ENERGY EFFICIENCY'S ROLE IN A ZERO ENERGY BUILDING: SIMULATING ENERGY EFFICIENT UPGRADES IN A RESIDENTIAL TEST HOME TO REDUCE ENERGY CONSUMPTION

By

Andrew Griffin Frye

Approved:

Prakash Dhamshala
Professor of Engineering
(Director of Thesis)

Sumith Gunasekera
Professor of Mathematics
(Committee Member)

Philip Kazemersky
Professor of Engineering
(Director of Thesis)

Charles Knight
Professor of Engineering
(Committee Member)

ENERGY EFFICIENCY'S ROLE IN A ZERO ENERGY BUILDING: SIMULATING ENERGY EFFICIENT UPGRADES IN A RESIDENTIAL TEST HOME TO REDUCE ENERGY CONSUMPTION

by

Andrew Frye

A thesis submitted in partial fulfillment of
the requirements for the degree of

M.S. Mechanical Engineering

University of Tennessee at Chattanooga

May 2011

UNIVERSITY OF TENNESSEE AT CHATTANOOGA

ABSTRACT

Energy Efficiency's Role in a Zero Energy Building: Simulating Energy Efficient Upgrades in a Residential Test Home to Reduce Energy Consumption

by Drew Frye

Chairperson of the Thesis Committee: Dr. Prakash R. Dhamshala
College of Engineering

With the steady rise in power consumption, automobile usage, and industrial production worldwide for the past century, countries have realized that meeting these ever-growing energy demands could potentially devastate the environment. In the United States, generating electrical power constitutes the largest source of carbon dioxide emissions and the majority of this power is used to electrify buildings both in the commercial and residential sectors. It is estimated that 21% of all electrical power generated in the United States is consumed by residential buildings. To reduce the total amount of electricity that need be generated (and therefore, the amount of pollution) governments have invested heavily into energy efficiency research especially in the major power consuming sector of residential buildings. The ultimate goal of energy efficient measures is to cut the power consumption of a building enough that all of the energy needs can be met by an on-site renewable energy system such as photovoltaic solar panels. This would result in what many call a "zero energy building." This paper quantitatively investigates the effectiveness of potential energy efficient upgrades in a residential home through various building energy simulation techniques including the computer building load and energy requirement software entitled "Transient Analysis of Building Loads and Energy Requirements" or TABLER. Energy savings from energy efficient upgrades were investigated in the areas of residential lighting, building envelope infiltration mitigation, advanced insulating materials, advanced window technologies, electrical plug-load reduction strategies, and energy efficient appliance options. Results of simulations show significant energy savings for various energy efficient upgrades can be achieved either by a reduction in the electrical power consumed directly by the device (lighting, electronics, and appliances) or by a reduction in power consumption of the home heating, ventilation, and air-conditioning (HVAC) equipment used to remove or add heat to the conditioned space throughout the year. The effectiveness of individual upgrades as compared to the total investment required to implement them is a matter of opinion slanted by whether energy conservation or return on investment is the ultimate goal.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

TC	Total Cooling Capacity
SC	Sensible Cooling Capacity
T_a	Ambient Air Temperature
W_c	Cooling Mode Heat Pump Electrical Power Consumption
TH_{hp}	Total Heat Pump Capacity
W_h	Heating Mode Heat Pump Electrical Power Consumption
F_{ul}	Light use Factor
F_{sa}	Light Special Allowance Factor
CLF_{el}	Lighting Cooling Load Factor
r	Reflectance
t	Light Transmittance
I_{LLDN}	Direct Normal Illuminance
I_{LLDH}	Diffuse Horizontal Illuminance
I	Air Exchange Rate
Q	Volumetric Flow Rate
V	Volume
Δp	Pressure Difference between indoor and outdoor
p_o	Static Pressure
p_{wind}	Wind Pressure
pi	Interior Pressure
ρ	Density
g	Gravitational Constant
C_w	Wind Coefficient
C_s	Stack Coefficient
AL	Leakage Area
A_c	Building Leakage Area
C_p	Specific Heat
h_{fg}	Latent Heat of Vaporization

W	Humidity Ratio
R	Resistance
U	Overall Heat Transfer Coefficient
I_t	Total Solar Load
I_{dirr}	Direct Solar Radiation
I_{diff}	Diffuse Solar Radiation
I_{ref}	Reflected Solar Radiation
$I_{diff,horiz}$	Diffuse Horizontal Solar Radiation
θ	Angle of Incidence
β	Surface Tilt
n	Julian Day Counter
δ	Declination Angle
E_t	Equation of Time
L_{st}	Longitude of Standard Time
L_{loc}	Longitude of Location
ώ	Angle Hour
t_{sol}	Solar Time
α	Altitude Angle
φ	Latitude
Z	Zenith Angle
χ	Solar Azimuth Angle
ε	Surface Azimuth
Azs	Surface Asimuth to the North
P_{max}	Maximum Power
V_{oc}	Open Circuit Voltage
V_{mp}	Voltage at Maximum Power
I_{sc}	Short Circuit Current
I_{mp}	Current at Maximum Power

Chapter 1

Introduction

With the steady rise in power consumption, automobile usage, and industrial production worldwide for the past century, countries have realized that meeting the growing energy demands of the public could potentially damage the environment [1]. Scientists and engineers have been examining the environmental impact of pollution for years; and dangerous trends of high contamination levels have been observed contributing to a host of environmental problems collectively termed "global climate change," or "global warming." In December 2009, political leaders, scientists, engineers, and economic/environmental advisors gathered in Copenhagen, Denmark for a symposium entitled the "United Nations Climate Change Conference." Here the implications of impending global climate change were discussed, and limits for noxious emissions, such as carbon dioxide, sulfur dioxide, and nitrogen oxides, for countries (individually or collectively) were examined. From these talks, a document entitled the "Copenhagen Accord" was drafted by several countries including the United States, China, Brazil, and India. This document basically states that global climate change is one of the greatest challenges of present day and that actions should be taken to mitigate contributing factors such as carbon dioxide emissions. One hundred and thirty eight countries have signed this agreement pledging to examine different ways of reducing emissions in their respective countries. Countries are asked to "spell out" by the following year (2010) their promises and plans for cutting carbon emissions by 2020 [1][1].

Limiting dangerous emissions, such as carbon dioxide, will be essential to combating global climate change. A stark look at major pollution contributors in each country will reveal potential opportunities for improvements. According to the U.S. Energy Information Administration (EIA), 39% of anthropogenic (caused by humans) carbon dioxide emissions in the United States in 2002 were attributed to the combustion of fossil fuels for the generation of electricity [2]. A breakdown of carbon dioxide emissions by energy source taken from the EIA's Annual Energy Review of 2009 is shown in Figure 1.1.

ivv————————————

[1] Reference Materials Used are listed at the end of this Article in the Bibliography Section

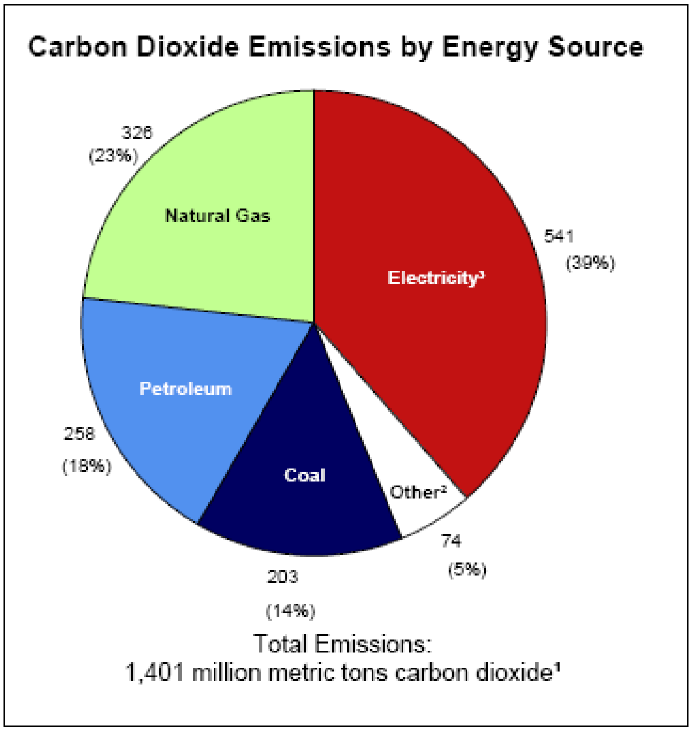

Figure 1.1: Carbon Dioxide Emissions by Energy Source from Annual Energy Review 2009 [2]

In 2009, 74% of the electricity produced in the United States came from environmentally harsh fossil fuels [2]. Of that number, 54% of the country's electricity was generated by coal combustion power plants making them the country's single largest contributor to air pollution [3]. Many scientists and engineers have been working towards generating power in more environmentally "friendly" ways by utilizing nuclear power, hydrostatic power generation, and a multitude of renewable energy sources, resulting in an engineering task of massive scale and economic investment.

While power generation technologies are examined and improved with regards to carbon emissions, a major push to examine how to reduce the amount of power that utilities must ultimately produce has been underway for many years now. This push is known as energy conservation. Energy conservation is defined as "efforts made to reduce energy consumption." Sometimes the term energy efficient is used as a substitute for energy conservation, but there is a subtle difference in definition. Being energy efficient is defined as "efforts made to reduce the amount of energy required to provide the same products and services." This may seem like a meaningless distinction; however, some people working in this industry are insistent upon the correct use of the two terms.

For example, energy conservation could simply be the practice of turning off half of the lights in a room when watching television to reduce the amount of energy the room is consuming. On the other hand, this would not be considered energy efficient because the "same products and services" (the amount of light in the room) is not the same as before. Instead, energy efficient light bulbs could be installed that use a fraction of the electricity as traditional light bulbs while providing the same amount of light in the room as before. This would be known as being energy efficient.

Despite the terminology differences, to effectively reduce the amount of power that utilities must ultimately produce, an assessment of the destination, or "end-use" of this energy must be completed. In the United States, 36% of the electricity produced is consumed by the residential market (highest percentage by sector) [4]. In a broader energy discussion (all energy types not just electricity but natural gas and other forms of energy as well); the Department of Energy (DOE) estimates that 39% of the primary energy sources in the U.S. are consumed by commercial and residential buildings [5]. Figure 1.2 shows the DOE break down of the U.S. primary energy consumption sectors (Industrial, Transportation, and Buildings) and the primary energy end-uses of the "Buildings" (commercial and residential) sector in 2006.

According to the DOE energy consumption breakdown, 21% of U.S. energy (electricity, natural gas, etc) is consumed by the residential sector, while 18% is consumed by commercial buildings. This segment of energy usage has been targeted by many industry leaders, government agencies (DOE and EIA), and conservation activist as a possible area where great improvements and energy savings could be made by integrating new energy efficient technologies [5].

Further investigation into this DOE energy end-use study reveals that the top energy consuming applications in the residential sector are heating and cooling, lighting, and appliances/electronics.

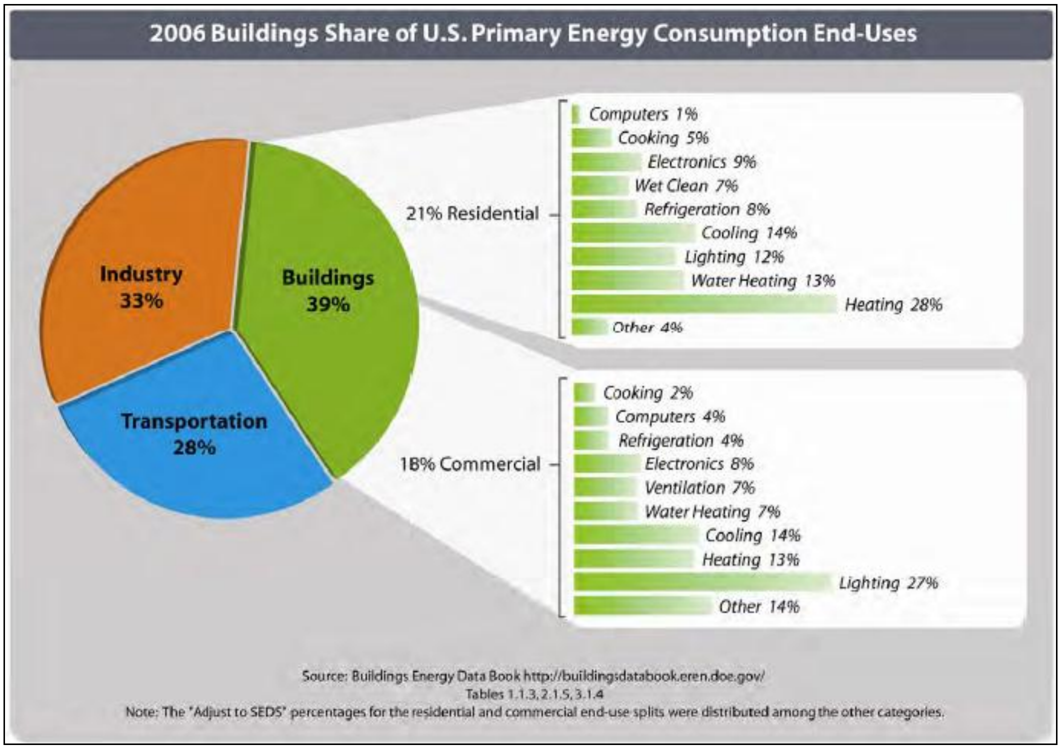

Figure 1.2: Department of Energy U.S. Primary Energy Consumption End-Uses 2006 [5]

According the Department of Energy, 42% of a home's total energy consumption is directed towards heating and cooling (28% and 14%, respectively) needs [5]. The DOE estimates that 56% of the electricity demand for a typical U.S. home comes from heating and cooling needs. This value is of course geographically contingent. According to Austin Energy (out of Austin, Texas), during summer months the air conditioning demands for a typical Austin home will be 60 – 70% of the total electrical demand for that home [6]. Since heating and cooling represent the largest area of energy consumption for a typical U.S. home, there is a great potential for energy savings by utilizing energy efficient heating/cooling systems such as high efficiency heat pumps, split energy systems, and other high efficiency HVAC units.

Making sure a home has an energy efficient HVAC (heating, ventilation, and air conditioning) system is just a small step in reducing the buildings' heating and cooling energy consumption. A large, sometimes over-looked, aspect of mitigating the heating and cooling energy requirements of a home is limiting the unintentional heat gained during the summer and heat lost during the winter months to the outside environment.

Limiting the air exchange (infiltration) of outside ambient air with indoor conditioned air, utilizing advanced window technologies, and making use of advanced insulations can reduce the heating and cooling loads of a typical building.

1.1 Thesis Research Purpose

This thesis is intended to identify, understand, simulate, and evaluate energy efficient upgrades related to residential (1) lighting, (2) infiltration mitigation, (3) advanced insulation, (4) advanced windows, and (5) plug and process loads. From simulations potential energy and utility savings for these upgrades will be examined for a specific test home in hopes of creating a zero-energy building in a somewhat cost effective manner.

According to the Department of Energy, the third largest area of energy consumption in a typical U.S. home is lighting. This study states that 12% of the total energy a home consumes is used for lighting [5]. Several emerging technologies in the field of advanced lighting techniques have increased lighting efficiency. The energy savings from Compact Fluorescent Lights (CFLs) and Light Emitting Diodes (LEDs) are two emerging lighting technologies which will be presented in Chapter 3 after describing the test home in Chapter 2.

Altogether, heating/cooling, lighting, and appliances/electronics account for about 72% of the energy needs of a typical U.S. home; however, this value can increase wildly depending on the season and geographical location of a home to upwards of 90% [5]. Energy efficient upgrades to infiltration mitigation, insulation, windows, and appliances/electronics are presented in Chapters 4, 5, 6, and 7, respectively.

It is also indicated in [5] that 18% of the total energy of a typical residential home is consumed by appliances and electronics. This category includes but is not limited to: refrigerators, clothes washing and drying machines, dishwashers, and various electronics such as the television, computer, and other entertainment devices. This thesis will briefly identify potential savings by upgrading to energy efficient appliances and will catalogue the energy consumption of common electronics that are found in a typical U.S. home in hopes of identifying possible areas of energy savings.

