
<thead>
<tr>
<th>Components</th>
<th>Minimum Value (kWh/h)</th>
<th>Maximum Value (kWh/h)</th>
<th>Baseline Value (kWh/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qt</td>
<td>-1.03</td>
<td>-17.61</td>
<td>-5.88</td>
</tr>
<tr>
<td>Qv/i</td>
<td>-0.75</td>
<td>-4.46</td>
<td>-2.14</td>
</tr>
<tr>
<td>Qsol</td>
<td>+0.60</td>
<td>+5.64</td>
<td>+2.30</td>
</tr>
<tr>
<td>Qe</td>
<td>+0.36</td>
<td>+1.14</td>
<td>+0.56</td>
</tr>
<tr>
<td>Qp</td>
<td>+0.09</td>
<td>+0.39</td>
<td>+0.24</td>
</tr>
</tbody>
</table>

**Table 50** Qsys component min, max, and baseline values for heating energy consumption

• **Qsys Baseline – Heating Energy Consumption:** For the baseline values (for heating), the baseline heating consumption Qsys is calculated by Equation 36 as:

\[
Q_{sys} \text{ (baseline)} = 4.92 \text{ kWh/h}
\]

• **Load Component Baselines – Cooling Energy Consumption:** Cooling load component baseline values are established from mean values as calculated in the previous sections and provided in Table 51. For the Qsys cooling energy consumption calculations, all of the components are considered to be heat gains, which are illustrated by positive values.

<table>
<thead>
<tr>
<th>Components</th>
<th>Minimum Value (kWh/h)</th>
<th>Maximum Value (kWh/h)</th>
<th>Baseline Value (kWh/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qt</td>
<td>-0.21 (Loss)</td>
<td>3.66</td>
<td>0.13</td>
</tr>
<tr>
<td>Qv/i</td>
<td>-0.06 (Loss)</td>
<td>0.05</td>
<td>0.47</td>
</tr>
<tr>
<td>Qsol</td>
<td>0.60</td>
<td>5.64</td>
<td>2.30</td>
</tr>
<tr>
<td>Qe</td>
<td>0.34</td>
<td>0.99</td>
<td>0.66</td>
</tr>
<tr>
<td>Qp</td>
<td>0.09</td>
<td>0.39</td>
<td>0.24</td>
</tr>
</tbody>
</table>

**Table 51** Qsys component min, max, and baseline values for cooling energy consumption
**Qsys Baseline – Cooling Energy Consumption:** For the baseline values (for cooling), the baseline cooling consumption Qsys is calculated by Equation 36 as:

\[ Q_{sys} \text{ (baseline)} = 3.28 \text{ kWh/h} \]

**e) Impact Analysis**

The individual impact of components on Qsys is analyzed by calculating individual Diverging Qsys values and comparing them to the baseline consumption. The individual impact of components is only completed for parameters that show a divergence to the established baseline values.

The combined total impact of the components on Qsys is analyzed by comparing the total Qsys (min) and total Qsys (max), to the Qsys baseline values.

**Impact of Individual Components on “Qsys” Energy Consumption during Heating:** The Diverging Qsys value is calculated for each component separately by using Equation 36. The impact of each component is then determined by using the Diverging Qsys values in Equation 37 and completing the calculations for each component.

\[
\text{Parameter effect} = \frac{[\text{Diverging Qsys} - \text{Qsys (baseline)}]}{\text{Qsys (baseline)}}
\]

The results of the calculations and the impact analysis for all parameters are provided by Table 52 and further illustrated in Figure 61.

<table>
<thead>
<tr>
<th>Components</th>
<th>Baseline</th>
<th>Diverging Qsys Value</th>
<th>Impact on Qsys</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qt</td>
<td>-5.88 kWh/h</td>
<td>16.65 kWh/h</td>
<td>238% (Increase)</td>
</tr>
<tr>
<td>Qv/i</td>
<td>-2.14 kWh/h</td>
<td>7.24 kWh/h</td>
<td>47% (Increase)</td>
</tr>
<tr>
<td>Qsol</td>
<td>+2.30 kWh/h</td>
<td>1.58 kWh/h</td>
<td>68% (Decrease)</td>
</tr>
<tr>
<td>Qe</td>
<td>+0.56 kWh/h</td>
<td>4.34 kWh/h</td>
<td>12% (Decrease)</td>
</tr>
<tr>
<td>Qp</td>
<td>+0.24 kWh/h</td>
<td>4.77 kWh/h</td>
<td>3% (Decrease)</td>
</tr>
</tbody>
</table>

**Table 52** The “Qsys” impact analysis for heating energy consumption
Individual parameter impact on “Qsys” – Heating Energy Consumption

- **Combined Impact of Components on “Qsys” Energy Consumption during Heating:** For parameter minimum and maximum values, Qsys values are calculated by Equation 36 as follows:

\[
Q_{sys} (min) = 0.73 \text{ kWh/h} \quad Q_{sys} (baseline) = 4.92 \text{ kWh/h} \quad Q_{sys} (max) = 14.9 \text{ kWh/h}
\]

The joint impact of minimum and maximum component values on the system load is evaluated with Equations 38 and 39 as follows:

\[
Q_{sys \ min \ effect \ (H)} = \frac{[Q_{sys} (min) - Q_{sys} (base)]}{Q_{v/i} (base)} = -85\% \ (decrease) \quad Eq.38
\]

\[
Q_{sys \ max \ effect \ (H)} = \frac{[Q_{sys} (max) - Q_{sys} (base)]}{Q_{sys} (base)} = +203\% \ (increase) \quad Eq.39
\]

- **Individual Component Impact on “Qsys” during Cooling Energy Consumption:** The Diverging Qsys value is calculated for each component separately by using Equation 36. The impact of each component is then determined by using the Diverging Qsys values in Equation 37 and completing the calculations for each component. The results of the calculations and the impact analysis for all parameters are provided by Table 53 and further illustrated in Figure 62.

![Figure 61](image-url)
### Table 53  The “Qsys” impact analysis for cooling energy consumption

<table>
<thead>
<tr>
<th>Components</th>
<th>Baseline</th>
<th>Diverging Qsys Value</th>
<th>Impact on Qsys</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qt</td>
<td>0.13 kWh/h</td>
<td>6.81 kWh/h</td>
<td>108% (Increase)</td>
</tr>
<tr>
<td>Qv/i</td>
<td>0.05 kWh/h</td>
<td>3.7 kWh/h</td>
<td>13% (Increase)</td>
</tr>
<tr>
<td>Qsol</td>
<td>2.30 kWh/h</td>
<td>6.62 kWh/h</td>
<td>102% (Increase)</td>
</tr>
<tr>
<td>Qe</td>
<td>0.56 kWh/h</td>
<td>3.86 kWh/h</td>
<td>18% (Increase)</td>
</tr>
<tr>
<td>Qp</td>
<td>0.24 kWh/h</td>
<td>3.43 kWh/h</td>
<td>4% (Increase)</td>
</tr>
</tbody>
</table>

**Figure 62**  Individual parameter impact on “Qsys” – Cooling Energy Consumption

- **Combined Impact of Components on “Qsys” during Cooling Energy Consumption:** For parameter minimum and maximum values, Qsys values are calculated by Equation 36 as follows:

\[
Q_{sys} \text{ (baseline)} = 3.28 \text{ kWh/h} \quad Q_{sys} \text{ (min)} = 0.78 \text{ kWh/h} \quad Q_{sys} \text{ (max)} = 11.3 \text{ kWh/h}
\]

The joint impact of minimum and maximum component values on the system load is evaluated with Equations 40 and 41 as follows:

\[
Q_{sys \text{ min effect (C)}} = \frac{[Q_{sys} \text{ (min)} - Q_{sys} \text{ (base)}]}{Q_{v/i} \text{ (base)}} = -76\% \text{ (Decrease)} \quad \text{Eq.40}
\]

\[
Q_{sys \text{ max effect (C)}} = \frac{[Q_{sys} \text{ (max)} - Q_{sys} \text{ (base)}]}{Q_{sys} \text{ (base)}} = +244\% \text{ (Increase)} \quad \text{Eq.41}
\]
f) **Conclusions**

As illustrated in Figure 61 and Figure 62, the Diverging Qsys values for transmission heat flow “Qt” and solar gains “Qsol” differ significantly from the Qsys baseline for heating and cooling energy consumption. In addition, the Diverging Qsys values for infiltration and ventilation losses “Qv/i” differ significantly from the Qsys baseline for heating energy consumption. Thus, it can be concluded that:

- “Solar gains” and “transmission heat gain”, which are affected by fenestration and thermal envelope conditions, have higher impact on Qsys for both heating and cooling energy conditions.
- The “ventilation and infiltration losses”, which are affected by thermal envelope conditions and inside and outside temperature conditions, have higher impact on Qsys for heating energy conditions.

4.3.4.7 **Total Heating/Cooling Energy Consumption (Qtotal):**

a) **Equations and Modeling Paths**

The total energy consumption “Qtotal” for heating and cooling is calculated through Equation 8 (see Section 4.4.1).

\[
Q_{total} = \frac{Q_{sys} \times Na}{System \ Efficiency}
\]  

**Eq.8**

In Equation 8, “Qsys” is the system load, which is calculated in Section 4.3.4.6, “Na” are the total number of degree days, which are adjusted for the temperature difference. “SE” is the system efficiency for the respective heating or cooling equipment used in the building.
Figure 63 illustrates the modeling approach for calculating the total heating/cooling energy consumption. In this modeling path, first the “Qsys” values are determined from Section 4.3.4.6; then the Adjusted Total Degree Days “Na” are calculated separately for the heating and cooling energy consumption from the total degree days and temperature difference; finally the System Efficiency “SE” values determined from System Parameters separately for heating and cooling energy consumption. As a result, the total energy consumption is calculated by using Equation 8.
b) Consumption Influence Parameters

As illustrated in Figure 63, Parameter Groups I and II influenced by “Zip code”, “System Characteristics”, and “Year Built” are identified as Tier-1 relationships.

c) Parameter Sources

Five different types of sources of input are researched and applied for the modeling path to analyze the impact of relevant influence parameters on total heating/cooling energy consumption. The different types of sources of input include:

- Commonly accepted construction and engineering practices based on code requirements and design standards (ASHRAE 2006).
- Weather data based on historic data collected for the research location (Wunderground 2010, NWS 2010)
- Identified data calculation methods based on previous research (LBNL 2009)

From the different types of sources identified above and the values determined in previous sections, possible values for each influence parameter under Parameter Groups I, II, and III are determined individually. As a result, minimum, maximum, and mean values are established for each parameter under the parameter groups as provided below:

- **Parameter Group I – System Load (“Qsys” value):** The system loads for heating and cooling energy consumption are calculated separately in Section 4.3.4.6 as follows:

  \[
  \begin{align*}
  \text{Qsys (mean)} &= 4.92 \text{ kWh/h} & \text{Qsys (min)} &= 0.73 \text{ kWh/h} & \text{Qsys (max)} &= 14.9 \text{ kWh/h} & \text{(Heating)} \\
  \text{Qsys (mean)} &= 3.28 \text{ kWh/h} & \text{Qsys (min)} &= 0.78 \text{ kWh/h} & \text{Qsys (max)} &= 11.3 \text{ kWh/h} & \text{(Cooling)}
  \end{align*}
  \]

- **Parameter Group II – Inside and Outside Air Conditions (“Na” value):** During the impact analysis, the temperature parameter is defined as a seasonal average for heating and cooling separately in order to capture the temperature variations between winter and summer months (see Section 4.3.4.1c). Furthermore, during the analysis of space heating and cooling total energy flow, a modified version of the degree-day method is utilized. The degree-day method is a single-measure energy estimate calculation. It uses total number of degree days to calculate heating and cooling energy consumption for residential buildings in varying climates (Al-Homoud 2001). The total number of degree days is provided separately for heating and cooling season and identified
with the nomenclature “N”. The 24-hour average temperature is either less than 65°F for heating degree days, while it is more than 65°F for cooling degree days (Lindeburg 2006c). The total number of degree days is determined from weather data. It is mainly used by designers to account for extreme climate conditions while sizing building heating and cooling systems.

While calculating “Qtotal”, the total number of degree days is divided by the applicable temperature difference values. This modification is made as the temperature difference is already included during the calculations of relevant Qsys components. Temperature difference values are determined by subtracting the average design temperature of 65°F from the average seasonal temperatures. For Roanoke, Virginia, the mean To value for the heating season is determined as 40°F and the mean To value for the cooling season is determined as 71°F (see Section 4.3.4.1c). The temperature difference “ΔT” is calculated as 25°F for heating degree days and as 14°F for cooling degree days. In order to determine the Adjusted Total Degree Days (Na), the number of heating degree days default values are divided by 25°F and the number of cooling degree days default values are divided by 14°F. The different adjusted total degree day values (Na) are provided below:

- **Adjusted Heating Degree Days (“Nah”):** Adjusted heating degree days are determined from historic data for the research location. The three most commonly used sources are defined as follows:

  **Source #1:** Heating degree days of 174 days are used from this source. The value represents the mean heating degree days, which are calculated from normalized data over 42 years for Commonwealth of Virginia (ASHRAE 2006).

