Sustainability and Residential Development:
A Guide to Cost-Efficient Green Building Technologies

By

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B.S. Civil Engineering
Massachusetts Institute of Technology, 2013

SUBMITTED TO THE DEPARTMENT OF CIVIL & ENVIRONMENTAL ENGINERING IN PARTIAL FULLFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF ENGINEERING IN CIVIL & ENVIRONMENTAL ENGINEERING
AT THE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
June 2014

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ABSTRACT

Given the upward trend of global energy consumption in recent decades, it has become imperative that countries reduce the amount of energy used on an annual basis. In America, the residential sector is one of the primary energy consumers, but many homeowners lack reliable information about how to build sustainable homes. This lack comes from the difficulty found in trying to quantify energy savings and costs of different sustainable technologies. Focusing on the commonwealth of Massachusetts, this thesis has compiled costs and energy savings for four different sustainable technologies- geothermal heating, heat recovery ventilation, triple-pane windows and a range of insulation materials. Considering all of these options, an interactive computer code was designed to take in inputs from the user about their home, calculate the energy needs of the home, and optimize the technologies and materials chosen based on a budget given by the user. The final result is a list of insulation choices for the walls, roof and floor of a home, the heating and ventilation systems, and window types for the highest energy savings within the users budget.

Keywords: Sustainable design, energy-efficiency, energy optimization, residential development

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ACKNOWLEDGEMENTS

I wish to extend my thanks to Professor Connor and Pierre Ghisbain, without whom this thesis would not have been possible. Their patience and support were crucial to the work that I have accomplished.

I must also profoundly thank my fiancé, Derek Lax, whose comments, suggestions, and editing helped transform this work. Most especially, his knowledge of computer science helped eliminate redundancy and foolishness in my code.

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CHAPTER 1. INTRODUCTION

It has been well-established[1] that the Earth's finite resources cannot sustain the current upward trend of consumption. As more and more countries improve their standard of living, there is a growing need for sustainable development and technologies to help reduce the depletion of these resources. A focus in recent years has been on the consumption of energy. As seen in Figure 1, when considering the global consumption of energy, the United States is the second largest consumer, after only China. As a country, it uses 19% of the total energy consumed worldwide per year, even though its relative population is only 4.5%.[2] This per capita usage signifies a large potential for reduction.

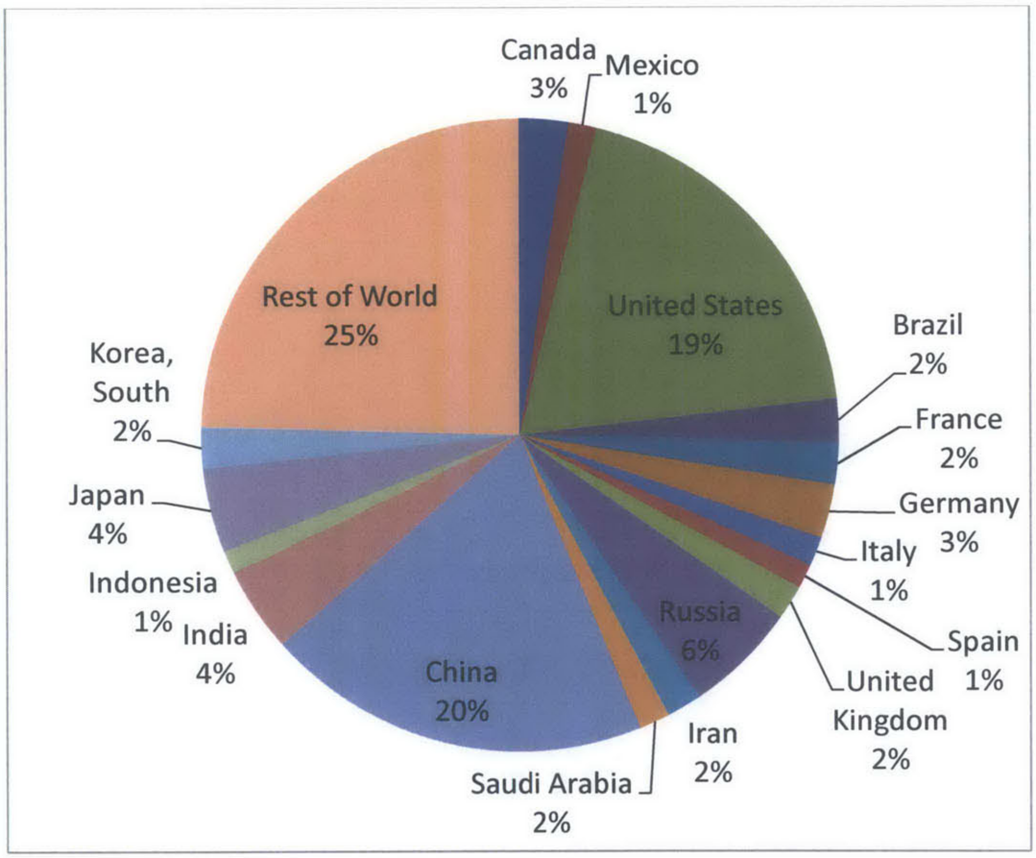

FIGURE 1: TOTAL PRIMARY ENERGY CONSUMPTION BREAKDOWN IN 2010[3]

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[1] Robins, 1999
[2] United States Census Bureau, 2014
[3] U.S. Energy Information Administration Independent Statistics & Analysis, 2014b

The United States' energy consumption, which was 95 quadrillion Btu in 2012, is sourced primarily from non-renewable sources.[4] As seen in Figure 2, the use of non-renewable energy sources such as petroleum and coal have decreased in recent years, but the majority of energy usage in the United States is still comprised of non-renewables. Given the dependence on these exhaustible resources, reducing energy consumption will have a large impact on global depletion of non-renewables.

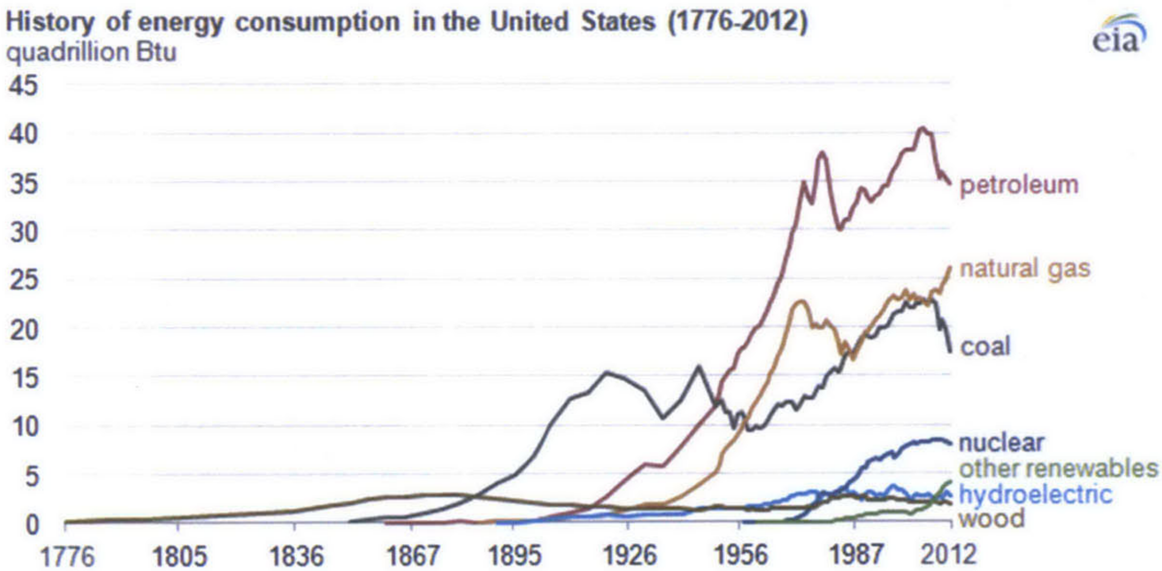

FIGURE 2: GRAPH SHOWING THE HISTORY OF ENERGY CONSUMPTION BY SOURCE[5]

While there are several sectors that consume a great deal of energy every year, including industry and transportation, the average American does not have the power to influence those consumption levels. However, a sizeable portion of energy every year (10% yearly) is used in the residential and commercial sector in building usage.[6] It is more feasible for an ordinary citizen to impact this sector, and for this reason this thesis will focus on the residential sector. Looking at Figure 3, the typical sources of energy come from natural gas and petroleum; however, homes also depend heavily on electricity, which is primarily created through coal and natural gas. While

