PRIORITIZING SMART SYSTEM MANAGEMENT OF ENERGY-RELATED OCCUPANT BEHAVIORS IN CODE COMPLIANT AND HIGH PERFORMANCE SINGLE-FAMILY HOMES IN NORTH CAROLINA

by

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Abstract

While residential building practices over the last couple of decades have been improving in the areas of technical performance and energy efficiency, much less attention has been focused on homeowner lifestyle and behavior. These neglected factors can have a significant impact on home energy performance, and may be more pronounced when green building practices are employed.

This study establishes a method for systematically prioritizing management of occupant behaviors that impact energy consumption in a home. It also allows further differentiation regarding which of those behaviors are most applicable to manage using smart home automation technologies. In addition, several secondary characteristics are explored to help the user gain a more well-rounded understanding of the behavior that is being managed. The overall objective is to provide a means for prioritizing management of occupant behaviors in code compliant and high performance homes.

Occupant behavior candidacy for smart home automation is determined using a ranking system that assigns individual scores ranging from 0-9. Based on this evaluation, eight out of twelve behaviors analyzed show differences in the potential for energy savings for the two types of home. These findings support the hypothesis that some behaviors should be prioritized differently in code compliant or high performance homes.

The tables developed in this paper summarize characteristics of energy-related occupant behaviors. They are user-friendly enough to be utilized by homeowners to assess potential home improvement options. The methodology used to establish characteristics for individual behaviors is laid out in a modular and transparent fashion, which allows members of the building industry to replace any pieces of data they wish with their own values. Furthermore, other behaviors that may be of interest can be easily evaluated using this methodology and added to the table using the same system. In this manner, results of this study can be used as an adaptable and continuously growing tool for both homeowners and industry professionals.

Acknowledgments

First and foremost, I would like to express my deepest gratitude to my thesis committee. Dr. Susan C. Doll, my Thesis Director, has been an enduring presence throughout my academic career at Appalachian State University. She has helped to guide me through the departmental honors curriculum, and never gave up on this project as it evolved through its many stages and forms into what it has become today. Dr. Andrew W. Windham, my Second Reader, brought a keen eye and insightful advice that helped push me to make this project more than I ever thought it could be. Each of you were vital in the writing of this thesis, and I thank you both for your continued counsel and support.

I would also like to extend my thanks to the many faculty, staff, and fellow students whom I have had the pleasure of learning alongside in my time in the STBE Department. So many of you have been an inspiration, and a source of heartfelt encouragement. I count myself lucky to be a part of this program.

Dedication

      This thesis is dedicated to my parents, Bruce and Lois, because without their unwavering support, encouragement, and moral teachings that have molded me into to the person I am today, this work may never have been written. Thank you.

      I also dedicate this work to the love of my life, Byron, who gave me the strength to continue when my resolve faltered, and who put up with many sleepless nights, piles of unwashed laundry, and mountains of dirty dishes as we fought our way to the finish line together. Thank you.

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List of Abbreviations

US .... United States

EPA .... Environmental Protection Agency

NASA .... National Aeronautics and Space Administration

OPEC .... Organization of Petroleum Exporting Countries

BTU .... British Thermal Unit

quad .... Quadrillion BTUs

DOE .... Department of Energy

USGBC .... United States Green Building Council

LEED .... Leadership in Energy and Environmental Design

RESNET .... Residential Energy Services Network

HERS .... Home Energy Rating System

ZERH .... Zero Energy Ready Home

HVAC .... Heating, Ventilation, and Air Conditioning

VOC .... Volatile Organic Compound

ICC .... International Code Council

NEC .... National Electric Code

ASHRAE .... American Society of Heating, Refrigerating,

and Air Conditioning Engineers

IECC .... International Energy Conservation Code

IgCC .... International Green Construction Code

HES .... Home Energy Saver

IAQ .... Indoor Air Quality

AC .... Air Conditioning

CFM$_{25}$ .... Cubic Feet per Minute at 25 Pascals

TVA .... Tennessee Valley Authority

ORNL .... Oak Ridge National Laboratory

CZ .... Climate Zone

LED .... Light-Emitting Diode

kWh .... kilowatt-hour

NREL .... National Renewable Energy Laboratory

gpm .... Gallons per Minute

ESIF .... Energy Systems Integration Facility

CHAPTER I
INTRODUCTION

Background

Historical Context of Energy Consumption

Awareness of human-environment interaction, including our widespread impact on atmospheric and oceanic conditions, is nothing new. The associated nomenclature may have changed over time, from "*global cooling*" in the sixties to "*global warming*" in the seventies, and finally the more all-encompassing "*climate change*" currently in common use today, but the basic idea that humans have a significant impact on our natural environment has persisted for more than fifty years.

The beginning of the greater environmental movement is often marked by the publication of Rachel Carson's *Silent Spring* in 1962. In it, Carson "influenced the environmental movement as no one had since the 19th century's most celebrated hermit, Henry David Thoreau, wrote about Walden Pond" (Griswold, 2012). In 1970, almost a decade later, the first ever Earth Day was held, which directly led to the formation of the United States (U.S.) Environmental Protection Agency (EPA) later that year, thanks to Wisconsin Senator, and Democrat, Gaylord Nelson. Even the National Aeronautics and Space Administration's (NASA) Apollo program was changing the way Americans viewed our home. The Apollo 17 mission yielded the iconic "Blue Marble" image taken in 1972 of our colorful, isolated planet from space, following the first ever "Earthrise" photograph taken years earlier during the Apollo 8 mission, and quickly become a symbols for the wave of environmentalist movements of the time.

Just as public awareness of climate change was building momentum, a number of energy-related societal events caused both scientist and citizen to make further connections to our reliance on fossil fuels.

In 1973, we Americans experienced our first serious energy crisis, when Arab members of the Organization of Petroleum Exporting Countries (OPEC) implemented an oil embargo designed to economically cripple nations supporting Israel in the Yom Kippur War (Corbett, 2013). This embargo highlighted U.S. vulnerability created by reliance on foreign oil imports, and resulted in a surge of interest in renewable energy and conservation that was, unfortunately, short-lived. By the 1990's, the U.S. had more than recovered, and was the world's largest consumer of energy, using 20% of all global energy, while housing less than 5% of the world's population. The U.S. kept its number one status until 2009, when China took its place (Institute for Energy Research, 2010).

Not long after the turn of the millennium, in 2006, *An Inconvenient Truth* was published by former Vice President Al Gore, jarring millions of everyday citizens into awareness of climate change, and motivating many to take action. It told Americans as bluntly as possible about the carbon dioxide emissions adding to the layer of greenhouse gases that blanket our planet, and how they subsequently are causing temperatures to rise at an unprecedented rate.

Finally, 2008 was the year that the United Nations Climate Change Conference began discussions of developing the Paris Agreement and the West Antarctic Ice Sheet's future collapse was determined to be unavoidable.

In short, scientists, politicians, and the public have all known what's happening for some time now. It is clear that human activity is having a measurable impact on the climate,

and scientists overwhelmingly make the connection to our penchant for fossil fuel combustion. The tricky part is figuring out what actions we can take will be the most effective in reversing our current energy use trends.

Present Day Energy Use in U.S. Buildings

In 2017, the U.S. total energy consumption was around 98 quadrillion british thermal units (BTUs) (quads), with industrial and transportation sectors each using about 30%, and the combined commercial and residential building sectors accounting for the remaining 40% of primary energy consumption (U.S. Energy Information Administration, 2018). As shown on Figure 1, our nation's commercial and residential buildings' energy consumption makes up over 6% of our global energy footprint. Considering our nation's population makes up only 4.3% of the global population, our buildings' consumption is a significant percentage (U.S. Census Bureau, 2016b).
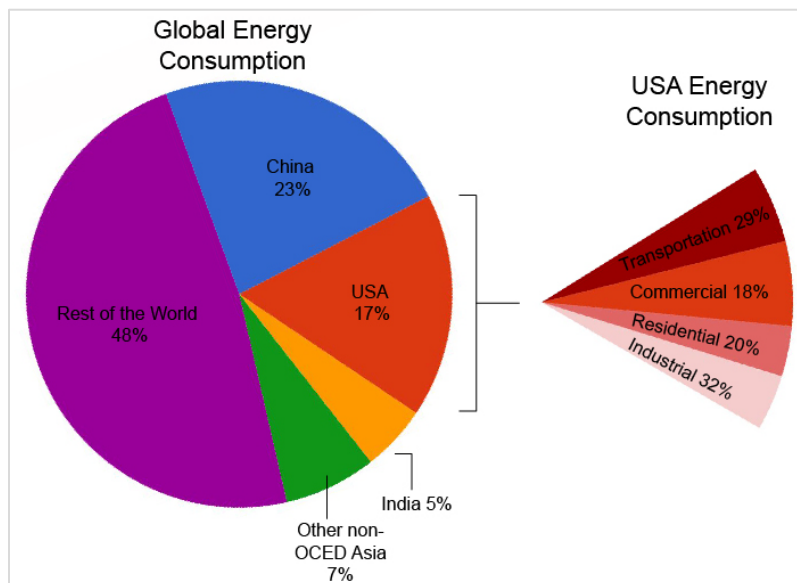

Figure 1. Energy Consumption by Sector. (U.S. Energy Information Administration, 2018).

Building Industry in the United States

The "building sector" encompasses two major categories of buildings: commercial and residential. Commercial construction differs from residential construction in several significant ways. Commercial buildings are designed and built to accommodate more people, a wider variety of activities, and must abide by more specific construction codes and regulations for public safety than residential buildings. In terms of energy demands and consumption, commercial buildings' largest single end-use is space heating, unlike residential buildings that use the most energy on plug loads and appliances, as can be seen in Figures 2 and 3 below.
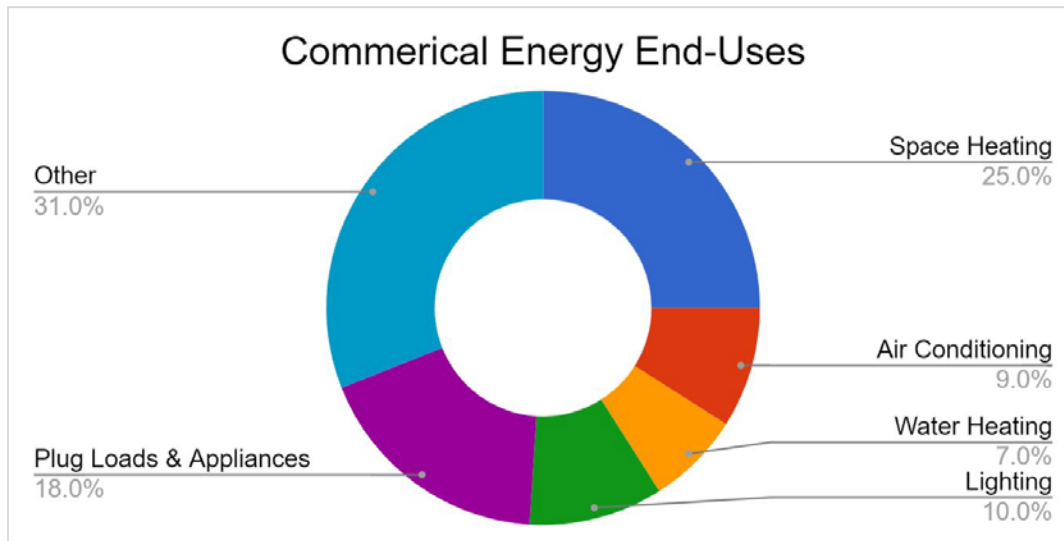

Figure 2. Commercial Building Energy Consumption by End-Use. (U.S. Energy Information Administration, 2015; U.S. Energy Information Administration, 2012).
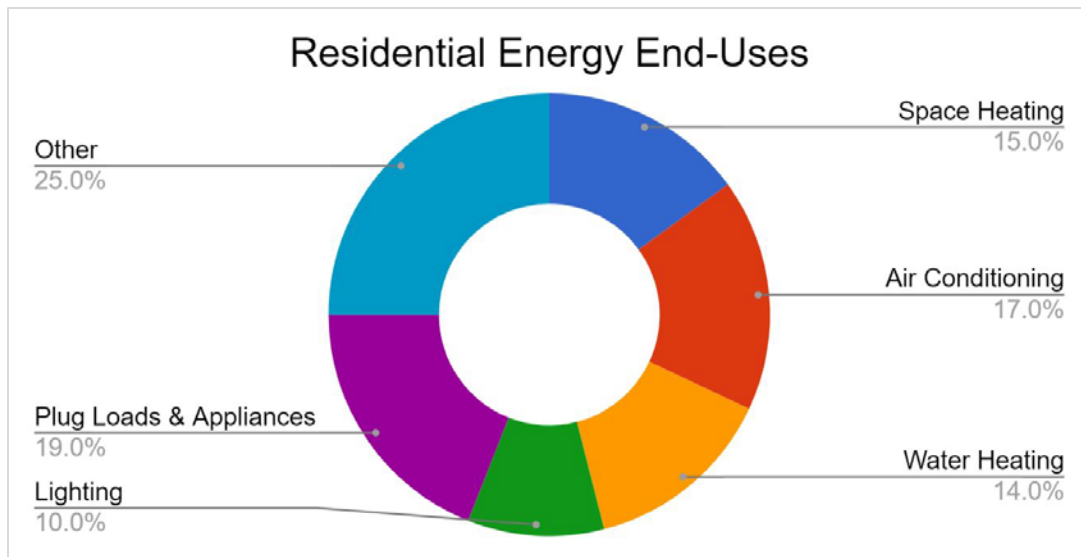
Figure 3. Residential Building Energy Consumption by End-Use. (U.S. Energy Information Administration, 2015; U.S. Energy Information Administration, 2012).