  **Source #2:** Heating degree days of 192 days are used from this source. The value represents the mean heating degree days recorded during the calendar year of 2009 in Roanoke, Virginia (Wunderground 2010).

  **Source #3:** Heating degree days of 171 days are used from this source. The value represents the mean heating degree days, which are calculated by National Weather Service (NWS) from normalized data over 30 years for Commonwealth of Virginia (NWS 2010).
From the three values listed above, the adjusted heating degree days values are determined as:
Nah (min) = 171 days (4,104 hours), Nah (max) = 192 days (4,608 hours), Nah (mean) = 177.8 days (4,267.2 hours).

- **Adjusted Cooling Degree Days ("Nac"):** Adjusted cooling degree days are determined from historic data for the research location. The three most commonly used sources are defined as follows:

  **Source #1:** Cooling degree days of 93 days are used from this source. The value represents the mean cooling degree days, which are calculated from normalized data over 42 years for Commonwealth of Virginia (LBNL 2009).

  **Source #2:** Cooling degree days of 79 days are used from this source. The value represents the mean cooling degree days recorded during the calendar year of 2009 in Roanoke, Virginia (Wunderground 2010).

  **Source #3:** Cooling degree days of 81 days are used from this source. The value represents the mean cooling degree days, which are calculated by National Weather Service (NWS) from normalized data over 30 years for Commonwealth of Virginia (NWS 2010).

From the three values listed above, the adjusted cooling degree days values are determined as:
Nac (min) = 79 days (1,896 hours), Nac (max) = 93 days (2,232 hours), Nac (mean) = 84 days (2,024 hours).

- **Parameter Group III - System Parameters ("SE" value):** The heating/cooling system efficiency is also analyzed separately regarding energy consumption. The system efficiency values for heating system, which utilize energy efficiency ratio “EER” values and Annual Fuel Utilization Efficiency “AFUE”, are identified by the nomenclature “SEh”. The system efficiency values for cooling system, which utilize seasonal energy efficiency ratio “SEER” values, are identified by the nomenclature “SEc”. Summary of “SEh” and “SEc” values for the most commonly used heating and cooling equipment by year (LBNL 2009) is provided in Table 54. The full data set is also provided in Appendix E.
In this section, the baseline values are established for each relevant parameter/component and utilized to calculate baseline values for Qtotal, separately for heating energy consumption and for cooling energy consumption. Mean values are calculated as baseline values for consumption influence parameters and components and are used for the impact analysis.

- **Parameter Group I – System Load Baseline**: Baseline values are established as:

  \[
  Q_{\text{sys}} \text{ (baseline)} = 4.92 \text{ kWh/h} \quad \text{Heating} \quad Q_{\text{sys}} \text{ (baseline)} = 3.28 \text{ kWh/h} \quad \text{Cooling}
  \]

- **Parameter Group II – Adjusted Degree Day Baseline**: Baseline values are established as:

  \[
  N_{\text{ah}} \text{ (baseline)} = 177.8 \text{ days (4,267.2 hours)} \quad \text{Heating} \\
  N_{\text{ac}} \text{ (baseline)} = 84 \text{ days (2,024 hours)} \quad \text{Cooling}
  \]

- **Parameter Group III – System Efficiency Baseline**: Baseline values are established as:

  \[
  SE_{\text{h}} \text{ (baseline)} = 1.03 \quad \text{Heating} \quad SE_{\text{c}} \text{ (baseline)} = 2.65 \quad \text{Cooling}
  \]

- **Qtotal Baseline for Heating Energy Consumption**: For the baseline values (for heating), the baseline total heating energy consumption is calculated by Equation 8 as:

  \[
  Q_{\text{total}} \text{ (baseline)} = 20,382 \text{ kWh/year}
  \]
**Qtotal Baseline for Cooling Energy Consumption:** For the baseline values (for cooling), the baseline total cooling energy consumption is calculated by Equation 8 as:

\[
\text{Qtotal (baseline)} = 2,505 \text{ kWh/year}
\]

Minimum, maximum and baseline values for the influence parameters and components are summarized in Table 55.

<table>
<thead>
<tr>
<th>Parameters / Components</th>
<th>Minimum Value</th>
<th>Maximum Value</th>
<th>Baseline Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qsys (heating)</td>
<td>0.73 kWh/h</td>
<td>14.9 kWh/h</td>
<td>4.92 kWh/h</td>
</tr>
<tr>
<td>Qsys (cooling)</td>
<td>0.78 kWh/h</td>
<td>11.3 kWh/h</td>
<td>3.28 kWh/h</td>
</tr>
<tr>
<td>Nah</td>
<td>4,104 hours (171 days)</td>
<td>4,608 hours (192 days)</td>
<td>4,267.2 hours (177.8 days)</td>
</tr>
<tr>
<td>Nac</td>
<td>1,896 hours (79 days)</td>
<td>2,232 hours (93 days)</td>
<td>2,024 hours (84 days)</td>
</tr>
<tr>
<td>SEh</td>
<td>3.30</td>
<td>0.5</td>
<td>1.03</td>
</tr>
<tr>
<td>SEc</td>
<td>3.32</td>
<td>1.62</td>
<td>2.65</td>
</tr>
</tbody>
</table>

Table 55 Parameter / Component min, max, and baseline values for Qtotal

**e) Impact Analysis**

The individual impact of influence parameters and components on Qtotal is analyzed by calculating individual Diverging Qtotal values and comparing them to the baseline consumption.

The combined total impact of the parameter groups on Qtotal is analyzed by comparing the total Qtotal (min) and total Qtotal (max), to the Qtotal baseline values.

- **Impact of Individual Parameter/Component on “Qtotal” Energy Consumption during Heating:** The Diverging Qtotal value is calculated for each parameter separately by using Equation 8. The impact of each parameter is then determined by using the Diverging Qtotal values in Equation 42 and completing the calculations for each parameter.

Parameter effect = \([\text{Diverging Qtotal} – \text{Qtotal (baseline)}] / \text{Qtotal (baseline)}\)

**Eq. 42**

The results of the calculations and the impact analysis for all parameters/components are provided by Table 39 and further illustrated in Figure 53.
Table 56 The “Qtotal” impact analysis for heating energy consumption

<table>
<thead>
<tr>
<th>Parameter Group</th>
<th>Parameters/Components</th>
<th>Baseline</th>
<th>Diverging Qtotal Value</th>
<th>Impact on Qtotal</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Qsys</td>
<td>4.92 kWh/h</td>
<td>61,727 kWh/year</td>
<td>202% (Increase)</td>
</tr>
<tr>
<td>II</td>
<td>Nah</td>
<td>4,267.2 hrs</td>
<td>22,011 kWh/year</td>
<td>8% (Increase)</td>
</tr>
<tr>
<td>III</td>
<td>SEh</td>
<td>1.03</td>
<td>41,987 kWh/year</td>
<td>106% (Increase)</td>
</tr>
</tbody>
</table>

Figure 64 Individual parameter impact on “Qtotal” – Heating Energy Consumption

- **Combined Impact of Parameter Groups on “Qtotal” Energy Consumption during Heating:**

For parameter minimum and maximum values, Qtotal values are calculated by Equation 8 as follows:

\[
Q_{\text{total}} \text{ (min)} = 908 \text{ kWh/year} \quad Q_{\text{total}} \text{ (baseline)} = 20,382 \text{ kWh/year}
\]

\[
Q_{\text{total}} \text{ (max)} = 137,318 \text{ kWh/year}
\]

The joint impact of minimum and maximum parameter/component values total heating energy consumption is evaluated with Equations 43 and 44 as follows:

\[
Q_{\text{total}} \text{ min effect (H)} = \frac{Q_{\text{total}} \text{ (min)} - Q_{\text{total}} \text{ (base)}}{Q_{\text{total}} \text{ (base)}} = -96\% \text{ (decrease)} \quad \text{Eq.}43
\]

\[
Q_{\text{total}} \text{ max effect (H)} = \frac{Q_{\text{total}} \text{ (max)} - Q_{\text{total}} \text{ (base)}}{Q_{\text{total}} \text{ (base)}} = +574\% \text{ (increase)} \quad \text{Eq.}44
\]
- **Individual Parameter/Component Impact on “Qtotal” Energy Consumption during Cooling:** The Diverging Qtotal value is calculated for each parameter separately by using Equation 8. The impact of each parameter is then determined by using the Diverging Qtotal values in Equation 42 and completing the calculations for each parameter. The results of the calculations and the impact analysis for all parameters are provided by Table 57 and further illustrated in Figure 53.

<table>
<thead>
<tr>
<th>Parameter Group</th>
<th>Parameters/Components</th>
<th>Baseline</th>
<th>Diverging Qtotal Value</th>
<th>Impact on Qtotal</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Qsys</td>
<td>3.28 kWh/h</td>
<td>8,630 kWh/year</td>
<td>245% (increase)</td>
</tr>
<tr>
<td>II</td>
<td>Nac</td>
<td>2,024 hrs</td>
<td>2,763 kWh/year</td>
<td>10% (increase)</td>
</tr>
<tr>
<td>III</td>
<td>SEh</td>
<td>2.65</td>
<td>4,098 kWh/year</td>
<td>64% (Increase)</td>
</tr>
</tbody>
</table>

**Table 57** The “Qtotal” impact analysis for cooling energy consumption –

![Qtotal Parameter Impact Analysis - Cooling Energy Consumption](image)

**Figure 65** Individual parameter impact on “Qtotal” – Cooling Energy Consumption

- **Combined Impact of Parameter Groups on “Qtotal” Energy Consumption during Cooling:**
For parameter minimum and maximum values, Qtotal values are calculated by Equation 8 as follows:

\[
Q_{\text{total}} \text{(min)} = 445 \text{ kWh/year} \\
Q_{\text{total}} \text{(baseline)} = 2,505 \text{ kWh/year} \\
Q_{\text{total}} \text{(max)} = 15,569 \text{ kWh/year}
\]
The joint impact of minimum and maximum parameter/component values total heating energy consumption is evaluated with Equations 45 and 46 as follows:

\[
Q_{\text{total min effect}}(C) = \frac{Q_{\text{total min}}(\min) - Q_{\text{total base}}(\min)}{Q_{\text{total base}}(\min)} = -82\% \text{ (decrease)} \quad \text{Eq.45}
\]

\[
Q_{\text{total max effect}}(C) = \frac{Q_{\text{total max}}(\max) - Q_{\text{total base}}(\max)}{Q_{\text{total base}}(\max)} = +521\% \text{ (increase)} \quad \text{Eq.46}
\]

\[f\] Conclusions
As illustrated in Figure 64 and Figure 65, the Diverging Qtotal values for system load “Qsys” and system efficiency “SE” differ significantly from the Qtotal baseline for heating and cooling energy consumption. Thus, it can be concluded that “Qsys” and “SE” has the most impact on Qtotal for heating and cooling energy consumption.

4.4 Energy Consumption Influence Matrices

The results of the parameter impact analysis are also used to develop energy consumption influence matrices for the consumption domains. A separate matrix is developed for space heating and cooling and the rest of the energy consumption domains due to the differences in the impact analysis and results.