[4] U.S. Energy Information Administration Independent Statistics & Analysis, 2013
[5] U.S. Energy Information Administration Independent Statistics & Analysis, 2012
[6] U.S. Energy Information Administration Independent Statistics & Analysis, 2012

there has been a marked increase in the use of renewable resources in the residential sector, a more productive change may be to simply reduce the energy consumption of the average home.[7]

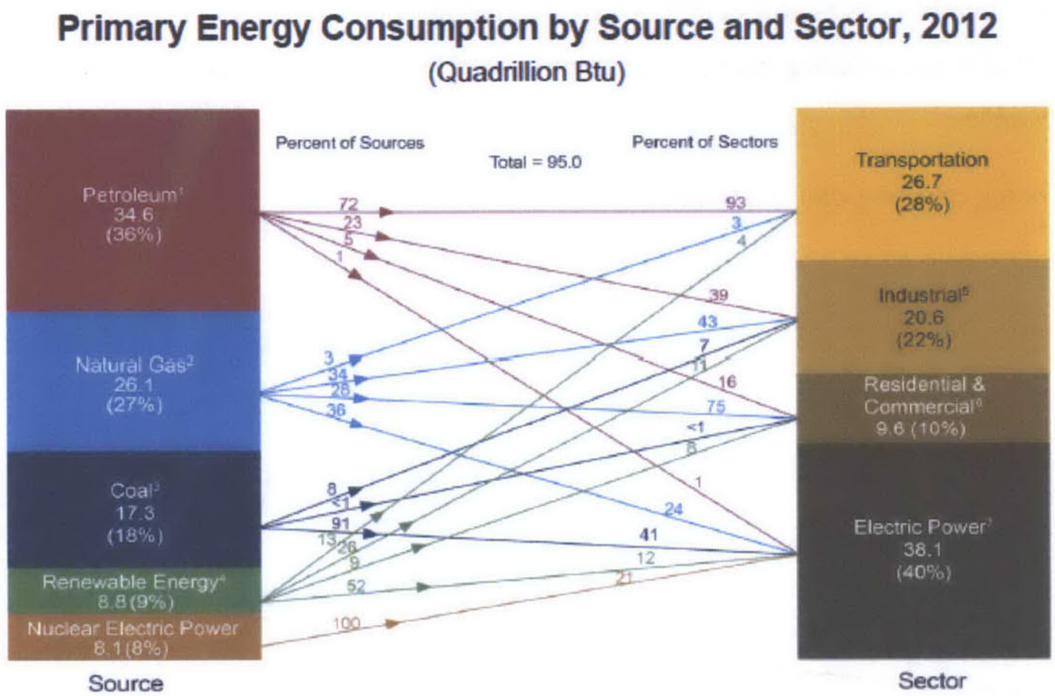

FIGURE 3: UNITED STATES ENERGY CONSUMPTION BY SOURCE AND SECTOR [8]

In residential development, the consumption of energy is spread over a variety of tasks. The primary four tasks are space heating, air conditioning, water heating, and appliances, electronics and lighting. Based on the Residential Energy Consumption Survey data collected in 2009, the primary energy sink in a house is space heating, followed by appliances, electronics and lighting and then water heating (Figure 3). Air conditioning is a relatively small portion of the total energy used in a home, averaging just 6% of the total in 2009. For this reason, this thesis focuses

[7] U.S. Energy Information Administration Independent Statistics & Analysis, 2014a
[8] U.S. Energy Information Administration Independent Statistics & Analysis, 2012

primarily on the heating loads and systems within a home, and does not exploring cooling.

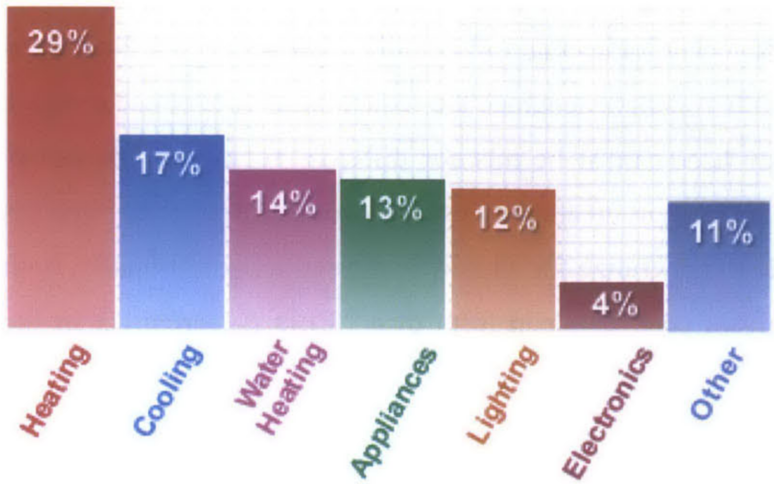

FIGURE 4: ENERGY USE IN HOMES BROKEN DOWN BY SECTOR [9]

Each of these energy sinks is influenced by a variety of factors, including insulation, appliance efficiency, HVAC (heating, ventilation and air conditioning) system choice, and many other design choices. A great deal of research has been done in improving these factors, and great strides have been made in increasing the efficiency of appliances and HVAC systems. Indeed, although the square footage of houses has almost tripled in the last 20 years, the energy used per household has remained almost the same.[10] Still, much more can be done by considering multiple sustainable technologies rather than focusing on a single technique. There are two major barriers to this improvement- the first is the lack of information or misinformation, and the second is cost.

A typical American homebuilder will not know about sustainable technologies when they go to build their own home. While many Americans are interested in sustainable practices and green design, very few have any background in these fields. As a result, building a green home requires a great deal of initiative on their part, which can be a large deterrent, especially those without a clear understanding of what sustainability in home design means. Further complicating the problem, many companies tout their "green" technology with phrases such as "low cost" or

[9] Energy Star, 2009
[10] U.S. Energy Information Administration Independent Statistics & Analysis, 2014a

"high efficiency." Other resources that a homebuilder might consider would be sustainable rating systems such as LEED or the Living Building Challenge. Unfortunately, these rating systems lack practical definitions of sustainable technologies that can be utilized or directions for how to implement them in the home. While both systems encourage the reduction of energy use in space heating, or require that certain energy levels must be met for different sectors of the home, neither give step-by-step instructions on how to create the desired outcome of sustainability, as these instructions would be impossible to generalize for all new construction. Additionally, both rating systems require a sizeable up-front cost, either in form of a LEED AP architect or the purchase of the manual, plus the costs of inspections and certification.[11] A cost-conscientious citizen, then, will find that LEED and other design specifications like it are not useful in increasing their knowledge of green home design. Thus the homebuilder is left at the mercy of the internet and his developer for this information.

This lack of readily available information stems from the specific nature of cost-efficient sustainable design for homes. While a list of sustainable techniques can be found simply via Google, determining the energy reduction, cost savings, and upfront costs of these techniques is virtually impossible. The reason for this is the variety allowed in home design. An incomplete list of factors which determine the potential energy savings and upfront costs for a home includes the size of the home, its location and orientation, the type of insulation chosen, and what kind of appliances and electronics are expected to be used. Accordingly, the estimation of benefits is an imprecise and often inaccurate task, making developers hesitant to hand out this information.

This thesis details a computer code which utilizes data from various developers to optimize spending for energy efficiency in new homes. This code will take several construction parameters into consideration and present a cost and benefit analysis at the technical level of the average consumer. The scope of this study will be limited to the state of Massachusetts, as a study of costs throughout the country is a much more intensive undertaking, but the hope is that this interface will be applicable to other states once cost and energy efficiency data is collected.

[11] LEED, 2014

CHAPTER 2. SUSTAINABLE TECHNOLOGIES

There are numerous ways to increase the sustainability and energy efficiency of a house. These range from the material choices made during construction to different home heating and cooling systems. Because of the wide variety of options available, this study focuses on technologies that have been identified as more common in new construction. The purpose of this limitation is to provide the homeowner with a reasonably sized and detailed set of options.