Chapter 8 of this thesis combines the individual energy simulations of the preceding chapters into a "whole building" energy simulation and the combined savings of each energy efficient upgraded will be presented. Reducing a building's energy requirement is a significant step towards creating what is known as a zero-energy building (ZEB). A ZEB is a structure that over a period of time (usually a year) consumes as much energy as it produces. Recently, the U.S. government set milestones for new commercial construction that is directed towards all new construction being "zero-energy" by 2030, and all (already built) commercial buildings being retrofit to meet zero-energy criteria by 2050 [5]. Chapter 9 of this thesis presents the potential solar power generation for the residential test home in hopes that combining energy efficient upgrades with renewable solar power generation will lead towards a possible zero-energy building.

The focus of this research is geared towards making energy efficient upgrades to a residential building, but similar techniques and upgrades can be extended to other business sectors especially the commercial sector to reach the U.S. government commercial milestones.

Chapter 2

Residential Test House

The residential home under investigation in this thesis is located in Ooltewah, Tennessee (Latitude 35.16, Longitude -85.06) which is a suburb situated slightly North-East of Chattanooga, Tennessee. The home was completed 1988 and was custom designed by the head of the Tennessee Valley Authority Solar Division at that time. The home has since been slightly modified from the original designs adding indoor living area and outdoor decking area. Despite the changes, no structural modifications were made from the original architectural designs.

2.1 Floor Plan / Home Design

The test home has 3 bedrooms and 2 bathrooms in 2,300 square feet of conditioned, indoor living area predominantly on a single level. The only "second level" space was added as a modification to the original design and made use of free space that was originally attic/storage. This upstairs space is open to the main living area (open windows) and does not have ductwork or ventilation from the main heating and cooling equipment of the home. This means the upstairs space can be lumped into the same heating/cooling area as the main space of the building (can be seen as an extension of dining/living room space). A computer generated drawing of the home floor plan is presented in Figure 2.1. This figure is drawn to scale and shows some important structural dimensions. The open, upstairs space mentioned before is located over the kitchen and laundry rooms. Although the majority of the living floor space is on a single story, the abnormally tall ceiling (nearly 20 feet in some locations) means the home is sometimes considered a two-story structure when viewed from the exterior (the importance of this is explained in the Infiltration section of this report when needed).

The floor plan of this home is what is considered an "open concept" meaning a large portion of the living space is unimpaired by interior walls or partitions. In fact, the living room, dining room, kitchen, back entry way, front entry way, upstairs open space, and hallway are all open to each other with no full interior walls to separate them.

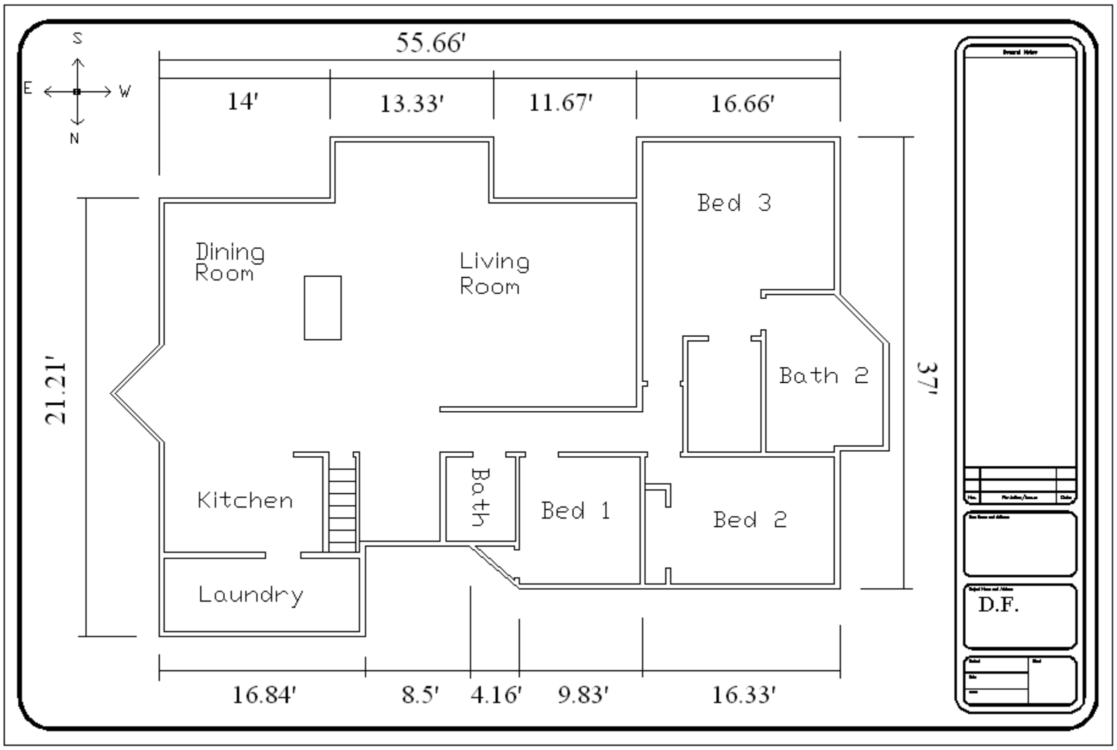

Figure 2.1: Conditioned Space Dimensioned Floor Plan

This accounts for about 59% of the floor living space (~1348 ft^2). This open floor plan concept allows unobstructed air flow throughout the majority of the home. The interior walls in this home are un-insulated or have significantly less insulation relative to exterior walls. Because of the lack of internal heat transfer resistance (no interior wall insulation), open floor-plan layout, and relatively simple (approximately square) shape, this home can be considered a "single heating/cooling zone," and appropriate single zone modeling procedures were used for various sections of this thesis for determining required heating and cooling building loads.

This home was designed by a particular advocate of solar techniques; therefore, many features of this home make it attractive for both passive and active solar applications. For a full explanation of these design features, an understanding of the test home orientation and exterior design are needed. Figures 2.2 – 2.5 are pictures taken from the outside of the test home showing the exterior faces of the home in each cardinal direction: north, south, east, and west.

Figure 2.2: North Face of Test Home

Figure 2.3: South Face of Test Home

Figure 2.4: East Face of Test Home

Figure 2.5: West Face of Test Home

The home is situated with the “front” facing north (Figure 2.2) and “back” facing south (Figure 2.3). This of course was a strategic decision based on the lot position relative to the street (transportation access) and other natural features (lake/water access). The southern facing portion of the home (Figure 2.3) contains large areas of glass features in the form of windows and doors. In fact, about 37.7% of the southern facing wall area is made of glass (218 ft^2 out of 578 ft^2). In this location, the sun rises in the east and sets in the west always following a southern route; therefore, this southern facing glass area allows solar radiation to penetrate the home creating what is known as “solar heat gain” inside the building. This heat gain can be beneficial in the winter months but detrimental in the hot, summer months raising the cooling load of the building. Appropriate over-hangs have been constructed over southern facing glass surfaces to mitigate solar heat gain in the summer months since the sun is higher in the sky (steeper angle of altitude – discussed later in the Window chapter of this report) during the summer. On the other hand, the sun is lower in the sky during the winter months and the over-hangs do not impede the beneficial heating aspects of the solar heat gain. An example of these southern over-hangs is shown in Figure 2.6. A building design feature such as this is known as a passive solar application. It is termed passive because techniques like these make use of solar energy without using mechanical or electrical components such as pumps.

Figure 2.6: Window Over-hang on Southern Windows

Another home design feature to point out in Figure 2.4 and Figure 2.5 is the lack of window or glass area on the eastern and western facing walls respectively. Windows and glass doors offer little resistance to heat gain or heat loss to/from the outside environment as compared to insulating materials found in walls. Therefore, minimizing glass area in locations where solar gain is not applicable is a smart design choice for minimizing heat transfer with the environment. In fact, the eastern facing surface of this building (Figure 2.4) is only about 3.4% glass (17 ft^2 out of 492.5 ft^2), and the western facing surface of this building (Figure 2.5) is only about 3.5% glass (18 ft^2 out of 510 ft^2).

One home design feature that will be addressed later in this thesis is the roof construction and the possibility of adding Photovoltaic ("PV") Solar Panels to the structure to generate electrical power. As can be seen in Figure 2.3, this home was constructed in such a manner that a large roof surface area faces south (towards the sun). This area would be ideal for active solar applications such as PV panels and solar collector systems such as solar hot water heaters. Solar power generation for this house will be discussed in later sections of this report but for now all that need be known about solar systems is that it is sometimes beneficial to be "titled" towards the south (sun) at certain angles. The roof of this home was constructed on such an incline and this can be seen in Figure 2.7.

Figure 2.7: Southern Roof Tilt for Solar Systems

The home features discussed so far show that the engineers who designed this home paid careful attention to possible energy savings and held an eye for future systems that could reduce energy consumption. Today, this would be called a "green design" or a "sustainable design." All the information from this section was taken from direct measurement of the home, observation, or from the approved architectural drawings.

2.2 Heating Ventilation and Air Conditioning (HVAC) System

Most of the energy efficient upgrades that will be evaluated in this research center around saving energy (and therefore money) by cutting the energy required to cool and heat the conditioned space. Heating and cooling for the main conditioned space of the home is handled by a "Split-System Heat Pump." A split-system heat pump is a heating, air-conditioning, and ventilation system divided between two connected units, one indoor and one outdoor. The outdoor unit houses the compressor, reversing valve, and a copper coil that acts as a heat exchanger while the air circulation fan, inside copper coil, and auxiliary heating elements are housed in the indoor unit. The indoor and outdoor unit coils are connected by copper tubing in which refrigerant flows [7]. The term "indoor unit" may be misleading; the indoor unit for this home is located under the home in what is essentially a large, unconditioned crawl space.

During winter (heating) months, the system refrigerant absorbs heat from the ambient air moving over the coil in the outside unit where it evaporates the refrigerant into a gas before it passes through the compressor. The compressor raises the gas temperature up to over 140 degrees Fahrenheit. The hot gas then moves to the indoor unit coil (heat exchanger) where it condenses back to a liquid passing heat to air in the ventilation system. This air is then piped throughout the home providing heat. In essence, the split system heat pump is an air-conditioning unit that reverses the cooling process in order to warm the inside air of the home. When the outside, ambient air temperature drops below about 32 degrees Fahrenheit, using a heat pump in this manner becomes very inefficient and auxiliary heating systems must be used. Auxiliary heating systems can be inefficient electric resistance heating coils or a system that utilizes gas heating.

During summer (cooling) months, heat (and moisture) within the home is removed from the conditioned space by passing the indoor air over the indoor unit copper coil. In this heat exchanger (or evaporator) the heat is removed from the indoor air and passed to the refrigerant. The cooled inside air is then re-circulated through the home by the fan distribution unit. The now hot refrigerant moves through the compressor and passes through the coil (condenser) in the outside unit. The heat (removed from the inside air) moves through the coil in the outside unit which then releases the heat to the outside environment [7].

From the manufacturer's name-plate information listed on the HVAC unit, it was determined that a Payne Heating and Cooling Company (Model: PH12 036-G) Split-System Heat Pump is used to heat and cool this home. This split system has a total cooling capacity of about 3 tons (~34,200 Btu/h) with an Energy Efficiency Rating (EER is the steady state efficiency of an air-conditioning system operating at 95 degrees F ambient outside temperature and 80 degrees F indoor) of 10.9. The heating capacity at high temperature is near 36,000 Btu/h with a Coefficient of Performance (COP is the ratio of the change in heat at the output of a heat pump to the supplied input work) of 3.3. The cooling capacity at low temperature is near 23,000 Btu/h with a COP of 2.4. The reduction in COP shows the drop in air-conditioner performance with outside air temperature. The Heating Seasonal Performance Factor (HSPF) for this unit is listed as 7.7 [8]. The cooling and heating performance data for this split-system heat pump was taken from Payne literature and are shown in Table 2.1 and Table 2.2, respectively. The auxiliary heating system used to supplement heating requirements in the cold, winter months is a York gas-fired (Latitude Series TG9S100C20) furnace. This gas-furnace has 5 burners, an Annual Fuel Utilization Efficiency (AFUE) rating of 95.5% with a nominal air flow rate of 2,000 Cubic Feet per Min (CFM). The "100" in the model number means the unit was rated for 100,000 Btu input energy but at 95.5% efficiency the Btu rating output equates to about 95,500 Btu [9].

As a reference, an online, quick calculator estimated the size of an air-conditioning system needed for a home of this size and it was determined that a system with a capacity of 3.3 – 3.5 tons refrigeration would be needed [10]. Therefore, it is assumed that the sizing of the Payne split-system heat pump is correct and actual peak cooling and heating loads (loads used for proper equipment sizing) will be calculated and discussed later in this thesis.

From the HVAC performance data given in Table 2.1 and Table 2.2, several equations describing the performance of this specific split-system heat pump were curve-fitted to evaluate energy consumption of this unit in later sections of this thesis. These equations are for an air flow rate of 1200 CFM, evaporator wet bulb temperature (EWB) of 63 ˚F in the summer (cooling) months, and the evaporator dry bulb temperature (EDB) of 70 ˚F in the winter (heating) months. These values represent the “mid-points” of each data tables. More complex cooling equations can be generated that vary the evaporator wet bulb temperatures, but since wet bulb temperature variations are generally much less than dry bulb temperature variations, this assumption was seen as sufficient.

Table 2.1: Cooling Performance Characteristics of Payne PH12 036-G Split-System Heat Pump [8]

Evaporator Air		CONDENSER ENTERING AIR TEMPERATURE ˚F											
		85			95			105			115		
CFM	EWB	Capacity (Mbtuh)		Total kW	Capacity (Mbtuh)		Total kW	Capacity (Mbtuh)		Total kW	Capacity (Mbtuh)		Total kW
		Tot	Sens		Tot	Sens		Tot	Sens		Tot	Sens	
1050	72	38.2	19.3	2.86	36.8	18.8	3.13	35.2	18.2	3.43	33.6	17.6	3.77
	67	35.1	24.8	2.83	33.8	24.3	3.10	32.3	23.7	3.40	30.8	23.1	3.73
	63	32.8	24.2	2.81	31.5	23.6	3.08	30.1	23.0	3.38	28.7	22.4	3.70
	62	32.4	30.2	2.81	31.1	29.5	3.08	29.8	28.9	3.38	28.5	28.1	3.70
	57	31.7	31.7	2.80	30.6	30.6	3.07	29.5	29.5	3.37	28.4	28.4	3.70
1200	72	38.7	20.1	2.92	37.2	19.6	3.20	35.6	19.0	3.50	33.9	18.5	3.83
	67	35.6	26.4	2.89	34.2	25.8	3.17	32.7	25.2	3.47	31.1	24.6	3.80
	63	33.2	25.6	2.87	31.9	25.0	3.15	30.5	24.4	3.44	29.0	23.8	3.77
	62	33.0	32.1	2.87	31.8	31.3	3.14	30.5	30.4	3.44	29.2	29.2	3.77
	57	32.7	32.7	2.87	31.6	31.6	3.14	30.5	30.5	3.44	29.2	29.2	3.77
1350	72	39.0	20.9	2.98	37.5	20.4	3.26	35.9	19.9	3.56	34.2	19.3	3.90
	67	35.9	27.8	2.96	34.5	27.3	3.23	33.0	26.7	3.53	31.4	26.1	3.86
	63	33.6	26.9	2.94	32.3	26.4	3.21	30.7	25.8	3.51	29.2	25.1	3.84
	62	33.6	33.5	2.94	32.4	32.4	3.21	31.2	31.2	3.51	29.9	29.9	3.84
	57	33.6	33.6	2.94	32.4	32.4	3.21	31.2	31.2	3.51	29.9	29.9	3.84

Table 2.2: Heating Performance Characteristics of Payne PH12 036-G Split-System Heat Pump [8]