During the space heating and cooling impact analysis (see Section 4.3), the influence of each applicable parameter under all heat flow categories was analyzed separately. The results of these analyses are summarized in the Heating & Cooling Energy Consumption Influence Matrix in Table 58.
<table>
<thead>
<tr>
<th>Heat Flow Categories</th>
<th>Heating and Cooling Energy Consumption Influence Matrix</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Parameters</td>
</tr>
<tr>
<td>Qt</td>
<td>$U_w$</td>
</tr>
<tr>
<td></td>
<td>$U_r$</td>
</tr>
<tr>
<td></td>
<td>$U_f$</td>
</tr>
<tr>
<td></td>
<td>$U_{gr}$</td>
</tr>
<tr>
<td></td>
<td>$A_r$</td>
</tr>
<tr>
<td></td>
<td>$A_f$</td>
</tr>
<tr>
<td></td>
<td>$T_i$</td>
</tr>
<tr>
<td></td>
<td>$TETD$</td>
</tr>
<tr>
<td>Qv/i</td>
<td>CFM</td>
</tr>
<tr>
<td></td>
<td>$T_i$</td>
</tr>
<tr>
<td></td>
<td>$T_o$</td>
</tr>
<tr>
<td>Qsol</td>
<td>$A_f$</td>
</tr>
<tr>
<td></td>
<td>$S C$</td>
</tr>
<tr>
<td></td>
<td>$S H G F$</td>
</tr>
<tr>
<td>Qe</td>
<td>$Q_l$</td>
</tr>
<tr>
<td></td>
<td>$Q_s/a$</td>
</tr>
<tr>
<td>Qp</td>
<td>Occupancy Pattern</td>
</tr>
<tr>
<td>Qsys</td>
<td>$Q_t$</td>
</tr>
<tr>
<td></td>
<td>$Q_{v/i}$</td>
</tr>
<tr>
<td></td>
<td>$Q_{sol}$</td>
</tr>
<tr>
<td></td>
<td>$Q_e$</td>
</tr>
<tr>
<td></td>
<td>$Q_p$</td>
</tr>
<tr>
<td>QTOTAL</td>
<td>$Q_{sys}$</td>
</tr>
<tr>
<td></td>
<td>$N a h$</td>
</tr>
<tr>
<td></td>
<td>$S E h$</td>
</tr>
</tbody>
</table>

**Table 58** Heating and Cooling Energy Consumption Influence Matrix

The impact analysis in Section 4.3 was conducted separately for the remaining energy consumption domains. Different modeling paths were utilized for appliances and electronics,
interior lighting, and domestic hot water energy consumption domains. The results of these analyses are summarized in Remaining Domains Energy Consumption Influence Matrix and Energy Consumption Model Influence Matrix in Table 60 and Table 60 respectively.

<table>
<thead>
<tr>
<th>Energy Domains</th>
<th>Remaining Domains Energy Consumption Influence Matrix</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Parameters</td>
</tr>
<tr>
<td>Appliances &amp; Electronics</td>
<td>Available Energy Sources</td>
</tr>
<tr>
<td></td>
<td>System Characteristics</td>
</tr>
<tr>
<td></td>
<td>Occupancy Patterns</td>
</tr>
<tr>
<td>Interior Lighting</td>
<td>Total Square Footage</td>
</tr>
<tr>
<td></td>
<td>Number of Rooms</td>
</tr>
<tr>
<td></td>
<td>Ages of Occupants</td>
</tr>
<tr>
<td></td>
<td>Number of Occupants</td>
</tr>
<tr>
<td>Domestic Hot Water</td>
<td>System Characteristics</td>
</tr>
<tr>
<td></td>
<td>Occupancy Patterns</td>
</tr>
<tr>
<td></td>
<td>Ages of Occupants</td>
</tr>
<tr>
<td></td>
<td>Number of Occupants</td>
</tr>
</tbody>
</table>

Table 59  Remaining Domains Energy Consumption Influence Matrix
Table 60  Energy Consumption Model Influence Matrix

<table>
<thead>
<tr>
<th>Energy Domains</th>
<th>Parameter Impact</th>
<th>Modeling Path Influence</th>
<th>Simplified Model Recommendations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Appliances &amp; Electronics</td>
<td>“Occupancy Pattern” parameter influences consumption more than power consumption</td>
<td>Consumer Studies provide values that are 90% of what is provided by HES</td>
<td>Simplified model using consumer studies should be used to calculate this energy consumption</td>
</tr>
<tr>
<td>Interior Lighting</td>
<td>“Occupancy Pattern” parameter influences consumption more than illumination requirements</td>
<td>N/A</td>
<td>“Occupancy Pattern” should be provided through homeowner input to more accurately calculate consumption</td>
</tr>
<tr>
<td>Domestic Hot Water</td>
<td>“Occupancy Pattern” parameter influences consumption more than system parameters</td>
<td>Consumer Studies provides values that are 98% of what is provided by HES</td>
<td>“Occupancy Pattern” should be provided through homeowner input to more accurately calculate consumption</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A ratio of ½ is observed between the two scenarios for sources 2 &amp; 3.</td>
<td>Simplified model using consumer studies and the ratio to account for variation in number of occupants should be used to calculate this energy consumption</td>
</tr>
</tbody>
</table>

4.5  Total Building Energy Consumption “Qbldg”

In the previous sections, parameter impact on each consumption domain is analyzed individually. In this section, the impact of energy consumption domains (and their parameter groups) on total building energy consumption “Qbldg” is analyzed. The total building energy consumption “Qbldg” includes all of the energy consumed under the designated domains and is determined by summing up all domain energy consumption as shown in Equation 47. However, it should be noted that the Qbldg values are determined for the sample house in the research location and according to the assumptions made throughout the calculations. Therefore, the values provided below do not represent total building energy consumption for different types of residential homes, other climate conditions and assumptions other than those identified throughout this document.

The analysis conducted for Qt in Section 4.3.4.1e) is utilized during the Qbldg impact analysis. The combined total impact of the consumption domains on Qbldg is analyzed by comparing a
total Qbldg (min) and total Qbldg (max), to the Qbldg baseline values. The individual impacts of consumption domains and influence parameter groups on Qbldg are analyzed by calculating and comparing individual Diverging Qbldg values to the baseline consumption.

- **Combined Impact of Domains on “Qbldg” Energy Consumption:** For domain energy consumption minimum, maximum, and baseline values, total building energy consumption “Qbldg” values are calculated by Equation 47 as follows:

\[
Q_{\text{bldg}} = Q_a/e + Q_l + Q_{\text{dhw}} + Q_{\text{total (h)}} + Q_{\text{total (c)}}
\]

\[Eq. 47\]

- **Combined Impact of Domains on “Qbldg” Energy Consumption:**

\[Q_{\text{bldg}} \text{ (min)} = 6,651.34 \text{ kWh/year}\]

\[Q_{\text{bldg}} \text{ (baseline)} = 34,154 \text{ kWh/year}\]

\[Q_{\text{bldg}} \text{ (max)} = 173,604.7 \text{ kWh/year}\]

The joint impact of minimum and maximum domain consumption values on total building energy consumption is evaluated with Equations 48 and 49 as follows:

- **Combined Impact of Domains on “Qbldg” Energy Consumption:**

\[Q_{\text{bldg \ min \ effect}} = \frac{Q_{\text{bldg \ (min)}} - Q_{\text{bldg \ (base)}}}{Q_{\text{bldg \ (base)}}} = -81\% \text{ (decrease)} \]

\[Eq. 48\]

\[Q_{\text{bldg \ max \ effect}} = \frac{Q_{\text{bldg \ (max)}} - Q_{\text{bldg \ (base)}}}{Q_{\text{bldg \ (base)}}} = +408\% \text{ (increase)} \]

\[Eq. 49\]

- **Individual Domain Impact on “Qbldg” Energy Consumption:** The Diverging Qbldg value is calculated for each domain and parameter group separately by using Equation 47. The individual impact is then determined by using the Diverging Qbldg values in Equation 50 and completing the calculations. The results of the calculations and the impact analysis for all domains and parameter groups are provided by Table 61 and Table 62 respectively. The results are also further illustrated in Figure 66 and Figure 67 respectively.

\[\text{Domain effect} = \frac{[\text{Diverging Qbldg} - \text{Qbldg (baseline)}]}{\text{Qbldg (baseline)}} \]

\[Eq. 50\]
### Table 61  Full Building Analysis for the Sample House based on Domains

<table>
<thead>
<tr>
<th>Energy Domains</th>
<th>Minimum Value</th>
<th>Maximum Value</th>
<th>Baseline Value</th>
<th>Percentage of Qbldg (*)</th>
<th>Diverging Qbldg Value</th>
<th>Impact on Qbldg</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Appliances &amp; Electronics “Qa/e”</strong></td>
<td>2,765 kWh/year</td>
<td>15,297 kWh/year</td>
<td>4,000 kWh/year</td>
<td>12%</td>
<td>45,451 kWh/year</td>
<td>33% (Increase)</td>
</tr>
<tr>
<td><strong>Interior Lighting “Ql”</strong></td>
<td>931 kWh/Year</td>
<td>2,484 kWh/year</td>
<td>1,361 kWh/year</td>
<td>4%</td>
<td>35,277 kWh/year</td>
<td>3% (Increase)</td>
</tr>
<tr>
<td><strong>Domestic Hot Water “Qdhw”</strong></td>
<td>1,602.34 kWh/year</td>
<td>9,775.7 kWh/year</td>
<td>(**) 5,906 kWh/year</td>
<td>17%</td>
<td>38,023.7 kWh/year</td>
<td>11% (Increase)</td>
</tr>
<tr>
<td><strong>Space Heating “Qtotal (h)”</strong></td>
<td>908 kWh/year</td>
<td>137,318 kWh/year</td>
<td>20,382 kWh/year</td>
<td>60%</td>
<td>151,090 kWh/year</td>
<td>342% (Increase)</td>
</tr>
<tr>
<td><strong>Space Cooling “Qtotal (c)”</strong></td>
<td>445 kWh/year</td>
<td>15,569 kWh/year</td>
<td>2,505 kWh/year</td>
<td>7%</td>
<td>47,218 kWh/year</td>
<td>38% (Increase)</td>
</tr>
<tr>
<td><strong>Total Values</strong></td>
<td>6,651.34 kWh/year</td>
<td>173,604.7 kWh/year</td>
<td>34,154 kWh/year</td>
<td>100%</td>
<td>38,612 kWh/year</td>
<td>13% (Increase)</td>
</tr>
</tbody>
</table>

* percentages are calculated for baseline values

** denotes average of baseline values for Scenarios A and B, which are 3930.71 kWh/year and 7881.86 kWh/year respectively
<table>
<thead>
<tr>
<th>Energy Domains</th>
<th>Parameters Groups / Heat Flow Categories</th>
<th>Full Building Analysis for the Sample House based on Parameter Groups</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Energy Domain Baseline Consumption Value</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Qbldg</td>
</tr>
<tr>
<td>Qtotal (h)</td>
<td>Occupancy Pattern</td>
<td>7,881.86 kWh/year</td>
</tr>
<tr>
<td></td>
<td>System Characteristics</td>
<td>7,881.86 kWh/year</td>
</tr>
<tr>
<td></td>
<td>Transmission Heat Flow</td>
<td>20,382 kWh/year</td>
</tr>
<tr>
<td></td>
<td>Ventilation &amp; Infiltration Losses</td>
<td>20,382 kWh/year</td>
</tr>
<tr>
<td></td>
<td>Solar Gains</td>
<td>20,382 kWh/year</td>
</tr>
<tr>
<td></td>
<td>Heat Gain from A&amp;E and Lighting</td>
<td>20,382 kWh/year</td>
</tr>
<tr>
<td></td>
<td>Heat Gain from Occupants</td>
<td>20,382 kWh/year</td>
</tr>
<tr>
<td></td>
<td>System Load</td>
<td>20,382 kWh/year</td>
</tr>
<tr>
<td>Qtotal (c)</td>
<td>Transmission Heat Flow</td>
<td>2,505 kWh/year</td>
</tr>
<tr>
<td></td>
<td>Ventilation &amp; Infiltration Losses</td>
<td>2,505 kWh/year</td>
</tr>
<tr>
<td></td>
<td>Solar Gains</td>
<td>2,505 kWh/year</td>
</tr>
<tr>
<td></td>
<td>Heat Gain from A&amp;E and Lighting</td>
<td>2,505 kWh/year</td>
</tr>
<tr>
<td></td>
<td>Heat Gain from Occupants</td>
<td>2,505 kWh/year</td>
</tr>
<tr>
<td></td>
<td>System Load</td>
<td>2,505 kWh/year</td>
</tr>
</tbody>
</table>

**Qbldg Baseline Consumption Value**:

34,154 kWh/year

*Table 62  Full Building Analysis for the Sample House based on Parameter Groups*
Figure 66 Analysis of Consumption Domain Impact on Qbldg

Figure 67 Analysis of Consumption Group Impact on Qbldg
• **Conclusions:** As provided in Table 61, domain contributions to total building energy consumption are ranked from highest to lowest as: space heating “Qtotal (h)”, domestic hot water “Qdhw”, appliances and electronics “Qa/e”, space cooling “Qtotal (c)”, and interior lighting “Ql”. However, the Diverging Qbldg values for consumption domains are listed from highest to lowest value as: Qtotal (h), Qtotal (c), Qa/e, Qdhw, and Ql. Thus, it can be concluded that Qtotal (c) and Qa/e domains can have more impact on total building energy consumption than Qdhw domain regardless of its contribution to the total building energy consumption. This can be attributed to the differences in variation of duration of use parameter group for Qa/e, occupancy pattern parameter group for Qdhw, and solar gains heat flow category for Qtotal (c).