There are three common sub-categories of homes that make up the residential building sector. Single-family, detached homes are characterized by having an independently freestanding structure designed to house only a few individuals or a single family. Single-family, attached homes are designated based on the structure sharing at least one common wall with another housing unit. Multi-family homes are housing units that are connected to three or more other units in one structural complex.

Construction processes used for residential homes include tract, speculative, and custom home building. Tract building is known for constructing large numbers of houses on tight budgets and condensed timelines. Speculative building is conducted with design decisions made by the builder with the intent to guess the most desirable features for the current market. Custom building allows a homeowner to decide each and every facet of the final product, often comes with a hefty price tag, and can take longer to build.

Each construction process comes with its own advantages and challenges. Some of the major drawbacks of tract home construction are the increased likelihood for houses to be constructed using poorer quality materials and appearing as clones of each other, with very little ability for a homeowner to customize an individual home's layout or appearance (Nea Homes, 2018). Speculative home building is one of the most common processes by which a home can be constructed, and is often turned to as the middle ground between tract homes and custom homes. This strategy can be low-risk and time-efficient in terms of getting a home built, on the market, and sold quickly and easily, while still allowing some input from the future homeowner (2018). Custom homes offer the most flexibility in terms of involving the buyer, and future homeowner, in decisions from the very beginning (2018).

Historically, there has been little motivation for incorporating high performance measures and other green building practices, such as ensuring a sealed building envelope, plenty of insulation, or water conservation, in homes where extra dollars could be spent on other, more visible, aspects of the home. However, the residential building industry is far from static.

Progress Towards Energy Efficiency

Over the last couple of decades, both the techniques and technologies used by builders have progressed in a clear trend toward energy efficiency. Homes built between 2000 and 2005 use nearly 15% fewer BTUs per square foot of heated floor space than homes built before 1950 (Pacific Northwest National Laboratory and D&R International, Ltd., 2012). This is, in large part, due to a newfound emphasis on sealing homes from water, air, and vapor infiltration, passive design principles, and weatherization programs. Additionally,

the emergence of a number of certification programs designed to incentivize energy efficient, environmentally friendly, and resilient building practices have helped stimulate growth in what has come to be known as the field of "green building." Some of the most popular of these programs are: the Department of Energy (DOE) and EPA's Energy Star program, the United States Green Building Council's (USGBC) Leadership in Energy and Environmental Design (LEED) program, the Residential Energy Services Network (RESNET)'s Home Energy Ratings System (HERS) Index, and the DOE's Zero Energy Ready Home (ZERH) program. Each of these programs excel in some areas, but fall short in others.

Energy star.

In 1992, the Energy Star certification was established by the DOE and the EPA to help consumers choose products intelligently while shopping, in the hopes that they would guide the market in the direction of greater efficiency. An Energy Star label indicates that a product has been tested to achieve significant energy savings over other models that provide equivalent services, and will recover its investment price within a reasonable amount of time after purchase (Energy Star, n.d.d). On average, Energy Star products save 23.5% of the energy a household would use on non-rated appliances (Energy Star, 2018a, Energy Star, 2018b, Energy Star, 2018c, Energy Star, 2018d, Energy Star, n.d.a, Energy Star, n.d.b). While this certification is most applicable to consumer products, it serves as a worthwhile resource for energy-efficiency shopping, although listed ratings may be lower than can be realistically expected outside of lab testing conditions. Energy Star labels can also apply to new homes that are constructed according to the program's energy efficiency requirements (Energy Star, n.d.c).

LEED.

Established by the USGBC in 2000, LEED is perhaps one of the most popular building certification programs in the world. This program hinges on a points system that credits the building for a range of design choices, such as sustainable site selection, materials selection, resource use and disposal, energy performance, and innovation. However, one of the common criticisms of LEED is that it does not maintain a strong base for measured performance after the building is occupied, prioritize localized needs and conditions, or look closely at the process that goes into creating end products (Boschmann & Gabriel, 2013; Flows, 2014; Cater, 2010, Orr, n.d.). Nonetheless, LEED has expanded from just commercial new construction, to existing buildings, and even single-family homes (U.S. Green Building Council, 2014). In fact, the number of LEED for Home certified units has experienced consistent growth from 31 units in 2006 to almost 18,500 in 2013, as can be seen in Figure 4 below.
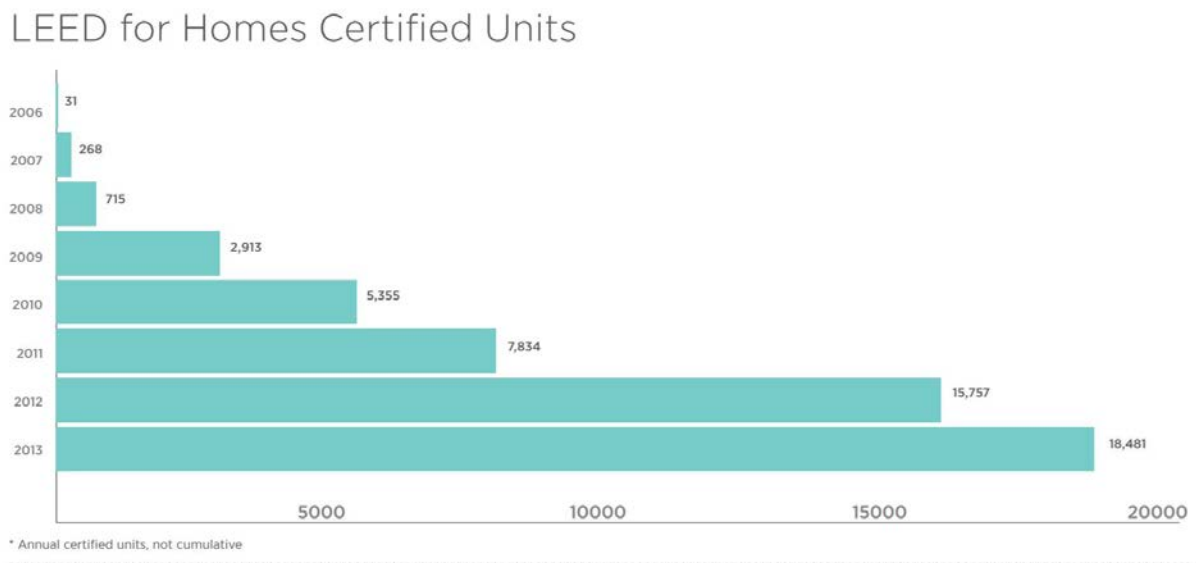

Figure 4. LEED for Homes Certified Units. (US Green building Council, 2014).

HERS index.

RESNET, founded in 1995 as an independent, non-profit organization to help homeowners reduce the cost of their utility bills by making their homes more energy efficient, developed the HERS Index. This system compares the energy efficiency of a home to the performance of a "RESNET Reference Home," built to meet the 2004 International Energy Conservation Code, which scores a 100 on the HERS Index. The DOE has found that the average resale home in the U.S. scores 130 (HERS Index, n.d.). The lower the HERS score of a tested home, the greater percentage improvement in efficiency over the average resale and reference homes. A home's score is calculated based on a variety of technical specifications, including r-values of assemblies, heating, ventilation, and air conditioning (HVAC), and water heating system efficiencies, and air leakage values. One of the disadvantages of this rating system lies in the potential inconsistency of scores across raters. Although HERS raters must undergo training and certification, the system is criticized for being inconsistent in its results (Bailes, 2014).

Zero energy ready homes.

In 2008, the DOE took the Energy Star program one step further, and created the ZERH program. Zero Energy Ready Homes combine existing Energy Star, Indoor airPLUS, WaterSense, and HERS certification programs into one building-wide program that accounts for system efficiencies as well as sustainable architectural design, with an emphasis on individual renewable energy generation. The weakness of this program lies in the designer's ability to compensate for less efficient techniques by simply increasing the quantity of renewable energy technologies employed on site.

The above certifications are only four of the plethora of programs designed to encourage efficient and sustainable building practices, but are fairly representative of the whole. They provide a means of introducing the energy performance aspects of buildings, but do not address the role of homeowners or smart monitoring systems in improving efficiency.

The Role of the Homeowner

Many building performance measures hinge on thoughtful design strategies, but ultimately some things are outside the control of the designer or builder, and in fact lie in the realm of the homeowner. For instance, occupants may choose to use any combination of air-conditioning, fans, or open windows to adjust the temperature in a home, and sometimes waste considerable energy by combining open windows with mechanical air-conditioning! In addition, according to an article in Green Building Advisor, as much as 46% to 88% of the total electricity use in low-energy-use homes can be due to plug loads, which include energy consumed by household devices plugged into outlets, such as appliances, lighting, electronics, and other miscellaneous equipment (Holladay, 2009). Anything from a homeowner's lifestyle and socio-economic background, to their operation and maintenance strategies as informed by their education and access to information about their home can make profound differences in a home's cost and performance over its lifetime.

Smart Home Automation

Smart home automation is rising in popularity as a strategy to improve convenience, safety, and energy savings in homes (Safewise, 2018). Smart home systems can keep track of and automate certain elements of a home's operation so the homeowner doesn't have to.

Some infrequent occupant behaviors can be managed through a calendar-based reminder system or "tips" database. Other behaviors are homeowner choices such as envelope weatherization upgrades, energy efficient appliance selection, careful furniture placement around vents, choosing finishings with no volatile organic compounds (VOCs), or strategically landscaping for controlled heat gains. Other everyday operational choices can be automated to be transparent to the homeowner, such as with setting thermostat temperatures to a wider deadband between heating and cooling, lowering water heating temperatures, and setting washing machines to a lower water temperature to save energy with every use. Motion-sensing and remote access technologies can be used to turn off lights in unoccupied spaces, disconnect chargers and shut down computers when not in use. Even seemingly spontaneous choices can be guided with weather-based alerts, reminding homeowners when opening or closing a window would save energy, or when it would be appropriate to line-dry clothes instead of using the mechanical dryer. Until recently, building automation technologies were only found in commercial buildings, but the industry is expanding quickly to incorporate programmability into a wide variety of residential applications, including those that monitor and manage home efficiency measures (Safewise, 2018; Smart Home, 2018).

Problem Statement

Summary

There are clear historic trends in the environmental movement that illuminate the need for meaningful action to reduce energy consumption. The role of fossil fuel consumption evident in the building sector of our nation's energy profile presents an

opportunity to make significant progress in reversing our current energy trends. While building practices over the last couple of decades have been improving in the areas of technical performance and energy efficiency, much less attention has been focused on homeowner lifestyle and behavior, which can have a significant impact on a home's performance, and may even be more pronounced when green building practices are employed. Therefore, building strategies that don't address homeowner influence will never maximize the potential benefits of a high performance design.

Purpose

Identifying a list of occupant behaviors that impact energy consumption, and developing a method for prioritizing ways that a smart home system could involve the homeowner in the successful energy management of their home, may encourage not only homeowners, but also builders and code officials to consider occupant influence as a vital facet of residential building practices.

Research Questions

In order to better address the problem outlined above, a multi-part research question was formulated to be answered in the following pages:

1. What are homeowner behaviors that impact energy performance and could be monitored by smart home systems in code compliant and high performance homes?
a. What are the fundamental differences between current code compliant homes and high performance homes?

b. What interactions does a homeowner have with their home that both impact its performance, and can be monitored by smart home systems?

c. How do these occupant behavior impacts differ between code compliant and high performance homes?

Limitations

There are wide variations in typical residential design characteristics, code requirements, and climate considerations across the fifty states, so this study will focus only on single-family, detached homes in North Carolina. The data used in calculations in this paper are referenced from several different sources for individual measures that may use dissimilar methods, and limits the ability to assess additive impact of using measures together. There is a need in the literature for more current studies detailing the tested efficiency of home appliances and behavior changes. Because of the current imprecise and dated state of the data, this study has limited generalizability.

CHAPTER II

LITERATURE REVIEW AND BACKGROUND

History of the Residential Building Industry

Residential building has evolved over time into the industry it has become today through social influences, the rise of building codes, and the more recent advent of high performance building standards. It's important to understand these transitions in order to appreciate the differences between modern code compliant and high performance homes, and the energy demands that homeowners impose on residential buildings. These topics will be explored in further detail below.