PH12 036-G OUTDOOR SECTION WITH TYPICAL PF1MN(A,B)042 INDOOR SECTION													
INDOOR AIR		OUTDOOR COIL ENTERING AIR TEMPERATURE ˚F											
		-3			7			17			27		
		Capacity (Mbtuh)		Total kW	Capacity (Mbtuh)		Total kW	Capacity (Mbtuh)		Total kW	Capacity (Mbtuh)		Total kW
EDB	CFM	Tot	Integ		Tot	Integ		Tot	Integ		Tot	Integ	
65	1050	16.1	14.8	2.5	19.5	17.9	2.59	23	20.9	2.68	26.8	23.8	2.77
	1200	16.4	15	2.54	19.7	18.1	2.62	23.2	21.2	2.69	27.1	24.1	2.78
	1350	16.6	15.3	2.58	20	18.4	2.65	23.5	21.4	2.72	27.4	24.4	2.8
70	1050	15.7	14.4	2.59	19.2	17.6	2.69	22.7	20.7	2.79	26.5	23.5	2.89
	1200	16	14.7	2.63	19.5	17.9	2.72	23	21	2.81	26.8	23.8	2.9
	1350	16.2	14.9	2.67	19.7	18.1	2.76	23.3	21.2	2.84	27.1	24.1	2.92
75	1050	15.2	14	2.69	18.8	17.3	2.79	22.5	20.5	2.91	26.2	23.3	3.02
	1200	15.5	14.3	2.73	19.1	17.6	2.82	22.7	20.7	2.93	26.5	23.6	3.02
	1350	15.8	14.5	2.77	19.4	17.8	2.86	23	21	2.95	26.8	23.8	3.04

INDOOR AIR		OUTDOOR COIL ENTERING AIR TEMPERATURE ˚F (Cont.)											
		37			47			57			67		
		Capacity (Mbtuh)		Total kW	Capacity (Mbtuh)		Total kW	Capacity (Mbtuh)		Total kW	Capacity (Mbtuh)		Total kW
EDB	CFM	Tot	Integ		Tot	Integ		Tot	Integ		Tot	Integ	
65	1050	31.1	28.3	2.89	36	36	3.02	42.1	42.1	3.23	48.5	48.5	3.47
	1200	31.5	28.7	2.88	36.4	36.4	3.01	42.6	42.6	3.2	49.2	49.2	3.43
	1350	31.8	29	2.89	36.8	36.8	3.01	43.1	43.1	3.2	49.7	49.7	3.42
70	1050	30.8	28	3.01	35.5	35.5	3.16	41.5	41.5	3.37	47.8	47.8	3.62
	1200	31.2	28.4	3.01	36	36	3.14	42.1	42.1	3.34	48.5	48.5	3.57
	1350	31.5	28.7	3.01	36.4	36.4	3.14	42.5	42.5	3.33	49	49	3.56
75	1050	30.4	27.7	3.15	35.1	35.1	3.3	41	41	3.51	47.1	47.1	3.77
	1200	30.8	28	3.14	35.6	35.6	3.28	41.5	41.5	3.48	47.8	47.8	3.72
	1350	31.1	28.3	3.14	36	36	3.27	42	42	3.46	48.4	48.4	3.7

After "curve-fitting" the performance data in the previous tables via Microsoft Excel, it was determined that The Payne split-system heat pump total cooling capacity, TC (in thousands of Btu/hr) is given by the equation:

$$TC = 39.87882081 - 0.00800156\ T_a^{1.5} - (6.6478)^*\ (T_a^3 / 10^7)$$

In the above equation, and the equations to follow, T_a represents the outside, dry-bulb ambient air temperature in degrees Fahrenheit (˚F).

The sensible cooling capacity, SC (in thousands of Btu/hr) is given by the equation:

$$SC = 30.7 - 0.06^*Ta$$

The system total cooling heat pump electric power consumption W_c (kW) is given by:

$$W_c = 1.342634727 + 0.001950107^*(T_a^{1.5}) + 2.55132^*\ (e^{Ta} / 10^{52})$$

This Payne heat pump's total heating capacity, TH_{hp} (thousands of Btu/hr) is given by:

$$TH_{hp} = -8.55940959 + 0.781162788^*T_a + (363.5952833 / T_a) - (1516.8494 / T_a^2) + 15.69985891^*e^{-Ta}$$

This heat pump total heating capacity (TH) is what Table 2.2 refers to as the "Integrated" (Integ) heating value. The integrated heating values are the total heating capacities of the heat pump unit minus the "defrost effect," or the energy needed to defrost frozen heat exchanger coils for use. The Btu/h heating from supplement heating systems (gas-fired furnace in this case) should be added to these values to obtain the systems total heating capacity.

The heat pump total heating power consumption W_h (kW) is given by:

$$W_h = 2.659019896 + 0.009960354 - 0.00010845^*T_a^2 + (2.50001^*\ (T_a^3 / 10^6)) - (1.7111^*(e^{Ta} / 10^{31}))$$

These equations can be used to determine the power consumption due to the heating and cooling loads of a home throughout the year. This process is described in depth when applicable in later sections of this thesis.

2.3 Typical Power Consumption of Home

Before investigating any possible energy savings, it is important to understand the typical energy being consumed by this test home throughout the year. Data in this section comes directly from home utility billing information. Information about electricity consumption comes from the Volunteer Energy Cooperative (VEC) and residential records, and information about natural gas consumption comes from the Chattanooga Gas ™ (AGL Resources) Company and residential records. Energy consumption data and trends date back to the start of 2009. Any annual and monthly average usage values cover the past 2 years (2009-2010).

In 2009, the test home under investigation consumed 17,468 kWh of electricity; however, in 2010 the test home consumed 21,292 kWh of electricity that is 3,824 kWh (~18%) more than the preceding year. Therefore, the average ('09/'10) annual electricity consumed by this home over the two years was determined to be 19,380 kWh. The breakdown of monthly average electricity consumption is shown in Figure 2.8. As was expected, electricity consumption was the greatest during the summer months of June, July, and August when there is a high requirement for air-conditioning; and electricity consumption was the least during mild temperature months like April, March, and October.

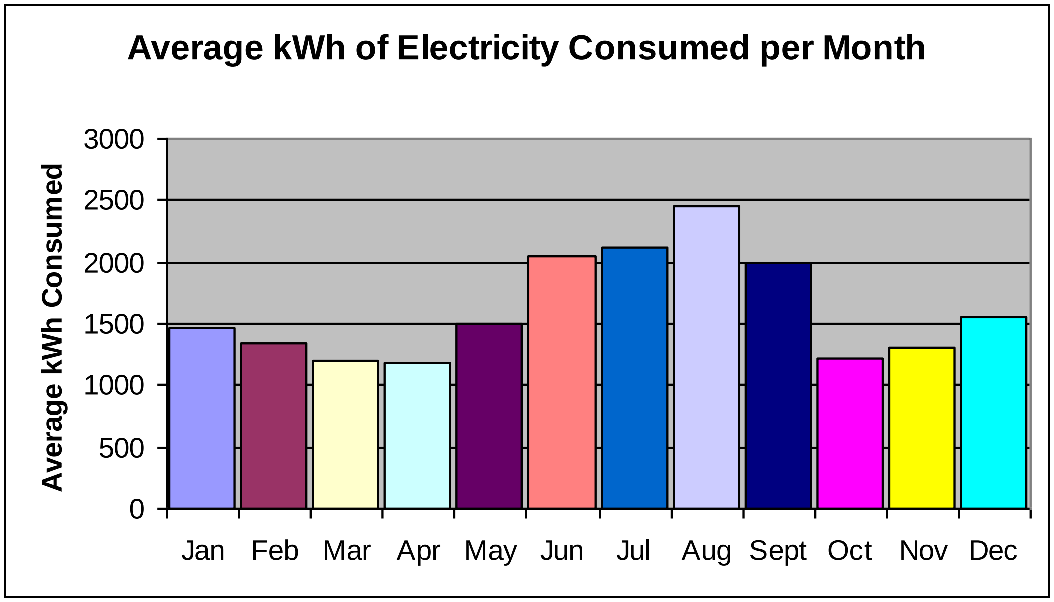

Figure 2.8: Average Monthly Home Electricity Consumption

In 2009, electricity utility payments totaled $1,553.19; however, in 2010, electricity utility payments totaled $1,866.85. This was a $313.66 (16.8%) increase from the previous year. Note that electricity consumption over this time rose 18% while expenditures only rose 16.8%; the reason for this difference is the Tennessee Valley Authority Fuel Cost Adjustment (FCA) which makes calculating an average annual electricity rate difficult. The FCA is a variable energy rate that can fluctuate each quarter with TVA's fuel and purchased power costs. The FCA affects energy (per kWh) charges for all customers (electricity distributors) using a firm rate schedule and this charge is passed along to utility consumers [11]. Since FCA information is shown on each billing statement an "average monthly fuel cost adjustment" could be calculated. Monthly average (over '09/'10) Fuel Cost Adjustment information is shown in Figure 2.9. This average value is only a rough estimate since the FCA is controlled by many factors and only TVA can set the true rate. The average monthly FCA was calculated to be 0.0040363 $/kWh. Adding the average FCA to the standard electricity flat rate of 0.086130 $/kWh, an average "adjusted" electricity rate was determined to be 0.090 $/kWh. This value will be used in later simulations as the total rate/cost of electricity.

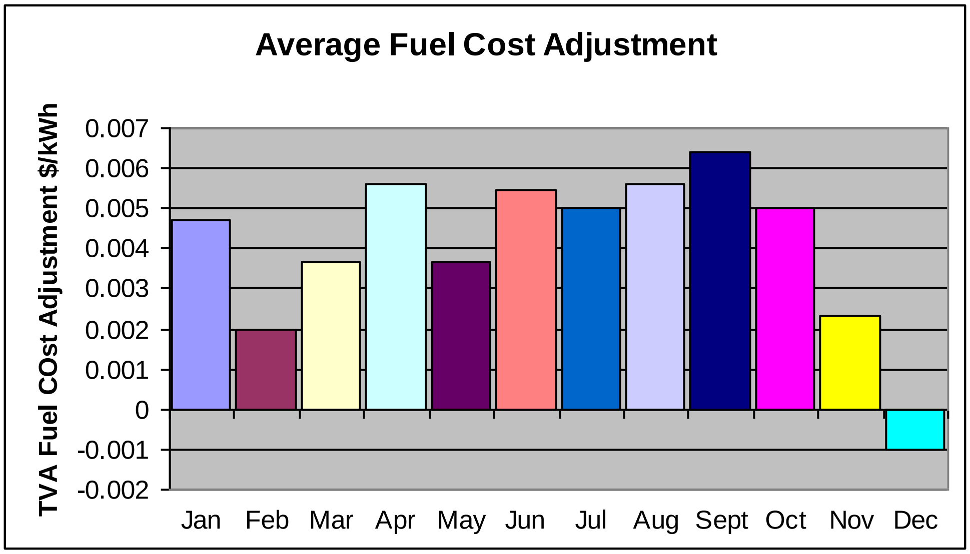

Figure 2.9: Average Monthly TVA Average Fuel Cost Adjustments

Referring back to home utility billing information, the average (‘09/’10) annual expenditure on electricity was $1,710.02, and this value will be used as a comparison for energy savings later in this report. This value is 2% less than if the cost was calculated using the adjusted electricity cost (0.09 $/kWh) calculated above. This was to be expected since the FCA was adjusted to be less than normal (a slight “payback”) in 2010 after TVA discovered slight over charging in previous years [11].

As mentioned previously, natural gas is used for auxiliary heating purposes in the home split-system heat pump unit, and natural gas is also used to heat hot water for the home. In 2009, the test home under investigation consumed 640.5 thousand cubic feet (CCF) of natural gas (646.25 Therms). The 2009 natural gas expense was $651.13. This equates to a 2009 average natural gas price of 1.008 $/Therm. In 2010 the test home consumed only 588 CCF of natural gas (596.22 Therms). The 2010 natural gas bill was $661.32. This equates to a 2010 average natural gas price of 1.109 $/Therm. This constitutes a 9.11% increase in gas pricing. Therefore, this test home on average (over ‘09/’10) consumes 614.25 CCF (621.233 Therms or 18,202 kWh) of natural gas that costs $656.23 annually. A breakdown of average monthly natural gas usage for the test home is shown in Figure 2.10. As was expected, natural gas is consumed more during the cold months of February, January, and March than in warm summer months like June and July because of the auxiliary heating requirements.

In 2009, the test home under investigation spent $2,204.32 on electricity and natural gas utilities. In 2010 this value increased 12.8% to $2,528.17. The increase was due to an increase in electricity consumption and an increase in natural gas pricing. Therefore, for financial savings investigated later in this investigation, an average annual total utility expenditure was calculated to be $2,366.25. A monthly breakdown of average total utility expenses (electricity and natural gas) is shown in Figure 2.11.

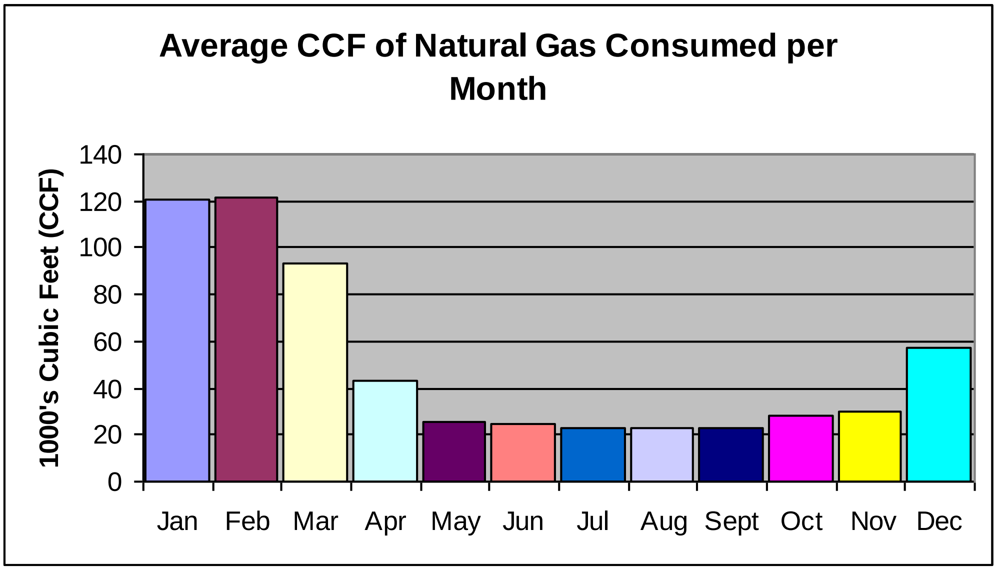

Figure 2.10: Average Monthly Natural Gas Consumption

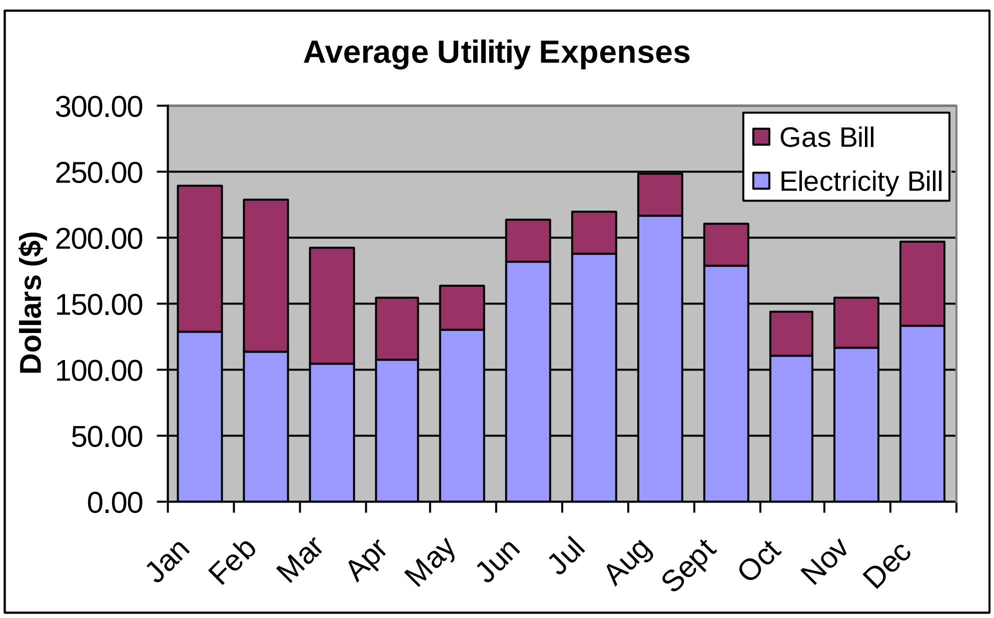

Figure 2.11: Average Monthly Utility Expenses for Electricity and Natural Gas

A review of pertinent utility information discussed in this section is shown in Table 2.3. With typical (average) home energy consumption and expenditures now known, energy savings due to energy efficient upgrades investigated in later sections of this research can be compared and evaluated strategically with an eye towards actual utility (consumption and expenditure) savings.