2.1 INSULATION

Insulation choices in a home can be instrumental in the overall performance of the structure, as they provide the first line of defense against the loss of hot or cold air (depending on the season). However, the thermal performance of a home does not come from just the labeled insulation that is traditionally thought of. Rather, every part of the structure influences the overall R-value of the walls. The R-value is a measurement of the thermal resistance of a material, as defined in Equation 1:

$$R = \frac{Q'_A}{\Delta T} = \frac{L}{k} \qquad \text{Eq. 1}$$

Q'_A: Heat transfer per unit area per second

ΔT: Temperature difference across material

L: Thickness of material

k: Thermal conductivity of material

The R-value is calculated based on every material that separates the interior and exterior of a building, including the walls, roof, and floor. And, similar to the idea that wrapping yourself in many blankets will keep you warmer than a single blanket, R-values are additive- each layer of material in the structure increases the overall thermal resistance of the building. The higher the thermal resistance (R-value) of the building, the less the ambient air will affect the internal temperature of the house. In the Commonwealth, this is far more critical in winter, when temperatures can dip below zero while comfortable interior temperatures range between 55°-75°F. For this reason, the insulation choices prompted in this analysis focus on lowering the heating needs of the house, and insulation is considered as it applied to winter conditions.

2.2 Geothermal Heating

Geothermal heating is the process of using latent ground heat in order to provide heating or cooling to the home. This technology has been used since the late 1940s, and is more efficient than standard HVAC systems because the ground temperature stays at a more moderate level year-round than the ambient air.[12] In Massachusetts, the average ground temperature is 50 degrees, with small variations depending on the season.[13] With winter temperatures that can fall below zero, this technology decreases the amount of energy needed to heat the home. Because Massachusetts is in the Northeast region and experiences longer winters than summer, the critical aspect of the geothermal system is how well it is able to heat the home. For this reason, geothermal systems are sized in Massachusetts based on the house's heating load, or the energy required to keep a home at a specific temperature over the period of an hour.[14] This calculation is explained in detail in Section V: Manual J.

Geothermal systems come in several different forms. They all use some form of a closed or open loop that transports a fluid (typically water) throughout the home, where convective heat transfer brings the air and liquid to temperature equilibrium.[15] At the end of the loop, the water exits the home and returns to the ground, where a similar process reverts its temperature back to the ground temperature. The method by which it returns to the ground is where the differentiation of the systems comes from. The first distinction is between vertical and horizontal systems. Vertical geothermal systems are wells, where a deep hole is drilled into the ground and fills with water. There are two types of geothermal well systems- closed loop and open loop. As the names suggest, the difference between the two lies in whether or not the water that travels through the house is in a closed circuit or an open one. A closed loop well keeps the water contained at all times within the piping that circulates the water between the ground and the home. An open loop well, on the other hand, allows the natural groundwater to flow into the piping, circulate through the house, and then be redeposited in the well. Open loop wells are less common than closed

[12] U.S. Department of Energy, 2012
[13] McQuay Air Conditioning, 2002
[14] U.S. Department of Energy, 2011
[15] Ibid

loop due to the regulations that exist with groundwater removal and usage.[16] For this reason, they are not considered in this thesis as potential options for the average homebuilder. Closed loop wells also have certain restrictions on them, but are common in sites where a large amount of open space is not available.[17]

If the site of the house has sufficient space, horizontal loops are preferred over wells for several reasons including cost. Horizontal loops involve digging a long, narrow trench below the frost line and placing the piping within. While this trench is slender, typically four to six inches wide, it can be hundreds of feet long depending on the heating load of the home.[18] Therefore horizontal loops are only installed in homes that have a certain amount of yard space.

The efficiency of a geothermal system is measured based on the change in temperature achieved by running the loops in close contact with the ground. The difference between the leaving water temperature and the entering water temperature averages between 6°-8° F for a "good" system.[19] While this value may appear small, in reality this difference makes a marked change in the performance of the home, and causes a large increase in efficiency of the system.[20] As a result, geothermal systems provide significant energy savings compared to traditional methods.

2.3 Heat-Recovery Ventilation

Another significant source of heat loss is through the ventilation of the house. Based on the comfort standards defined by the American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE), a residential home must have a certain amount of ventilation to provide fresh air.[21] The amount of ventilation (V) required depends on the occupancy level of the home as well as its size. This formula is shown in Equation 2.

$$V = R_p * P_z + R_a * A_z \qquad \text{Eq. 2}$$

R_p: Outdoor airflow rate required per person based on occupancy

[16] Simon, 2014
[17] U.S. Department of Energy, 2011
[18] Simon, 2014
[19] Ibid
[20] U.S. Department of Energy, 2011
[21] ASHRAE, 2013

P_z: Occupancy of home (number of people)

R_a: Outdoor airflow rate required per unit area

A_z: Net occupiable floor area of the ventilation zone

The default occupancy for dwelling units is two persons minimum for a single bedroom, plus one person for each additional bedroom.[22] The outdoor airflow rates are taken from ASHRAE specification 62.2 2013.

Ventilation causes heat loss when fresh air enters the home at the temperature of the ambient air outside. In a controlled temperature environment, this will negatively impact the temperature in the home and cause more energy to be spent moderating the temperature. Heat recovery ventilation is a process that was designed to mitigate this problem. It uses a gas-based heat exchanger to reduce the temperature difference of the incoming air.[23] An example of this is shown in Figure 5. This process reduces heat loss due to ventilation while still preserving the air quality of the home.

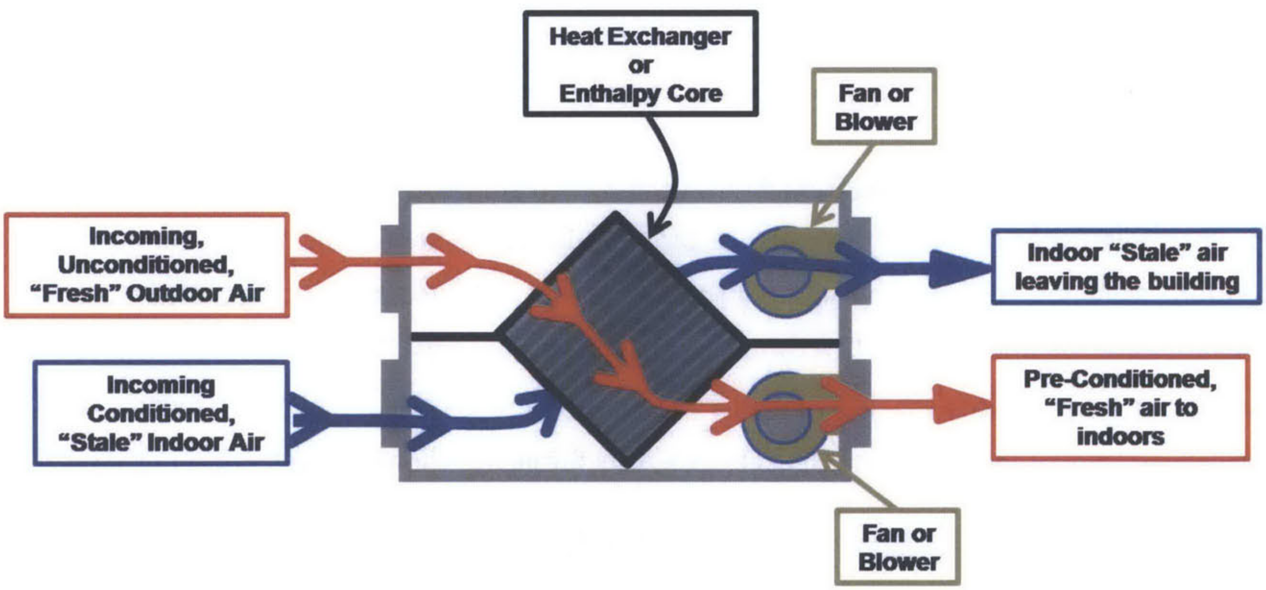

FIGURE 5: HEAT RECOVERY VENTILATION

[22] ASHRAE, 2013

[23] Rudd, 2011

2.4 Windows

Fenestration in the exterior of a home reduces the benefits provided by the insulation. Windows in particular cause a home to have a lower thermal resistance due to the high emissivity of glass. Current energy-efficient windows have features such as double or triple panes, gas filled spacing, and low-emissivity coatings.[24] Each of these features lowers the rate of heat loss of the window: multiple panes creates several layers of glass for the temperature difference to work across, effectively doubling or tripling the base R-value of the glass. By filling the gaps between these panes with different types of gas such as argon, krypton or xenon, which have a higher thermal resistance than air, yet another layer of thermal resistance is added to the overall structure. Finally, low-emissivity coatings on the glass help increase the reflection of heat, which helps keep heat inside during the winter and heat from the sunlight out during the summer.