The Modern Single-Family Home

While there are many types of housing available in the world today, the detached single-family home has historically been held in especially high regard. For hundreds of years, if not longer, the achievement of becoming a homeowner has been highly sought after by many in society. In the 1700's, during the early years of the United States of America, less than 17% of residents were able to afford a single-family home (Schmitz, 2000).

After the end of the Second World War, bolstered by the post-war economic boom, veterans and their families led a mass exodus from the *whirlpool cities*, as H.G. Wells prophetically referred to them (Wells, 2006). They sought refuge from the urban noise and social discord, and settled into what would become the American middle-class suburbia. Here, nuclear families could find an emotional, rather than economic, center of residence that

set boundaries between work and family life (Fishman, 1987). This transition was more than simple relocation. It highlighted shifting homeowner attitudes toward their homes.

Homeowners demanding more and more of their homes has dramatically changed what the typical American detached, single-family home looks like. As cars came into the financial reach of the middle class and urban sprawl began to lengthen commutes in the late 1940s and 1950s, carports and garages started appearing on homes. By the 1970s, larger multi-level homes had grown in popularity, requiring more energy to condition. In the early 2000's, products like pre-wired surround sound systems and cell-phones caused electric and plug loads to increase. Electricity consumption by the average American household in 2001 had dramatically increased by 3100% since the start of World War II (Willis et al., 2017). By 2013, the overall size of the American home had grown 80% from those in the 1940's (Kolko, 2013). All of these changes spurred by the post-war economic housing boom of the 1950's had a lasting impact on American homeownership.

Although nuclear families have since become one of many accepted living arrangements, and demographics have diversified, evidence of the 1960's American dream of the home with a white picket fence perseveres (Livingston, 2014). Socially and psychologically, owning a home is proof of both status and independence (Woo & Salviati, 2017). Owning a home also offers a boldly visual display of self-expression in the form of architecture, interior design, and landscaping, but with it comes a significant responsibility to its maintenance. Homeowners have a direct and vested interest in home's performance and resilience, from the sturdiness of the envelope to the efficiency of the utilities, and they bear the financial brunt of all the bills incurred by their home's use and upkeep (Beals, 2012). However, the homeowner has assistance in ensuring the livability of their home. Building

codes, developed and enforced by local, regional, state and national organizations and agencies, are vital benchmarks by which homeowners can hold builders accountable for the safety, stability, and sustainability of their homes.

Code Compliance in Homes

Societally accepted standards for the proper construction of homes have been around since at least 1754 BCE (Hammurabi, 2017; The Book of Deuteronomy). Over the centuries, laws regulating the built environment have evolved to encompass more than basic structural faults, culminating in a unified system of codes recognized across local jurisdictions. It is through these modern building codes that we can define a *code compliant* home.

The International Code Council (ICC) has compiled a comprehensive set of construction codes that can be easily interpreted and applied across regional and national boundaries (About ICC, 2018). In North Carolina, I-Codes for buildings, existing buildings, fire, fuel gas, mechanical, plumbing, residential construction, energy conservation, and green construction have all been adopted (International Code Council, 2018). The I-Codes are designed to complement other building codes, such as the National Electric Code (NEC) and American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) standards 62.1 and 62.2, which are the standards for ventilation and indoor air quality, respectively (ICC Officially Recognizes, 2012). While building codes have historically been reactionary in nature, with amendments added in response to the occurrence of new kinds of failures in building performance, there is precedent for a shift toward more proactive code changes in support of sustainable construction practices (Vaughan & Turner, 2013; Vierra, 2016).

Two sets of codes in particular, the 2012 International Energy Conservation Code (IECC) and the 2012 International Green Construction Code (IgCC), address the economic and environmental sustainability of buildings over their lifecycle. The IECC is an extension of the building codes that focus on construction measures that ensure minimal wasted energy in operation of the building (International Code Council, 2012b). The IgCC serves to broaden the scope of building codes to encompass more indirect threats to occupant safety and quality of life, such as wasted natural resources and poor maintenance leading to premature product lifespan (International Code Council, 2012a). Overall, *code compliant* homes must adhere to many standards and restrictions that ensure homes are built according to a basic degree of safety and sustainability.

High Performance Standards in Homes

High performance homes are built with their namesake in mind: high performance. The term "performance" as it is used in the context of this research refers to the amount of energy consumed by or expected to be necessary to meet the operational needs associated with standard use of the home, including but not limited to HVAC, lighting, plug loads, and water heating. One trait that all high performance homes share is their adherence to building and design standards significantly more stringent than required building codes. The DOE has been a pioneer in offering programs to educate homeowners and certify buildings that go above and beyond mandatory codes. Some of these programs include Home Energy Saver (HES), Energy Star, Solar Decathlon, and ZERH, all of which have had a measurable impact on the building industry.

When HES was first released by the DOE in 1994, it was the only home energy consumption calculator on the market. This tool allowed homeowners to enter specific information about their home, and easily see estimated costs of operation, potential upgrades ranked by payback period, as well as possible savings should the recommended upgrades be implemented. Today, HES has reached over 6 million people, with one out of every three users reporting implementation of recommended upgrades (Home Energy Saver, 2018).

There are many, however, who want to take further control of their home performance, and it is for those homeowners that the DOE partnered with the EPA to introduce the Energy Star program. Homes that meet the checklist requirements for the Energy Star label are 15% to 30% more energy efficient than equivalent code compliant homes (Energy Star, 2018f). With products and strategies backed by current building science research, the checklists necessary for certification center around five major topics: thermal enclosure, HVAC, water management, appliances, and independent inspections (Energy Star, 2018e). Since its inception in 1995, recognition and popularity of Energy Star labeled homes has grown dramatically, with one out of every ten homes built in 2015 achieving the certification (2018).

As the gradual shift toward renewable energy began influencing the residential sector, the Solar Decathlon Competition was launched by the DOE in 2002. This program is an international student competition to design and build an energy-efficient home that will be judged in ten performance categories. Due to the intermittent nature of both solar resource and home energy consumption, it became necessary for participants to thoroughly consider homeowner behaviors and lifestyle in the energy modeling of their solar-powered homes. In fact, teams in the competition started demonstrating principles of home automation and

interactive screens for homeowner use in 2005 (Simon, Doris, Farrar, 2017). It is important

to note that many of the competitors' achievements pre-date the release of the first Apple

IPad or NEST smart thermostat, and what is now the $47 billion dollar smart home industry

(2017). Figure 5 shows the approximate timeline of development for various smart home

technologies, including years that Solar Decathlon participants demonstrated their use.

Clearly, the Solar Decathlon competition has had a profound influence on the research and

development of tools that educate homeowners about the operation of their home, as well as

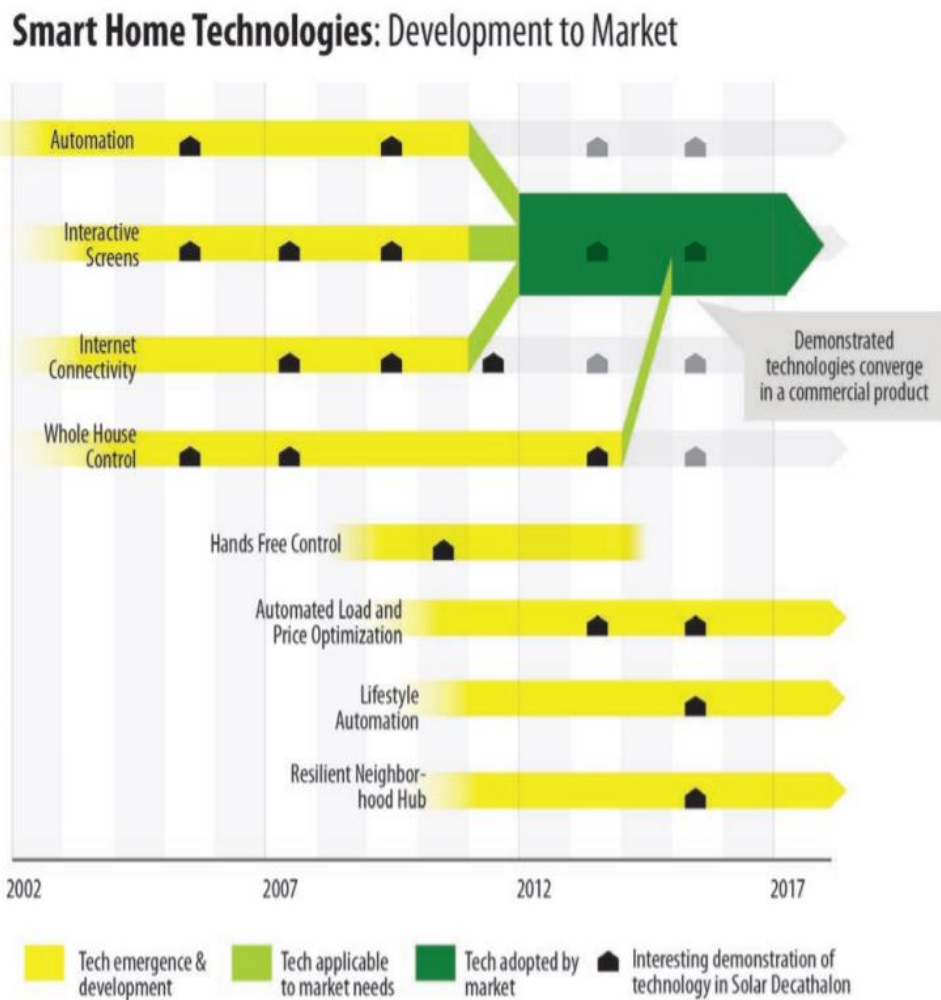guide more sustainable, energy saving behaviors.

Figure 5. Solar Decathlon Home Automation Technology Development to Market Adoption.
(Simon, Doris, Farrar, 2017).

The final DOE sponsored program described here is the ZERH certification. This program bridges the gap between designing and building highly efficient homes with very low net energy consumption, and homes with zero or even negative net energy consumption. ZERHs generally score around 50 on the previously described HERS Index, and achieve energy savings of up to $40 per month over an equivalent 2012 IECC compliant home (Energy Efficiency and Renewable Energy, 2018; Energy Star, 2016; Department of Energy, 2015). *High performance* houses are united as a category by their reputations for energy savings, sustainability, and occupant comfort that go above and beyond that of *code compliant* homes.

The Role of Homeowner Behavior on Home Performance

As was mentioned in the previous pages, homeowners began demanding more of their homes with the rise of suburbia. Today, many types of occupant behavior have been known to influence home energy consumption, including usage patterns, appliances, HVAC and preventative upgrades, design choices, and the use of smart home monitoring systems. Each of these topics will be further explored below in order to gain a better grasp of each one's presence in the literature.

Usage Patterns

The ways people interact with their building can be complex. Socioeconomic background, weather, complexity of the building, and variations in the occupant's personal schedule can all influence usage patterns (Azar & Menassa, 2011). Occupants can develop bad energy habits that detrimentally effect the energy consumption in a home (Azar &

Menassa, 2011). Some of the most researched types of usage patterns include light switching

and the length and frequency of showers (Guo, Tiller, Henze, and Waters, 2010; Pays to Live

Green, 2009).

Appliances

One significant contributing factor of homeowner behavior impacting energy use in

homes is the purchase and maintenance of appliances and fixtures within the home. The

Second Law of Thermodynamics introduces the idea of *entropy*, and the appliances used in

occupants' day-to-day lives are no exception (Merriam-Webster, 2018). Over time, they will

inevitably perform less efficiently than they once did (Goetzler, Sutherland, Kar, & Foley,

2011; NOPEC, 2018; Rogers, 2016; Wang & Hong, 2013). However, the rate at which an

appliance degrades over time can be influenced by the level of maintenance it receives

(Neme et al., 1999; Wang & Hong, 2013). Likewise, if a higher quality and more efficient

appliance is purchased to begin with, it will take longer for its efficiency to depreciate to the

level of a less efficient appliance.

HVAC and Preventative Upgrades

One of the most critical systems in a home, especially a high performance home with

a tight envelope, is the HVAC equipment, as it ensures both adequate comfort levels and

healthy indoor air quality (IAQ). Unfortunately, HVAC systems are often one of the more

neglected sets of equipment in a home. Even though 87% of US households had air

conditioning (AC) as of 2011, only 42% of those with central AC had it serviced annually

(U.S. Energy Information, 2011). In a study conducted by Downey and Proctor (2002) of

8,873 residential systems, 65% were in need of repairs, with 56% suffering from improper refrigerant charge, and nearly 20% suffering from low airflow across the inside coil.

According to one study, there are three major categories of maintenance associated with heat pump performance: refrigerant charging, adequate airflow, and duct sealing (Neme et al., 1999). Improper refrigerant charging can result in excess wear and tear on the compressor if overcharged, and inadequate cooling if undercharged. Once charged to the proper level, this maintenance measure can save approximately 13% of the energy used to operate the system (Neme et al., 1999). Common mistakes that can cause inadequate airflow include undersized return ducts and vents, incorrect fan speed settings, dirty filters, and duct runs that are long and circuitous. Airflow problems can reduce system efficiency by about 7% (Neme et al., 1999). The average duct leakage for homes is about 270 cubic feet per minute at 25 pascals (CFM_{25}), and can result in a 10-15% energy savings once the leaks are sealed (Neme et al., 1999). Overall, good maintenance of a residential heat pump in existing homes result in an average 25% energy savings on heating and cooling, and an average 35% in new construction (Neme et al., 1999).