As provided in Table 62, the Diverging Qbldg values for “duration of use / occupancy pattern” parameter groups for Qa/e, Ql, and Qdhw differ significantly from the Qbldg baseline value when compared to the Diverging Qbldg values for the other parameter groups. Therefore, it can be concluded that power requirements for equipment, electronics, fixtures, and appliances have less of an impact on the total building energy consumption compared to their usage patterns.

As illustrated in Figure 67, the system load for space heating “Qsys (h)” can cause the largest impact on Qbldg. The Diverging Qbldg value for Qsys (h) is the highest compared to the rest of the Diverging Qbldg values. This is due to calculating Qsys (h) value by summing up all space heating heat flow category values. As a result, the combined variations of all of the heat flow category values are reflected in this Diverging Qbldg value. As shown in Table 62, the Diverging value for space heating transmission heat flow “Qt (h)” is the second highest compared to the rest of the Diverging Qbldg values. This can be attributed to the impact of thermal envelope and the air temperature conditions on space heating energy consumption (see Section 4.3.4.1e).

Through the Diverging Qbldg values provided in Table 62, Solar gains “Qsol”, heat gain from appliances and electronics “Qa/e”, and heat gain from occupants “Qp” are determined to cause an overall decrease in Qbldg. When the impact of Qsol on heating and cooling energy consumption is combined, Qsol can cause up to 32% decrease in Qbldg. However, it should also be noted these results are only valid for the sample house and an increase in Qsol does not always cause a decrease in Qbldg. The total fenestration (window) area “Af” is a common parameter used during both Qsol and Qt calculations. An increase in Af can cause an increase in both Qsol and Qt. The
increase in Qsol can cause a reduction in Qbldg while an increase in Qt can cause a increase in Qbldg.

When the impact of Qa/e on heating and cooling energy consumption is combined, Qa/e can also cause up to 7% reduction in Qbldg. Similarly, when the impact of Qp on heating and cooling energy consumption is combined, Qp can cause less than 1% reduction in Qbldg. Therefore, if no special circumstances are present (e.g., in-laws residing permanently in the dwelling, gym / workout room used frequently, etc.), the effect of Qp on Qbldg can be neglected or simply addressed as a single 1% correction factor.

4.6 Energy Consumption Domains & Influence Parameter Classification

The different energy consumption models discussed in Section 4.3 can be classified under five main energy consumption domains. The initial classification is made according to the framework provided by Balaras et al. (2000). However, this classification is expanded to include all of the primary energy consumption items and meet Research Objective #3: “Establish energy consumption influence parameter groups and map them to designated energy domains to generate a framework”. Research Objective #3 is met by the following two tasks. First, a comprehensive list of energy consumption domains is determined by expanding the framework provided by Balaras et al. (2000). In a second task, the consumption influence parameters are then classified under the different energy consumption domains according to the relationships identified in Sections 4.1, 4.2, and 4.3.

4.6.1 Energy Consumption Items by Energy Consumption Domain

To further analyze parameter impact on energy efficiency in buildings, now on a higher macro level, different energy consumption domains are established based on a methodology provided by Balaras et al. (2000). In their classification, they identified the four main energy consumption domains as: space heating, space cooling, domestic hot water and artificial lighting. However, this classification was established to identify significant energy conservation measures for residential construction. So, it was not designed to include all of the consumption items identified in Section 4.1. Therefore, this initial set is expanded to include appliances and electronics as a separate, additional energy consumption domain. The justification for this expansion is due to fact that appliances and electronics account for 11 - 15% of the overall residential energy consumption.
(DOE 2011). In addition, this domain includes energy consumption items such as cooking equipment, washers, dryers, other household appliances, TVs, computers, and various electronic items, which are not covered by any other energy consumption domain.

The artificial lighting energy consumption domain is reduced to only include interior lighting due to the minimal contribution of exterior lighting as determined in Section 4.3.2. A list of various energy consumption items categorized by consumption domain is provided in Table 4.

4.6.2 Influence Parameters for each Energy Consumption Domain

Individual consumption influence parameters can now be classified under one or multiple energy consumption domains, depending on their contribution to one or more consumption items as discussed in section 4.2. This classification is conducted for all energy consumption influence parameters as identified in Section 4.1. The relationships established for consumption influence parameters in Sections 4.1, 4.2, and 4.3 are used as the basis for this classification. The established relationships between influence parameters and consumption items are now utilized to map them directly to energy consumption domains.

![Figure 68 Mapping of Influence Parameters to Domains through Consumption Item Relationships I](image)

Furthermore, as illustrated in Table 63, there are some consumption items that have impact on multiple energy consumption domains.
<table>
<thead>
<tr>
<th>Energy Consumption Domains</th>
<th>Related Energy Consumption Item</th>
<th>Nature of the Relationship</th>
</tr>
</thead>
<tbody>
<tr>
<td>Space Heating</td>
<td>Heating System</td>
<td>Impact through “QTOTAL”</td>
</tr>
<tr>
<td></td>
<td>Lighting Fixtures</td>
<td>Impact through “Ql”</td>
</tr>
<tr>
<td></td>
<td>Appliances &amp; Electronics</td>
<td>Impact through “Qa/e”</td>
</tr>
<tr>
<td>Space Cooling</td>
<td>Cooling System</td>
<td>Impact through “QTOTAL”</td>
</tr>
<tr>
<td></td>
<td>Lighting Fixtures</td>
<td>Impact through “Ql”</td>
</tr>
<tr>
<td></td>
<td>Appliances &amp; Electronics</td>
<td>Impact through “Qa/e”</td>
</tr>
<tr>
<td>Domestic Hot Water</td>
<td>Domestic Water Heaters</td>
<td>Impact through power consumption</td>
</tr>
<tr>
<td></td>
<td>Heating System</td>
<td>Impact through “Tamb” &amp; ΔT</td>
</tr>
<tr>
<td></td>
<td>Cooling System</td>
<td>Impact through “Tamb” &amp; ΔT</td>
</tr>
<tr>
<td>Interior Lighting</td>
<td>Lighting Fixtures</td>
<td>Impact through power consumption</td>
</tr>
<tr>
<td>Appliances &amp; Electronics</td>
<td>Appliances &amp; Electronics</td>
<td>Impact through power consumption</td>
</tr>
</tbody>
</table>

**Table 63** Consumption Item – Energy Domain Relationships

Through these additional relationships, the impact of an individual parameter on a single energy consumption item can influence multiple energy consumption domains.

**Figure 69** Mapping of Influence Parameters to Domains through Consumption Item Relationships II

As a result of all the established relationships, a relationship matrix for energy consumption influence parameters and energy consumption domains is developed as provided by Figure 60.
<table>
<thead>
<tr>
<th>Energy Consumption Influence Parameters</th>
<th>Energy Consumption Domains</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Space Heating</td>
</tr>
<tr>
<td>Year Built</td>
<td>X</td>
</tr>
<tr>
<td>Orientation</td>
<td>X</td>
</tr>
<tr>
<td>Total Square Footage</td>
<td>X</td>
</tr>
<tr>
<td>Footprint Area</td>
<td>X</td>
</tr>
<tr>
<td>Volume</td>
<td>X</td>
</tr>
<tr>
<td>Perimeter Length</td>
<td>X</td>
</tr>
<tr>
<td>Form Factor</td>
<td>X</td>
</tr>
<tr>
<td>Shape of the House</td>
<td>X</td>
</tr>
<tr>
<td>Interior Ceiling Height</td>
<td>X</td>
</tr>
<tr>
<td>Number of Stories</td>
<td>X</td>
</tr>
<tr>
<td>Number of Rooms</td>
<td>X</td>
</tr>
<tr>
<td>Number &amp; Size of Windows</td>
<td>X</td>
</tr>
<tr>
<td>Number &amp; Size of G. Doors</td>
<td>X</td>
</tr>
<tr>
<td>Number &amp; Size of Skylights</td>
<td>X</td>
</tr>
<tr>
<td>Number of Occupants</td>
<td>X</td>
</tr>
<tr>
<td>Ages of Occupants</td>
<td></td>
</tr>
<tr>
<td>Building Thermal Envelope</td>
<td>X</td>
</tr>
<tr>
<td>Space Usage Characteristics</td>
<td>X</td>
</tr>
<tr>
<td>Infiltration</td>
<td>X</td>
</tr>
<tr>
<td>Ventilation</td>
<td>X</td>
</tr>
<tr>
<td>Zip code</td>
<td>X</td>
</tr>
<tr>
<td>Local Surroundings</td>
<td>X</td>
</tr>
<tr>
<td>Available Energy Sources</td>
<td>X</td>
</tr>
<tr>
<td>System Characteristics</td>
<td>X</td>
</tr>
<tr>
<td>Occupancy Patterns</td>
<td>X</td>
</tr>
<tr>
<td>Exposure to Elements</td>
<td>X</td>
</tr>
</tbody>
</table>

Table 64  Energy Consumption Influence Parameter Classification
4.7 Minimum Set of Parameters

In this section, research objective # 5 is met and influence matrices are developed for the energy consumption domains based on the results of impact analysis in Section 4.3. Research Objective # 5: “Identify a minimum set of parameters for conducting residential energy consumption assessment based on influence parameter analyses” is met by condensing the parameters listed in the parameter influence matrix (Figure 25) from Section 4.2 according the results from the parameter impact analysis in Section 4.3. Initially, the parameters that are not classified as Tier-1 relationships during the impact analysis are deducted from the comprehensive list of parameters (Figure 25). The list is further refined according to the results of parameter impact analysis as displayed with consumption influence matrices (see Section 4.4) as well as full building analysis as provided in Table 61 and Table 62. During this process, the list is reduced to only include those parameters that are required to complete the simplified energy consumption assessment. As a result, the minimum set of parameters is derived as provided in Table 65.

The process from which this minimum set of parameters derived through represents the core contribution of this research. However, it should be noted that the minimum set of parameters are determined for the sample house in the research location and according to the assumptions made throughout the calculations. Therefore, this set does necessarily contain the minimum set of parameters required to determine the energy consumption for different types of residential homes, other climate conditions and assumptions other than those identified throughout this document.
<table>
<thead>
<tr>
<th>The Minimum Set of Energy Consumption Influence Parameters</th>
<th>Energy Consumption Domains</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Space Heating</td>
</tr>
<tr>
<td>Year Built</td>
<td>X</td>
</tr>
<tr>
<td>Total Square Footage</td>
<td>X</td>
</tr>
<tr>
<td>Footprint Area</td>
<td>X</td>
</tr>
<tr>
<td>Volume</td>
<td>X</td>
</tr>
<tr>
<td>Perimeter Length</td>
<td>X</td>
</tr>
<tr>
<td>Form Factor</td>
<td>X</td>
</tr>
<tr>
<td>Shape of the House</td>
<td>X</td>
</tr>
<tr>
<td>Interior Ceiling Height</td>
<td>X</td>
</tr>
<tr>
<td>Number of Stories</td>
<td>X</td>
</tr>
<tr>
<td>Number of Rooms</td>
<td>X</td>
</tr>
<tr>
<td>Number &amp; Size of Windows</td>
<td>X</td>
</tr>
<tr>
<td>Number of Occupants</td>
<td>X</td>
</tr>
<tr>
<td>Ages of Occupants</td>
<td>X</td>
</tr>
<tr>
<td>Building Thermal Envelope</td>
<td>X</td>
</tr>
<tr>
<td>Space Usage Characteristics</td>
<td>X</td>
</tr>
<tr>
<td>Infiltration</td>
<td>X</td>
</tr>
<tr>
<td>Ventilation</td>
<td>X</td>
</tr>
<tr>
<td>Zip code</td>
<td>X</td>
</tr>
<tr>
<td>System Characteristics</td>
<td>X</td>
</tr>
<tr>
<td>Occupancy Patterns</td>
<td>X</td>
</tr>
</tbody>
</table>

**Table 65** Minimum Set of Consumption Influence Parameters
5 Conclusions

Currently, most of the residential energy efficiency assessment tools are derivatives of sophisticated energy models, such as the well-known DOE-2 simulation engine. Some other tools utilize a reduced and simplified input process, but are mostly modifications of comprehensive tools. They utilize the same sophisticated simulation models, which were originally designed for commercial or industrial applications. In many instances, the simplified input process is achieved by setting many of the input variables to default values. Consequently, no tool has achieved energy performance modeling with a credible accuracy and confidence level. Ultimately, no tool has yet provided reliable energy consumption assessment and energy saving predictions that can be used for confident retrofit decision-making in residential homes.

This research attempted to simplify the energy consumption assessment for residential homes while building the foundation towards the development of prediction tools that can achieve a credible level of accuracy for confident decision making. The energy consumption analysis consisted of reducing the number of energy model equations, while utilizing a critical, limited set of parameters. The results of the analyses were used to develop a minimum set of consumption influence parameters and to illustrate how their variations impact each energy consumption domain.