The second component of a window is the frame in which the glass is placed. The frame keeps the glass aligned properly and allows the window to be easily installed. Frames are typically made of wood, aluminum, vinyl, fiberglass, or a composite of these materials.[25] They can be selected for a variety of different factors, including style, cost, weight and upkeep. Energy efficiency in framing comes from the material choices and the tightness of construction- even the frame with the highest thermal resistance will be inefficient if there are gaps in between the frame and the wall of the house.

The final component of a window is the spacer, which separates and maintains the space between the panes of glass (assuming a multi-pane window). The spacer influences the thermal resistance of the window depending on its conductance e.g. metal spacers conduct temperature more easily than wooden spacers. Spacers are therefore chosen based on their material properties, and materials with lower conductivity are better for energy efficiency. Given the scope of this project, however, spacers were not considered in calculating the overall thermal resistance of the window.

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[24] National Fenestration Rating Council, 2012
[25] National Fenestration Rating Council, 2012

CHAPTER 3. DATA SOURCES

To begin this analysis of cost-efficient sustainable technologies in residential construction, data was collected from a variety of Massachusetts-based companies that specialize in different areas related to green construction. The data collected ranged from material properties, installation and equipment costs, energy efficiency, and cost savings over time.

3.1 EKOTROPE

The first of these companies is an MIT startup called Ekotrope, which specializes in gathering information about wall, floor and roof insulation to provide homebuilders with cost analysis for different home materials. Ekotrope's data includes more than 20 of the most common wall, floor and roof material choices (Table 1). This data was compiled through relationships with many construction companies and developers nationwide who gave data on the cost of common insulation choices for construction.[26] These costs were taken from existing projects, and so are averages of many different projects throughout the states. Because there are fluctuations in prices depending on the geographic location of the house, Ekotrope's data was discretized based on the state the project is built in, which allows for a more accurate cost estimation. In addition to cost data, Ekotrope also determined standard depths for these insulation choices. Most of the materials listed can be of any thickness, but several types of insulation come in "standard" sizes, meaning that they are sold only in a specific shape. An example of this would be asphalt shingles, which are typically manufactured in 0.5 inch thicknesses.[27]

3.2 ENERGYSQUID

A second source of data was a consulting company called EnergySquid. This company focuses primarily on geothermal heating systems, and has over two decades of experience with residential installation. EnergySquid is a local company and works primarily in the Northeast, and so the data they have provided is relevant to the local costs in Massachusetts. In particular, this company provided information regarding the choice of loops based on site conditions, the calculations behind efficiency and coefficients of performance for equipment, and the costs of

[26] Sisler, 2014
[27] Ekotrope, 2014

the equipment and installation. Because the size of a geothermal system is based on the heating load of the home, EnergySquid provided the total cost and heating loads of previously erected homes in Massachusetts. Their data ranged between $6,000 - $10,000 per ton.[28]

3.3 HOMEWYSE

The third company that provided data is an online reference tool called Homewyse. This company, founded in 2006, focuses on compiling data from home design and construction professionals nationwide. Their data is taken from existing projects across America. Their goal is to offer comparisons for vendor quotes by providing an upper and lower bound for similar projects in the same area, as well as an average cost for the same service. The data includes material and labor costs for heat-recovery ventilation systems and for double and triple pane windows.

Heat recovery ventilation systems are measured by flow rate in cubic feet per minute (cfm), and by efficiency.[29] While Homewyse offers pricing for systems below 82% efficient, this thesis assumes that any HRV system installed would be greater than 82% and so only considers those costs. There are three options for the volume of air circulated every minute- 125 cfm, 175 cfm, and 250 cfm. Because there is a range of prices, depending on the vendor and other factors, Homewyse provides a low and a high estimate for each of these options. They also include the quality of the unit, which has three options- basic (builder grade), better (value grade), and premium grade. To simplify these options, an average unit quality cost was assumed (value grade), and the average of low and high estimates was taken for each option. The installation was assumed to be performed by a licensed and bonded contractor.

Homewyse also offers a range of prices for different windows. In particular, they supply the labor and installation costs for windows of several different sizes. This installation is assumed to be performed by the vendor and was a basic grade window.

[28] Simon, 2014
[29] Homewyse, 2014b

3.4 Lowes & Home Depot

Lowes and Home Depot are retail stores that sell home improvement and construction products. They provide services at more than 3,900 locations in North America and Australia and offer a selection of windows for home owners.[30] Their online products were used to provide cost data for different window types.

[30] United States Securities and Exchange Commission, 2011

CHAPTER 4. DATA

The data used in this thesis was collected from a variety of sources, including census polls, the Energy Information Agency, and several Massachusetts-based companies. The values used for each insulation material, window option, heating system and ventilation method are shown in the following sections.

4.1 INSULATION DATA

All insulation data was used with permission from Ekotrope. There are two types of insulation shown in Table 1- the first has a variable depth, and corresponding costs and R-values per inch of depth. The second type of insulation has a standard depth, and for the purpose of this thesis this depth was not editable by the user.

TABLE 1: INSULATION MATERIALS WITH R-VALUES, COST AND TYPICAL DEPTHS FROM EKOTROPE[31]

Materials with Variable Depths	R-Value per Inch of Depth	Cost per Sq. Ft. per Inch of Depth	Typical Depth (in.)
XPS	5.00	$ 1.15	n/a
EPS	3.90	$ 0.85	n/a
Polyisocyanurate (Foil Faced)	6.50	$ 1.20	n/a
Spray Foam (LD Polyurethane)	3.70	$ 0.35	n/a
Spray Foam (HD Polyurethane)	6.50	$ 1.05	n/a
Cellulose Spray	3.20	$ 0.40	n/a
Cellulose Blown	3.70	$ 0.35	n/a
Fiberglass Dense Pack	4.00	$ 0.35	n/a
Fiberglass Batts	3.50	$ 0.15	n/a
Mineral Wool Batts	3.30	$ 0.25	n/a
Fiberboard	2.60	$ 1.40	n/a
Particle Board	1.10	$ 0.70	n/a
Brick	0.22	$ 2.20	n/a
Cellulose (attic)	3.70	$ 0.15	n/a
Concrete / Stucco / Cement Block	0.15	$ 0.15	n/a

31 Ekotrope, 2014

Standardized Materials	R-Value	Cost per Sq. Ft.		Typical Depth (in.)
Plywood / OSB	0.63	$	0.50	0.50
Sheetrock	0.45	$	0.82	0.50
Siding Wood	0.60	$	3.00	0.50
Shingles (wood)	0.60	$	3.00	0.50
Shingles (asphalt)	0.30	$	1.25	0.50
Carpet	2.00	$	2.00	0.75
Finish Wood	1.00	$	7.50	0.75
1/2 in. insulated sheathing	3.40	$	1.45	0.50
1 in insulated sheathing	6.20	$	2.08	1.00
Housewrap	0.10	$	0.10	0.10
Siding Vinyl	0.15	$	1.00	0.25

4.2 Geothermal Data

The variability in geothermal costs causes collecting accurate data to be very difficult. The data shown in Figure 6 is a collection from several sources including EnergySquid. Each data point represents costs incurred by the type of loop chosen, the surrounding topology of the site, the size of the lot the house is placed on, and other factors that are unique to each.[32,33,34] For this reason a best approximation has been chosen, assuming a linear relationship between the cost and the tonnage of heating required. A value of $7,500 per tonnage of heating was used in all calculations.