Design Choices

While most design choices are made before occupancy, there are some ongoing design decisions that can impact overall energy consumption in a home. Two often forgotten examples include furniture location and landscaping. Furniture location can directly impact the airflow to and from ductwork, which affects the ability of HVAC systems to perform at their best (Neme et al., 1999). Landscaping can be used to strategically shade certain areas of the home during certain seasons, as well as help provide windbreaks in areas more exposed

to weather (Landscape for Life, 2018). It isn't news that good management of occupant behaviors can prolong positively impact energy consumption. The trickier problem is communicating the necessity for homeowner management in ways that work with occupants and not against them to effect meaningful change.

Smart Home Monitoring Systems

Home energy management systems have been undergoing rapid development and increasing in popularity in recent years, thanks to the expansion of accessibility, convenience, and affordability through smartphone and tablet connectivity (Zhou et. al., 2016). The idea of the "smart home" attracts a wide variety of homeowners, from aging populations who desire a safety net for their growing forgetfulness to young professionals with environmentally friendly aspirations. Most smart home systems are currently specialized to cater to one or two specific areas of building automation, such as space heating and cooling, lighting, security, or appliance scheduling. Figure 6 shows some of the services that smart home automation can provide grouped by specialized motivations.
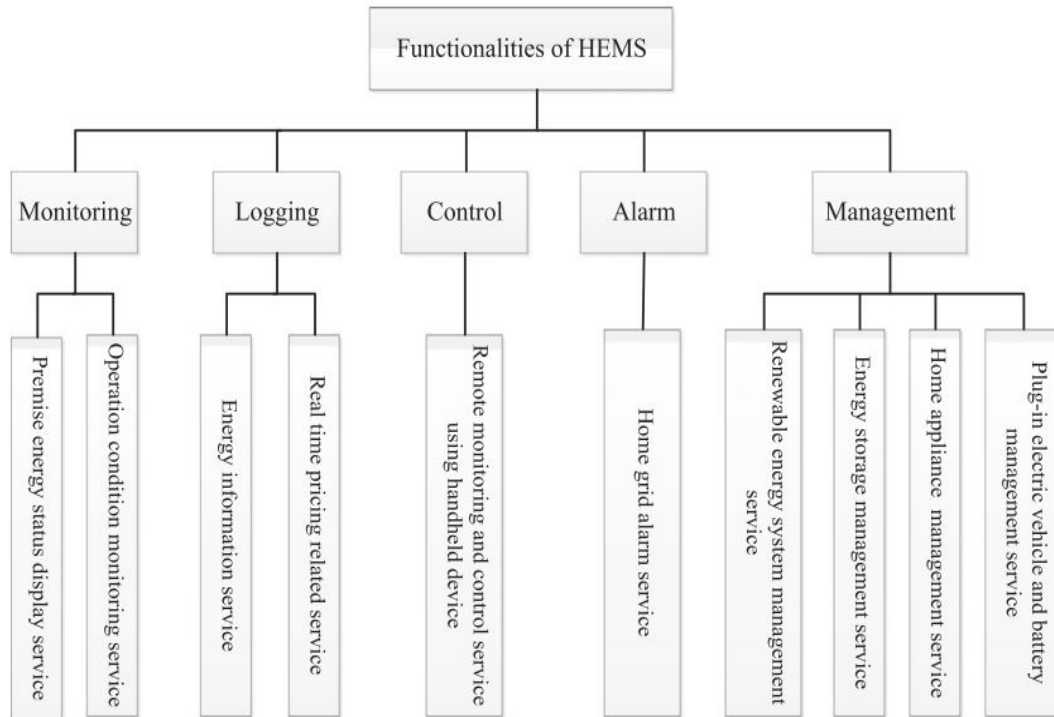
Figure 6. Functionalities of Home Energy Management Systems. (Zhou et. al., 2016).

The technology exists to assist homeowners with many behaviors that impact their home's energy performance, comfort level, or IAQ. Even without controlling operations of a home, a smart home system can offer valuable feedback on the type, amount, and cost of energy use in the home. Knowledge is power, and occupant awareness of how their home operates impacts their home's performance in a measurable way. Immediate, direct feedback on energy consumption can result in behavior changes that save 5-15% of energy use (Darby, 2006). Other behavior-based feedback strategies include goal-setting, action steps, personal comparisons, and social comparisons (Ehrhardt-martinez & Laitner, 2010). Given the success of feedback and awareness measures in smart home systems' impact on home performance, the integration of behavior management into smart home systems represents a prime opportunity for energy savings.

CHAPTER III

METHODOLOGY

Purpose

This chapter provides the methodology developed to address two key aspects of this research: (1) developing a structured approach for assessing energy impact of occupant behaviors and (2) identifying those behaviors that best lend themselves to smart home system assistance.

Based on the available literature, there is not a comprehensive resource that documents the comparative energy impacts, and the potential for energy saving, of behavior-based consumption in a building. Results of this research will provide such a resource in a concise format, and be designed for builders, designers, analysts, and homeowners alike to use. It will include a number of occupant behaviors and several relevant attributes that affect the degree of opportunity to manage these behaviors using smart home technology. This resource is not meant to be exhaustive, but rather represents major themes in behavioral impacts on energy consumption. It also acknowledges the existence of non-energy behavior impacts on both the home and its occupants. It is intended to facilitate the assessment of specific technologies, appliances, and related behaviors in order to best determine a prioritized course of action for smart home automation to reduce a home's energy consumption.

Design

   A second review of literature with a narrowed scope will be conducted to gather

existing data related to consumption behaviors that have potential energy impact. These

behaviors will then be evaluated to identify *types of behavior*. Based on the overall research

objective to compare how well certain occupant behaviors lend themselves to smart home

automation, three *evaluation characteristics* will be employed: frequency of action, level of

effort, and technological viability. Using these criteria, each behavior's *candidacy for smart

home automation* will be assigned a ranking.

   In addition, several *secondary characteristics* will be explored that will not be

included in the smart home automation candidacy ranking. These characteristics include:

non-energy related impacts of behaviors and the total annual energy savings associated with

implementing suggested behaviors in code compliant and high performance homes. They are

important to consider alongside each behavior's candidacy ranking, as they help the user gain

a more well-rounded understanding of the behavior that is being managed.

Types of Behavior

   The types of behavior are the major categories by which the reader can quickly find a

specific behavior of interest, and imparts a basic sense of organization. These categories are

developed by grouping behaviors based on a review of the motivations behind each behavior

and their common characteristics. Specific behaviors are selected to represent each category

based on their prevalence in the literature, as well as by having a measurable impact on

residential energy consumption.

Evaluation Criteria

Descriptions of the three evaluation criteria used to assess the potential for smart home monitoring are provided below with rationale and relevance of each for ranking decisions.

Frequency of action.

An important consideration in effective behavior management lies in the frequency of action, which provides a reference for ranking how often a behavior occurs. The ranking approach uses a three point scale with options "habitual", "intermediate", or "rare". Habitual behaviors are indicated by choices or actions made at least once every few days, or as often as multiple times per day. Intermediate behaviors are those that present opportunities for action once or twice per year, or on a seasonal basis. Rare behaviors occur once every few years, although they may have significant enough impacts to be worth considering from an energy management standpoint.

Ranking decisions are made based on the author's academic and professional experience, and examples from the literature. For instance, some behaviors, like light switching may easily fit into a clear category based on the author's experience, which is "habitual" in this case. However, other behaviors may not be as clear, as with appliance usage. According to Energy Star (2018b; n.d.a; n.d.b) articles, adding together the average annual frequency of use for a dishwasher, clothes washer, and clothes dryer results in a little more than twice a day average usage for one household, which also leads to a ranking of "habitual."

The importance of this criterion can be best understood from a psychological perspective. As Karen Ehrhardt-Martinez (2008) explains in her report, individuals are

motivated by many factors other than financial reasons or energy efficiency, and it would be inappropriate to manage a rare behavior, like purchasing a new Energy Star refrigerator, the same way one might manage a habitual behavior, such as turning off the lights when leaving a room. Differences in how often these behaviors occur can indicate the need for different management strategies. To expand on the examples listed above: light-switching and other habitual behaviors may be easily managed by occupancy sensors, whereas rare behaviors, like the purchase of new and more efficiently performing appliances, would be better managed using an educational calendar application integrated into a smart home energy display.

Level of effort.

The level of effort criterion is utilized as a means of evaluating how difficult or not it would be to affect meaningful change in a behavior purely through occupant choices, without the help of technological aids. The options for this three point scale include "easy", "intermediate", and "difficult" for behaviors that present increasing challenges to overcome in order to effect meaningful change without the assistance of smart home automation.

Ranking decisions are made based on the author's academic and professional experience, and examples from the literature. For instance, Energy Star product sales totaled 300 million in 2015 alone, and by 2017, over 90% of Americans knew to look for the Energy Star label when shopping (Energy Star, n.d.e). These statistics combined with the fact that Energy Star labels clearly show the potential for energy savings right there on each product make appliance purchasing an "easy" behavior to influence.

Level of effort assessment is important, because it compares behaviors in the context of human choice and habit, and the homeowner will always have the final say. It might be

relatively easy to remember to mark a calendar for equipment maintenance, for instance, but remembering to turn off the lights when leaving a room has proven to be a much more difficult habit to change (Bartram & Woodbury, 2011).

Technological viability.

Some behaviors are best managed using the assistance of technological applications, rather than relying on purely human choice and habit. Assessment of technological viability uses a three point scale with options "$", "$$", and "$$$." Fewer dollar signs indicate lower cost of installation and wider availability to the general public, and more dollar signs indicate higher cost and less availability to the general public.

Ranking decisions are made based on examples from the literature and general commercial availability of off-the-shelf technologies. For example, there are many smart thermostats on the market today, with the Nest Learning Thermostat likely the most popular. Despite the relatively high upfront cost at $200, the energy savings it reaps allow it to pay for itself in under two years (Nest, 2018). Therefore, given smart thermostats broad market penetration and rapid payback period, this behavior ranks as a "$" in technological viability.

With the advent of advanced capabilities for data monitoring, many behaviors that will be evaluated can now be influenced using technological solutions. As with any evaluation of efficacy, it is important to weigh the benefits and costs to aid in determining whether a technology is worth implementing. An additional consideration is that some behavioral modification may be more challenging to solve with purely technological solutions, as illustrated by the following two examples. Programmable light bulbs and occupancy sensors are widely available at affordable costs, which makes turning off lights when leaving a room an easily modified behavior (Guo, Tiller, Henze, and Waters, 2010). On

the other hand, there is not a readily available means of technology that can be used to guide landscaping plans to maximize passive heating and cooling, or decisions to include daylighting in a home.

Candidacy for Smart Home Automation

This section succinctly describes the approach for creating a prioritized list denoting which energy-related occupant behaviors are best suited for smart home automation technologies. Candidacy for smart home automation is designed to rank behavioral changes based on the overall frequency of impact they have on energy consumption, how difficult it would be to achieve said impact, and the degree of applicability for smart home technology to better manipulate the necessary changes in behavior. This ranking is assigned based on something akin to a Likert scale, with combined values for the three evaluation criteria of 0-3 indicating "Poor" candidacy, 4-6 resulting in "Good" candidacy, and 7-9 resulting in "Excellent" candidacy.

    Combining evaluation criteria rankings.