Table 2.3: Test Home Utility Information

Electricity		**Natural Gas**	
Annual Electricity Consumption	19,380 kWh	Annual Gas Consumption	614.25 CCF
Annual Electricity Expenses	$1,710.02	Annual Gas Expenses	$656.23
Monthly Fuel Cost Adjustment	0.004036 $/kWh	Annual Therm Consumption	621.23 Therms
Adjusted Electricity Rate/Cost	0.090 $/kWh	Annual Natural Gas Rate	1.058 $/Therm
Total Utilities			
Annual Total Home Energy Consumption (Electricity + Natural Gas)			37,582 kWh
Annual Total Utility Expenses			$2,366.25

Chapter 3

Lighting

Lighting is one of the top electrical energy sectors in residential and commercial buildings. The Department of Energy (DOE) estimates that lighting is the top energy "end-use" of commercial buildings consuming 27% of the building's total energy. For residential buildings, lighting is the fourth highest end-use of building energy behind heating, cooling, and water heating. Lighting accounts for about 12 % of a residential building's total energy use [5]. In terms of electricity only, the United States Energy Information Administration (EIA) reports that about 208 billion kWh of electricity was consumed in 2009 by the residential sector to produce light. This is equal to about 15% of all residential electricity consumption [12].

Lighting becomes an even larger area of focus for energy efficiency studies because not only does lighting represent a major energy (electricity) consumer, but lighting also adds greatly to the cooling load of a building. The cooling load is likewise consistently one of the top energy end-uses for both commercial and residential buildings. According to the DOE, cooling is the second largest energy end-use for both commercial and residential buildings consuming 14% of the building's total energy [5]. This information comes from the DOE 2009 study discussed earlier in Chapter 1 (refer to Figure 2.1 for statistics). Therefore, not only can significant electricity savings be seen with energy efficient lighting upgrades, but a reduction in summer time total (and peak) cooling load can be expected.

The majority of energy used by lights ends up as heat inside the building rather than illumination. In fact, 90% of the electricity consumed by a typical incandescent light bulb is used to generate heat, while only 10% or less is used to generate light [3]. For commercial and residential buildings, lighting is one of the largest sources of internal heat gain. Therefore, when attempting to mitigate the energy impact of lighting it is important to focus not just on pure electricity savings, but also on heat generation reduction which will lead to a reduced cooling load for the air-conditioning system.

3.1 Light Efficiency and Efficacy

There is much debate about the proper wording of lighting efficiency versus lighting efficacy. In a purely scientific approach, efficiency is the “ratio of the work done or energy developed by a machine, engine, bulb, etc., to the energy supplied to it, usually expressed as a percentage” [3]. Many will argue that all the energy produced by a light bulb will ultimately end up in the form of heat. Some energy will be immediately emitted as infrared radiation (heat) while the rest of the energy, seen as “light” will eventually be absorbed by other materials resulting in more heat later due to “thermal lag” resulting from a spaces’ thermal storage. Therefore, all 60 Watts of a typical 60 Watt incandescent light bulb will be seen as heat given enough time. Due to this fact, the term efficiency is sometimes looked down upon as a lighting measurement. Instead, lighting efficacy is a term being introduced by many researchers and light bulb manufactures. Lighting efficacy is “a measure of the output of a lamp/bulb in lumens, divided by the power (electricity) drawn by the lamp/bulb” [13]. The typical units of light efficacy are reported as lumens per Watt (lm/W). A lumen (lm) is a unit of the total light output from a light source. Should a light source be surrounded by a “transparent bubble;” the total light output is seen as the light flowing through this bubble at some instant in time. Measurement devices called “spot meters” are used in the photography field to measure light output at a particular location. For most applications, the terms efficiency and efficacy are used interchangeably accurate or not.

3.1.1 Incandescents

Incandescent lighting is the most widely used lighting technique to date. The first incandescent bulb was studied in the early 1800’s, but the typical tungsten filament bulb known by today’s standards was not adopted until the early 1900’s. Typical incandescent lamps consist of a wire filament made of tungsten that produces visible light when heated to high temperatures. The heating is accomplished by passing an electrical current through the filament. Unfortunately, 90% - 95% of the power consumed by the hot filament is emitted as infrared (heat) radiation making incandescent bulbs highly “inefficient” (low efficacy). Although inefficient from an energy standpoint (low lumens of light emitted per Watt electricity), the luminous filament of typical incandescent bulbs can be made quite small. This offers excellent opportunities for beam control in a very small, affordable bulb package [13]. Despite the low cost of incandescent filaments, the operational life of incandescent bulbs is rather short because the extremely high temperatures of the filament eventually weaken the brittle, tungsten wire.

Incandescent bulbs come in a wide range of “Wattages.” A standard incandescent bulb used in most residential fixtures is the 60 Watt version. A typical 60 Watt (Sylvania®) bulb produces about 850 lumens of light and is rated to last approximately 1,000 hours in operation. This gives a standard 60W incandescent bulb an efficacy of 14.17 lm/W. Bulbs like this cost approximately $0.31 each at local retail stores. Other Wattage options for incandescent bulbs such as 75 and 100 Watt bulbs are available. These bulbs are slightly more expensive ($0.63 per bulb), but can provide more light output (lumens). A 75 Watt (Sylvania®) bulb produces about 1,055 lumens (14.07 lm/W efficacy), while a 100 Watts (Sylvania®) bulb will produce about 1,560 lumens (15.6 lm/W efficacy). These bulbs have comparable life expectancies to the typical 60 Watt bulb (1,000 - 1,250 hours). All of these values were taken directly off the packaging information for each type of light bulb.

In 2005, nearly 2 Billion light bulbs were sold in the United States alone, and nearly 90% of those bulbs were based on the old incandescent technology. However, incandescent lighting will soon be phased out in the United States [14]. In 2007, Congress passed the “Energy Independence and Security Act of 2007” which sets standards essentially “banning” ordinary incandescent bulbs by 2014 because of a set minimum efficacy level [15].

3.1.2 Fluorescents

Fluorescent lighting comes in two forms, linear and compact fluorescent lamps (CFLs). A basic fluorescent lamp contains low pressure mercury vapor and inert gases in a partially evacuated phosphor lined glass tube. Electricity is used to excite the low pressure mercury vapor causing the excited ions to produce short-wave ultraviolet radiation that causes the phosphor lining on the glass tube to "fluoresce" producing visible light [13]. All fluorescent lamps need a ballast to operate. The ballast of a fluorescent lamp primarily provides cathode heating, initiates the lamp arc with high-voltage, provides the lamp's operating power, and stabilizes the lamp arc by limiting the electrical current. Ballasts also provide secondary functions like lighting controls such as dimming, and input power quality correction functions. Electronic ballast have come to dominate the market for fluorescent lamps because they are generally more efficient, weigh less, and are quieter than magnetic ballast options. The efficacies (lumens per Watt) of fluorescent lamps vary widely with lamp wattage, ballast type, and quality. For example, the efficacy of a 5 Watt compact fluorescent lamp on a low-quality magnetic ballast can be as low as 27 lm/W. On the other hand, two 36 Watt compact fluorescent lamps powered by a single, high-quality electronic ballast can operate with an efficacy of nearly 77 lm/W [13].

Linear fluorescent lights have been used in commercial settings for many years as a means of producing light "more efficiently;" while compact fluorescent lights (CFLs) are gaining popularity as incandescent replacements in common lighting applications such as typical home light fixtures. CFLs (and all fluorescents) generate their light more directly than incandescent bulbs. Approximately 70% of the electricity a CFL consumes is used to generate light and only 30% generates heat. Another benefit of fluorescent lighting is the life expectancy of the bulbs [16]. Typical fluorescent bulbs have an operating life of 10,000 to 12,000 hours (nearly 10 times that of an incandescent bulb). CFLs have been substituted for incandescent lamps using the "rule-of-thumb" that a CFL uses only 20% to 25% the power to deliver the same light output. Many researchers have drawn attention to the exaggeration of CFL product literature that miss-represents "equivalent" CFL lighting. For example, a CFL may be advertised as a replacement for a 75 Watt 1,200 lumen light, but it may only produce 1,000 lumens of light. Common "rounding-up" has taken place within the CFL manufacturer literature and care must be taken to compare actual lumen (light) output when deciding to replace standard incandescent bulbs with new CFL lamps [13]. Lumacoil® offers an "energy saving compact fluorescent lamp to replace a 60 Watt incandescent bulb." This CFL uses only

13 Watts of power to produce 900 lumens of light (69.2 lm/W efficacy), and boasts a life expectancy of 12,000 hours. These incandescent replacements are more expensive costing about $1.65 per bulb. AM Conservation Group INC. offers a 75 Watt incandescent replacement bulb that uses 20 Watts of power to produce 1,200 Lumens of light (60 lm/W efficacy). The life-span of this bulb is listed as 10,000 hours and it costs about $2.53 per bulb. Once again this information comes from retail pricing and operational information given on the bulb packing. Many retail CFL options are currently available to consumers and they will be discussed more in later sections of this chapter.

Every fluorescent lamp (compact and linear) uses mercury. The amount of mercury in a CFL's glass tubing is small, about 4 mg, but every product that contains mercury should be handled with care and disposed of in a proper way. Home improvement stores such as The Home Depot® have started collection programs to help the consumers responsibly recycle fluorescent lamps.

3.1.3 Light Emitting Diodes

Light Emitting Diodes (LEDs) are part of a category of lights known as "solid-state lighting." A Light Emitting Diode is a semiconductor diode that radiates light through a process called "electroluminescence" when an electrical current passes through the diode in the forward direction. When a current passes through the layers of semiconductor material electrons move about the material and "fall into" other energy levels during their transit of the "p-n junction" (P-N junction referrers to the contact of different types of semiconductor materials). When these electrons make the transition to a lower energy level, they give off a photon of light. This photon may be in the infrared region, or just about anywhere across the visible spectrum up to and into ultraviolet regions of the wave spectrum [13].

LEDs have been in operation for many years in instrumentation boards, decorative lights, and even small flashlights, but until recent years the application of LEDs was limited to single bulb, small scale projects. It was not until designs incorporating "clusters" of LEDs packed together that a viable incandescent bulb replacement was created. Today, LED light bulbs are made using as many as 180 LEDs per cluster encased in diffuser lenses which spread the emitted light out into wider beams. Now available with standard bases which fit common household light fixtures, LEDs are the next generation in home lighting. The high cost of producing LEDs has been a road block to their widespread adoption; however, researchers at Purdue University have recently developed a process for using inexpensive silicon wafers to replace the expensive "sapphire-based" technology of past LED lights [14]. This advancement promises to bring LEDs into competitive pricing with incandescent lighting in the future. LEDs use only a fraction of the power that a standard incandescent bulb would consume. Also, LEDs remain relatively cool producing only 3.4 Btu's/hour of heat as compared to 85 Btu's/hour for a standard incandescent bulb [16]. The reduced power consumption, relatively low heat generation, and long life expectancies (25,000 – 50,000 hours) of LED lights make them the future lighting focus for government mandates to replace incandescent lights by 2014.

Two companies have brought (or are about to bring) competitive LED lighting technologies into the market place. The Philips EnduraLED™ uses only 12 Watts of power to produce 806 lumens of light. This corresponds to the light production of a typical 60 Watt incandescent bulb but with an efficacy of nearly 67.17 lm/W. These lights are rated to last 25,000 hours but are much more expensive than tradition bulbs. Phillips estimates each bulb will cost about $50.00, and expects them to be commercially available by the end of 2010 (early 2011). Likewise, The Home Depot® has produced its own brand of LED light called the EcoSmart™ LED A19. This bulb uses 8.6 Watts of power to produce 429 lumens of light (comparable to a 40 Watt incandescent bulb). This corresponds to an efficacy of 49.88 lm/W. Despite having less light output (lumens) than a standard 60 Watt incandescent bulb, the EcoSmart™ boasts a 50,000 hour life rating and will only cost $17.97 per bulb at Home Depot stores worldwide.

A comparison of some of the lighting options (Incandescents, Fluorescents, and LEDs) commercially available at local, home improvement stores are shown in Tables 3.1, Table 3.2, and Table 3.3. These tables list the power consumption (wattage), light production (lumens), efficacy (lm/W), life-time rating (hours of operation), and cost of each bulb for various light options that will be important later in this chapter. All of these values (except for the calculated efficacy numbers) were taken directly off the packaging information for each light bulb option.

Table 3.1: Incandescent Light Bulbs Commercially Available

Incandescent Lights	Power (W)	Light Output (lm)	Efficacy (lm/W)	Life (hrs)	Price ($/bulb)
GE 40 Decorative Pointed Display Bulb	40	455	11.38	1,500	1.37
Sylvania Soft White 60 Standard Bulb	60	850	14.17	1,500	1.91
Sylvania Soft White Double Life 75	75	1085	14.47	1,500	1.91
Sylvania Soft White Double Life 100	100	1590	15.90	1,500	1.91
Sylvania Soft White Double Life 150	150	2740	18.27	750	3.14
Sylvania 15172 BR30 Indoor Flood Light	65	580	8.92	2,000	4.15
Energy Wise 50 Narrow Indoor Flood	50	660	13.20	2,500	6.95
SLI Lighting 150 Outdoor Flood Light	150	1730	11.53	5,000	2.80
GE Halogen Outdoor Flood	90	1310	14.56	6,000	9.87
Sylvania Halogen Outdoor Flood	75	980	13.07	2,500	9.28

Table 3.2: Fluorescent Light Bulbs Commercially Available

Fluorescent Lights	Power (W)	Light Output (lm)	Efficacy (lm/W)	Life (hrs)	Price ($/bulb)
Linear Fluorescent 40W T12 Commercial	40	2000	50.00	20,000	1.30
EcoSmart 7 Decorative Bulb Regular CFL	7	350	50.00	8,000	3.32
EcoSmart 9 Regular CFL	9	470	52.22	8,000	4.99
Bright Effect 11 Regular CFL	11	400	36.36	6,000	4.88
Sylvania Micro-mini 13 Regular CFL	13	820	63.08	12,000	3.49
Bright Effects 13 Regular CFL	13	825	63.46	8,000	2.49
Lumacoil Energy Saving Regular CFL	13	900	69.23	12,000	1.65
EcoSmart 14 Regular CFL	14	465	33.21	8,000	4.99
Phillips Energy Saver 16 Regular CFL	16	630	39.38	8,000	11.98
AM Conservation Group AM20PERM CFL	20	1200	60.00	10,000	2.53
Bright Effects 20 Regular CFL	20	1250	62.50	10,000	2.03
Phillips Marathon Regular CFL	20	930	46.50	8,000	11.99
Sylvania Micro-mini 23 Regular CFL	23	1640	71.30	12,000	3.99
EcoSmart 14 Indoor Flood CFL	14	640	45.71	8,000	4.49
GE Energy Smart Indoor Flood CFL	15	750	50.00	10,000	4.88
GE Energy Smart Indoor Flood CFL	15	720	48.00	6,000	11.00
GE Energy Smart Indoor Flood CFL	23	1185	51.52	10,000	7.16
EcoSmart 23 Indoor Flood CFL	23	1100	47.83	8,000	7.97
GE Energy Smart Outdoor Flood CFL	23	1185	51.52	10,000	8.13
Bright Effects Outdoor Flood CFL	26	1300	50.00	8,000	6.68