[32] Geothermal Genius, 2011
[33] Geothermal Genius, 2013
[34] Simon, 2014

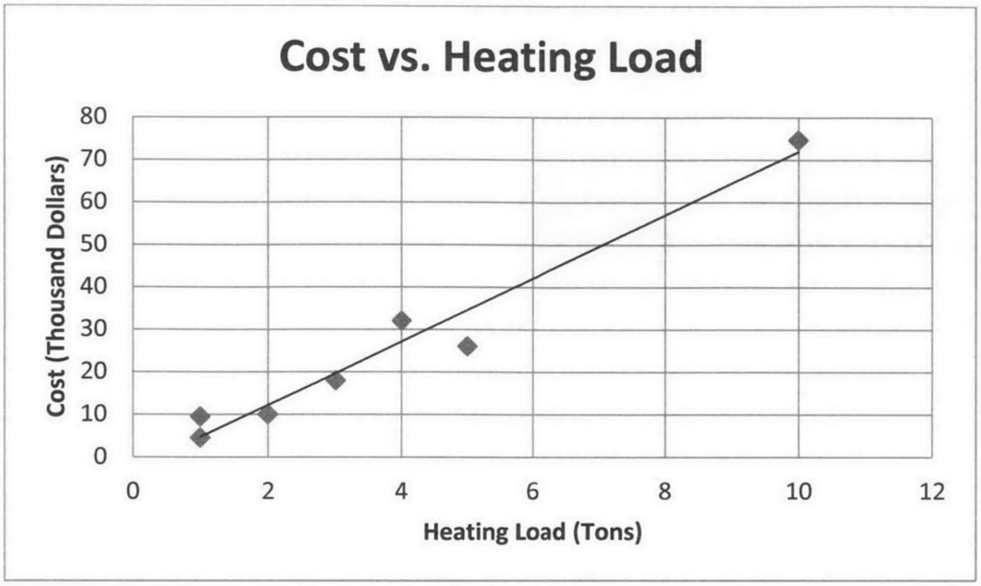


FIGURE 6: COSTS AND HEATING LOADS FOR GEOTHERMAL SYSTEMS IN NEWLY CONSTRUCTED HOMES[35,36,37]

4.3 Heating System Data

The comparable cost of heating a home without using a geothermal system is difficult to measure, given that there are many different options for heating. Different sources of fuel, different types of pumps, and different efficiency levels are some of the variations that make estimation difficult. Therefore instead of using specific pieces of equipment or individual heating systems, the heating cost was estimated based on the average cost of HVAC per square foot. Using data taken from the National Association of Home Builders, which catalogued the average price of HVAC systems to be $8,760 and the average size of the homes queried to be 2,311 square feet, a value of $3.79 per square foot was used in all calculations.[38]

4.4 Ventilation Data

The data take from Homewyse is a set of average costs for three different sizes of ventilation needs. While these averages are necessary for a complete analysis, they do eliminate some of the variability that comes with all construction estimates. Table 2 shows the averages for each of the three possible heat-recovery ventilation systems.

[35] Water Energy, 2014
[36] Geothermal Genius, 2013
[37] Simon, 2014
[38] Taylor, 2011

TABLE 2: HEAT RECOVERY VENTILATION COSTS, TAKEN FROM HOMEWYSE[39]

	Materials	Labor	Total
≥ 82% Efficient			
125 cfm	$ 1,303.83	$ 403.50	$ 1,707.33
175 cfm	$ 1,709.50	$ 403.50	$ 2,113.00
250 cfm	$ 2,342.00	$ 403.50	$ 2,745.50

4.5 Window Data

Window costs and insulation values were taken from Homewyse, Lowes and Home Depot. Homewyse provided the installation and labor costs for a window of five different possible sizes: for double pane glass, there are 3'x2', 3'x3', 3'x4', and 3'x5,'and for triple pane glass there is a 3'x3'. Both Home Depot and Lowe's sell similar, if not identical products, and so an average cost for each of the five windows was calculated for windows sold in Massachusetts. Each window was chosen based on its size, but also had a low emissivity glazing but no insulating gas between panes. Table 3 shows the installation costs, product costs and U-Value for each of the five window sizes.

TABLE 3: U-VALUE, INSTALLATION AND UNIT COSTS FOR WINDOWS[40,41,42]

	Window Size				
	3'x2'	3'x3'	3'x3'	3'x4'	3'x5'
Number of Panes	2	2	3	2	2
Installation Cost	$ 235.90	$ 235.90	$ 235.90	$ 236.05	$ 241.05
Unit Cost	$ 74.00	$ 82.00	$ 335.00	$ 179.00	$ 181.00
Total Cost	$ 309.90	$ 317.90	$ 570.90	$ 415.05	$ 422.05
U-Value	0.32	0.32	0.21	0.34	0.34

[39] Homewyse, 2014b
[40] Homewyse, 2014a
[41] Lowe's, 2014
[42] Home Depot, 2013

CHAPTER 5. ANALYSIS METHOD

This section details the equations and logic used to create the interactive computer code (Appendix I) that performs a cost-benefit analysis based on the user's input. This code allows to user to input the home's current design, including number of floors, square footage, number of windows and doors, and insulation choices for the walls, roof and floor. From these choices, the user can select an initial sum of money that the user is willing to pay upfront in addition to the cost of their current design for a more sustainable house. It then performs an exhaustive search through all of the possible options to return a list of the most energy-efficient choices for insulation, heating system, ventilation and window selection that fit within that specified budget.

The first step of this energy efficient cost-benefit analysis is to determine the necessary heat required per hour to keep a house at a constant temperature. This is calculated using code written by the Air Conditioning Contractors of America (ACCA) called Manual J. This code takes into account many factors that define how well a house absorbs and retains heat, including geographic location, orientation to the sun, insulation, window choice, shading, ventilation levels, number of occupants, and internal loads from electronics, lighting and appliances.[43] For the purpose of this thesis, only those factors that influence the heating load were considered.

5.1 MANUAL J

In order to determine the heating load of the home, the user is asked for specifics regarding their home. The first components the user is asked for are the windows and doors: the number of external doors in the home, the number of windows in the home, the number of panes for each window, and the average size of each window. The equation for the heat loss (Q) for windows is shown in Equation 3.[44]

$$Q = nCA \qquad \text{Eq. 3}$$

n: Number of windows in home

C: Coefficient of heat loss: 1.4 for single pane windows, 0.9 for double pane windows, and 0.6 for triple pane windows

[43] Burdick, Arlan, 2011

[44] City of Brainerd, 2009

A: Average area of a window

The equation for heat loss through doors is similar (Equation 4).

$$Q = nCA \qquad \text{Eq. 4}$$

n: Number of external doors in home

C: Coefficient of heat loss, 2.2

A: Average area of a door (typically 2880 in^2)

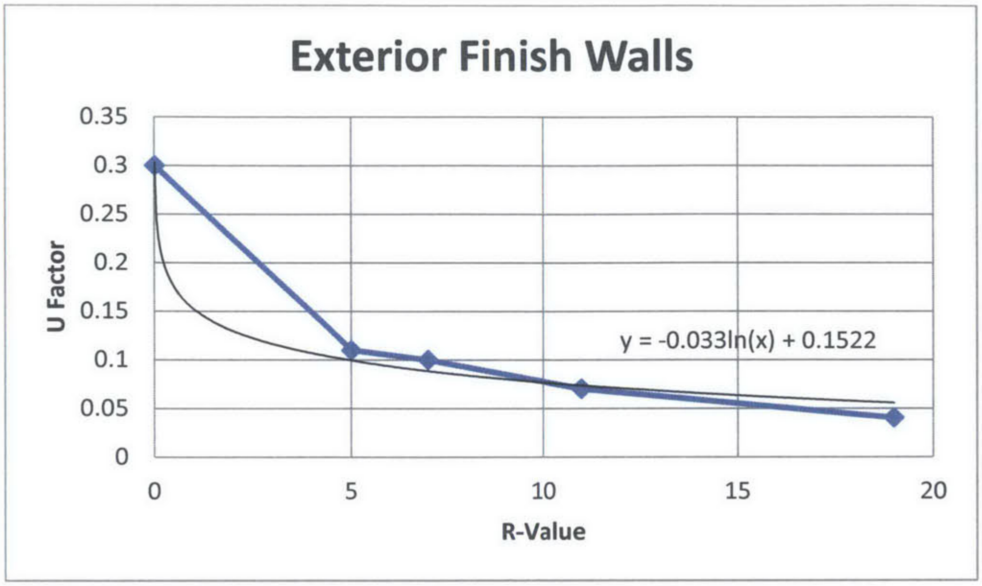
Once the heat loss for the windows and doors has been calculated, the heat lost through insulation is calculated. There are three parts of a home that require insulation- the walls, the roof, and the floor. The heat loss from each of these surfaces is calculated using Equation 5.