The overall candidacy numeric values are found by combining the scores from the previously described Frequency of Action, Level of Effort, and Technological Viability columns to generate a sum, as can be seen in Figure 7 below.
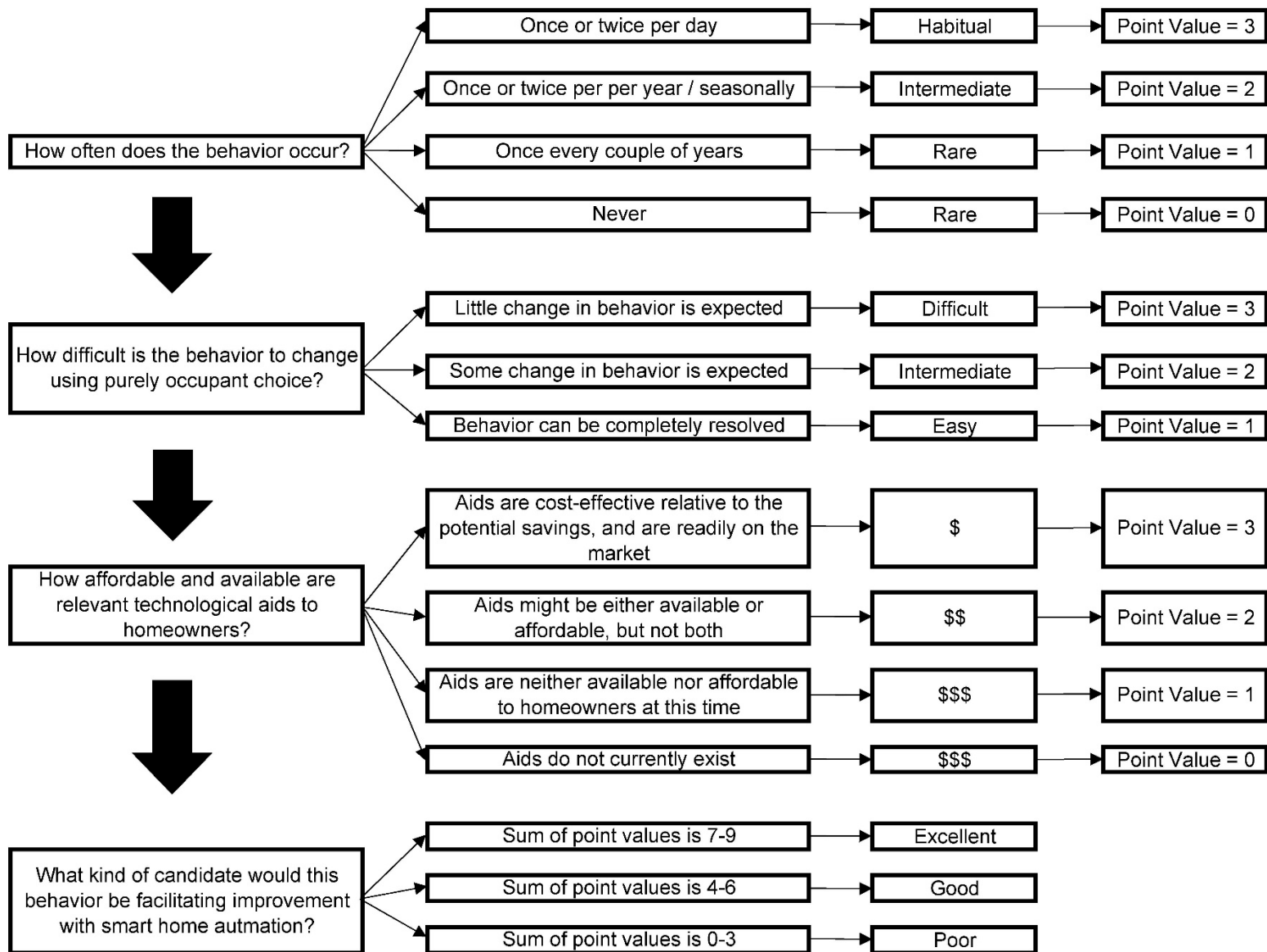
	How often does the behavior occur?			
		Once or twice per day	Habitual	Point Value = 3
		Once or twice per per year / seasonally	Intermediate	Point Value = 2
		Once every couple of years	Rare	Point Value = 1
		Never	Rare	Point Value = 0

How difficult is the behavior to change using purely occupant choice?			
	Little change in behavior is expected	Difficult	Point Value = 3
	Some change in behavior is expected	Intermediate	Point Value = 2
	Behavior can be completely resolved	Easy	Point Value = 1

How affordable and available are relevant technological aids to homeowners?			
	Aids are cost-effective relative to the potential savings, and are readily on the market	$	Point Value = 3
	Aids might be either available or affordable, but not both	$$	Point Value = 2
	Aids are neither available nor affordable to homeowners at this time	$$$	Point Value = 1
	Aids do not currently exist	$$$	Point Value = 0

What kind of candidate would this behavior be facilitating improvement with smart home autmation?		
	Sum of point values is 7-9	Excellent
	Sum of point values is 4-6	Good
	Sum of point values is 0-3	Poor

Figure 7. Candidacy Decision Tree.

This strategy results in a single numerical value that represents a multi-faceted analysis of behavior based energy consumption management. Using this method, the reader can easily identify behaviors that are "Excellent" candidates for smart home automation. For example, light switch usage receives high individual and combined scores due to the habitual nature of the behavior, the inherent difficulty in effecting meaningful change in light switch usage through purely human choice, and the widespread and financially feasible availability of technological solutions. The reader can then refer to the Total Annual Energy Savings Columns (described below) to get an estimate of how much energy they can expect to save by effectively managing this behavior. This approach allows builders, designers, analysts, and homeowners to easily prioritize behavior-based energy management strategies for homes.

Secondary Characteristics

Descriptions of the two secondary characteristics used to evaluate the behaviors from a more well-rounded perspective are provided below with rationale and relevance of each for ranking decisions.

Non-energy related impacts.

With some energy-saving behaviors, the scope of savings is beyond simply the impact of lowering the number of kilowatt-hours a home consumes. Savings from behavior change can also apply to water consumption, thermal comfort, psychological well-being, and more. These brief phrases will be assigned as descriptors in the table to indicate when management of a particular behavior has significant non-energy related impacts.

These non-energy related impacts will be assessed with literature-backed examples as well as the author's academic and professional experience. One straightforward case where these secondary characteristics play a role is managing the length and frequency of showers. By attempting to limit the electricity used in water heating, the actual amount of water consumed is lowered as well, impacting the qualitative experience of a shorter duration or lower flow shower. A more complicated example arises with weatherization, where sealing the thermal and moisture envelope to lower energy losses may result in the need for additional mechanical ventilation and filtration, lest the indoor air quality be adversely affected and cause sick building syndrome (Joshi, 2008).

The non-energy related impacts of residential behavior management represent a significant opportunity for further research into improving homes in the broader sense of sustainability. A more detailed discussion of the relevance and influence of the non-energy impacts will be explored in the analysis chapter.

Total annual energy savings.

A major factor in prioritizing which energy-saving behaviors should be addressed first is the potential quantitative savings associated with implementing suggested behaviors. The total annual energy savings associated with good management of a particular behavior will be calculated as a percentage of total energy use within the home and in the form of kilowatt-hours. The percentage values will then be classified by user-friendly labels, "low" for savings between 0-4.9%, "medium" for savings between 5-9.9%, and "high" for savings of 10% or more.

A narrow-scope review of literature will be conducted for each behavior to identify previous studies that have calculated values for percent savings associated with technology-

assisted behavior changes. These values will then be applied to an appropriate representation

of the average baseline end-use distribution of energy consumption for both a standard code

compliant home and a high performance home (Christian, 2011, p.7). Multiplying the

potential savings for each behavior by the relevant end-use percentage will provide an

estimated percent savings for each type of home.

Baseline end-use distributions.

The end-use distribution information that will be used to calculate energy savings is

based on actual data gathered from two houses (one code compliant and one high

performance) in a comparative report published by the DOE in collaboration with the

Tennessee Valley Authority (TVA), Oak Ridge National Laboratory (ORNL), and Habitat

for Humanity (Christian, 2011, p. 15). Both homes are 2,632 square feet, which closely fits

the average of 2,671 square feet for newly constructed houses built in the southern region of

the U.S. in 2016 (U.S. Census Bureau, 2016a). The standard code compliant home values are

based on a Building America Benchmark Building, which is rated with a HERS score of 104.

Considering the standard resale home scores an average of 130, and a standard code

compliant new home scores an average of 100, this Benchmark is a reasonable representation

of a standard code compliant home (RESNET, 2018). As for the high performance home

values, the ZEH5 home presented in Christian's report (2011) was deemed appropriate, given

its HERS score of 43, as well as its location in the TVA area with similar climate zone

requirements (Climate Zone (CZ)3 and CZ4) as in central and western North Carolina.

The baseline end-use distributions used for the code compliant and high-performance

homes can be seen in Figures 8 and 9, respectively. Due to technology advances in the seven

years since the study, the end-use percentage for lighting is likely not representative of

current standards. In recognition of the sharp decline in the use of incandescent lighting, this

specification was altered to 100% fluorescent lighting in the code compliant home and 100%

light-emitting diode (LED) lighting in the high performance home for purposes of this study
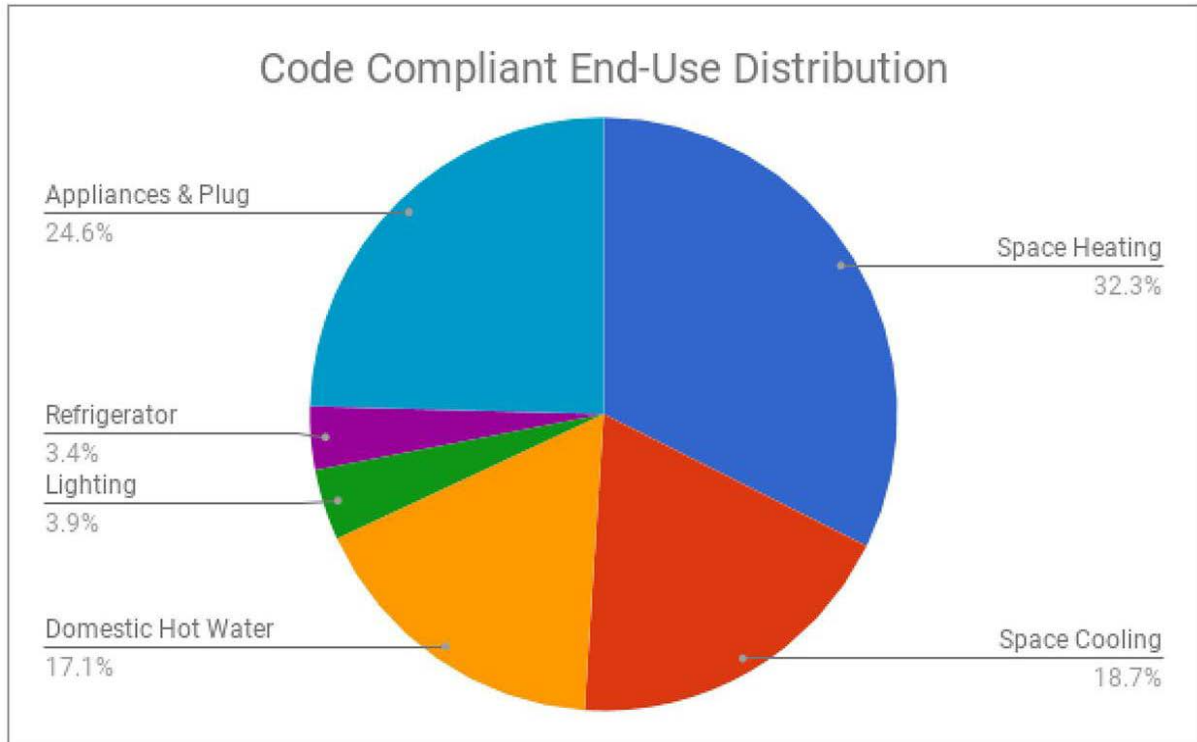
(Department of Energy, n.d.a).

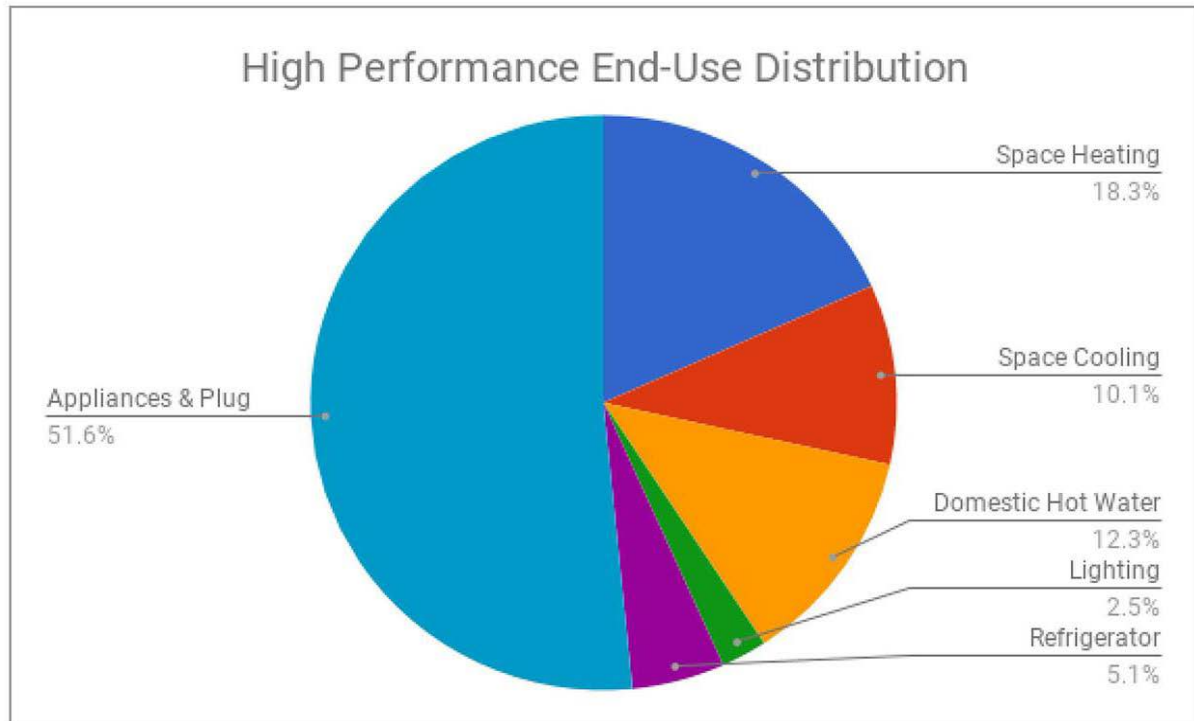*Figure 8.* Baseline End-Use Distribution for a Code Compliant Home (Christian, 2011).