This research study provided the following four main contributions while meeting the five research objectives.

- **Contribution # 1 – “A Comprehensive Set of Influence Parameters for Residential Energy Consumption Assessment”**: While meeting Research Objective # 1, energy consumption items were identified as: heating system, cooling system, domestic hot water, lighting sources, appliances, and electronics from various sources. The energy consumption influence parameters were identified through current tools in use, previous research in the field of study, building science fundamentals, and documentations of commonly accepted business practices. The selection of each influence parameter was justified by its relationship to the various energy consumption items. The resulting comprehensive set of consumption influence parameters and parameter groups is provided in Figure 70. For a more detailed listing of sub-parameters in the different parameter groups please see Section 4.3.
**Contribution # 2 – “Energy Consumption Influence Parameter Relationship Map”:** As a part of the efforts to meet *Research Objective # 2*, a thorough analysis was conducted to determine inter-relationships among the identified influence parameters. The analysis on inter-relationships was conducted only for relationships classified as primary relationships, which are direct effects between two parameters or related consumption item.
The relationships among parameters were classified based on information provided by current software tools, peer reviewed research studies, books on building science fundamentals, and published commonly accepted business practices.

As a result, parameter inter-relationships were identified as illustrated in Figure 71. In addition, the inter-relationships illustrated in Figure 71 were expanded to include the parameter relationships with energy consumption items in order to develop the overall parameter relationship map as illustrated in Figure 25.

**Figure 71** Energy Consumption Influence Parameter Inter-Relationships
• **Contribution # 3 – “Parameter Impact Analysis”:** One of the main contributions of this research is the framework developed for the parameter impact analysis. During the development of this framework, the parameter impact analysis for the sample house was used to demonstrate the process. This parameter impact analysis was conducted for each energy consumption domain separately to meet Research Objective # 4. Also, impact analysis was conducted for the sample house as whole to determine the impact of energy consumption domains on total dwelling energy consumption.

During the impact analysis, the influence of each relevant parameter in energy consumption models was evaluated individually against the baseline scenarios. For some domains, such as space heating and cooling, the individual influence of parameters on relevant heat flow categories was analyzed directly. For other domains different modeling approaches and occupancy scenarios were used to determine the impact of parameter groups on the respective consumption domains.

The results of these analyses are provided in Section 4.4 and Section 4.5, and build the basis for modeling recommendations towards developing a simplified energy consumption model. For the simplified model development process, those parameters that significantly influence the different energy consumption domains should be considered with special care for correct assessment. The sources of input for these parameters should be carefully selected. In order to minimize the inaccuracies introduced by the homeowners, alternative ways of capturing the data for these components should be explored.

• **Contribution # 4 – “Parameter Classification & Minimum Set of Parameters”:** Another main contribution of this research study is the framework developed to derive a minimum set of parameters. During these development efforts, parameters were classified and the results of the impact analysis for the sample house were utilized to derive the minimum set of parameters. Although the minimum set cannot necessarily be generalized for other type of buildings in different climate conditions with different occupancy patterns, the framework still qualifies for generalizability.

Also, Research Objective # 3 was met by identifying energy consumption domains and subsequently, classifying the influence parameters under these domains (see Table 65). This classification was completed through the relationships established between the influence
parameters and the modeling approaches used throughout the impact analysis. In order to meet Research Objective # 5, a minimum set of parameters was developed by condensing the comprehensive list of parameters according to the results of parameter impact analysis (see Figure 72).

Similar to Contribution # 3, the tools developed while meeting research objectives # 3 and # 5 provide a basis for modeling recommendations towards developing a simplified energy consumption model. For the simplified model development process, the minimum set of parameters developed should be used as baseline. The baseline consumption model should be developed based on the minimum set of parameters and according to the modeling paths provided by this study.

- Year Built
- Total Square Footage
- Footprint Area
- Volume
- Perimeter Length
- Form Factor
- Shape of the House
- Interior Ceiling Height
- Number of Stories
- Number of Rooms
- Number and Size of Windows
- Number of Occupants
- Ages of Occupants
- Building Thermal Envelope
- Space Usage Characteristics
- Infiltration
- Ventilation
- Zip code
- System Characteristics
- Occupancy Patterns

Figure 72 Minimum Set of Consumption Influence Parameters
6 Future Research

This research provides the foundation for the development of a simplified baseline energy model for residential energy consumption assessment and savings predictions for retrofit scenarios. The minimum set of influence parameters that were determined from the results of the parameter impact studies should be used to develop a simplified baseline energy model.

The following recommendations for future research, which meet Research Objective # 6: “Provide recommendations for the development of a simplified baseline model for residential energy consumption based on framework, which utilizes the minimum set of parameters to achieve confidence for decision-making”, can be grouped into six sections:

- **Simplified Baseline Energy Model Development:** A simplified baseline energy model can developed by utilizing the minimum set of parameters and the respective energy modeling paths listed in section 4.3.

- **Simplified Baseline Energy Model Evaluations:** The simplified baseline model can be evaluated against the credible levels of accuracy and confidence by using available energy modeling simulation programs. These evaluations should be conducted by the researchers for a validated set of test data in order to minimize inaccuracies introduced through homeowner input. Necessary iterations can be made to the baseline model to develop expanded models according to the findings of the initial evaluation.

- **Expanded Energy Model Evaluations:** A follow-up pilot study can be conducted to further evaluate the expanded model. The expanded model can then be evaluated against the confidence and accuracy levels by utilizing the consumption data for the pilot community. Necessary iterations can be made to the expanded model according to the findings of the pilot study.

- **Consumer Study Evaluations:** A persona should be developed and utilized to characterize the capabilities, level of understanding, needs, and expectations of the novice homeowner. Supplement to the persona, available consumer studies conducted by the industry can be explored to determine homeowner expectations and preferences. Necessary iterations can then be made to the expanded baseline model and its parameters according to the findings of the evaluations.
• **Parameter Input Evaluations:** The amount and the technical content required for the parameters to be entered by the homeowner can be further explored to reduce potential data inaccuracies. Different options such as minimizing the technical content of the parameters to be entered by the homeowner, incorporating visual aids and representations to depict the technical information sought, and maximizing parameters for which the input is derived from other sources can be further investigated. Depending on the findings, necessary adjustments can be made to the parameter set and the expanded model.

• **Final Tool Evaluation:** After all design iterations are completed, the expanded energy consumption assessment model consisting of the minimum set of optimized parameters can be developed. This final model with the set of optimized parameters can be assessed by conducting expanded tests. The testing community can be selected to include single-family dwellings with varying construction characteristics. The results of this assessment can be utilized to validate the energy consumption assessment of the expanded model with the minimum set of optimized parameters for the credible level of accuracy and confidence.

6.1 **Expected Outcome from Future Research**

The expected outcome from future research is the development of simplified energy performance model for residential homes, which offers credible level of accuracy and confidence for retrofit decision-making. If the outcome is successful and the model is adopted by the broader public, the potential impacts could include:

- educating residential stakeholders and increasing awareness in the realm of energy efficiency in local pilot communities.
- developing and utilizing different energy efficiency options and scenarios in order to help reduce utility costs and resource consumption
- using the tool in order to make energy efficiency retrofit decisions.
- identifying and breaking down barriers for the use of new technologies
- promoting the use of new technologies for homeowners.

In addition, the project can potentially set the stage for future multi-disciplinary research, which can:
• Utilize the model to develop a comprehensive energy efficiency options tool that provides a financial decision-making framework for residential construction and possible incorporation into an online portal
• Develop guidelines for usability of the application portal and interfaces
• Utilize the application portal as a means to collect information in order to determine further research needs with residential applications
• Foster the use of collected data by graduate students to conduct further research, which again can result in new capstone experiences throughout various education and outreach programs
• Utilize the application portal and research findings from user ratings and discussions to develop a WIKI system, where answers will be collectively developed.
References Cited


Annotated Bibliography


This study surveyed over 100 energy efficiency option tools including those recommended by energy modeling experts, those listed on the U. S. Department of Energy’s (DOE) Building Energy Software Tools Directory (DOE 2009) as well as those analyzed in Lawrence Berkley National Laboratory (LBNL) by Mills (2004). Fifteen of the tools were reviewed in greater detail to determine the level of prediction accuracy. As a result, two versions (mid-level and complete versions) of Home Energy Saver (HES) developed by LBNL, REM/Rate, an accredited and widely used Home Energy Rating System software and SIMPLE, a simplified spreadsheet based modeling program with 32 data points, were selected for more in-depth analysis. The analysis was conducted in order to determine the accuracy of energy use prediction, audit time and ease of use.


This report presents long-term projections of energy supply, demand, and prices through 2030, based on results from EIA’s National Energy Modeling System. It also summarizes the projections for energy markets. The analysis focuses primarily on a reference case, low and high economic growth cases, and low and high oil price cases. Results from a number of other alternative cases also are presented, illustrating uncertainties associated with the reference case projections for energy demand, supply, and prices. Available online at http://www.eia.doe.gov/oiaf/aeo/pdf/0383(2009).pdf


This report reviews the world trends in energy demand and the major macroeconomic assumptions used in deriving the stated projections, along with the major sources of uncertainty in
the forecast. The time frame for historical data begins with 1980 and extends to 2006, and the projections extend to 2030. High economic growth and low economic growth cases were developed to depict a set of alternative growth paths for the energy projections. The two cases consider higher and lower growth paths for regional gross domestic product (GDP) than are assumed in the reference case. This report also includes a high oil price case and, alternatively, a low oil price case. Available online at http://www.eia.doe.gov/oiaf/ieo/pdf/0484(2009).pdf


The module projects future residential sector energy requirements based on projections of the number of households and the stock, efficiency, and intensity of use of energy-consuming equipment. The projections begin with a base year estimate of the housing stock, the types and numbers of energy-consuming appliances servicing the stock, and the “unit energy consumption” by appliance. The projection process adds new housing units to the stock, determines the equipment installed in new units, retires existing housing units, and retires and replaces appliances. Available online at http://www.eia.doe.gov/oiaf/aeo/assumption/pdf/residential.pdf


This paper examined the differences in total life-cycle energy, greenhouse gas emissions and cost between a standard residential home in Michigan and its’ simulated energy efficient counterpart. The energy efficiency modeling was conducted by ensuring a functional equivalence to the standard house, while making modifications to achieve desired thermal characteristics according to the best available technology. The occupant habitation phase accounted for 91% of the life cycle energy over a lifetime of 50 years. The energy efficient house simulation resulted in 60% reduction in life cycle energy and 64% reduction in greenhouse gas emissions. Due to higher mortgage and equipment installation costs at the time, there was not a significant reduction in overall cost despite the reduction in energy costs.

In this study, 50 web-based residential tools and 15 disk-based tools were analyzed. Many of them were found not to provide an analysis of energy saving options. In addition, they were found to be incapable of evaluating significant building energy issues and efficiency features. The tools provided a wide range of whole-house energy bills inaccurately as a result of many programming and algorithm errors.


This study explored the non-energy benefits of energy efficient technologies as a residential homeowner motivation tool. Several non-energy benefits (such as improved indoor environment, comfort, health and safety, reduced noise, labor and time savings for lower maintenance, improved process control, increased amenity and convenience, water savings and waste minimization, direct and indirect economic benefits from downsizing of equipment) were further explored non-energy benefit categories. In addition, the paper provided detailed examples of some technologies and their non-energy benefits.


Based on a multiple case study of four Dutch building contractors, the paper shows that contractors that actively gather information and build internal technical capacity are keener on adopting energy-efficient technologies. Findings also reveal that it will be a major challenge for the construction industry to communicate the advantages of clean technologies to (potential) home buyers and create market demand.

In this study, a survey of 60 cases from nine countries was conducted in order to explore the differences between conventional buildings, built according to the applicable building codes, solar houses, designed to be oriented to exploit maximum solar energy, and passive houses, designed to fully exploit passive technologies. Solar houses, with a lifetime of 50 years, decreased the life cycle energy demand by 50% when compared to conventional buildings. Passive houses, with a lifetime of 80 years, decreased the life cycle energy demand by 66% when compared to solar houses.


In this study, a life cycle assessment for different residential heating and cooling systems was conducted in order to determine the most significant energy consumers and the largest source of emissions in the lifetime of a house. Warm-air furnace and air conditioner, hot water boiler and air conditioner and air-air heat pump were selected as the different technologies to be compared. Minnesota, Oregon, Pennsylvania and Texas were chosen as different testing locations to examine the effects of different climate conditions and composition of energy generation.