$$Q = AU_f \qquad \text{Eq. 5}$$

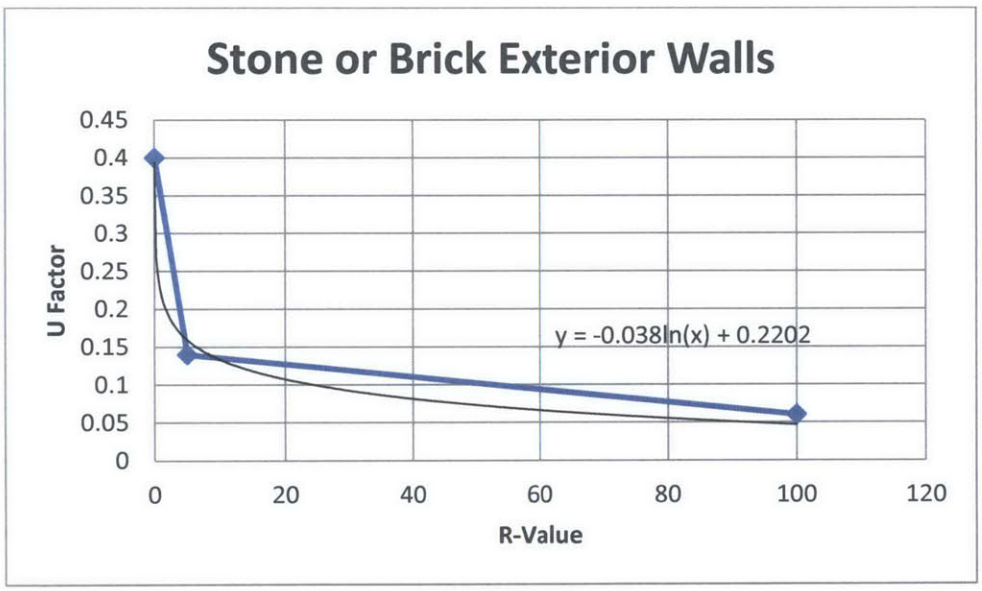
U_f: U-Factor multiplier relating to the R-value of the insulation, taken from Manual J Table 2

A: Net area of surface: Gross surface area minus window and door areas

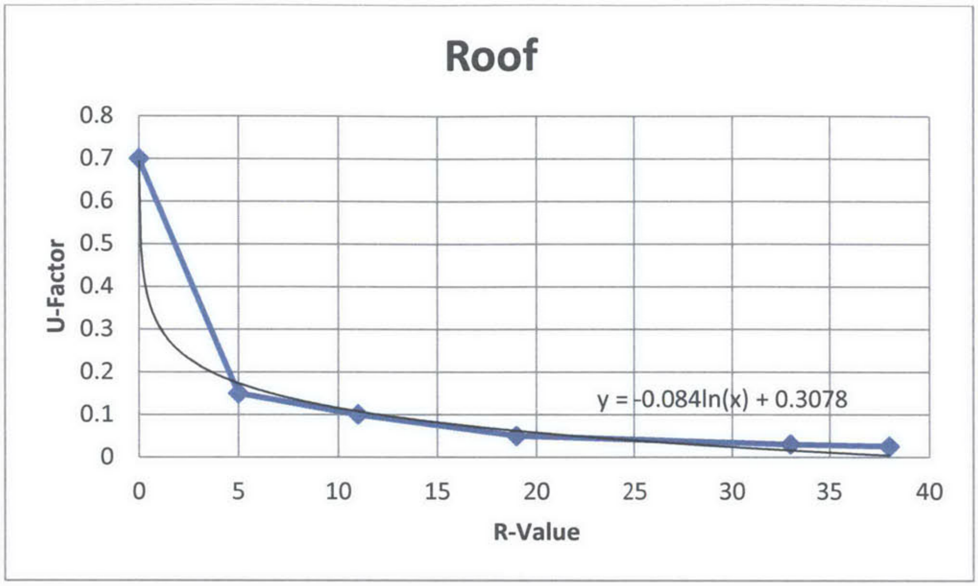
The U-Factor is determined through interpolation of the data provided in Manual J Table 2. It is based on the total R-value of the surface, which comes from the insulation selected for the home. Because the insulation for each home can vary significantly, and thus have a range of R-values, the data provided in Manual J Table 2 was plotted and U-Factors were determined using a best fit line, as seen in Figure 7 (a)-(d).



Exterior Finish Walls
U Factor
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
5
10
15
20
R-Value
y = -0.033ln(x) + 0.1522



Stone or Brick Exterior Walls
U Factor
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
20
40
60
80
100
120
R-Value
y = -0.038ln(x) + 0.2202



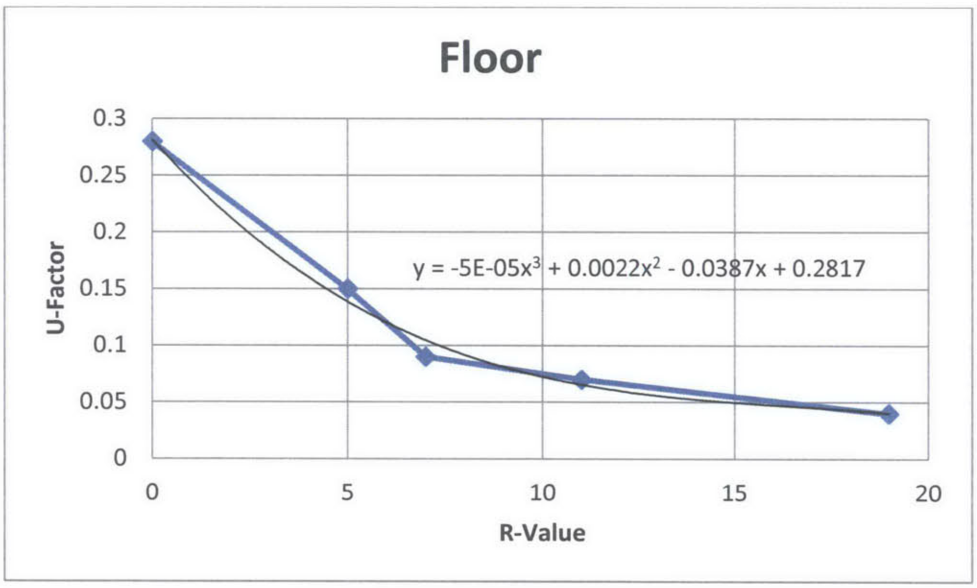


FIGURE 7: DATA FROM ACCA MANUAL J SHOWING RELATIONSHIP BETWEEN U-FACTOR AND R-VALUE[45]

Each of these U-Factors is measured per degree Fahrenheit temperature difference between the desired indoor temperature and the ambient air. Massachusetts is a marine climate, with an average winter temperature of 5° F.[46] The indoor design temperature in winter is 75° F, providing a difference of 70° F. Therefore the U-Factor multiplier used to calculate the heat loss is taken from one of the graphs in Figure 7 times a 70 degree temperature difference.

[45] ACCA, 2014

[46] U.S. Department of Energy, 2009

The total heat loss is then the combination of heat loss from the windows, doors, and insulation from the walls, floor and roof. This heat loss is calculated in Btu and then converted to heating tons, using the conversion:

$$12{,}000\ Btu = 1\ ton$$

This heating load is subsequently used for energy efficiency optimization in the home's design choices.

5.2 Energy Savings

Once the heating load is calculated, the energy savings per year for each of the possible options in insulation, heating systems, ventilation, and windows was determined. For insulation, these energy savings were calculated in the following manner. Due to the scope of this thesis, a maximum of four layers of insulation was considered. For each layer, the user is allowed to select one of the insulation materials from Table 1, with the caveat that unrealistic inputs (such as insulation that is several feet thick) will generate nonsense results. Using dimensional analysis, each R-value is translated into Btus expended per year (Equation 6).

$$Btu = \frac{t*T*A}{R} \qquad \text{Eq. 6}$$

t: Time in hours, = 365*24 = 8760

T: Temperature difference across the insulation surface, in °F, = 70

A: Area of insulation surface, in ft^2

The energy used per year is calculated for all insulation options, which functions as an effective performance comparison between them.

The same formula and process is used to measure the energy savings of the window choices, with the main difference being that the area is much smaller and is calculated as the average area of a window multiplied by the number of windows in the home, both of which are user inputs. The thickness of a window pane is assumed to be 1/8 inch, so a double pane window would have a thickness of 1/4 inch.

The user is presented with two options for a heating system- either a traditional HVAC or a geothermal system. The energy savings of the system chosen are calculated based on the coefficient of performance. Energy efficient systems that are not geothermal have a slightly different metric called the annual fuel utilization efficiency (AFUE), which measures the same efficiency of energy in divided by energy produced.[47] Current furnaces and other heating systems have an AFUE of up to 97, or 97% efficient.[48] Geothermal systems are much more efficient with fuel, however, due to their ability to use passive heating from the earth, and have a much higher range of coefficients, typically between 300 – 600%.[49] For the purpose of this analysis, an AFUE of 97 was assumed for a non-geothermal heating system, and a CoP of 450% was assumed for the geothermal system. This creates a difference in efficiency of 353%, which becomes the energy savings per year of a geothermal system using Equation 7:

$$C = \frac{Q}{W} \qquad \text{Eq. 7}$$

C: Percent difference in efficiency

Q: Heat energy outputted annually, Btus

W: Energy inputted annually, Btus

Taking Q to be the heating load of the home as calculated by Manual J, the difference in energy inputted annually can be found in order to compare the geothermal and non-geothermal system.