Figure 9. Baseline End-Use Distribution for a High Performance Home (Christian, 2011).

Example calculations for plug load savings.

The following equations are used to determine *S_t(%),* the percentage of total energy

saved and *S_t(kWh),* kWh saved, by implementing a particular behavior in each type of home:

$$S_e(\%) \times C_e(\%) = S_t(\%) \tag{1}$$

$$S_t(\%) \times C_t(kWh) = S_t(kWh) \tag{2}$$

In equation 1, $S_e(\%)$ is the percent of energy saved in the end-use category as

described in the literature, and $C_e(\%)$ is the percent of total energy consumed by the end-use

as indicated in Figures 8 and 9. In equation 2, $C_t(kWh)$ is the total number of kilowatt-hours

(kWh) consumed by the home.

A recent study found that plug load consumption can be reduced by 21% (S_e) by

employing occupancy-based control (Sun and Tianzhen, 2016, p.53). Calculations are

36

performed using total household energy consumption in the benchmark code compliant home

of 19,471 kWh and 9,281 kWh in the high performance home, as well as the percentage of

energy consumed by plug loads of 28.03% *(C_e)* in the benchmark code compliant home and

56.71% *(C_e)*in the high performance home (Christian, 2011, p.7).

Thus, the calculations for a code compliant home:

$$21\% \times 25\% \approx 5\% \tag{1}$$

$$5\% \times 19{,}471\ kWh \approx 974\ kWh \tag{2}$$

These results indicate that 6% or about 1,168 kWh can be saved in a standard, code

compliant home by implementing occupancy-based control on plug loads, which would be

labeled as "medium" energy savings.

Using the same equations and values from Figure 9 for a high performance home:

$$21\% \times 52\% \approx 11\% \tag{1}$$

$$11\% \times 9{,}281\ kWh \approx 1{,}021\ kWh \tag{2}$$

The savings due to the same plug load measures implemented in a high performance

home are equal to 12% or about 1,114 kWh, which would be labeled as "high" energy

savings.

Similar calculations performed for each individual behavior being evaluated will offer

insight to the reader in predicting the degree of direct energy savings that can be expected

from effective management of a selected behavior, and can help guide decisions regarding

which behaviors to pursue. It is important to note, however, that energy savings values

calculated for management of individual behaviors cannot simply be added together if

managing more than one behavior, as the energy saving factors may interact in ways that

change the combined value.

CHAPTER IV

RESULTS AND ANALYSIS

The findings of this study are presented in three forms: (1) a concise table (Table 1) showing the candidacy rankings for each behavior evaluated for smart home automation, (2) an expanded table (Table 2) illustrating the qualitative characteristics of each behavior evaluated, and (3) a written explanation of the factors and resources incorporated into each behavior's analysis to determine its overall level of prioritization.

Candidacy for Smart Home Automation

The table below (Table 1) summarizes the results for the three evaluation criteria developed to compare to compare how well certain occupant behaviors lend themselves to smart home automation. As described in the previous chapter, the candidacy evaluation criteria include *frequency of action, level of effort,* and *technological viability*. Scores for the three criteria, ranging from 0 to 3, are added together into a single numeric ranking from 0-9 for the candidacy ranking of each behavior. This metric allows the reader to easily see which of the behaviors analyzed in this study are most appropriately suited to be managed with the aid of smart home automation technologies.

Categories	Occupant Behaviors That Impact Home Energy Use	Frequency of Action	Level of Effort	Technological Viability	Candidacy for Smart Home Automation
Usage Patterns	Light Switch Usage	3	3	3	9
	Length/Frequency of Showers	3	3	3	9
Appliances	Plug Loads	3	2	3	8
	Frequency of Appliance Use	3	3	2	8
	Appliance Purchasing	1	1	0	2
HVAC	Thermostat Setpoints	2	2	3	7
	Mechanical/Natural Ventilation	3	1	2	6
Preventative / Upgrades	Equipment and Appliance Tuning/Maintenance	2	1	3	6
	Equipment and Appliance Repair	2	1	1	4
	Weatherization	1	2	3	6
Design Choices	Furniture Location	2	1	0	3
	Landscaping	2	3	0	5

Table 1. Rankings of Occupant Behaviors That Impact Home Energy to Assess Candidacy for Smart Home Automation.

Qualitative Characteristics

Results of the qualitative assessment for each behavior are shown in Table 2. These include the descriptors for the factors and results from the candidacy calculation, and for the two secondary characteristics previously described. Potential *non-energy related impacts* were identified during the extensive literature reviews for this research. Calculations for the *total annual energy savings associated with implementing suggested behaviors* are provided in Appendix 1 for both code compliant and high performance homes. Total annual energy savings associated with implementing each behavior are indicated in Table 2 as "Low" for 0-4% "Medium" for 5-9% as Medium, and "High" for 10-13%. These variables are included to further guide the reader's decision to prioritize management of a specific behavior, and provide some insight into other aspects of the home that will be impacted by choosing to manage a specific behavior. Further discussion for assessment of each individual behavior is provided in the next section.

Categories	Occupant Behaviors That Impact Home Energy Use	Frequency of Action	Level of Effort	Technological Viability	Candidacy for Smart Home Automation	Non-Energy Related Impacts	Total Annual Energy Savings Associated With Implementing Suggested Behaviors	
							Code Compliant Homes	High Performance Homes
Usage Patterns	Light Switch Usage	Habitual	Difficult	$	Excellent	Psychological	Low	Low
	Length/Frequency of Showers	Habitual	Difficult	$	Excellent	Water Consumption	Medium	High
Appliances	Plug Loads	Habitual	Intermediate	$	Excellent	Product Life	Medium	High
	Frequency of Appliance Use	Habitual	Difficult	$$	Excellent	Water Consumption	Low	Low
	Appliance Purchasing	Rare	Easy	$$$	Poor	Product Life	Medium	N/A*
HVAC	Thermostat Setpoints	Intermediate	Intermediate	$	Excellent	Thermal Comfort	Medium	Low
	Mechanical/Natural Ventilation	Habitual	Easy	$$	Good	IAQ	Medium	Medium
Preventative / Upgrades	Equipment and Appliance Tuning/Maintenance	Intermediate	Easy	$	Good	Thermal Comfort/Product Life	High	Medium
	Equipment and Appliance Repair	Intermediate	Easy	$$$	Good	Thermal Comfort	Low	Low
	Weatherization	Rare	Intermediate	$	Good	Envelope Tightness/IAQ	Medium	Low
Design Choices	Furniture Location	Intermediate	Easy	$$$	Poor	Thermal Comfort	Medium	Low
	Landscaping	Intermediate	Difficult	$$$	Good	Pyschological	High	Medium

*- Characteristic is not applicable due to energy efficient appliances being a prerequisite of many high performance standards, therefore indicating that energy savings due to this behavior have already been accounted for in the baseline end-use distribution.

Table 2. Qualitative Characteristics of Occupant Behaviors That Impact Home Energy Use.

<center>**Individual Behavior Analyses**</center>

The following sub-sections present the references and assumptions used in evaluating each behavior's candidacy for smart home automation. They address each variable presented in Table 2, and provide the background information that led to the conclusion of the most appropriate label for each. The calculations used to determine total potential annual energy savings associated with implementing suggested behaviors can be found in *Appendix 1*.

Light Switch Usage

Frequency. It is evident from personal experience that switching lights on and off in a home is a behavior that occurs all the time, often without the occupant themselves even noticing.

Level of Effort. Throughout eighteen studies since 2008, attempts to change light switching behaviors using manual methods were less than half as effective in reducing energy consumption as those using technological aids (Staddon, Cycil, Goulden, Leygue, & Spence, 2016).

Technological Availability. Philips Hue light bulbs retail for under $15, and can communicate with a variety of other smart technology platforms, including Amazon Alexa, Google Assistant, and Apple Home Kit (Best Buy, 2018).

Non-Energy Impacts. Supplementary daylighting can improve occupants' overall sense of wellbeing and productivity, according to a technical report conducted by the National Renewable Energy Laboratory (NREL) (Edwards, L. and Torcellini, P., 2002). It is reported that regular exposure to full-spectrum lighting is correlated with fewer dental cavities, better learning retention, and faster healing of injuries.

Potential for Energy Savings. Studies have shown that lighting energy use in private offices decreases by 25% after manual switching systems are replaced with occupancy sensors with a sensor time delay of 20 minutes (Guo, Tiller, Henze, and Waters, 2010).

Length/Frequency of Showers

Frequency. Most Americans take a shower nearly once a day (Soakology, 2016; Kantar World Panel, 2015). In warm and humid climates, like North Carolina, the average frequency of showers rises even higher.

Level of Effort. In the author's experience, altering this behavior can be a major challenge, not only because of how often it occurs and the potential enjoyment factor, but also due to the social pressures associated with bathing. Cleanliness is a profound social standard, which may outweigh the ecological or economical values of limiting hot water consumption to occupants.

Technological Availability. Showersmart is an audiovisual display timer that retails for $120 (WaterSmart Technology, 2017). Shower Manager is a timer with audio reinforcement and the ability to limit water flow by two-thirds at a specified interval that retails for $150 (Shower Manager, 2016). EvaDrop is an application-based timer, temperature control, flow control, and usage tracker that has not yet been released for production (EvaDrop, 2017).

Non-Energy Impacts. Significant water waste savings can be achieved by decreasing the length, frequency, and flow rate of showers in a home.

Potential for Energy Savings. WaterSense certified showerheads are permitted to use no more than 2 gallons per minute (gpm) (U.S. Environmental Protection Agency, 2018).

3.159 kWh are used in a 10 minute shower (Pays to Live Green, 2009). Assuming use of an electric water heater, a decrease of 1.5 minutes from the average 10 minute shower length would save 0.525 kWh per shower. Assuming the occupant showers once every day, a decrease in water use equivalent to one shower per week would lead to a savings of 164.268 kWh over the course of a year (2009). If a family of six were able to do this, the household energy savings would be 985.608 kWh.

Plug Loads

Frequency. With the increase in mobile electronics, plug load usage and impact have become ubiquitous (U.S. General Services Administration, 2017).

Level of Effort. Some of the measures that can be taken to control plug loads include manually unplugging devices and chargers from outlets when not in use and making sure to set computers to sleep mode or off when not in use. Despite the apparent simplicity of taking these measures, occupants often forget them, which indicates that it may be a challenge to change this behavior without the aid of technology.

Technological Availability. Advanced power strips can be controlled in a variety of ways, from a timer, to activity sensors, and more, depending on what type of device the strip is best suited for (NREL, 2013). Many smart plug and power strips are designed to connect to a mobile app that allows users to control or program the devices plugged into each outlet, as well as view how much power each outlet actually consumes.

Non-Energy Impacts. By avoiding overcharging of electronic devices, those products' service life will be extended (Whitney, L, 2017).

Potential for Energy Savings. These miscellaneous sources of energy consumption can add up to 50% of the loads in highly efficient buildings (2017). Occupancy-based plug load control can save 21.2% of energy consumed by plug loads in a home (Sun and Tianzhen, 2016, p.53).

Frequency of Appliance Use

Frequency. The average number of dishwasher cycles run in the American household per year is 215 (Energy Star, n.d.b). Similarly, the average American family washes 300 loads of laundry per year (Energy Star, 2018b). Refrigerators run on a constant basis.

Level of Effort. In the author's experience, changing these behaviors is very challenging due to the social pressures of personal hygiene related to some appliances like clothes washers and dryers, and because the usage patterns of refrigerators and dishwashers are related to dietary patterns.

Technological Availability. There are live weather forecasts available on many smart home applications, but they require the homeowner to make connections like it being a good day to line dry clothes rather than use an electric dryer. There is one smart clothesline clip that will send an alert to the homeowner's phone when rain is imminent which reminds them to bring clothes inside, but the product is still in development, as is reported to be expensive when it reaches the market (Edwards, 2016).

Non-Energy Impacts. By limiting the use of water consuming appliances, from clothes washers and dishwashers to refrigerators, the home's overall all water consumption will also decrease.

Potential for Energy Savings. The average number of dishwasher cycles run in the American household per year is 215, and the maximum annual energy usage for an energy star certified dishwasher is 270 kWh (Energy Star, n.d.b). This translates to 4 cycles per week, and 1.2558 kWh per cycle. If a family lowered their use per week by one cycle, they would save 65 kWh per year. Similarly, the average American family washes 300 loads of laundry per year, and the average energy star certified washing machine uses 280 kWh per year (Energy Star, 2018b). This translates to 0.933 kWh per load, and 5.769 loads per week. If a family lowered their use by one cycle per week, they would save 49 kWh per year. The maximum energy usage per load for a standard electric dryer is 2.15 kWh (Energy Star, n.d.b). Assuming the same number of loads as the washer above, this translates to 645 kWh per year. If a family reduced their number of loads per week by one, they would save 112 kWh per year. The sum of energy savings for implementing all of these measures is 226 kWh/year.