Table 3.3: LED Lights Commercially Available

LED Lights	Power (W)	Light Output (lm)	Efficacy (lm/W)	Life (hrs)	Price ($/bulb)
Phillips Deco 2.5 Regular LED	2.5	30	12.00	15,000	7.99
Phillips 5 Regular LED	5	240	48.00	25,000	24.97
Feit Electric Regular LED	6.5	340	52.31	30,000	18.98
Sylvania Ultra 8 Dimmable LED	8	430	53.75	50,000	19.98
Phillips 8 Regular LED	8	450	56.25	25,000	21.97
EcoSmart 8 Regular LED	8	450	56.25	50,000	29.97
Home Depot EcoSmart LED A19	8.6	429	49.88	50,000	17.97
Philips EnduraLED 60W Replacement	12	806	67.17	25,000	50.00
Phillips 12.5 Regular LED	12.5	800	64.00	25,000	39.97
Phillips 7 Indoor Flood LED	7	155	22.14	40,000	29.97
Feit Electric 8 Indoor Flood LED	8	350	43.75	30,000	24.97
EcoSmart 8 Indoor Flood LED	8	350	43.75	50,000	24.97
Phillips 11 Indoor Flood LED	11	430	39.09	25,000	49.97
EcoSmart 15 Indoor Flood LED	15	725	48.33	50,000	39.97
Feit Electric 16 Indoor Flood LED	16	728	45.50	30,000	59.98
Phillips 16 Indoor Flood LED	16	600	37.50	25,000	69.97
Sylvania Ultra 18 Indoor Flood LED	18	900	50.00	50,000	44.98
EcoSmart 18 Indoor Flood LED	18	850	47.22	50,000	44.97
Phillips 16 Outdoor Flood LED	16	850	53.13	20,000	64.97

3.2 Lighting Energy (Electricity and Thermal) Load

The adoption of new lighting technologies such as LEDs and CFLs will not only cut down on the total amount of power (electricity) required to produce sufficient light output, but it will also reduce the cooling load of a building's conditioned space by generating less of an internal thermal load from light-waste-heat. The lighting requirement for a building can be one of the top sources of internal heat gain within a structure [17]. The thermal load generated with lighting techniques is a uniquely sensible load; the heat produced by lighting has little to no effect on the humidity (moisture content) of the air inside the conditioned space. The instantaneous heat gain from lighting may be calculated from the equation:

$$q_{light} = W*F_{ul}*F_{sa}$$

The light total wattage (W) is a summation of all installed lighting both for general use and for display illumination. The lighting use factor (F_{ul}) is the ratio of the lighting wattage that is being used when load calculations are being made, to the total installed wattage (what installed wattage is actually turned on at an instant in time). The special allowance factor (F_{sa}) is for fluorescent fixtures or any fixture that is either ventilated or installed in such a way that only part of the heat generated enters into the conditioned space it is illuminating. For fluorescent fixtures this factor also accounts for ballast losses and can vary from1.04 to 1.37. For general applications (fluorescent fixtures) the American Society of Heating, Refrigeration, and Air-conditioning Engineers (ASHRAE) recommends using a special allowance factor value of 1.20 [17]. The 1997 ASHRAE Handbook of Fundamentals assumes a special allowance factor of 1.00 for incandescent (tungsten) lamps which are the primary lamp source for the building under examination in this report currently. Care must be taken when dealing with recessed lighting within a building space that contacts the air return space in ceilings (common in commercial buildings). Heat generated by the lights can be transferred to the air return supply and increase cooling loads without increasing the temperature of the cooling space. For the test house under investigation in this report no air return is located in the ceiling and all recessed lighting is surrounded by heat resistant, fire retardant insulation;

therefore, a special allowance factor of 1.00 with be assumed for these lights as well. For any type of light, a special allowance factor can always be measured experimentally by knowing that "the ratio of the actual power consumption to the rated power input" is another definition of the special allowance factor. A quick, simple test was conducted to verify the above assumptions for a tungsten filament lamp (special allowance factor assumed to be 1.00) and fluorescent lighting (special allowance factor assumed to be 1.20). First, a power meter was used to measure the power consumption of various tungsten (incandescent) light sources (lamps and recessed lights in this house) and the power consumed matched the bulb rating (wattage) in each case within the measurement uncertainty of the power meter; therefore, a special allowance factor of 1.00 is indeed an appropriate assumption. On the other hand, when the incandescent bulb was replaced with a new, compact florescent bulb with a rated Wattage of 13W, the power meter showed that the lamp was consuming 15W of power in steady state (2 to 5 minutes after power was turned on). This corresponds to a special allowance factor of 1.154 for this particular CFL bulb. Once again, this shows that the 1997 ASHRAE special allowance factor assumption of 1.20 is again appropriate for this CFL.

At any point in time, the space cooling load ($q_{cool,light}$) associated with the internal heat gain from lighting (q_{light}) can be estimated using the cooling factor load (CLF) method as:

$$q_{cool,light} = q_{light}*(CLF_{el})$$

CLF_{el} is the lighting cooling load factor and it is a "space parameter" that comes from the light fixture type, type of air supply or air return, space furnishings, and the thermal characteristics of the space in question. The effects of these space parameters were catalogued in the *Cooling and Heating Load Calculation Manual* by McQuiston and Spitler (1992) and were represented in tabular form as CLF values. These CLF values are based on two assumptions: (1) that the conditioned space is maintained at a constant temperature, and (2) that given long enough the cooling load will match the power input to the lights. The cooling load factors for lights (CFL_{el}) for various conditions are shown the appendix of this report (Appendix A), and the room "Zone

Types" needed to determine the CFL values can be determined from various "zone parameters" that are shown in Appendix B which is also in the appendix at the end of this report.

The second assumption listed above is what leads to the residential model calculations for this report. Since the HVAC system is available for operation 24 hours a day (365 days a year), all the input power used for lighting will eventually (given time) be seen by the conditioned space as heat and therefore a CFL value of 1.00 can be used [17]. This method will account for the entire cooling load due to lighting conditions, but may "shift" the cooling load times. For example, the instantaneous heat gain from a lighting source may be 1,340 Watts for the 6:00 pm hour of a typical week-day, but in all actuality, not all of this will be seen as a cooling load instantly (at that time). For example (percentages just chosen at random), perhaps only 30% of that power will be seen instantly as a cooling load (402 W which results in a room-air temperature increase). The other 70% will be absorbed, and released into the room in the following hours. Despite the "time-lag," all 1,340 Watts of light input power (when it is all converted to heat) will have to be removed from the conditioned space at some point; therefore, a more sophisticated modeling method must be employed when calculating the residential peak cooling load since this value would represent the highest cooling load at a specific instant in time. However, for the purposes of this chapter, a simple understanding of the total cooling load generated by various lighting conditions is seen as adequate for understanding the benefits of various energy efficient lighting technologies and the transient methods needed for more sophisticated analyses will be discussed in later chapters of this report.

3.3 Baseline Lighting Simulation Procedure

To understand the benefits of utilizing energy efficient lighting upgrades, a base-line, lighting simulation must be examined. To accomplish this, a detailed procedure was created to simulate the electrical energy usage and internal heat gain of various lighting conditions throughout a typical year for the test house under investigation. To start, a detailed inventory of current incandescent lighting conditions was created including the number and type of bulbs in current operation. Next, pertinent manufacturer's information was gathered for the various light bulbs including the light output (lumens), operational life (hours), electrical energy consumption (Wattage), and price of each bulb. For this test house, 86 incandescent light bulbs and 4 linear fluorescent light bulbs are currently installed. These 90 total light bulbs installed both inside and outside of the home can produce 78,130 total lumens of light while consuming 5,830 Watts of electricity. 15 of these lights are located outside of the home (or in the un-conditioned garage space) and do not add to the building's total cooling load via internal heat generations, but still add to the total energy (electrical) consumption of the house. The remaining 75 light bulbs are located inside the conditioned space of the home and can produce 57,765 lumens of light while consuming 4,090 Watts of electricity. These lights also produce heat that must be removed from the condition space according to space cooling load equation, and these cooling loads result in more energy consumption by the HVAC equipment.

Despite having a total installed home wattage of 5,830 Watts, not all of these lights are in operation at a given point in time. Therefore, a model was created to simulate the energy consumption (lighting and cooling load) due to lighting alone throughout the year. This model uses three "typical days" that when combined simulate the electrical energy consumption and internal heat generation for the given lighting conditions throughout a calendar year. The three typical days were termed "Weekday," "Weekend," and "Power Day." A typical "Weekday" simulates the 24-hour period where the conditioned space was generally un-occupied during the day-time, and therefore the lighting requirements during the day were much less than the lighting requirements at night when the occupants returned home from work and school. This simulation was based on light usage detailed notes taken at the test home during a typical Monday. Observations were made about which lights were used and how long each light was operating hour-by-hour throughout the 24-hour period. On the other hand, the "Weekend" day simulates the 24-hour period when occupants will be present during the day-time hours and the lighting requirements will be greater. This simulation was based on observations of light use in the test home on a typical Saturday. Five typical

"Weekdays" are followed by two typical "Weekend" days and this pattern is repeated for the 365 days of the calendar year. The last typical day was called a "Power Day." A "Power Day" takes into account monthly lighting needs that are not represented on the "Weekday" or "Weekend" simulations. This is lighting that is not used for very long, such as closets, stair-wells, decorative lighting, and lighting that is used for special occasions such as entertaining guests or holiday schedules. This day also accounts for the times when lights are left on accidentally. An estimate of this light usage for the month that is not recorded by the "Weekday" and "Weekend" simulation days was combined into one 24-hour period to create a typical "Power Day," and this was based on home-owner information and observation. One "Power Day" was substituted at the beginning of each month to evenly distribute the miscellaneous light usage throughout the year. Obviously, the injection of one "Power Day" disrupts the distribution of space cooling loads, because a large portion of lighting use (and therefore internal heat generation) is compacted into a short time frame (24 hours). The total (monthly or annual) space cooling load is all that will be discussed in the results section of this chapter, and this total will remain the same whether the load was distributed evenly throughout the month or all in the first day of the month. Combining these three typical days, an hour-by-hour account for 365 days of light usage was generated, and annual simulations were performed as a base-line model using manufacturer's information for the currently installed incandescent lighting conditions.

For this base-line simulation, the total electrical power consumption for lights during a typical "Weekday" was calculated to be 9.025 kWh/day. Also, the total lighting electrical power consumption during a typical "Weekend" was calculated to be 11.915 kWh/day, and the total lighting electrical power consumption for a typical "Power Day" was calculated to be 52.59 kWh/day. Remember the "Power Day" takes into account all lighting not counted on the typical "Weekend" or "Weekday" simulations (leaving lights on, days when owners use more than typical or the regular schedule is changed, holidays, guests, etc.) for the entire month. All of these days placed in sequence correspond to a total annual lighting power consumption of 4,105.91 kWh/year. Also in this base-line simulation, the internal heat generation (and therefore space cooling load addition since

CLF equals 1.0) during the summer months (mid-April to mid-November) due to the lighting conditions was determined to be 6,277,194.53 Btu or 1839.665 kWh (note: the simulation is broken down hour-by-hour throughout the year over 8,760 hours and each hours' space load "Btu/hr" will be used in HVAC calculations). To check the validity of this simulation procedure the lighting energy consumption was compared to the known, average total energy consumption of the test home. From home utility records, the total average annual energy consumption (electricity and natural gas) of this test home was 37,582.12 kWh/yr. Therefore, according to this simulation, the electrical power consumed by these baseline, incandescent lighting conditions accounts for about 10.93% of the test home's total energy consumption (21.2% of home electricity usage). According to the Department of Energy's study quoted in the "Lighting Basic Concepts and Terminology" section of this report, a typical residential home uses 12% of the total home energy consumption purely on lighting requirements. The 1.07% discrepancy between the DOE estimate and this energy model comes from the conservative light usage estimations used in this simulation, and the fact that the floor-plan of the test home makes greater use of solar day-lighting techniques than a typical residential home would. In any case, this simulation procedure can be seen as an appropriate, conservative evaluation of potential energy savings for new energy efficient lighting options. Utilizing the utility statistics from Chapter 2 of this thesis, the test home can expect to spend about $370 annually (21.64% current electricity expenditures) on electricity to simply light the home.

Utilizing the HVAC equations discussed in Chapter 2, the electrical consumption associated with removing the summer space internal heat created by the current lighting conditions can be determined. To do this, the ratio of the space load (cooling load / heat created by the lights) to the heat pump capacity (TC and/or SC) has to be determined, and this is contingent on the ambient outside temperature and the light usage at a given point in time. This ratio was done in energy simulations hour-by-hour throughout the year, and it can be seen as the amount of time the HVAC system must operate to remove the generated space load. For example, if at some point in time the heat pump has a cooling capacity of 40,000 Btu/hr and the lighting conditions generate 10,000 Btu/hr of added space cooling load, then the ratio 10,000/40,000 is 0.25, and this is the amount of capacity that must be used to remove the space load. The capacity (40,000 Btu/h here) is the maximum amount (heat) over the course of one hour (60 minutes) that can be removed by the HVAC system, but only one-quarter (0.25) of that capacity is needed for this load. Therefore, the HVAC only needs to operate for 0.25 of the whole hour (15 minutes) to remove 0.25 of the hourly capacity. Lastly, using the compressor power equation (compressor power consumption over an entire hour of operation) and multiplying this value by the ratio described above, determines the power required by the HVAC system to remove just the added space load (from lights in this case).

According to these simulations, the HVAC system in place will consume 462.46 kWh of electricity during the summer months (mid-April to mid-November) to remove the heat generated by the lights alone. This means that the home owner can expect to spend about $41.62 during the summer months to operate the heat pump in cooling mode to simply remove the heat generated by the current lighting scenario. This equates to a total annual expense of $411.15 to operate the current lights (produce light and remove generated space loads in the summer). Note that internal heat generation from lighting is a year round phenomenon, but it in the winter time this heat may not be necessarily a bad thing since the HVAC system may already be adding heat to the space due to the outside weather conditions and heat losses. Therefore, in this simulation only the summer months are investigated for potential HVAC savings estimates. Indeed, at times in the winter, heat (from internal sources such as lights) will still need to be removed from the conditioned space, but this scenario was neglected. The base-line (incandescent) energy simulation findings are presented in Table 3.4.

With the base-line energy simulation known, three different sets of energy efficient lighting conditions were simulated and the potential electrical energy savings along with the expected space cooling load reductions were determined. The three sets of energy efficient lighting conditions consisted of commercially available sets of:

(1) Compact Fluorescent Lights (CFLs) Only

(2) Light Emitting Diodes (LEDs) Only

(3) Combination of both Compact Fluorescent Lights and Light Emitting Diodes

Table 3.4: Base-Line Energy Simulation Data

Bulb Type	Annual Electricity Consumed for Lights (kWh)	Summer Cooling Load from Lights (Btu)	HVAC Electricity Consumed per Summer for Light Space Load (kWh)	Total Annual Electricity Consumed (kWh)	Total Annual Electricity Expense ($)
Incandescents	4,105.905	6,277,195	462.46	4,568.365	411.15

Energy efficient lighting substitutions were done on a "lumen to lumen" basis. This means that instead of merely substituting a commercial "energy efficient CFL 60 Watt replacement bulb" into the lighting conditions for a standard 60 Watt incandescent bulb, care was taken to make sure the new, energy efficient light bulbs would in fact match the light output of the traditional incandescent bulbs as closely as possible using the manufacturer data previously catalogued in Tables 3.2 and 3.3.

For each set in these simulations, every light bulb in the test home was to be replaced by an energy efficient model except for the four 40W T12 linear fluorescent light bulbs found in a closet and bathroom. The light output (2,000 lumens per bulb) from these bulbs could not be matched by readily available energy efficient models and the large, electronic ballasts for these linear fluorescent lights are already installed in their respective locations. Future energy simulations could account for replacement fixtures and energy efficient bulbs for these locations, but for simplicity and ease of implementation these bulbs will remain constant for all of the simulation sets.

Lighting substitutions were fairly straightforward for the strictly CFL and LED substitution sets. All that needed to be done was to match the light output of each respective energy efficient replacement bulb with the light output of the standard incandescent bulbs already installed. After noticing the large discrepancies between the prices of LED and CFL replacement bulbs and their proximity in energy savings, a third light substitution set was created combining both CFL and LED replacement bulbs. Designer judgment was used to decide which type of replacement bulb to use. For example, it makes little sense to spend $50.00 on a LED replacement bulb that only saves 2 Watts of electrical power more than a CFL bulb that costs only $4.00 if the light barely operates a few hours per year. Judgments as to which energy efficient bulb to use in this third ("combination") simulation set were based on: the bulb lumen output, bulb life, usage (hours used per year), potential energy savings (ΔW between energy efficient bulb options), and price. The entire list of energy efficient bulb substitutions made for each of the three simulation sets can be found in the Appendix C.