For heat recovery ventilation, EnergyStar has a list of requirements for a ventilator to qualify as 'high efficiency.' There are several requirements that must be met, including a "sensible heat-recovery efficiency (SRE)" that allows for fan energy, leakage and other energy gain and losses.[50] The SRE required is 65% at 32°F, and for the analysis that is the efficiency used. Given that ventilation accounts for approximately 30% of the total heating costs for a home,[51] the energy saved per year can be calculated as:

$$E_{annual\ savings} = (0.65)(0.30)HL \qquad \text{Eq. 8}$$

HL: Heating load calculated from Manual J, in Btu

[47] ASHRAE Handbook, 2004
[48] Energy Star, 2014
[49] U.S. Department of Energy, 2011
[50] Energy Star, 2010
[51] Akbari and Oman, 2013

From these calculations, the energy savings of the four different sustainable technologies are calculated on an annual basis.

5.3 Costs

The initial costs for each of the four sustainable technologies can be found in the "Data" section. The energy savings calculated in the previous section are translated into dollar savings using the average cost of electricity in Massachusetts in 2013. Given that 1 kWh = 3,412.1 Btu and that 1 kWh is $12.34,[52] the relationship between energy saved and dollars saved is approximately $0.00362 per Btu.

5.4 User Interface

The program begins with a set of instructions on how to use the interface. These instructions are meant to help eliminate user error or confusion. The instructions include the following:

- All areas must be entered in units of square feet
- All insulation thicknesses must be entered in units of inches
- Only positive numbers may be entered
- The button "Populate Typical Insulation Choices" will automatically set all 12 layers of insulation to typical materials and thicknesses for Massachusetts homes
- The button "'Update Insulation Thicknesses' will check all 12 insulation materials and populate the thicknesses for those materials that come in a 'standard' thickness

Once the user presses the "next" button, a series of dropdown boxes and text fields appears for user inputs. These include the choices for insulation material and thicknesses for all 4 layers of insulation for the floor, roof and walls, as well as inputs to calculate the manual J loading. These inputs include the number of windows and doors, the average area of the windows, the number of panes per window (either 2 or 3), the surface areas of the floor, roof and walls, the number of rooms, and the number of floors (Figure 8).

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[52] U.S. Energy Information Administration Independent Statistics & Analysis, 2014a

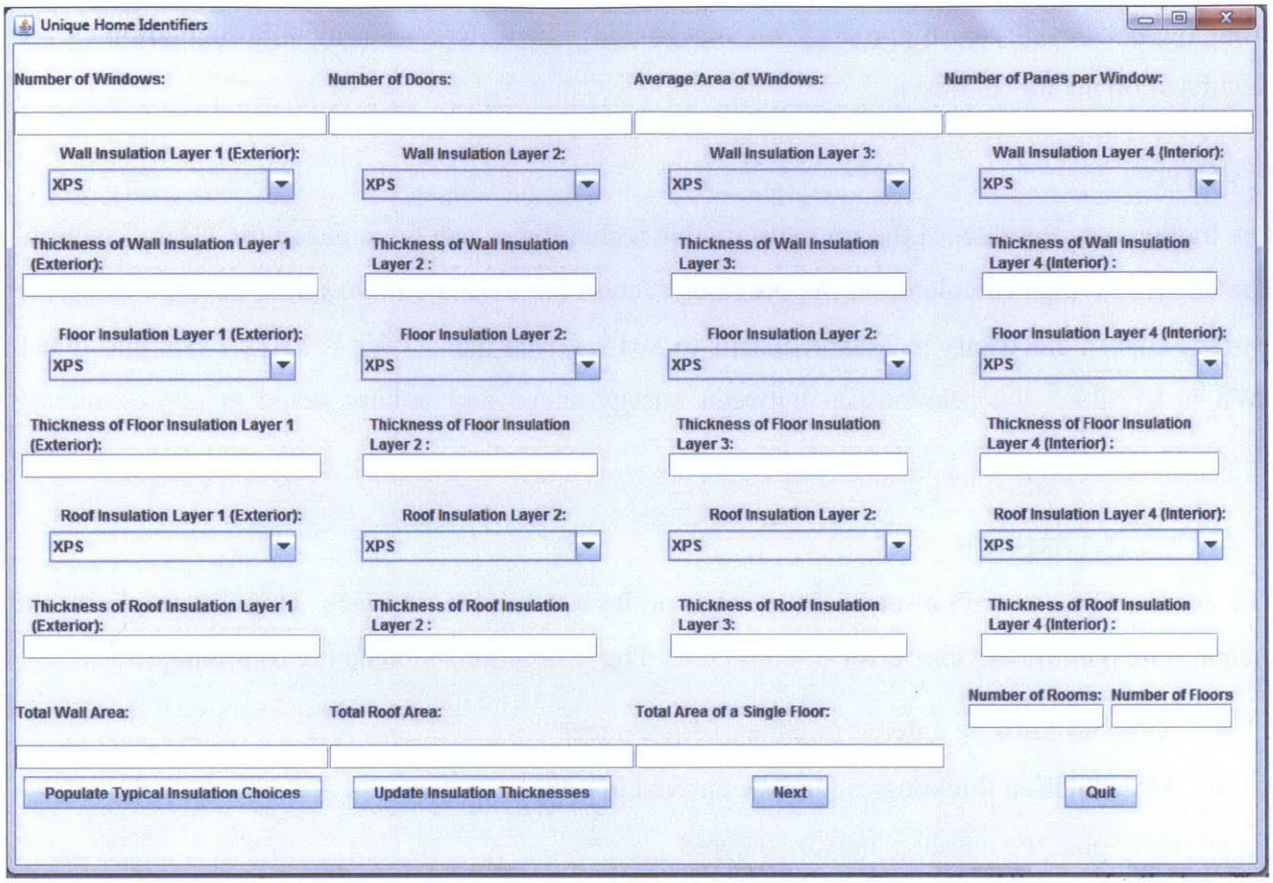

FIGURE 8: USER INTERFACE WINDOW

5.5 Optimization of Up-Front Costs

The first optimization this code performs assumes an upper bound for the amount of money the homebuilder is willing to spend out of pocket. This amount is an input that the user will put in, and can be any positive number. The code then determines the optimal choice of insulation layers, window type, heating system and ventilation to maximize energy savings while not exceeding the budget the user has specified.

This type of problem is known as a linear multiple-choice knapsack problem; there are distinct categories, each containing a set of options from which only one may be picked. The selection from each category is dependent on the size of the knapsack (in this case, the budget of the homebuilder), and its value (in this case, the energy savings). To skim the surface of the murky depths that is computational science, this problem has been determined to be NP-hard, which means there is no existing algorithm which give the optimal solution in polynomial time.[53] Problems that cannot be solved in polynomial time are solved in exponential time, which means that they require an exhaustive search through all possible options. With no restrictions on the selection of options for insulation, windows, heating system and ventilation, there are over 1.4 trillion possible combinations. In order to reduce this number several eliminations were made based on construction practicalities. The first eliminations came from the different layers of insulation for the floor, roof and walls. There are four layers for each insulation surface, and in the interface, the user can select any of the options shown in Table 1 for each layer. However, in real construction, a home must have weather-resistant materials on the exterior of the home, and interior materials that support the functionality of the surface (i.e. walking on the floor, leaning against the wall). This eliminates a sizeable number of insulation materials from the first and fourth layers. Additionally, the interior layers could not be those interior or exterior materials, and the assumption was made that they could not be duplicates (i.e. layer 2 and layer 3 could not both be fiberglass batts). Finally, because the code is expected to run on the average modern computer, the memory footprint was ensured to be less than 512MB. Accordingly, further eliminations were made for very similar materials and materials that are very energy efficient. Only LD spray foam was considered, as it has almost twice as large an R-Value per dollar as HD spray foam. Similarly spray cellulose, dense pack fiberglass, wood shingles, ½ inch insulated sheathing, and vinyl siding were all eliminated from the possible options for an optimal solution. Table xx shows the possible options for each layer for the floor, roof, and walls.