Appliance Purchasing

Frequency. Homeowners should expect to get an average of ten working years out of most large appliances (Rox, 2015). However, in the author's experience, not all appliances in a home tend to be the same age, so occupants end up purchasing about one major appliance every couple of years.

Level of Effort. Thanks to Energy Guide labels, the energy savings associated with most large appliances are clearly indicated for shoppers (Federal Trade Commission, 2015). Additionally, Energy Star product sales totaled 300 million in 2015 alone, and over 90% of

Americans knew to look for the Energy Star label when shopping by 2017 (Energy Star, n.d.e).

Technological Availability. While there are consumer resources, such as Energy Star, available to assist with appliance shopping, none are currently integrated into any smart home platforms.

Non-Energy Impacts. Intentionally shopping for well-rated products can also help ensure you purchase a product of higher quality, which will last longer than the baseline, and result in longer product life.

Potential for Energy Savings. Based on rating information for clothes washers, clothes dryers, dishwashers, refrigerators, heat pumps, and ventilation fans, Energy Star rated appliances save an average of 23.5% of the energy a household would use on non-rated appliances (Energy Star, 2018a, Energy Star, 2018b, Energy Star, 2018c, Energy Star, 2018d, Energy Star, n.d.a, Energy Star, n.d.b).

Thermostat Set-Points

Frequency. Thermostat adjustment is very difficult to categorize; some occupants set constant temperatures and adjust seasonally, and some constantly make adjustments throughout the day (Pritoni, Meier, Aragon, Perry, & Peffer, 2015).

Level of Effort. More than one hundred million Americans and Europeans have purchased energy saving thermostats in the last twenty years, which indicates a general desire and willingness to change set-point behaviors. However, using these thermostats effectively requires specific competencies of understanding that many occupants don't currently have (Pritoni, Meier, Aragon, Perry, & Peffer, 2015).

Technological Availability. The Nest Learning Thermostat is one of the most popular of these. Despite the $200 price point, the energy savings achieved by its use allows a Nest to pay for itself in just two years (Nest, 2018).

Non-Energy Impacts. In the author's experience, programming wide dead-bands can result in occupants needing to wear more layers in the home to be comfortable, and some occupants may be less satisfied with this caveat than others.

Potential for Energy Savings. Energy savings of up to 10% per year on heating and cooling can be achieved by setting back thermostats by 7-10 degrees for 8 hours a day from its normal setting; this percentage is even greater in milder climates, meaning those with smaller average changes in temperature across the thermal envelope boundary (Department of Energy, n.d.b).

Mechanical/Natural Ventilation

Frequency. While window-opening behaviors vary widely from occupant to occupant, and from season to season, generally windows are opened on a daily basis for some duration of time during conducive times of the year (D'Oca & Hong, 2014).

Level of Effort. Window opening behavior is relatively easy to change, given access to a range of acceptable thermal conditions provided by mechanical ventilation (D'Oca & Hong, 2014).

Technological Availability. While commercial scale building automation systems, such as at NREL's Energy Systems Integration Facility (ESIF) office building, are capable of notifying occupants via email when the weather is optimal to open windows rather than run mechanical HVAC full-blast, there are far more limited residential products on the market

that address this issue (Sheppy, Vangeet, & Pless, 2015). However, many smart thermostats such as Honeywell's Smart Color include live weather and forecast data that can display when the temperature outside is cooler than inside, although the occupant must make the final leap to the conclusion that opening a window and turning down the HVAC is the optimal choice (Honeywell, 2018). Also, smart thermostats like EcoBee can automatically switch from mechanical heating and cooling to ventilating outside air into the house when the conditions are appropriate (EcoBee, 2018).

Non-Energy Impacts. In the author's experience, open windows in the home during certain times of the year permit excess moisture or pollutants to enter the envelope and negatively affect the indoor air quality, which may necessitate the need for a dehumidifier.

Potential for Energy Savings. Occupants' window opening behavior can have a 17% impact on energy consumption for heating and cooling, due to mechanical HVAC equipment conditioning air that then flows out open windows, which results in wasted energy (Fabi, Andersen, Corgnati, and Olesen, 2012). This percentage of impact increases as the tightness of the building increases, because less energy is wasted to due passive infiltration through the envelope (2012).

Equipment and Appliance Tuning/Maintenance

Frequency. In the author's experience, and in most equipment instruction manuals, appliances and equipment within the home should be tuned or maintained on a seasonal or annual basis.

Level of Effort. There are many things that occupants should be sure to adjust for maximum energy savings, including: reduce water heater temperature; ensure HVAC filters

are replaced or cleaned, equipment is sealed properly, has the appropriate refrigerant charge, and has enough airflow; program refrigerator and freezer temperatures; and schedule regular maintenance check-ups on all major appliances. Some of these items are easy to forget without reminders in place.

Technological Availability. There are a variety of products available to help the homeowner properly tune and maintain their equipment, including Ecobee, a smart thermostat that automatically sends notifications when HVAC equipment is performing unusually and needs tuning, or is due for regularly scheduled maintenance (EcoBee, 2018). Google Calendar is an app that can also serve as a more customizable option for manually entered maintenance, and can be connected to smart home systems such as Google Home.

Non-Energy Impacts. Proper maintenance and tuning of HVAC appliances will result in greater thermal comfort for the occupant, as well as quieter operation and longer service life (Neme et al, 1999).

Potential for Energy Savings. By checking and maintaining refrigerant charge, air flow, and duct leakage in heat pumps, annual energy savings of 24% can be realized (Neme, Proctor, and Nadel, 1999).

Equipment and Appliance Repair

Frequency. Similar to equipment and appliance tuning, malfunctions and break downs of equipment can occur on a seasonal or annual basis, although this behavior tends to be more unpredictable.

Level of Effort. It's important to avoid "band-aid" fixes. Be sure to properly repair any malfunctions, like cleaning out clogged dryer vents, or replacing worn out refrigerator door gaskets.

Technological Availability. Alert systems that notify users of unusual energy performance that could indicate equipment malfunction are available for some appliances, but sensors can be expensive and difficult to connect to an existing smart home system. Some smart thermostats, like the Ecobee mentioned above, can monitor HVAC equipment for performance irregularities, but may not be able to integrate appliances such as refrigerators (EcoBee, 2018).

Non-Energy Impacts. Successful repair of malfunctioning HVAC appliances will result in greater thermal comfort for the occupant as well as energy savings (Neme et al., 1999).

Potential for Energy Savings. Refrigerators, alone, consume 14% of electricity in homes, and with deteriorated components may cost up to 60% more energy than their labeled usage. (Kim, Keoleian, and Horie, 2006).

Weatherization

Frequency. Homeowners should inspect and re-install sealants, caulking, insulation, and windows on a regular basis, such as once every 2-3 years, in accordance with the most recent energy conservation codes (Energy Saver, 2017). Additionally, renovations or additions may require the house be brought up to current code (2017).

Level of Effort. In the author's experience, weatherization is often not a priority for homeowners, and may be forgotten or postponed due to scheduling or financial constraints.

Technological Availability. Similar to the products that can aid in regular maintenance of appliances and HVAC equipment, calendar apps are available that can connect with smart home systems, such as Google Calendar and Google Home.

Non-Energy Impacts. Especially in older homes, improving the envelope in a home may require additional mechanical ventilation/filtration, lest the indoor air quality be adversely affected and cause sick building syndrome (Joshi, 2008).

Potential for Energy Savings. The US EPA estimates that 15% of energy used for heating and cooling can be saved by conducting proper air sealing and insulation maintenance (Energy Star, n.d.f).

Furniture Location

Frequency. In the author's experience, furniture location changes occur on an unpredictable basis, depending on the lifestyle preferences of the occupants. In general, furniture may be moved on a seasonal or annual basis.

Level of Effort. Since furniture location is such an infrequently altered behavior, good management would be relatively easy for the well-informed homeowner.

Technological Availability. There are no technological solutions available on the market to assist homeowners in laying out furniture in a way that facilitates good HVAC circulation and passive solar considerations.

Non-Energy Impacts. By preventing supply and return air blockages, the occupant will experience greater thermal comfort in these spaces. Careful placement to allow airflow between furniture and exterior walls in the winter time can also reduce the risk of condensation and subsequent mold growth.

Potential for Energy Savings. Improper airflow to HVAC equipment due to blocked vents and registers can raise energy usage by up to 14% (Domanski, Henderson, and Payne, 2014).

Landscaping

Frequency. As with furniture location, landscaping changes occur on an unpredictable basis, depending on the lifestyle preferences of the occupants. In general, new landscaping patterns may be implemented on a seasonal basis.

Level of Effort. Since landscaping is such a labor intensive behavior, and its effects on heat gains and shading of the home are complex, it can be difficult for the average homeowner to manage this behavior without guidance.

Technological Availability. There are no technological solutions available on the market to assist homeowners in laying out landscaping designs that benefit passive heating and cooling strategies.

Non-Energy Impacts. Views of greenery from a window has been shown in several studies to have beneficial effects on the wellbeing of building occupants (Gillis and Gatersleben, 2015).

Potential for Energy Savings. Good landscaping for controlled heat gains can save 25% of your heating and cooling costs annually (Department of Energy, n.d.c).

CHAPTER V

DISCUSSION, INTERPRETATION, AND CONCLUSIONS

Overall Findings

The graph below (Figure 10) summarizes findings for the differences in percentage of total annual energy savings potential associated with implementing suggested behaviors in code compliant (indicated in a lighter blue) and high performance (indicated in a darker orange) homes. In eight out of twelve behaviors, the potential for energy savings was different between the two homes. Specifically, *length/frequency of showers, plug loads,* and *appliance purchasing* were more impactful in high performance homes, while *thermostat setpoints, equipment and appliance tuning/maintenance, weatherization, furniture location,* and *landscaping* were all more impactful in code compliant homes. This supports the notion that some types of behavior should be prioritized differently in code compliant or high performance homes. Additionally, the behaviors under the HVAC, Preventative/Upgrades, and Design Choices categories had an equal or greater impact in the code compliant home, whereas, whereas behaviors under the Usage Patterns and Appliances categories had an equal or greater impact in the high performance home.
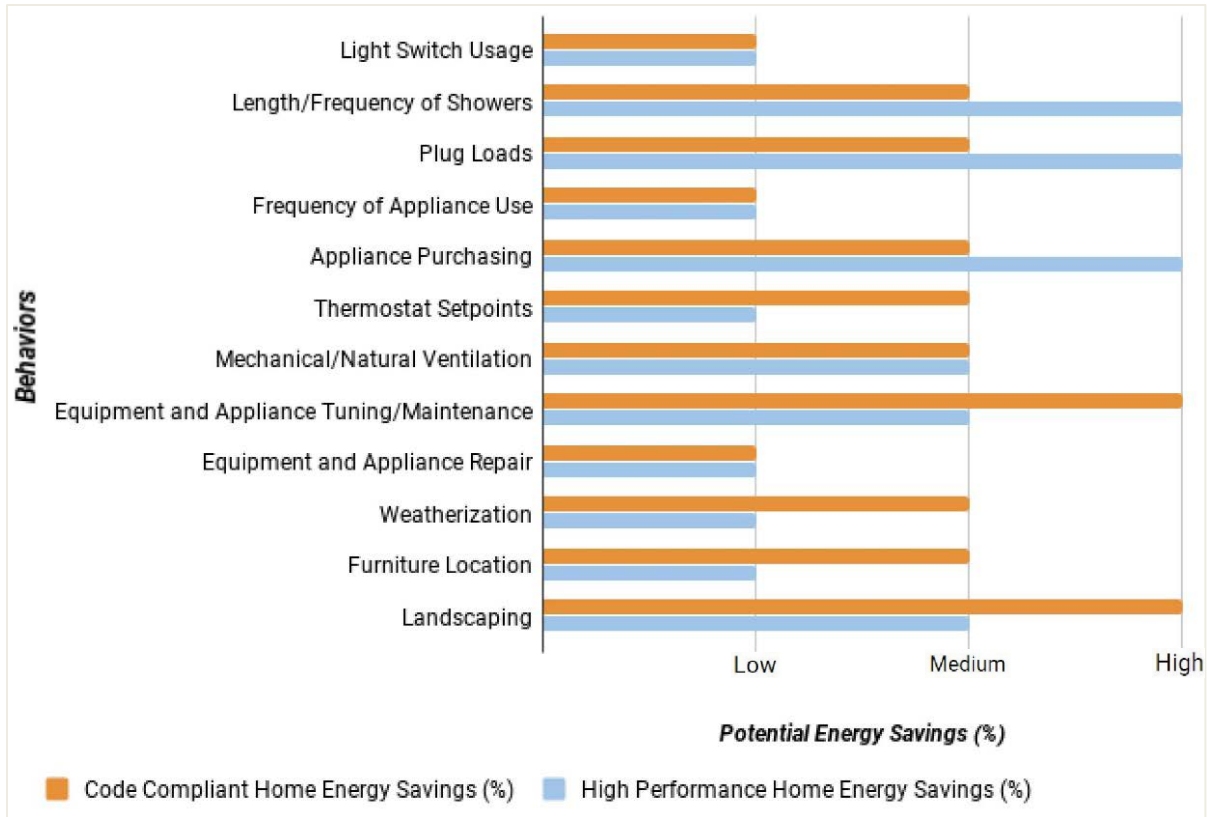
Figure 10. Energy Savings Potential (%) Due to Effective Behavior Management in a Code Compliant Home v. a High Performance Home.