3.4 Lighting Results / Savings Estimates

Several parameters/values for each simulation set will be discussed in the next sections, but the results for each set of energy efficient lighting upgrades can be broken down into a few important statistics. For example, the total electricity consumption for each set of lighting conditions is by far the most important marker for determining the effectiveness of energy efficient lighting upgrades. This value is a combination of not just the electricity consumed by the new bulbs to generate light, but also the electricity consumed by the HVAC system to remove the indoor cooling load generated by the lights in the summer months. From this total value, energy savings and total expenditure (electricity bill) savings can be determined. With the cost of each light bulb known, a simple "payback period" (in years) can be determined. This is the time it will take for the energy savings (and therefore utility savings) to match the purchase and installation costs of the new lighting conditions.

3.4.1 CFL Light Replacement Set

The first simulation set under examination is the set consisting of just compact fluorescent lighting options. In this set, when all of the incandescent light bulbs were replaced by CFL bulbs the total inside-outside lumen output from the lights dropped to 76,440 lumens (down 2% from the incandescent set); however, the inside lumen output increased to 62,030 lumens (up 7% from the incandescent set). This was due to the fact that new CFL bulbs do not exactly match the lumen output of traditional incandescent bulbs. This was evident when searching for replacement CFL bulbs for outside spotlights (high lumen outputs) that light the front and back porch areas of the test home. Despite the fact that the total lumen output is slightly less, the inside lumen output was greater than before (more light) and this was the best "matching" that could be done with the CFL replacement bulbs available at this time. For this set, the total inside-outside installed Wattage decreased 76% to 1,354 Watts, and the inside installed Wattage decreased 74% to 1,067 Watts compared to the base-line incandescent simulation. The "weekday" power consumption decreased 65% to 3.1884 kWh/day, the "weekend" power consumption decreased 67% to 3.7488 kWh/day, and the "power day" consumption decreased 74% to 13.6776 kWh/day for this simulation set. The total annual energy to produce light for this simulation set was determined to be 1,353.3 kWh/yr (down 67%). The summer time cooling load generated by the lights was reduced by 72% to 1776355.65 Btu for this set and this in turn reduced the HVAC power consumption (for these lighting loads) to 125.88 kWh (down 73% from the baseline). The total annual power consumption for the new CFL energy efficient lights (electricity to generate light and to cool space load) was **1**,479.21 kWh/yr (67.6% savings). This equates to a 3,089.16 kWh/yr annual power savings and a $278.02/yr power bill savings. The most important simulation results for the CFL light set are shown in Table 3.5. The total cost to replace every current incandescent light bulb with a comparable CFL bulb is $376.85 (this includes 10% sales tax). Therefore, with annual electricity savings of $278.08 a simple payback period of 1.36 years was calculated. This is a very reasonable payback period for most residential consumers considering CFL bulbs generally have a life expectancy of 12,000 hours. This means if the home owner kept a light on every-hour of the day (highly un-likely), a CFL bulb will last approximately 1.36 years (the length of the expected payback period above). Estimates from this model show that various lights in "high-use" areas of this house are in operation about 4,664 hours each year (47% of the year). This would mean a CFL bulb in this location could last about 2.6 years before it would need to be replaced (nearly twice the payback period for this set).

Table 3.5: Important CFL Simulation Results

Bulb Type	Annual Elec. for Light (kWh)	Light Summer Cooling Load (Btu)	HVAC Elec. Consumed for Light Space Load (kWh)	Total Annual Elec. (kWh)	Total Annual Elec. Expense ($)	Total Elec. Saved per Year (kWh)	Total Money Saved per Year ($)	Total Bulb Cost ($)	Pay Back Period (years)
Base-Line	4,105.9	6,277,195	462.46	4,568.4	411.15	x	x	x	x
CFL	1,353.3	1,776,356	125.88	1,479.2	133.13	3,089.2	278.02	376.85	1.36

3.4.2 LED Light Replacement Set

After LED replacement, the total inside-outside lumen output from the lights dropped to 68,822 lumens (down 12% from the incandescent set); however, the inside lumen output increased to 58,972 lumens (up 2% from the incandescent set). This imbalance was again due to the fact that outside, high lumen output lights that are LED are not available; however, once again the inside lumen output was near the same (slight increase). The total inside-outside installed Wattage decreased 82% to 1,054 Watts, and the inside installed Wattage decreased 79% to 870 Watts compared to the base-line simulation. The "weekday" power consumption decreased 83% to 1.494 kWh/day, the "weekend" power consumption decreased 80% to 2.362 kWh/day, and the "power day" consumption decreased 86% to 7.374 kWh/day for this simulation set. The total annual electricity consumed by the LED lights to produce light was determined to be 702.67 kWh/yr (down 82%). The summer time cooling load generated by the lights was reduced by 80% to 1,265,903 Btu for this set and this in turn reduced the HVAC power consumption (for light loads) to 89.296 kWh/yr (down 81% from the baseline). The total annual power consumption for the new LED energy efficient lights (electricity to generate light and to cool space load) was 791.96 kWh/yr (83% savings). This equates to a 3,776.41 kWh/yr annual power savings and a $339.88/yr power bill savings. The most important simulation results for the LED light set are shown in Table 3.6. The total cost to replace every current incandescent light bulb with a comparable LED bulb was $4,054.30. Therefore, a simple payback period of 11.96 years was found for the LED light set.

Table 3.6: Important LED Simulation Results

Bulb Type	Annual Elec. for Light (kWh)	Light Summer Cooling Load (Btu)	HVAC Elec. Consumed for Light Space Load (kWh)	Total Annual Elec. (kWh)	Total Annual Elec. Expense ($)	Total Elec. Saved per Year (kWh)	Total Money Saved per Year ($)	Total Bulb Cost ($)	Pay Back Period (years)
Base-Line	4,105.9	6,277,195	462.46	4,568.4	411.15	x	x	x	x
LED	702.67	1,265,904	89.29	791.96	71.28	3,776.41	339.88	4,054.30	11.96

As can be seen from the simulation sets, energy efficient LED lights hold the greatest promise for energy savings; however, the bulb high cost provide much longer payback periods based on the energy (utility bill) savings. Some LED lights list an operating life of 50,000 hours (some much less). If a home owner were to leave an LED light on every hour (highly un-likely) the light would last about 5.7 years (about half the payback time). However, if an LED light (50,000 hour life) was placed in a "high-use" area of this home (4,664 hours of use annually) then a life of 10.7 years would be expected. This does not even match the payback period determined above. Of course, not all lights will operate this amount of time, and most LED replacements would indeed live passed the expected payback time frame, but a high payback time frame will discourage most residential consumers from making the jump to purely LED lighting conditions until initial bulb costs decrease.

3.4.3 Combination of LED and CFL Light Replacement Set

The last simulation set under examination is a set that was designed to combine the energy savings of LED lights with the inexpensive implementation (short payback period) of CFL lights. To do this, a combination of LED and CFL bulbs were chosen at the discretion of the designer. After replacement, the total inside-outside lumen output from the lights dropped to 74,388 (down 5% from the incandescent set) while the inside lumen output increased to 59,978 (up 4% from the incandescent set). The total inside-outside installed Wattage decreased 77% to 1,246 Watts, and the inside installed Wattage decreased 77% to 959 Watts compared to the base-line simulation. The “weekday” power consumption decreased 78% to 2.0295/day kWh, the “weekend” power consumption decreased 77% to 2.7797 kWh/day, and the “power day” consumption decreased 83% to 8.9397 kWh/day for this simulation set. The annual electricity to produce light consumed by the combination set of lights was determined to be 898.71 kWh/yr (down 78.1%). The summer time cooling load generated by the lights was reduced by 76% to 1,489,841.3 Btu for this set and this in turn reduced the HVAC power consumption (for light loads) to 95.94 kWh (down 80% from the baseline). The total annual power consumption for the new combination energy efficient lights (electricity to generate light and to cool space load) was 994.65 kWh/yr (78% savings). This equates to a 3,573.72 kWh/yr annual power savings and a $321.63/yr power bill savings. The most important simulation results for this last light set are shown in Table 3.7. The total cost to replace every current incandescent light bulb with comparable LED and/or CFL bulbs (see appendix for the bulb replacement list C) was $1,670.38. Therefore, a simple payback period of 5.19 years was found for this combination light set.

A payback period of 5.19 years is “border-line” for residential consumers. Optimization of the process to choose replacement bulbs (CFL or LED) could be another step in further energy simulations, but several of the CFL bulbs used in this combination set are not rated to survive the determined payback period (however these CFL bulbs are the least expensive to replace). Combining LED and CFL bulbs in this manor shows great promise. This combination lighting set saves 94.6% of the energy (total kWh consumed) that the purely LED light set would save, but costs nearly 40% less to implement.

Table 3.7: Important Combination LED & CFL Simulation Results

Bulb Type	Annual Elec. for Light (kWh)	Light Summer Cooling Load (Btu)	HVAC Elec. Consumed for Light Space Load (kWh)	Total Annual Elec. (kWh)	Total Annual Elec. Expense ($)	Total Elec. Saved per Year (kWh)	Total Money Saved per Year ($)	Total Bulb Cost ($)	Pay Back Period (years)
Base-Line	4,105.9	6,277,195	462.46	4,568.4	411.15	x	x	x	x
LED & CFL	898.71	1,489,841	95.94	994.65	89.52	3,573.72	321.63	1,670.38	5.19

3.5 Daylighting Techniques

Daylighting techniques can be a great way to reduce home energy consumption due to lighting requirements. Residential buildings with day-time occupants can simply utilize solar illumination to provide indoor lighting in areas of the home that need extra light. Solar daylighting has been utilized for years with windows and skylights that let sun-light enter the building structure. The DOE has identified solar daylighting as one of the top energy efficient design upgrades for commercial structures [5]. Commercial structures are typically only occupied in the day and consume large amounts of power to "task light" certain office areas such as spaces where workers will be using computers or working at a desk. Daylighting energy savings can still be achieved in the residential sector with proper designing and planning. Residential buildings are occupied during daylight hours mostly on the weekends and holidays, but plenty of homes still have at least one occupant during the week (children, stay at home guardians, etc.), and solar daylighting can reduce the amount of electrical lights occupants must activate in order to perform daily tasks. Proper placement of daylighting features is key to their success. Solar daylighting should be placed in locations where they will be utilized the most such as common living areas, kitchens, laundry rooms, and any place the occupant will be located during the day time hours.

3.5.1 Sun Tubes – Solartubes®

For this section, solar daylighting effectiveness will be examined using a familiar daylighting feature called a "sun tube." Sun tubes are manufactured by several companies and can have many features. A basic sun tube is a metal tube that penetrates the building roof structure and allows sun light to be transmitted into the room below. The tube is topped with some type of protective dome that allows for the collection and transmission of light. The Australian based company Solartube® provides several new sun tube features and is the focus daylighting simulations in this section. Solartube® offers two sizes of sun tubes: model 160DS (10 inch diameter) and model 290DS (14 inch diameter). Each Solartube® model has a protective dome made of 0.22 inch thick clear acrylic CC2 light transmitting plastic material (plexi-glass) which has a light transmittance property of 92%. Solartube® domes are specially designed to maximize illumination capture area and have "Effective Daylight Capturing Surface" (EDCS) areas listed in the technical data as 0.1032 m^2 for the 10 inch diameter tube and 0.1871 m^2 for the 14 inch diameter tube. Inside the Solartube® dome is a patented daylight capturing lens called the Raybender 3000®. This lens is designed to capture larger amounts of diffuse and low angled (winter and morning/evening) sunlight. Inside the Raybender 3000® is a special light reflector called the LightTracker™. The LightTracker redirects the incident diffuse and low winter sun down into the coated metal tube which runs through the roof structure. Solartubes® have Spectralight® coated light tubes which have a visible reflectance of 99.7% [36]. A picture from the Solartube® sales brochure is shown in Figure 3.1.

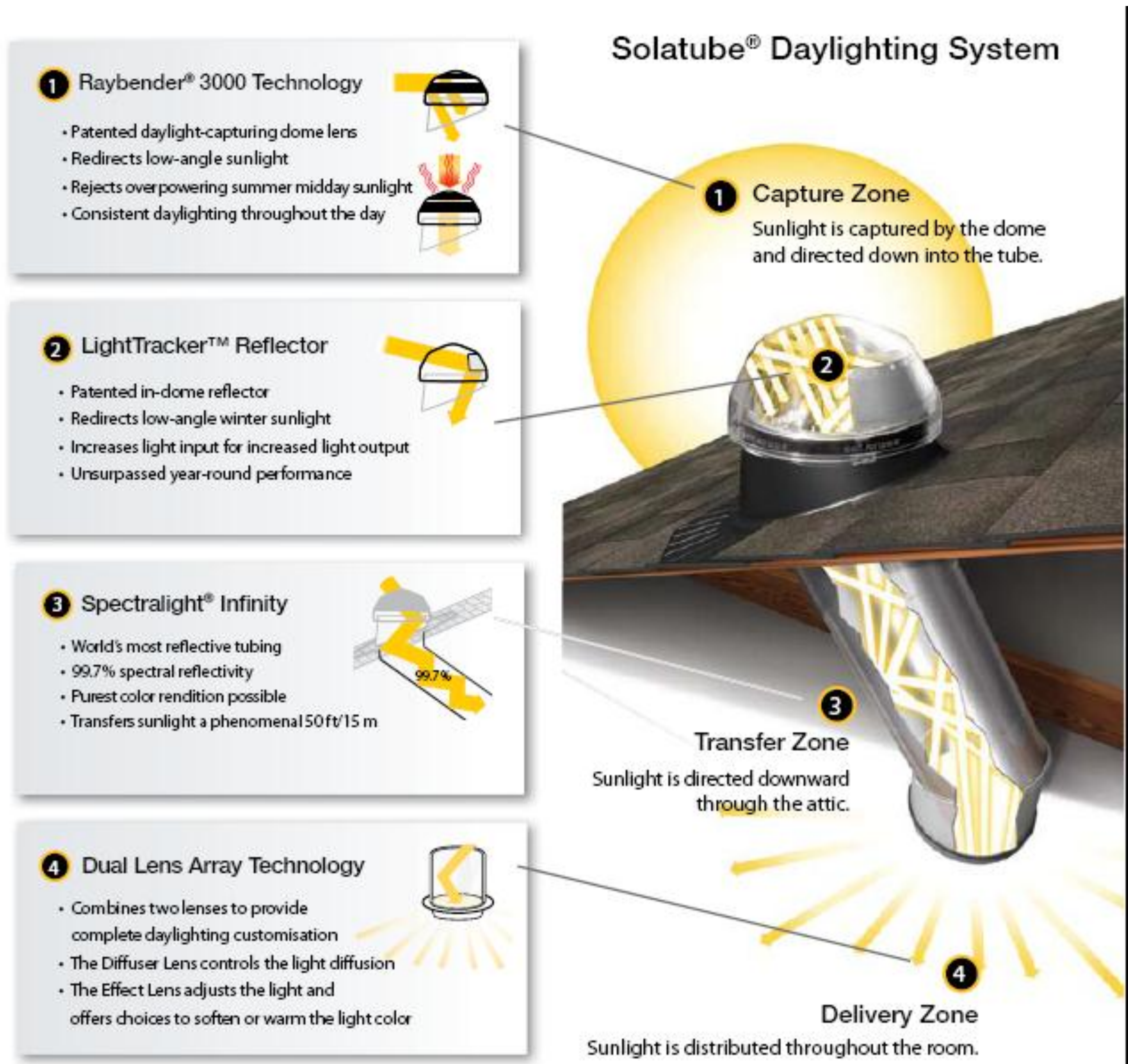

Figure 3.1: Solartube® Technologies Sun Tubes [36]

Knowing the 92% transmission of the acrylic dome, the 99.7% reflectivity of the metal tube, the fact that Solartube® performance data that shows only about 30% of diffuse illumination and 90% normal illumination is collected by the capturing lens, the expected daylight from one 10 inch diameter Solartube® will be examined for the test home under investigation. The lumen output at any instant in time of a Solartube® can be determined from the equation:

$$\text{Day Light Lumens} = r * \{t* [(0.90)*(Ill_{DN})*(EDCS) + (0.30)*(Ill_{DH})*(EDCS)]\}$$

Where r is the tube reflectance (0.997), t is the dome visible light transmission (0.92), Ill_{DN} is the normal direct solar illuminance at a specified location and time (lumens/m^2),

Ill_{DH} is the diffuse horizontal illuminance at a specified location and time (lumens/m^2), and EDCS is the Effective Daylight Capturing Surface area (m^2) of the tube dome (listed on brochure). The normal and diffuse illuminance can be determined from weather data sets (TMY3 data for Chattanooga, TN that is further discussed in later chapters) and appropriate approximations.