TABLE 4: FLOOR, ROOF AND WALL INSULATION CHOICES FOR OPTIMIZATION

Floor			
Layer 1	Layer 2	Layer 3	Layer 4
Housewrap	Fiberboard	XPS	Carpet
	Particle Board	EPS	
	Plywood / OSB	Polyisocyanurate (Foil Faced)	
	Sheetrock	Spray Foam (LD Polyurethane)	
		Cellulose Blown	

[53] Akbar et al., 2006

Roof			
Layer 1	Layer 2	Layer 3	Layer 4
Asphalt Shingles	Fiberboard	XPS	Sheetrock
Concrete / Stucco / Cement Block	Plywood / OSB	EPS	Fiberboard
	Sheetrock	Polyisocyanurate (Foil Faced)	Particle Board
	Housewrap	Spray Foam (LD Polyurethane)	Plywood / OSB
		Cellulose Blown	
		Fiberglass Batts	
		Mineral Wool Batts	

Walls			
Layer 1	Layer 2	Layer 3	Layer 4
Concrete / Stucco / Cement Block	Fiberboard	XPS	Sheetrock
Siding Wood	Plywood / OSB	EPS	Fiberboard
Siding Vinyl	Sheetrock	Polyisocyanurate (Foil Faced)	Particle Board
	Housewrap	Spray Foam (LD Polyurethane)	Plywood / OSB
		Cellulose Blown	
		Fiberglass Batts	
		Mineral Wool Batts	

Additionally, only two options were permitted for a heat recovery ventilator- having one or not. While there were several sizes of ventilator that were analyzed that had different costs, those are dependent on the size of the home, and so for the analysis, the cost of the heat recovery ventilator is selected from those three possibilities based on the size of the home.

With these restrictions placed on the possible combination, the exhaustive search examines approximately 22 million options. The calculations for this exhaustive search are found in the class Exhaustive (Appendix I). It begins by creating 15 Sets, which correspond to the 15 distinct choices that can be optimized (these include the four layers for the floor, roof and walls, and the windows, heating system and ventilation). Within each of these sets are two arrays that correspond to each suboption's cost and energy savings per year. For example, the Set for roof layer 1 has two possible suboptions, asphalt shingles and concrete. Thus this Set will have two arrays of length two, with the first index in both arrays corresponding to asphalt shingles and the second index corresponding to concrete.

Once all Sets have been created, several methods are implemented that perform an exhaustive search over all possible combinations. The combination with the highest energy savings whose cost does not exceed the users budget is selected as the optimal choice and displayed to the user.

CHAPTER 6. CONCLUSION

The primary output of this thesis is the interactive code, which can be found in Appendix I. However, the specifications of a "standardized" home were inputted into the code to ensure that all required functionality was met. Furthermore, optimization was done for a user budget of $1,000.

6.1 TYPICAL HOME VALUES

Standard insulation was chosen based on Ekotrope's default choices for insulation for a Massachusetts home. These choices are:

- Floor (from outside to inside): 0.1 inches of Housewrap, 6 inches of Fiberglass Batts, 0.5 inches of Plywood, and 0.75 inches of Finish Wood
- Roof (from outside to inside): 0.5 inches of Wooden Shingles, 6 inches of Fiberglass Batts, and 0.5 inches of Sheetrock
- Walls (from outside to inside): 0.5 inches of Wood Siding, 0.1 inches of Housewrap, 6 inches of Fiberglass Batts, and 0.5 inches of Sheetrock

Windows were assumed to be a size of 3'x3', as this is the median size of all the possible window options. They were double-pane windows, as triple-pane windows are not as commonly found and because triple-pane windows are the "energy-efficient" option in this optimization.

Floor and roof area was assumed to be 1000 square feet, while the gross wall area was assumed to be 5000 square feet. This house has five rooms, two floors, and three exterior doors. These inputs can be seen in Figure 9.

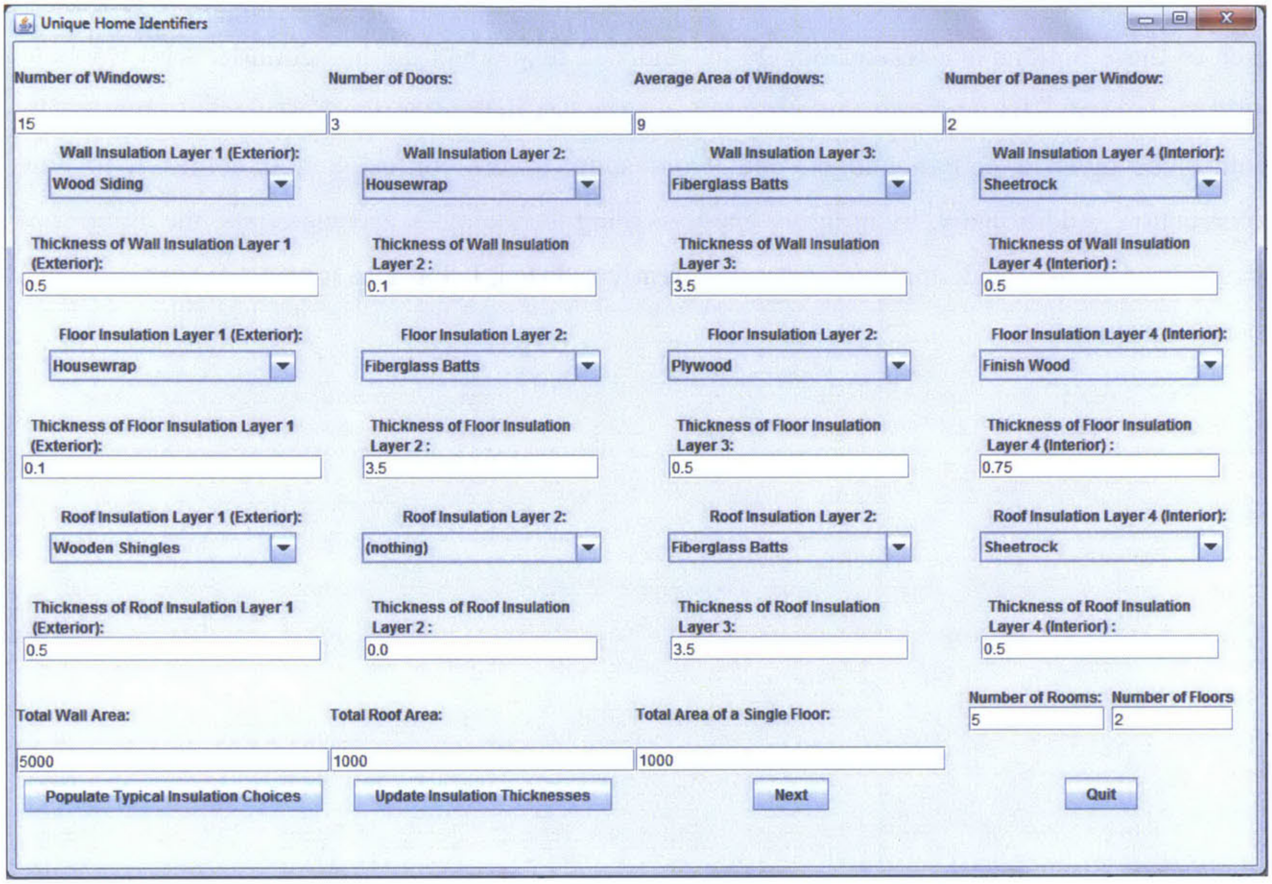

FIGURE 9: INTERFACE WITH "STANDARDIZED" INPUTS

6.2 Results

Using the above inputs, a user budget of $1000 was used to verify that the optimization functions properly. With this budget, the optimal solution was shown to be:

```
Floor Layer 1: Housewrap
Floor Layer 2: Fiberboard
Floor Layer 3: EPS
Floor Layer 4: Carpet
Walls Layer 1: Concrete
Walls Layer 2: Housewrap
Walls Layer 3: Polyisocyanurate
Walls Layer 4: Fiberboard
Roof Layer 1: Concrete
Roof Layer 2: Sheetrock
Roof Layer 3: Polyisocyanurate
Roof Layer 4: Plywood
Windows: Triple Pane Window
```

```
HRV: Standard Ventilation
Geothermal: Standard Heating System
```

Each of these options is a reasonable choice and will help direct the homebuilder who wants to build sustainably. By utilizing this program, a user can determine the best design choices for themselves given a certain budget, and avoid some of the confusion that comes with new construction. Additionally, by utilizing energy-saving technologies and materials, the amount of energy used in the residential sector can be greatly reduced, helping to lower America's overall energy consumption.

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CHAPTER 8. APPENDIX I

The source code for this project is hosted at: https://github.com/kvdeterm/SustainabilityCode