It is interesting to note that some behaviors (ie. *appliance purchasing* and *furniture location*) that scored low in the smart home automation candidacy ranking assessment were found to have medium or high impacts on energy total annual energy savings. While these behaviors may not be good candidates for smart home automation, they should be included in considerations for prioritizing behavior management without smart home automations.

In terms of broader categories, two showed uniform candidacy for smart home automation throughout every behavior within the category: *usage patterns*, with an "excellent" ranking, and *preventative/upgrades*, with a "good" ranking. These categories may benefit from a smart home automation strategy that integrates all of the behaviors within each category.

Research Questions Revisited

Throughout the course of this study, each of the research questions laid out in Chapter 1 were addressed. In the Chapter 2, the fundamental differences between current code compliant homes and high performance homes was determined to be based on the voluntary standards that high performance homes adhere to, above and beyond the mandated regulations that code compliant homes must meet. In Chapters 2 and 4, the literature revealed twelve well-documented behaviors that impact energy performance. The literature also contained varying levels of detail regarding the potential for each of these behaviors to be monitored by smart home systems. Finally, in Chapter 4, an analysis was conducted based on several evaluation characteristics and secondary characteristics to determine the differences between these behavior impacts in code compliant and high performance homes. These findings are listed in the sections above.

Significance of the Results

This study establishes a method for systematically prioritizing which energy-impacting occupant behaviors are most applicable to manage using smart home automation technologies. It also distinguishes secondary characteristics that should be considered to further guide the decision to pursue management of a specific behavior, and weighting of the importance of these characteristics can be tailored to individual homeowner priorities. For example, light switching and plug loads are both excellent candidates for smart home automation, but plug loads have a significantly higher potential for energy savings in both types of home, so plug loads should be prioritized before light switching in order to maximize energy savings.

The tables developed in this paper are user-friendly enough to be utilized by homeowners to assist in evaluating their priorities for home renovations. The methodology behind the calculations used in determining rankings is laid out in a modular and transparent fashion, which allows builders, designers, code officials, and other members of the building industry to replace any pieces of data they wish with their own values, whether they are found elsewhere in the literature or calculated themselves. Furthermore, other behaviors that may be of interest can be easily added to the table, and evaluated using the same system.

Potential for Future Research

While this study has laid the groundwork for prioritizing occupant behaviors in home energy management, there are a number of ways that this topic may be further investigated. This research has been focused on comparing energy saving impacts in code compliant and high performance homes, but there is also a need for comparing behavior management priorities for existing home retrofits and new construction. This could be a worthwhile addition in future versions of Table 2.

The state of the data related to increases in energy savings due to effective behavior management is lacking and dated, which compromises the current validity of the results. Additionally, because of the variety of sources used in data collection for calculations, the exact scope of each calculation is somewhat vague. In future versions of these tables, more current and transparent studies should be used in calculating the total annual energy savings associated with implementing suggested behaviors, and if such studies do not exist, then that is an excellent path for future inquiry. Another potential route for generating more accurate

data might be to use computer modeling programs to develop occupancy use schedules and apply them to each type of home.

Some behaviors, like Appliance Purchasing, were found to have no current technological aids for use in smart homes. One valuable path for future research is the design and production of smart home compatible solutions for these behaviors. For example, an application-based interactive database of energy star rated appliances that connects to Apple and Android home platforms might be an affordable solution to Appliance Purchasing.

Lastly, this study does not consider an important factor: occupant acceptance. There are a number of technological solutions available on the market that may not be desired or used effectively by some occupants. For instance, timers on showerheads that limit flow after a programmed period may not be received well by occupants, and this may significantly impact the success of that behavior management strategy, as well as that behavior's true candidacy for smart home automation. In future research, this factor should be explored alongside the secondary characteristics, and incorporated into an overall weighted priority for implementation ranking, using candidacy ranking calculations and secondary characteristics for a more complete picture of behavior management implications and incentives.

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APPENDIX 1

ENERGY SAVINGS CALCULATIONS

The following calculations are performed using the equations laid out in Chapter 3 and the data found in the individual behavior analyses section of Chapter 4. These calculations are designed to find the total annual energy savings associated with implementing suggested behaviors, with answers emphasized using boldface. The resulting percentages for both code compliant and high performance homes are used in Table 2.

Lighting Calculations

Using Equation 1 and 2, the baseline end-use distributions in Figures 8 and 9, and the relevant data in Chapter 4, the following calculations were used to determine the decrease in total energy consumption for a code compliant home:

$$25\% \times 3.9\% \approx \mathbf{1\%} \tag{1}$$

$$1\% \times 19{,}471\ kWh \approx \mathbf{195\ kWh} \tag{2}$$

Likewise, the following calculations were used to determine the decrease in total energy consumption for a high performance home:

$$25\% \times 2.5\% \approx \mathbf{1\%} \tag{1}$$

$$1\% \times 9{,}281\ kWh \approx \mathbf{93\ kWh} \tag{2}$$

Length/Frequency of Showers Calculations

Using Equation 1 and 2, the baseline end-use distributions in Figures 8 and 9, and the relevant data in Chapter 4, the following calculations were used to determine the decrease in total energy consumption for a code compliant home:

$$30\% \times 17\% \approx \mathbf{5}\% \tag{1}$$

$$5\% \times 19{,}471\ kWh \approx \mathbf{974\ kWh} \tag{2}$$

Likewise, the following calculations were used to determine the decrease in total energy consumption for a high performance home:

$$86\% \times 12\% \approx \mathbf{10}\% \tag{1}$$

$$10\% \times 9{,}281\ kWh \approx \mathbf{928\ kWh} \tag{2}$$

Plug Loads Calculations

Using Equation 1 and 2, the baseline end-use distributions in Figures 8 and 9, and the relevant data in Chapter 4, the following calculations were used to determine the decrease in total energy consumption for a code compliant home:

$$21\% \times 25\% \approx \mathbf{5}\% \tag{1}$$

$$5\% \times 19{,}471\ kWh \approx \mathbf{974\ kWh} \tag{2}$$

Likewise, the following calculations were used to determine the decrease in total energy consumption for a high performance home:

$$21\% \times 52\% \approx \mathbf{11}\% \tag{1}$$

$$11\% \times 9{,}281\ kWh \approx \mathbf{1{,}021\ kWh} \tag{2}$$

Frequency of Appliance Use Calculations

Using Equation 1 and 2, the baseline end-use distributions in Figures 8 and 9, and the relevant data in Chapter 4, the following calculations were used to determine the decrease in total energy consumption for a code compliant home:

$$5\% \times 28\% \approx \mathbf{1\%} \tag{1}$$

$$1\% \times 19{,}471\ kWh \approx \mathbf{195\ kWh} \tag{2}$$

Likewise, the following calculations were used to determine the decrease in total energy consumption for a high performance home:

$$5\% \times 57\% \approx \mathbf{3\%} \tag{1}$$

$$3\% \times 9{,}281\ kWh \approx \mathbf{278\ kWh} \tag{2}$$

Appliance Purchasing Calculations

Using Equation 1 and 2, the baseline end-use distributions in Figures 8 and 9, and the relevant data in Chapter 4, the following calculations were used to determine the decrease in total energy consumption for a code compliant home:

$$24\% \times 28\% \approx \mathbf{7\%} \tag{1}$$

$$7\% \times 19{,}471\ kWh \approx \mathbf{1{,}363\ kWh} \tag{2}$$

Because many high performance standards require the purchase and installation of energy efficient appliances, this calculation is not applicable for high performance homes. The energy savings for this behavior have already been accounted for in the baseline end-use distribution for the high performance home.

Thermostat Set-Points Calculations

Using Equation 1 and 2, the baseline end-use distributions in Figures 8 and 9, and the relevant data in Chapter 4, the following calculations were used to determine the decrease in total energy consumption for a code compliant home:

$$10\% \times 51\% \approx \mathbf{5\%} \tag{1}$$

$$5\% \times 19{,}471\ kWh \approx \mathbf{974\ kWh} \tag{2}$$

Likewise, the following calculations were used to determine the decrease in total energy consumption for a high performance home:

$$10\% \times 28\% \approx \mathbf{3\%} \tag{1}$$

$$3\% \times 9{,}281\ kWh \approx \mathbf{278\ kWh} \tag{2}$$

Mechanical/Natural Ventilation Calculations

Using Equation 1 and 2, the baseline end-use distributions in Figures 8 and 9, and the relevant data in Chapter 4, the following calculations were used to determine the decrease in total energy consumption for a code compliant home:

$$17\% \times 51\% \approx \mathbf{9\%} \tag{1}$$

$$9\% \times 19{,}471\ kWh \approx \mathbf{1{,}752\ kWh} \tag{2}$$

Likewise, the following calculations were used to determine the decrease in total energy consumption for a high performance home:

$$17\% \times 28\% \approx \mathbf{5\%} \tag{1}$$

$$5\% \times 9{,}281\ kWh \approx \mathbf{464\ kWh} \tag{2}$$

Equipment and Appliance Tuning/Maintenance Calculations

Using Equation 1 and 2, the baseline end-use distributions in Figures 8 and 9, and the relevant data in Chapter 4, the following calculations were used to determine the decrease in total energy consumption for a code compliant home:

$$24\% \times 51\% \approx \mathbf{12}\% \tag{1}$$

$$12\% \times 19{,}471\ kWh \approx \mathbf{2{,}337\ kWh} \tag{2}$$

Likewise, the following calculations were used to determine the decrease in total energy consumption for a high performance home:

$$24\% \times 28\% \approx \mathbf{7}\% \tag{1}$$

$$7\% \times 9{,}281\ kWh \approx \mathbf{650\ kWh} \tag{2}$$

Equipment and Appliance Repair Calculations

Using Equation 1 and 2, the baseline end-use distributions in Figures 8 and 9, and the relevant data in Chapter 4, the following calculations were used to determine the decrease in total energy consumption for a code compliant home:

$$60\% \times 3\% \approx \mathbf{2}\% \tag{1}$$

$$2\% \times 19{,}471\ kWh \approx \mathbf{389\ kWh} \tag{2}$$

Likewise, the following calculations were used to determine the decrease in total energy consumption for a high performance home:

$$60\% \times 5\% \approx \mathbf{3}\% \tag{1}$$

$$3\% \times 9{,}281\ kWh \approx \mathbf{278\ kWh} \tag{2}$$

Weatherization Calculations

Using Equation 1 and 2, the baseline end-use distributions in Figures 8 and 9, and the relevant data in Chapter 4, the following calculations were used to determine the decrease in total energy consumption for a code compliant home:

$$15\% \times 51\% \approx \mathbf{8\%} \tag{1}$$

$$8\% \times 19{,}471 \; kWh \approx \mathbf{1{,}558 \; kWh} \tag{2}$$

Likewise, the following calculations were used to determine the decrease in total energy consumption for a high performance home:

$$15\% \times 28\% \approx \mathbf{4\%} \tag{1}$$

$$4\% \times 9{,}281 \; kWh \approx \mathbf{371 \; kWh} \tag{2}$$

Furniture Location Calculations

Using Equation 1 and 2, the baseline end-use distributions in Figures 8 and 9, and the relevant data in Chapter 4, the following calculations were used to determine the decrease in total energy consumption for a code compliant home:

$$14\% \times 51\% \approx \mathbf{7\%} \tag{1}$$

$$7\% \times 19{,}471 \; kWh \approx \mathbf{1{,}363 \; kWh} \tag{2}$$

Likewise, the following calculations were used to determine the decrease in total energy consumption for a high performance home:

$$14\% \times 28\% \approx \mathbf{4\%} \tag{1}$$

$$4\% \times 9{,}281 \; kWh \approx \mathbf{371 \; kWh} \tag{2}$$

Landscaping Calculations

Using Equation 1 and 2, the baseline end-use distributions in Figures 8 and 9, and the relevant data in Chapter 4, the following calculations were used to determine the decrease in total energy consumption for a code compliant home:

$$25\% \times 51\% \approx \mathbf{13}\% \tag{1}$$

$$13\% \times 19,471\ kWh \approx \mathbf{2,531\ kWh} \tag{2}$$

Likewise, the following calculations were used to determine the decrease in total energy consumption for a high performance home:

$$25\% \times 28\% \approx \mathbf{7}\% \tag{1}$$

$$7\% \times 9,281\ kWh \approx \mathbf{650\ kWh} \tag{2}$$