This site provides a tool directory sponsored by the U.S. Department of Energy (DOE) to assist all stakeholders involved in building life-cycle. The tools consist of energy-efficiency technologies and renewable energy strategies and are sorted by country, platform, subject as well as alphabetical order.
Appendix A  Examples of Energy Efficiency Retrofit Decision-Making Tools

- **Facilities Energy Decision System:** Developed by Pacific Northwest Laboratory (PNL) for industrial building facility management, Facility Energy Decision System (FEDS) is one of the most complete energy efficiency decision making software programs (PNL 2009). FEDS intuitively estimates the unidentified building system parameters. It simulates the building/facility total energy load through developing performance models for HVAC systems as well as building envelope. It, then, calculates total energy consumption, electricity demand, optimum energy efficiency options with life cycle cost, net present value for implementation cost, investment payback period, energy savings and GHG emission savings.

- **Best Practice House:** This software application provides an interactive simulation of a single family dwelling developed by Energy Saving Trust (EST), where the users are able to select various components such as floors, walls, roofs, building envelope, and incorporated energy efficient technologies of a 3-Dimensional model for retrofits and new construction (EST 2009). In this model, all of the best available technologies are illustrated with guidance documents to educate homeowners and builders of the technical background. A boiler wizard is provided to help homeowners and contractors make capacity decisions on HVAC system components. A composition of applicable building codes are provided in the form of advanced construction details document. Lastly, a separate “Hard to treat homes” application is provided for older homes with energy efficiency challenges due to unfavorable climate conditions and poor construction. The tool website also incorporates an energy savings calculator, which was under construction at the time of this review.

- **Home Energy Audit:** The Audit tool, provided by ServiceMagic in the form of an online questionnaire, is designed to solicit basic information on building construction parameters and the homeowner primary improvement concerns (ServiceMagic 2009). However, it appears to be a sales tool, in the form of a very basic search engine rather than a decision making application, utilized to provide a list of contractors in the immediate vicinity of the dwelling.

- **Energy Efficiency and Savings Tools:** Similar to FEDS software, this application incorporates survey and assessment tools developed for the purposes of commercial facility management. The tools developed by Forging Industry Association (FIA), include a plant energy profiler,
which assesses the facility energy profile and identifies the best savings opportunities, a
process heating assessment designed to examine the thermal efficiency of the industrial
heating equipment and other audit tools that are designed to evaluate industrial CHP and air-
compressor systems to determine the energy efficiency (FIA 2009). The application also
includes documents on best business practices and case studies for individual industrial
manufacturing systems. However, it does not incorporate an economic analysis tool unlike
similar commercial applications.

- **HomeEnergySuite:** Developed by Apogee, this application is designed to provide homeowners
  with a basic understanding of energy use costs as they relate to the system and occupancy
  characteristics of a single family dwelling (Apogee 2009). The application provides a simple
drop down menu to input basic information on the construction characteristics of the house
such as the size, age, building envelope and dwelling type, occupancy conditions such as the
types and amount of appliance in the house and behavioral / habitual conditions such as
heating and cooling settings. Upon completion of the questionnaire, the homeowners are
provided with report that identifies estimated monthly and annual electricity and fuel costs.
The homeowners are also able to change the questionnaire inputs in order to calculate how
each characteristic and condition change can affect their estimated electricity and fuel costs.

- **Building Technologies Program:** This program, administered by DOE, strives to achieve a
  significant reduction in commercial and residential sector energy consumption demands and
net positive energy gain through energy production (DOE 2009a). The most significant
implication for commercial and residential sector is determined as the implementation of net-
zero energy buildings by 2025, which is supported by tax incentives, alliances, partnerships,
energy efficient technology standards, building energy codes, and energy modeling software
tools. Comprehensive resources that promoted saving energy and reducing consumption for
homeowners are also offered. Under the “Energy Saver” tab, thorough information is provided
for homeowners in order to conduct energy consumption audits by locating air leaks, annual
inspection of heating and cooling equipment, using energy efficient lighting fixtures and bulbs
and inspecting insulation for adequate installation and coverage. No-cost, low-cost and
remodeling options are also provided along with tax credit, rebate and financial assistance
programs.
• **Industrial Technologies Program:** This program, administered by DOE, consists of a brief online questionnaire developed to identify energy savings potential of an industrial facility, which is designed to help develop an energy savings action plan (DOE 2009b). Available system software tools for further assessment, technical resources, an information center, and a list of qualified specialists are also provided as aids throughout this process. The provided software and assessment tools consist of plant energy profiling applications, heating, ventilation, cooling, chilling and emission control system energy efficiency assessment tools.

• **Home Advisor:** This 4-question online survey is designed to provide energy efficiency recommendations for residential heating, cooling and water heater systems (Energy-Star 2009a). The recommendations do not consist of no-cost options, but they rather are do-it-yourself documents for upgrading and retrofitting current systems with energy star qualified products. There is also no information on the implementation costs, energy savings or payback periods.

• **Energy Star Yardstick:** This is another brief online questionnaire designed to solicit basic dwelling information such as location, number of residents, square footage, energy sources used, and monthly and annual total energy use (Energy-Star 2009b). Upon submission of the survey information, a comparison of energy use with other homes across the nation is provided along with GHG emission contribution and a yardstick score based on energy efficiency. However, the survey results are not designed to provide no-cost, low-cost or system upgrade recommendations or cost-benefit information on such options.

• **The Home Energy Saver:** Developed by Lawrence Berkeley National Laboratory (LBNL), the Home Energy Saver (HES) is advertised to be the first online self energy audit tool developed for consumers (LBNL 2009). The tool incorporates an “Energy Advisor” that calculates energy consumption by utilizing the DOE-2 building simulation program and estimates the effects for different efficiency option scenarios. The recommendations are provided with the upgrade/retrofit costs as well as the amortization period of the investment. In addition, the overall energy savings and reduction on emissions is provided as supplemental information.
Appendix B  Residential Decision-Making Tool Analysis

- **Best Practice House (EST 2009):**
  - Model used: N/A, Energy Savings Calculator is under construction
  - Scenarios provided: None available.
  - Accuracy of the results: N/A
  - Capability of the Tool: Provides an interactive simulation of a single family dwelling allowing users to select various components such as floors, walls, roofs, building envelope, and incorporated energy efficient technologies for retrofits and new construction. Best available technologies are illustrated with guidance documents to educate homeowners and builders on the technical background. A boiler wizard is provided to help homeowners and contractors to make capacity decisions on HVAC system components. A composition of applicable building codes are provided in the form of advanced construction details document. “Hard to treat homes” application is provided for older homes with energy efficiency challenges.
  - Expertise Required to use the Tool: Intermediate level of system, technology and building code knowledge
  - User audience: Mainly Building Professionals and could include knowledgeable / experienced homeowners.
  - Complexity of the system/decision making: N/A
  - Input required: N/A
  - Output provided: N/A
  - Comments: None

- **Home Energy Audit (ServiceMagic 2009):**
  - Model used: N/A
  - Scenarios provided: None available.
  - Accuracy of the results: N/A
  - Capability of the Tool: This is an online questionnaire, designed to solicit basic information on building construction parameters and the homeowner’s primary improvement concerns. It is a basic search engine rather than a decision making tool and is utilized to provide a list of contractors in the immediate vicinity of the dwelling.
  - Expertise Required to use the Tool: None
  - User audience: Novice homeowners
  - Complexity of the system/decision making: N/A
  - Input required: N/A
  - Output provided: N/A
  - Comments: None
• **HomeEnergySuite (Apogee 2009):**

- **Model used:** N/A
- **Scenarios provided:** Only different input options are provided in order for the homeowner to see the effects of different changes in terms of energy costs.
- **Accuracy of the results:** No verification provided
- **Capability of the Tool:** It is designed to provide homeowners with a basic understanding of energy use costs as related to building and occupancy characteristics of a house. It provides a simple drop down menu in order to input basic information on the construction characteristics of the house such as the size, age, building envelope and dwelling type, occupancy conditions such as types and the number of appliances in the house and behavioral / habitual conditions such as heating and cooling settings. Upon completion of the questionnaire, a report that identifies estimated monthly and annual electricity and fuel costs is generated. The homeowners are also able to change the questionnaire inputs in order to calculate how each characteristic and condition change can affect their estimated electricity and fuel costs.
- **Expertise Required to use the Tool:** None
- **User audience:** Novice homeowners
- **Complexity of the system/decision making:** It appears that every input option selected includes a pre-determined cost per unit. The total energy costs are calculated by multiplying unit cost and total energy use.
- **Input required:** Information on home type, year home built, square footage, occupants, heat type, heat setting, air conditioner, cooling setting, big screen TVs, water heater type, water heating setting, air leak description, windows, cook stove, dishwasher, washer, dryer and refrigerator are required.
- **Output provided:** Annual and monthly electricity and other fuel energy costs in addition to recommendations that consist of system and appliance upgrades and behavioral changes.
- **Comments:**
  - In addition, Appliance Energy & Lightning Calculators are also provided. These calculators consist of the same structure that incorporates more detailed options to choose for each selection. The wattage requirement for each selection is pre-determined (although it can be changed) and electric rate is fixed at $0.07/kWh. The output and cost calculation structure is the same as well.
  - There is also a disclaimer on the website that these calculations are approximations as they do not include hidden loads, variations in user behavior, taxes, surcharges and multi-tier price calculations.
• **Energy Savers (DOE 2009d):**

- Model used: N/A
- Scenarios provided: None available
- Accuracy of the results: No verification provided
- Capability of the Tool: Information is provided for homeowners in order to conduct energy consumption audits by locating air leaks, annual inspection of heating and cooling equipment, using energy efficient lighting fixtures and bulbs and inspecting insulation for adequate installation and coverage. No-cost, low-cost and remodeling options are also provided along with tax credit, rebate and financial assistance programs.
- Expertise Required to use the Tool: None
- User audience: Novice homeowners
- Complexity of the system/decision making: N/A
- Input required: N/A
- Output provided: N/A
- Comments: None

• **Home Advisor (Energy-Star 2009a):**

- Model used: N/A
- Scenarios provided: Sealing leaks, adding more insulation, replacing HVAC system, replacing water heater, replacing windows, replacing lighting and installing programmable thermostat are provided.
- Accuracy of the results: No verification provided
- Capability of the Tool: This 4-question online survey is designed to provide energy efficiency recommendations for residential heating, cooling and water heater systems. The recommendations do not consist of no-cost options. They are do-it-yourself documents for upgrading and retrofitting current systems with energy star qualified products. There is no information on the initial costs, energy savings or payback periods.
- Expertise Required to use the Tool: None
- User audience: Novice homeowners
- Complexity of the system/decision making: There is no decision making component, but rather a re-determined set of recommendations that utilizes energy star product upgrades.
- Input required: Zip code, heating and cooling system type and water heater type
- Output provided: Set of recommendations with Do-It-Yourself instructions
- Comments: None
• *Energy Star Yardstick (Energy-Star 2009b)*:

- Model used: N/A
- Scenarios provided: None available
- Accuracy of the results: No verification provided
- Capability of the Tool: It solicits basic dwelling information such as location, number of residents, square footage, energy sources used, and monthly and annual total energy use. Upon submission, a comparison of energy use with other homes across the nation is provided along with GHG emission contribution and a yardstick score based on energy efficiency. However, the survey results are not designed to provide no-cost, low-cost or system upgrade recommendations or cost-benefit information on such options.
- Expertise Required to use the Tool: None
- User audience: Novice homeowners
- Complexity of the system/decision making: It appears that national and local averages are pre-determined for each fuel type and calculations are made according to these values. However, no information is provided as to how these values are obtained or the comparisons / scoring are made for the input provided.
- Input required: Zip code, number of occupants, total square footage, fuel types used, annual or monthly energy use for each fuel type in appropriate units and the cost in dollars.
- Output provided: GHG Emissions contribution and a yardstick score.
- Comments: The website was very slow and it took 10 attempts before a result screen was displayed for the first time. The second and third attempts to gather more information for different fuel types did not provide any results. Even though these separate attempts were made on different days, the application did not provide any results and generated error messages for inaccurate URL address. It appears that there are some technical difficulties with the application.