The daylighting illumination (light) inside the building seen from a 10 inch diameter Solartube® will now be simulated throughout at typical year in Chattanooga, TN. Since the local solar illumination varies with time, the daylight produced by the Solartube® inside the structure will also vary with the time of the day and be heavily dependent on the season of the year. Obviously, daylighting techniques are only applicable during daylight hours and according to these simulations the top daylighting illumination time ranges from 12:00 pm till about 4:00 pm (maximum light near 3:00 pm depending on the season of the year). Figure 3.2 shows the 10 inch diameter Solartube® light output (lumens) seen in the house for February 5th. An early February sample day was chosen to illustrate the lower limit of solar tube effectiveness since the solar illumination is less in these winter months. As can be seen in Figure 3.2, over 1,468 lumens of light will be seen through the Solartube® at 3:00 pm on this day. Assuming a typical 60 Watt incandescent light bulb produces 850 lumens of light, Figure 3.3 shows how many 60 Watt incandescent light bulbs this one Solartube® replaces during February 5th.

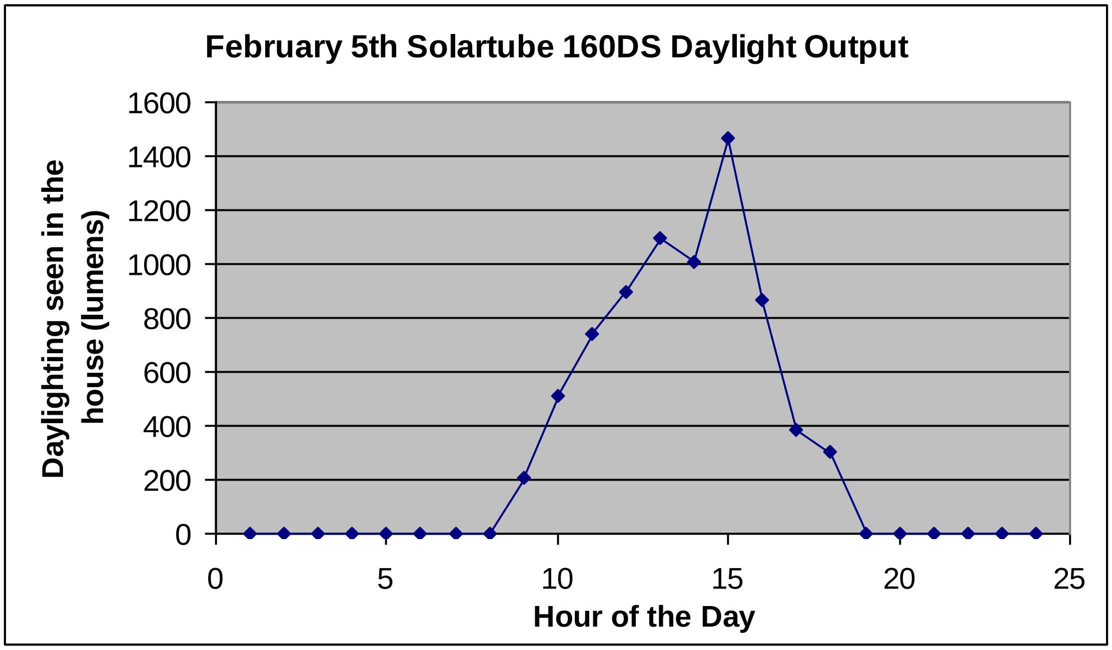

Figure 3.2: Solartube® 160DS Light Output for February 5th

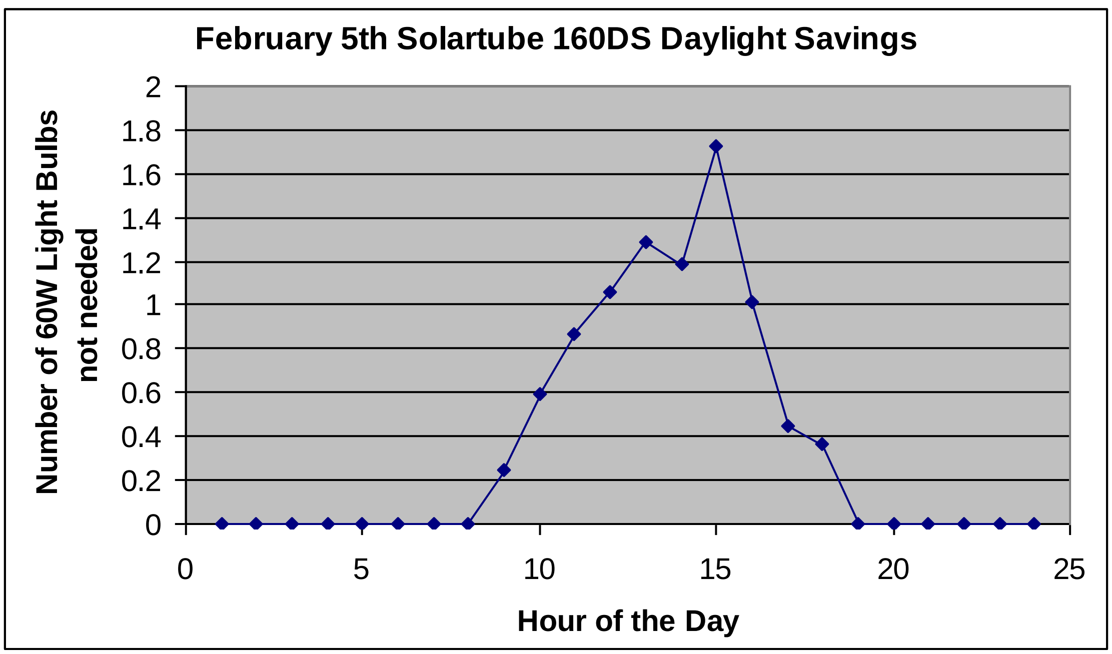

Figure 3.3: 60 Watt Incandescent Light Bulbs Replaced on February 5th

According to these simulations a 10 inch Solartube® could replace 1.7 standard 60 Watt incandescent light bulbs at 3:00 pm on February 5th, but the tube would average just under 1 standard 60 Watt throughout all of the daylight hours (9 hours for February 5th).

To illustrate an upper limit on the 160DS Solartube® daylighting effectiveness, the same information will be examined for July 4th. Figure 3.4 shows the 10 inch diameter Solartube® light output (lumens) seen in the house for a typical July 4th. This early July sample day was chosen to illustrate the upper limit of solar tube effectiveness since the solar illumination is much greater in these hot, clear, summer months. As can be seen in Figure 3.4, over 6,000 lumens of light will be seen through the Solartube® at 3:00 pm on this day. Assuming a typical 60 Watt incandescent light bulb produces 850 lumens of light, Figure 3.5 shows how many 60 Watt incandescent light bulbs this Solartube® replaces on July 4th. According to these simulations a 10 inch Solartube® could replace 7.1 standard 60 Watt incandescent light bulbs at 3:00 pm on July 4th. Averaged over the daylight hours (12 hours of daylight for July 4th) this Solartube® could replace the light of over 4 standard 60 Watt incandescent bulbs throughout July 4th.

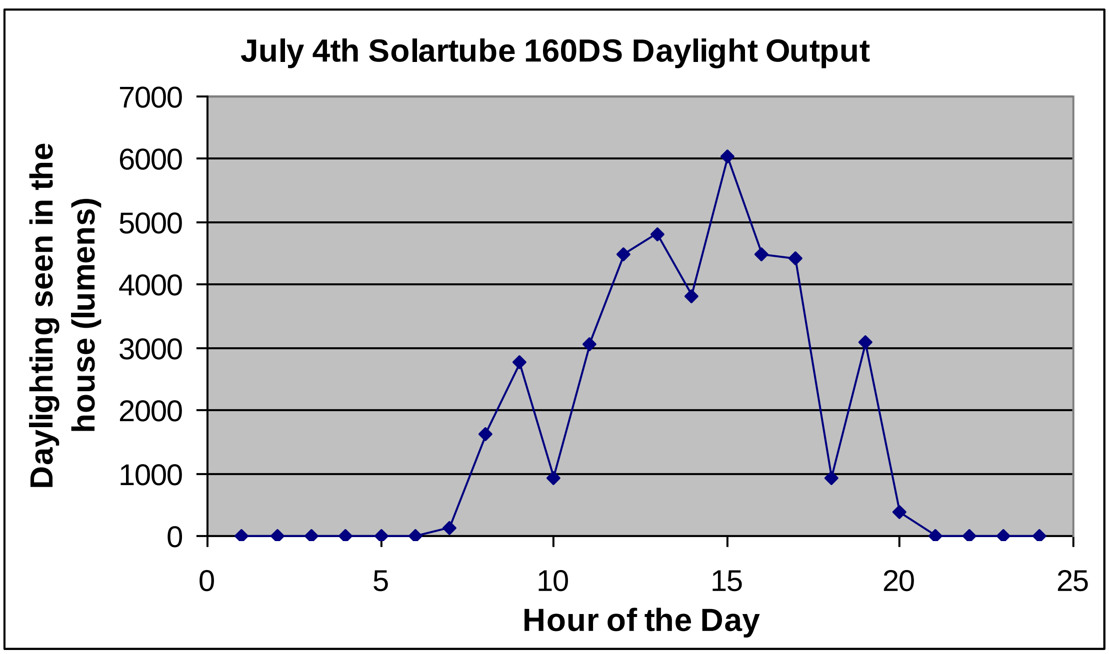

Figure 3.4: Solartube® 160DS Light Output for July 4th

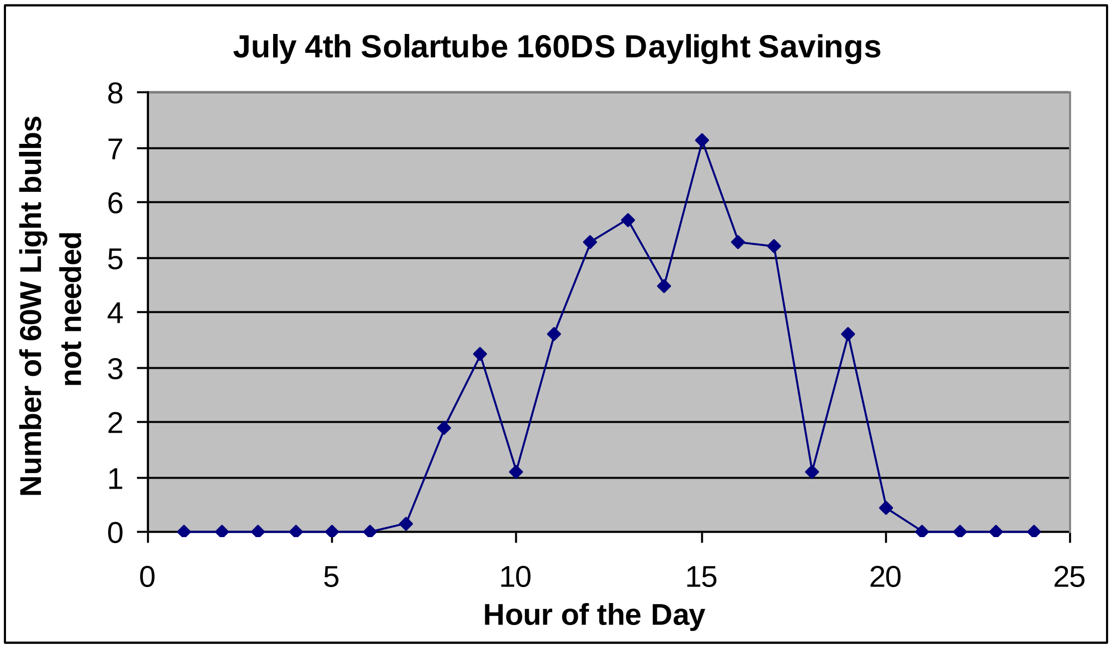

Figure 3.5: 60Watt Incandescent Light Bulbs Replaced on July 4th

As can be seen from the previous figures, the amount of light produced from daylighting techniques such as sun tubes is greatly contingent on the time if the day and the season of the year. Figure 3.6 shows the average daily lumen light output (during daylight hours only) from a 10 inch (160DS) Solartube® throughout a typical calendar year. As was expected, the daylighting seen in the building is far less in January and December than the other months. Light output from this Solartube® was a maximum in April, June, and October. The average daylight-hour, lumen output in April was 3,747.5 lumens. What this means is that on average, during the daylight hours in April, the light output from a 160DS Solartube® would be expected to replace 4.4 standard 60 Watt incandescent light bulbs**.** Figure 3.7 shows the average number of 60 Watt incandescent light bulbs this Solartube® could replace (lumen per lumen matching) throughout the year. Since there are about 360 daylight hours in April, the replacement of 4.4 standard 60 Watt light bulbs running over that same time would save 95.04 kWh of power and $8.55 on electricity expenditures in April alone (assuming 4.4 standard 60 Watt bulbs are active all the daylight hours in April).

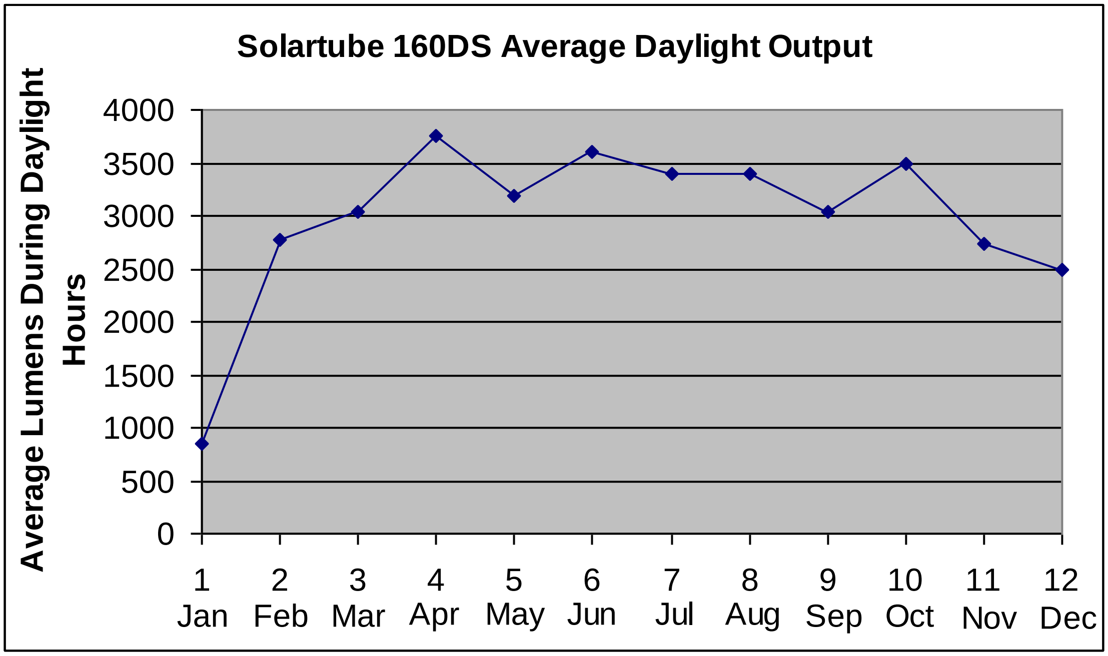

Figure 3.6: Solartube® 160DS Monthly Average Lumen Output During Daylight Hours

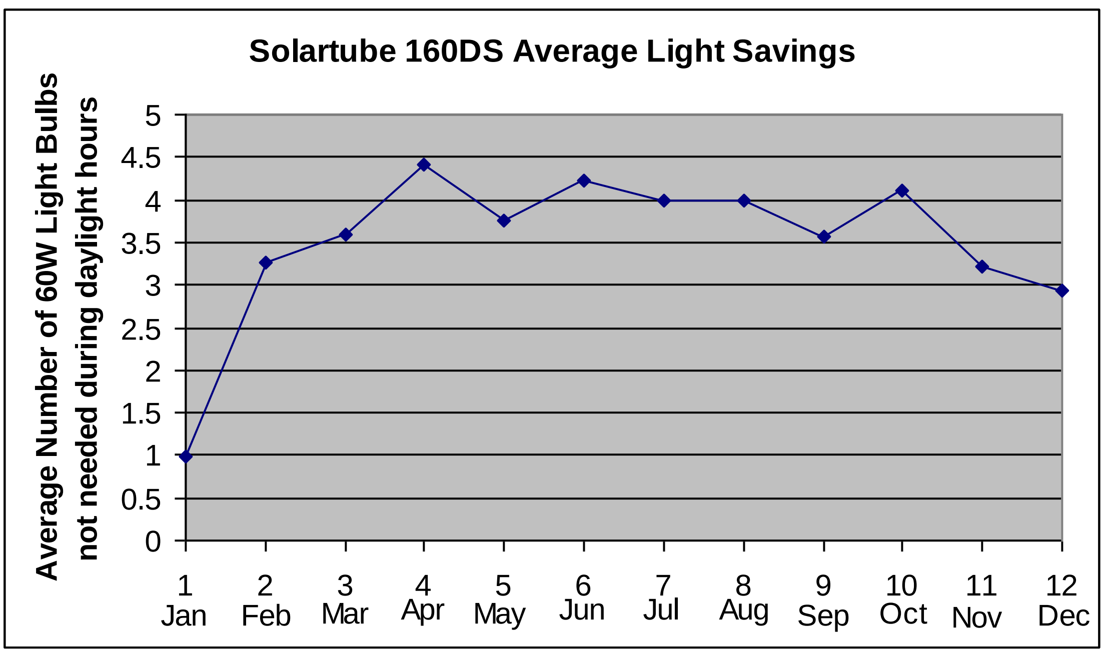

Figure 3.7: Solartube® 160DS Monthly Average Number of 60 Watt Light Bulbs Replaced