• *Home Energy Saver (LBNL 2009)*:

- Model used: DOE-2 Building Simulation Program which performs approximately 8760 hourly calculations for a full *annual* simulation
- Scenarios provided: Several low and no and high cost options for ducts, sealing, landscaping, solar systems, water heating, appliances, home office & electronics, windows, doors & skylights, lighting and daylighting are provided.
- Accuracy of the results: It was found to be inaccurate by recent research studies.
- Capability of the Tool: It is an online self energy audit tool developed for consumers. It incorporates an “Energy Advisor” that calculates energy consumption by utilizing the DOE-2 building simulation program and estimates the effects of different energy efficiency for different efficiency option scenarios. The recommendations are provided
with the upgrade/retrofit costs as well as the amortization period of the investment. In addition, the overall energy savings and reduction on emissions is provided as supplemental information

- **Expertise Required using the Tool:** Users need a general understanding of the construction of their property.
- **User audience:** Novice homeowners
- **Complexity of the system/decision making:** The decision making appears to be somewhat complex compared to most of the other tools in use. It provides annual savings, energy savings over lifetime, upgrade cost, return-on-investment (ROI) and payback period for all upgrade options provided.
- **Input required:** The input is multi-tier. The first part consists of input areas for zip code, general information of the house, equipment, appliances, envelope and construction. The second tier solicits more detailed information on construction, water heating, lighting, heating and cooling and appliances.
- **Output provided:** An upgrade report is provided with several options with individual costs, CO2 / energy consumption savings, payback period, energy cost savings and return on investment.
- **Comments:**
  - No-cost alternatives are not provided in the recommendations. They are just provided as tips for the homeowner in a separate section. This section does only provide a compilation of other websites such as DOE and Energy Star that provide very brief information about the technologies. There is no information on the possible cost savings for these options.
  - The website incorporates links and information for different users, FAQs, Glossary and testimonial section for feedback.
  - Although, the calculation is completed fast, the second tier information could be too burdensome for an average homeowner due to the length and the detailed type of information being solicited.

- **Hohm Beta Version (Microsoft-Corporation 2009):**

  - **Model used:** DOE-2 Building Simulation Program through advanced analytics licensed from the Lawrence Berkeley National Laboratory and U.S. Department of Energy.
  - **Scenarios provided:** Multiple low and no and high cost options for computers, lighting, appliances, thermostats, insulation, heating & cooling, water heating, windows, sealing, building envelope are provided. The scenarios are provided with upgrade cost, annual cost and energy /CO2 emission savings.
  - **Accuracy of the results:** Assumed to be inaccurate due to utilizing DOE-2 engine, which has inherent flaws when utilized for residential construction.
✓ **Capability of the Tool:** In addition to all the capabilities provided by the Home Energy Saver tools (as discussed above), this tool incorporates financial and energy savings information for low-no cost upgrade options as well as CO2 emissions reduction

✓ **Expertise Required using the Tool:** Users need a general understanding of the construction of their property.

✓ **User audience:** Novice homeowners

✓ **Complexity of the system/decision making:** There is not much information as to how the decision making is conducted. It appears to include pre-determined local energy cost information provided for comparisons. Each recommendation provides pre-existing information on annual savings, upgrade cost, break-even point, and CO2 reduction benefits. However, this information does not seem to be calculated separately for each instance or customized according to the data entered by the homeowner. In addition, no ROI information is provided.

✓ **Input required:** The input required consists of home profile and energy data. The home profile section solicits very detailed information on the house characteristics, structure, doors and windows, heating and cooling, water heating, appliances, lighting, pumps and pools. The energy data solicits information on energy usage for all sources in cost and units consumed.

✓ **Output provided:** An energy report is generated as an outcome. This report includes local energy usage information, a set of recommendations with savings and cost information and a do-it-yourself section for each alternative, which has step-by-step instructions and tools needed to complete each task.

✓ **Comments:**
  - The application also provides a library of several recommendations for different upgrades and energy saving tips
  - The information required could be very burdensome to average homeowners due to the length and the nature of the information being solicited.
  - The cost and energy saving data and breakeven period appear to be predetermined rather than customized for each user.
  - The website requires a Microsoft Live ID to be created.

• *Energy Aide (Energy-New-England 2009):*

✓ **Model used:** Information unavailable

✓ **Scenarios provided:** Information unavailable

✓ **Accuracy of the results:** According to the website: ”Massachusetts-certified energy auditors have performed testing and validation during development, and in the field”

✓ **Capability of the Tool:** According to the website, the tool evaluates insulation, heating systems, windows, doors, water heating systems and lighting. The tool is designed to generate a report that includes energy saving options in a nontechnical language.
Expertise Required using the Tool: Users need a general understanding of residential energy conservation

User audience: Mainly designed for conservation service providers, audit programs, weatherization service providers and educational organizations.

Complexity of the system/decision making: Information unavailable

Input required: Information unavailable

Output provided: Information unavailable

Comments:
  o The tool could not be further investigated as the tool is not free.
  o The tool does not appear to incorporate any cost/savings data or financial decision making application.
  o The disclaimers provided state that the application is not capable of performing full building load calculations and is not designed for new construction.

Home Energy Tune-Up (CMC 2009):

Model used: No core modeling programs used, it is composed of calculations used in the industry and algorithms provided by U.S. Department of Energy

Scenarios provided: Information unavailable

Accuracy of the results: According to the website:” Total savings estimates for each report validated on the basis of billing data. Software was tested with BESTEST”

Capability of the Tool: According to the website, the tool is designed to identify energy efficiency upgrades in order to reduce energy consumption. The recommendations are based on 1,000 calculations preloaded in the application and the data collected from the house. The tool is also designed to provide savings, cost and payback period information for each identified upgrade.

Expertise Required using the Tool: Extensive knowledge of home inspection process and basic training on the software is required.

User audience: Mainly designed for home inspectors, who complete a 2 day training provided by the software company

Complexity of the system/decision making: Information unavailable

Input required: 100 pieces of Data is collected from each house

Output provided: 20 + page report

Comments:
  o The tool could not be further investigated as it is restricted to home inspectors, who complete the training.
  o The tool does appear to only incorporate upgrade options with long term payback periods (up to 30 years).
  o The disclaimers provided state that the application is not designed to evaluate new construction.
  o construction
• **Energy Efficient Rehab Advisor (DHUD 2009):**

- **Model used:** Information unavailable
- **Scenarios provided:** Low and moderate cost options for ducts, sealing, heating and cooling, water heating, appliances, electronics, windows, doors, lighting and water consumption are provided.
- **Accuracy of the results:** No formal testing has been conducted. All the information is based on Energy Star specifications
- **Capability of the Tool:** The tool is a list of different upgrades (low and moderate cost) for homeowner. Each option is provided with added cost, savings and payback period. The options are provided for the whole house as well as separate sections.
- **Expertise Required using the Tool:** None required
- **User audience:** Novice Homeowners mainly. The information is too basic for industry professionals or academicians (although it is claimed otherwise on the website)
- **Complexity of the system/decision making:** Information unavailable
- **Input required:** 4 pull-down menus, where the user selects appropriate responses for type of building, climate, age of the building and their role.
- **Output provided:** Lists of different upgrade options that are predetermined.
- **Comments:**
  - The information provided, which includes the option, cost, savings and payback period, is predetermined, and not customized according to responses.
  - The options are very limited and they do not include no and high cost options.
Appendix C  Thermal Conductance for Building Envelope Components ("U" values)

- Thermal Conductance of the Exterior Walls "Uw":

<table>
<thead>
<tr>
<th>Source</th>
<th>Material Type</th>
<th>Year Available</th>
<th>U Value (W/m²K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diybanter (2010)</td>
<td>11&quot; brick-block cavity un-insulated</td>
<td>N/A</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>11&quot; brick-block cavity insulated</td>
<td>N/A</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>Cavity wall insulated</td>
<td>1971 beyond</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>Cavity wall un-insulated</td>
<td>Pre-1970</td>
<td>1.6</td>
</tr>
<tr>
<td></td>
<td>9&quot; solid brick</td>
<td>N/A</td>
<td>2.16</td>
</tr>
<tr>
<td></td>
<td>Stone / solid brick</td>
<td>Pre-1976</td>
<td>0.55</td>
</tr>
<tr>
<td></td>
<td>Stone / solid brick</td>
<td>1976 - 1982</td>
<td>0.45</td>
</tr>
<tr>
<td></td>
<td>Stone / solid brick</td>
<td>1983 - 1995</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td>Stone / solid brick</td>
<td>1996 - 2002</td>
<td>0.30</td>
</tr>
<tr>
<td></td>
<td>Stone / solid brick</td>
<td>2003 beyond</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>Solid brick / un-insulated cavity wall</td>
<td>Pre-1976</td>
<td>1.6</td>
</tr>
<tr>
<td></td>
<td>Solid brick / un-insulated cavity wall</td>
<td>1976 - 1982</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>Solid brick / un-insulated cavity wall</td>
<td>1983 - 1995</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>Solid brick / un-insulated cavity wall</td>
<td>1996 - 2002</td>
<td>0.45</td>
</tr>
<tr>
<td></td>
<td>Solid brick / un-insulated cavity wall</td>
<td>2003 beyond</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td>Cavity wall insulated</td>
<td>Pre-1976</td>
<td>0.50</td>
</tr>
<tr>
<td></td>
<td>Cavity wall insulated</td>
<td>1976 - 1982</td>
<td>0.40</td>
</tr>
<tr>
<td></td>
<td>Cavity wall insulated</td>
<td>1983 beyond</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td>System build – external insulation</td>
<td>Pre-1976</td>
<td>0.55</td>
</tr>
<tr>
<td></td>
<td>System build – external insulation</td>
<td>1976 - 1982</td>
<td>0.45</td>
</tr>
<tr>
<td></td>
<td>System build – external insulation</td>
<td>1983 - 1995</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td>System build – external insulation</td>
<td>1996 - 2002</td>
<td>0.30</td>
</tr>
<tr>
<td></td>
<td>System build – external insulation</td>
<td>2003 beyond</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Table 66  Thermal Conductance of the Exterior Walls (Uw)
**Thermal Conductance of the Roof “Ur”**

<table>
<thead>
<tr>
<th>Source</th>
<th>Material Type</th>
<th>Year Available</th>
<th>U Value (W/m²K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diybanter (2010)</td>
<td>Pitched with felt - 100mm insulation</td>
<td>N/A</td>
<td>0.34</td>
</tr>
<tr>
<td></td>
<td>Flat roof - no insulation</td>
<td>N/A</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>Pitched roof with insulation between joists</td>
<td>Pre - 1975</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>Pitched roof with insulation between joists</td>
<td>1976 - 1982</td>
<td>0.68</td>
</tr>
<tr>
<td></td>
<td>Pitched roof with insulation between joists</td>
<td>1983 - 1990</td>
<td>0.40</td>
</tr>
<tr>
<td></td>
<td>Pitched roof with insulation between joists</td>
<td>1991 - 1995</td>
<td>0.29</td>
</tr>
<tr>
<td></td>
<td>Pitched roof with insulation between joists</td>
<td>1996 - 2002</td>
<td>0.26</td>
</tr>
<tr>
<td></td>
<td>Pitched roof with insulation between joists</td>
<td>2003 - 2006</td>
<td>0.16</td>
</tr>
<tr>
<td></td>
<td>Flat Roof</td>
<td>Pre-1975</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>Flat Roof</td>
<td>1976 - 1982</td>
<td>0.68</td>
</tr>
<tr>
<td></td>
<td>Flat Roof</td>
<td>1983 - 1990</td>
<td>0.40</td>
</tr>
<tr>
<td></td>
<td>Flat Roof</td>
<td>1991 - 2002</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td>Flat Roof</td>
<td>2003 - 2006</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>Pitched roof with insulation between rafters</td>
<td>Pre - 1975</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>Pitched roof with insulation between rafters</td>
<td>1976 - 1982</td>
<td>0.68</td>
</tr>
<tr>
<td></td>
<td>Pitched roof with insulation between rafters</td>
<td>1983 - 1990</td>
<td>0.40</td>
</tr>
<tr>
<td></td>
<td>Pitched roof with insulation between rafters</td>
<td>1991 - 2002</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td>Pitched roof with insulation between rafters</td>
<td>2003 - 2006</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td>Pitched roof with insulation between joists</td>
<td>Pre - 1984</td>
<td>0.68</td>
</tr>
<tr>
<td></td>
<td>Pitched roof with insulation between joists</td>
<td>1985 - 1991</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>Pitched roof with insulation between joists</td>
<td>1992 - 1999</td>
<td>0.29</td>
</tr>
<tr>
<td></td>
<td>Pitched roof with insulation between joists</td>
<td>2000 beyond</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>Flat Roof</td>
<td>Pre -1978</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>Flat Roof</td>
<td>1978 - 1984</td>
<td>0.68</td>
</tr>
<tr>
<td></td>
<td>Flat Roof</td>
<td>1985 - 1991</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>Flat Roof</td>
<td>1992 beyond</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td>Pitched roof with insulation between rafters</td>
<td>Pre - 1978</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>Pitched roof with insulation between rafters</td>
<td>1978 - 1984</td>
<td>0.68</td>
</tr>
<tr>
<td></td>
<td>Pitched roof with insulation between rafters</td>
<td>1985 - 1991</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>Pitched roof with insulation between rafters</td>
<td>1992 beyond</td>
<td>0.35</td>
</tr>
</tbody>
</table>

*Table 67*  Thermal Conductance of the Roof (Ur)
• Thermal Conductance of the Windows “Uf”

<table>
<thead>
<tr>
<th>Source</th>
<th>Material Type</th>
<th>Year Available</th>
<th>U Value (W/m²K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diybanter (2010)</td>
<td>Single glazed with uvpc frame</td>
<td>N/A</td>
<td>5.0</td>
</tr>
<tr>
<td>FAERO (2006)</td>
<td>Single glazed with metal frame</td>
<td>N/A</td>
<td>5.8</td>
</tr>
<tr>
<td></td>
<td>Single glazed</td>
<td></td>
<td>4.8</td>
</tr>
<tr>
<td></td>
<td>Double glazed</td>
<td>Pre - 2002</td>
<td>3.1</td>
</tr>
<tr>
<td>Energy Saving Trust</td>
<td>Double glazed</td>
<td>2002 beyond</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>Double glazed without low-e coating</td>
<td>2000 beyond</td>
<td>3.1</td>
</tr>
</tbody>
</table>

**Table 68** Thermal Conductance of the Windows (Uf)

• Thermal Conductance of the Floors / Ground Slab “Ugr”

<table>
<thead>
<tr>
<th>Source</th>
<th>Material Type</th>
<th>Year Available</th>
<th>U Value (W/m²K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diybanter (2010)</td>
<td>Floor on concrete slab</td>
<td>N/A</td>
<td>0.80</td>
</tr>
<tr>
<td>Diydata (2010)</td>
<td>Suspended timber floor on concrete slab</td>
<td>N/A</td>
<td>0.68</td>
</tr>
<tr>
<td></td>
<td>Floors semi or not exposed to concrete slab</td>
<td>1991 - 2002</td>
<td>0.51</td>
</tr>
<tr>
<td></td>
<td>Floors semi or not exposed to concrete slab</td>
<td>2003 - 2006</td>
<td>0.25</td>
</tr>
</tbody>
</table>

**Table 69** Thermal Conductance of the Floors / Ground Slab (Ugr)
Appendix D  Shading Coefficient & Solar Heat Gain Factor for Windows (“SC” & “SHGF” values)

- **Shading Coefficient for Windows “SC”:**
  
  a. *Tao and Janis (2001a):*

<table>
<thead>
<tr>
<th>Type of Window</th>
<th>Shading Coefficient “SC”</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Glass with Regular Sheet</td>
<td>1.0</td>
</tr>
<tr>
<td>Single Glass with Grey Sheet</td>
<td>0.78</td>
</tr>
<tr>
<td>Heat Absorbing Plate / Float</td>
<td>0.72</td>
</tr>
<tr>
<td>Insulating Glass – Regular Sheet</td>
<td>0.90</td>
</tr>
<tr>
<td>Insulating Glass – Regular Plate / Float</td>
<td>0.83</td>
</tr>
</tbody>
</table>

  **Table 70**  Shading Coefficient for Windows _ Reference # 1

  b. *ARCA53 (2010):*

<table>
<thead>
<tr>
<th>Type of glass</th>
<th>Shading Coefficient “SC”</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Single Glazing Double glazing</td>
</tr>
<tr>
<td></td>
<td>Open horizontal blind</td>
</tr>
<tr>
<td>Clear</td>
<td>1.00</td>
</tr>
<tr>
<td>Bronze tinted</td>
<td>0.82</td>
</tr>
<tr>
<td>Reflecting</td>
<td>0.64</td>
</tr>
</tbody>
</table>

  **Table 71**  Shading Coefficient for Windows _ Reference # 2

  c. *Stein et al. (2005a):*

<table>
<thead>
<tr>
<th>Type of Window</th>
<th>Shading Coefficient “SC”</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Glass - Clear</td>
<td>0.94</td>
</tr>
<tr>
<td>Single Glass – Heat Absorbing</td>
<td>0.58</td>
</tr>
<tr>
<td>Insulating Glass – Clear</td>
<td>0.83</td>
</tr>
<tr>
<td>Insulating Glass – Heat Absorbing</td>
<td>0.55</td>
</tr>
<tr>
<td>Insulating Glass – Reflected Coated</td>
<td>0.40</td>
</tr>
</tbody>
</table>

  **Table 72**  Shading Coefficient for Windows _ Reference # 3
- **Solar Heat Gain Factor for Windows “SHGF”**:

  a. *Tao and Janis (2001a):* For the values listed in Table 73, the dwelling is considered to be in Roanoke, Virginia. The windows are assumed to be only on north and south facing walls and distributed equally. The values are normalized hourly values derived from half-day totals for windows on north and south walls combined.

<table>
<thead>
<tr>
<th>Date for the Peak Value</th>
<th>Solar Heat Gain / Loss Factor “SHGF” (kW / m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>January 21</td>
<td>0.55</td>
</tr>
<tr>
<td>February 21</td>
<td>0.56</td>
</tr>
<tr>
<td>March 21</td>
<td>0.51</td>
</tr>
<tr>
<td>April 21</td>
<td>0.41</td>
</tr>
<tr>
<td>May 21</td>
<td>0.35</td>
</tr>
<tr>
<td>June 21</td>
<td>0.35</td>
</tr>
<tr>
<td>July 21</td>
<td>0.53</td>
</tr>
<tr>
<td>August 21</td>
<td>0.40</td>
</tr>
<tr>
<td>September 21</td>
<td>0.50</td>
</tr>
<tr>
<td>October 21</td>
<td>0.55</td>
</tr>
<tr>
<td>November 21</td>
<td>0.54</td>
</tr>
<tr>
<td>December 21</td>
<td>0.52</td>
</tr>
</tbody>
</table>

  Table 73  Solar Heat Gain Factor for Windows _ Reference # 1

  b. *Stein et al. (2005a):*

<table>
<thead>
<tr>
<th>Type of Window</th>
<th>Solar Heat Gain Factor “SHGF” (kWh / m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Glazing – Uncoated</td>
<td>0.65</td>
</tr>
<tr>
<td>Single Glazing – Reflective Stainless Steel</td>
<td>0.23</td>
</tr>
<tr>
<td>Double Glazing – Uncoated</td>
<td>0.48</td>
</tr>
<tr>
<td>Double Glazing – Low-e</td>
<td>0.45</td>
</tr>
<tr>
<td>Triple Glazing – Clear</td>
<td>0.54</td>
</tr>
<tr>
<td>Triple Glazing – Low-e</td>
<td>0.31</td>
</tr>
</tbody>
</table>

  Table 74  Solar Heat Gain Factor for Windows _ Reference # 2
Appendix E  System Efficiency for Heating “SEh” – AFUE / EER Values
& System Efficiency for Cooling “Sec” – SEER Values

- **System Efficiency for Heating “SEh” – AFUE / EER Values:** The EER ratings are converted to reflect kW to kW conversions and AFUE ratings and percentage values (LBNL 2009).

<table>
<thead>
<tr>
<th>Year</th>
<th>Electric Furnace (AFUE)</th>
<th>Electric Heat Pump (EER)</th>
<th>Gas Boiler (AFUE)</th>
<th>Gas Furnace (AFUE)</th>
<th>Gas Wall Furnace (AFUE)</th>
<th>Oil Boiler (AFUE)</th>
<th>Oil Furnace (AFUE)</th>
<th>Propane Furnace (AFUE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1970</td>
<td>98</td>
<td>1.8</td>
<td>70</td>
<td>60</td>
<td>50</td>
<td>72</td>
<td>70</td>
<td>60</td>
</tr>
<tr>
<td>1972</td>
<td>98</td>
<td>1.8</td>
<td>72</td>
<td>63</td>
<td>60</td>
<td>75</td>
<td>74</td>
<td>63</td>
</tr>
<tr>
<td>1975</td>
<td>98</td>
<td>1.8</td>
<td>72</td>
<td>63</td>
<td>60</td>
<td>75</td>
<td>74</td>
<td>63</td>
</tr>
<tr>
<td>1976</td>
<td>98</td>
<td>2.1</td>
<td>72</td>
<td>66</td>
<td>60</td>
<td>75</td>
<td>74</td>
<td>66</td>
</tr>
<tr>
<td>1977</td>
<td>98</td>
<td>2.1</td>
<td>72</td>
<td>66</td>
<td>60</td>
<td>75</td>
<td>75</td>
<td>66</td>
</tr>
<tr>
<td>1979</td>
<td>98</td>
<td>2.1</td>
<td>72</td>
<td>69</td>
<td>60</td>
<td>75</td>
<td>75</td>
<td>69</td>
</tr>
<tr>
<td>1980</td>
<td>98</td>
<td>2.4</td>
<td>72</td>
<td>69</td>
<td>60</td>
<td>75</td>
<td>76</td>
<td>71</td>
</tr>
<tr>
<td>1981</td>
<td>98</td>
<td>2.4</td>
<td>78</td>
<td>69</td>
<td>63</td>
<td>77</td>
<td>77</td>
<td>71</td>
</tr>
<tr>
<td>1983</td>
<td>98</td>
<td>2.4</td>
<td>78</td>
<td>69</td>
<td>63</td>
<td>77</td>
<td>78</td>
<td>73</td>
</tr>
<tr>
<td>1984</td>
<td>98</td>
<td>2.7</td>
<td>78</td>
<td>69</td>
<td>63</td>
<td>77</td>
<td>78</td>
<td>73</td>
</tr>
<tr>
<td>1985</td>
<td>98</td>
<td>2.7</td>
<td>78</td>
<td>69</td>
<td>63</td>
<td>77</td>
<td>79</td>
<td>73</td>
</tr>
<tr>
<td>1986</td>
<td>98</td>
<td>2.7</td>
<td>78</td>
<td>69</td>
<td>63</td>
<td>82</td>
<td>80</td>
<td>74</td>
</tr>
<tr>
<td>1988</td>
<td>98</td>
<td>2.7</td>
<td>79</td>
<td>75</td>
<td>63</td>
<td>82</td>
<td>80</td>
<td>75</td>
</tr>
<tr>
<td>1989</td>
<td>98</td>
<td>2.7</td>
<td>80</td>
<td>75</td>
<td>66</td>
<td>83</td>
<td>80</td>
<td>75</td>
</tr>
<tr>
<td>1990</td>
<td>98</td>
<td>3.0</td>
<td>80</td>
<td>75</td>
<td>66</td>
<td>83</td>
<td>80</td>
<td>77</td>
</tr>
<tr>
<td>1991</td>
<td>98</td>
<td>3.0</td>
<td>80</td>
<td>78</td>
<td>66</td>
<td>83</td>
<td>81</td>
<td>77</td>
</tr>
<tr>
<td>1992</td>
<td>98</td>
<td>3.3</td>
<td>80</td>
<td>78</td>
<td>66</td>
<td>83</td>
<td>81</td>
<td>82</td>
</tr>
<tr>
<td>1996</td>
<td>98</td>
<td>3.3</td>
<td>80</td>
<td>78</td>
<td>66</td>
<td>83</td>
<td>81</td>
<td>83</td>
</tr>
<tr>
<td>2003</td>
<td>98</td>
<td>3.3</td>
<td>80</td>
<td>83</td>
<td>66</td>
<td>83</td>
<td>81</td>
<td>83</td>
</tr>
</tbody>
</table>

*Table 75  AFUE / EER Ratings for Common Heating Equipment by Model Year*
- *System Efficiency for Cooling – SEER Values “SEc” (LBNL 2009):*

<table>
<thead>
<tr>
<th>Year</th>
<th>Central Air Conditioner (SEER)</th>
<th>Electric Heat Pump (SEER)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1970</td>
<td>1.92</td>
<td>1.62</td>
</tr>
<tr>
<td>1973</td>
<td>2.0</td>
<td>1.83</td>
</tr>
<tr>
<td>1975</td>
<td>2.06</td>
<td>1.76</td>
</tr>
<tr>
<td>1980</td>
<td>2.21</td>
<td>2.21</td>
</tr>
<tr>
<td>1983</td>
<td>2.50</td>
<td>2.41</td>
</tr>
<tr>
<td>1985</td>
<td>2.62</td>
<td>2.53</td>
</tr>
<tr>
<td>1990</td>
<td>2.74</td>
<td>2.79</td>
</tr>
<tr>
<td>1993</td>
<td>3.12</td>
<td>3.21</td>
</tr>
<tr>
<td>1995</td>
<td>3.15</td>
<td>3.24</td>
</tr>
<tr>
<td>2000</td>
<td>3.24</td>
<td>3.30</td>
</tr>
<tr>
<td>2003</td>
<td>3.27</td>
<td>3.32</td>
</tr>
</tbody>
</table>

*Table 76*  SEER Ratings for Common Cooling Equipment by Model Year