Throughout the course of a calendar year, the average daylight-hour lumen output of this 10 inch Solartube® was calculated to be 2,278.35 lumens which would replace nearly 2.68 standard 60 Watt incandescent light bulbs. The purchase and installation costs of sun tubes vary based on geographical location, but a price quote from a contractor was as little as $900 for one 10 inch diameter Solartube® and installation (note: homeowners have installed tubes themselves for less than $200). The payback period on an investment such as this is difficult to estimate for a residential application since the energy and utility savings are a function of how much light would be used in a home during the time when a Solartube® could replace that light. Referring back to the lighting requirements for a typical day in the test home under investigation in this report (Section 3.3), it is seen that lighting is indeed used throughout the test home during daylight hours on both the typical "weekday" simulation and the typical "weekend" simulation. The most plausible areas to install a Solartube® for this home would the in the living room and over the desk area since these are the areas that could get the most light savings during daylight hours. When comparing the possible average hourly light output of a 160DS Solartube® versus the required lighting currently being provided by electrical lights during daylight hours, it was simulated that 493.48 kWh/yr of power would be saved annually if the light from two 160DS Solartube® were used to illuminate the living and office space of this home instead of the current incandescent lights. This would correspond to a $44.41/yr savings in electricity bills. This is of course an annual estimation based on the average light output from the Solartube® simulation and some times throughout the year standard electrical lights will need to supplement the Solartube® when not enough natural illumination is available. Based on these simulations, the payback period for two 160DS Solartube® (assumed total cost $1,000) will be 22.5 years. This payback period seems relatively high, but the energy savings are contingent on the lighting requirements during daylight hours which is not that great in this test home since most day-time lighting needs are already provided by windows and not electrical lights. Solartube® and other daylighting techniques hold great promise not just in the residential section, but in the commercial sector since a large portion of commercial lighting needs occur during daylight hours.

3.6 Brief Remarks on Lighting

A review of all the important simulation results for each of the three lighting sets is shown in Table 3.8. Figure 3.8 graphically shows the total electricity consumption for each lighting simulation set broken down into the electricity consumption for solely producing light and the electricity consumption by the HVAC system to remove the cooling load attributed to the heat generated by each lighting condition.

The LED lighting set showed the most energy savings of all the simulation sets. The LED lighting conditions annually consumed 791.96 kWh of electricity. This is an 82.7% electrical energy savings from the 4,568.3 kWh incandescent (base-line) condition. This would reduce the annual utility cost associated with the lights from $411.17 to $71.28. Despite showing the most energy (and money) savings, the LED lights would cost a staggering $4,054.30 to purchase and install. This makes the LED light substitutions unattractive for most home owners with a high payback period of 11.9 years. LED lighting techniques hold great promise for energy efficient lighting when the initial cost is reduced.

Table 3.8: Important Simulation Results

Bulb Type	Annual Elec. for Light (kWh)	Light Summer Cooling Load (Btu)	HVAC Elec. Consumed for Light Space Load (kWh)	Total Annual Elec. (kWh)	Total Annual Elec. Expense ($)	Total Elec. Saved per Year (kWh)	Total Money Saved per Year ($)	Total Bulb Cost ($)	Pay Back Period (years)
Base-Line	4,105.9	6,277,195	462.46	4,568.3	411.15	x	x	x	x
CFL	1,353.3	1,776,356	125.88	1,479.2	133.13	3,089.16	278.02	376.85	1.35
LED	702.6	1,265,904	89.29	791.96	71.28	3,776.4	339.88	4,054.30	11.9
CFL & LED	898.7	1,489,841	95.94	994.65	89.52	3,573.72	321.63	1,670.38	5.19

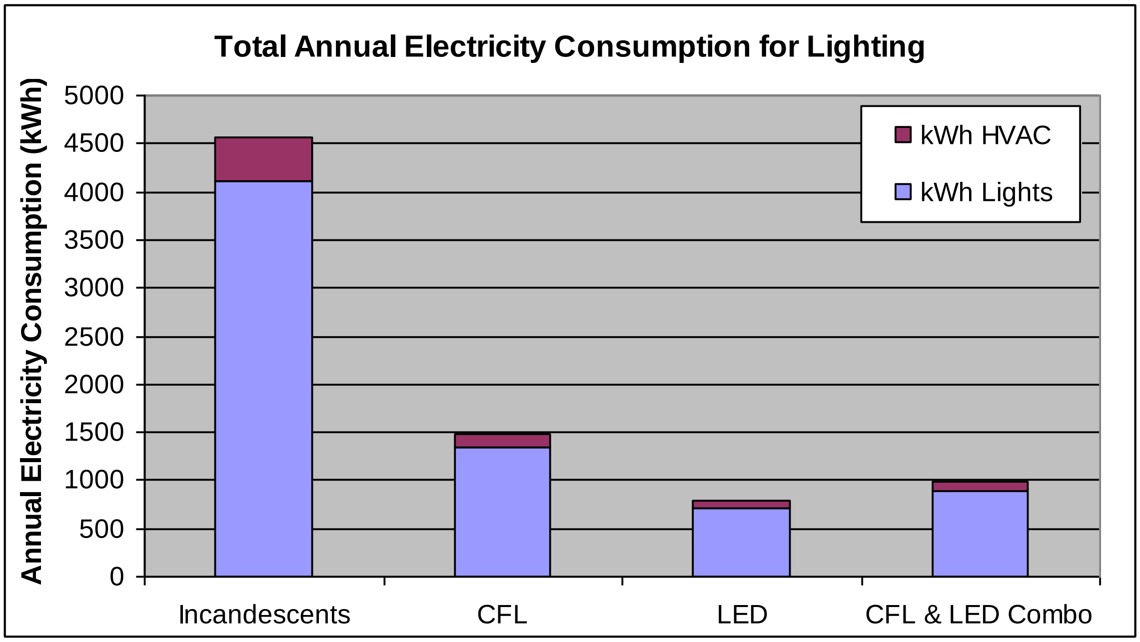

Figure 3.8: Energy Consumption Due to Lighting Conditions

The CFL lighting set showed the least energy savings of the three simulation sets; however, the energy savings for full CFL lighting conditions over incandescents is still significant savings. The CFL lighting conditions annually consumed 1,479.2 kWh of electricity. This is a 67.6% electrical energy savings from the 4,568.3 kWh incandescent (base-line) condition. This would reduce the annual utility cost associated with the lights from $411.17 to $133.13. The major selling feature of the CFL lighting set is the relatively inexpensive purchase and installation cost. The CFL light substitutions would only cost $376.85 to implement. This makes CFL replacements very attractive for home owners with a low payback period of only 1.35 years.

The combination set of LED and CFL bulbs shows great promise for both energy savings and cost minimization. The combination set annually consumed 994.65 kWh of electricity which is a 78.2% energy savings over the base-line lighting set. This would reduce the annual utility cost associated with the lights to $89.52. The combination set would cost $1,670.38 to implement, which is still a fairly large investment for most home owners. Future optimizations should be done to decide the proper mixture of CFL and LED bulbs. This should be aimed at reducing the initial investment while maintaining the most energy savings possible.

Chapter 4

Infiltration Mitigation

The ventilation and infiltration characteristics of a building are only a small part of the overall acceptable indoor air quality (IAQ) standards and thermal comfort procedures HVAC engineers are primarily concerned with. The comfort and indoor air quality of a building depend on many factors such as: thermal regulation, internal and external pollutant control, supply of acceptable fresh air, removal of unacceptable stagnant air, occupant activities and preferences, and proper operation/maintenance of building systems. Care must be taken when modifying building systems that influence indoor air quality and all actions should be under the direction of a registered, professional engineer with expertise in HVAC analysis since any changes to ventilation and infiltration systems may be against local building codes. Projects concerning building ventilation and air quality should conform to current industry standards found in handbooks such as ASHRAE Standard 62, “Ventilation for Acceptable Indoor Air Quality,” and ASHRAE Standards 119 and 136 on “Infiltration in Residences.” Most of the information in this chapter was taken from the ASHRAE 1997 Handbook of Fundamentals chapter concerning ventilation and infiltration systems [18].

4.1 Infiltration Basic Concepts and Terminology

Outdoor airflow through a building is often used a means of diluting and removing indoor air contaminants, but the energy required to “condition” this outdoor air to comfortable inside levels (temperature and moisture control) can represent a significant portion of the building heating/cooling load. This exchange between outdoor air and inside air can be divided into two main categories: ventilation and infiltration.

Ventilation is the intentional introduction of air from the outside (or a fresh air source) into a building to displace old, polluted, stagnant air. Forced ventilation uses mechanical fans or intake/exhaust vents and is sometimes called “mechanical ventilation.” Natural ventilation makes use of open windows, doors, grilles, or other intentional envelope penetrations. In natural ventilation (sometimes called “free” ventilation) air exchange is driven by natural pressure gradients between the inside space and the outside environment.

On the other hand, infiltration is the uncontrolled flow of outdoor air into a building through cracks, punctures, gaps, and other unintentional penetrations in a building envelope or through normal, daily activities by occupants such as opening and closing doors. Infiltration varies with weather conditions, building operation, and building use. Infiltration is also known as “air leakage” into a building. If the air from inside the building leaks into the outside environment it is called “exfiltration.”

4.1.1 Air Exchange Rate

The air exchange rate (I) of a space compares the volumetric air flow rate (Q with units m^3/s), which may be entering or leaving the space, to the interior volume (V with units m^3) of a space/building shown by the equation:

$$I = Q / V$$

The air exchange rate (I) of a building or internal space has units of 1/time, in this case, 1/s. When the unit of time is hours, the air exchange rate is called the Air Changes per Hour (ACH). This is a commonly known/used building parameter.

Typical infiltration values for North American homes vary by a factor of about 10. Newer, tightly constructed structures have air changes per hour (ACH) values of 0.2, while older, loosely constructed buildings can have air exchange rates as large as 2.0 ACH. Figure 4.1 and Figure 4.2 show infiltration rates measured in two different samples of North American housing (new construction versus older, low-income housing).

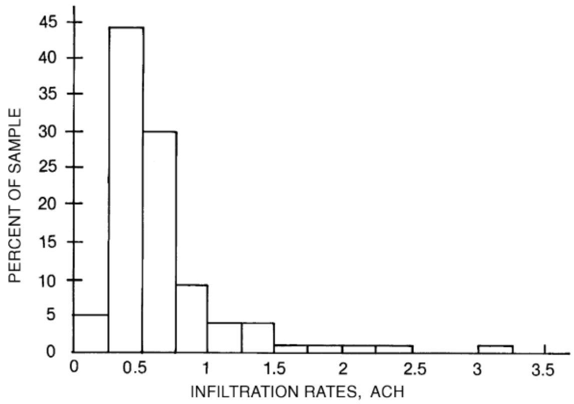

Figure 4.1: ACH New Construction [19]

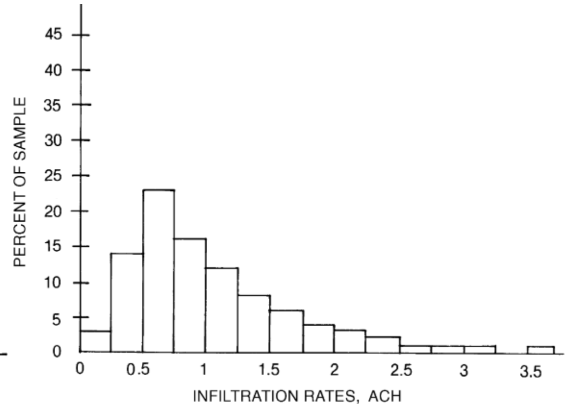

Figure 4.2: ACH Low-Income Housing [19]

Figure 4.1 shows the average seasonal infiltration rates of 312 "new, energy efficient" houses located in different areas of North America. The median infiltration value of this sample was 0.5 ACH**. Figure 4.2** shows the seasonal infiltration values for 266 houses classified as "low-income construction" located in 16 different U.S. cities. The median value of this sample was 0.9 ACH [19]. The differences result from construction techniques, quality of construction materials, and housing designs.

4.1.2 Infiltration Driving Mechanisms

It is commonly known that air will flow from areas of high pressure to areas of low pressure in the absence of another driving force, and the infiltration air exchange of a building operates on this principle. Airflow to/from a building is driven by pressure differences within the building, and by pressure differences between the conditioned space and the outside environment. These are called the "Driving Mechanisms" of infiltration and natural ventilation techniques. The driving mechanisms of infiltration and natural ventilation are the (1) pressure differences across the building envelope caused by wind; (2) air density differences due to temperature differences between outdoor and indoor air (stack effect); and (3) operation of appliances, such as combustion devices, leaky forced-air thermal distribution systems, and mechanical ventilation systems [18]. The absolute indoor-outdoor pressure difference at a particular location within a structure depends on the magnitude of these driving mechanisms as well as the characteristics of the opening/puncture in the building envelope (i.e. their locations and the relationship between pressure difference and airflow through each unique opening). These pressure differences across the building envelope are based on the requirement that the mass flow of air into the building is equal the air mass flow out. In general practice, this assumption holds true because there is only a small, negligible difference in the density of the outside and inside air; therefore, the volumetric airflow rate into the building space equals the volumetric airflow rate out of the building space.

(1) Driving Mechanism - Wind

When wind is incident on a building surface, such as an exterior wall, it creates a distribution of static pressures that depend on the wind direction, wind speed, air density, surface orientation, and surrounding conditions. If there is no significant opening for the air to flow through, the pressure distribution on the outside of the surface is independent of the pressure inside (p_i) the building. However, if cracks or envelope penetrations are present then the pressure distribution on the outside of the exterior surface is also a function of the pressure inside the building. If (1) no other forces act on the building; (2) there is a negligible indoor-outdoor temperature difference; and (3) there are no appliances forcing air through the building, then the pressure difference between the outdoors and indoors at a particular location is determined by the equation:

$$\Delta p = p_o + p_{wind} - p_i$$

The pressure difference between the outdoors and indoors at a particular location (Δp), the static pressure at a reference height in undisturbed flow (p_o), the wind pressure (p_{wind}), and the interior pressure at the height of the particular location (p_i) all have units of pressure such as Pascals (Pa).

If no indoor-outdoor temperature difference exits, the interior static pressure (p_i) decreases linearly with height at a rate dependent on the particular interior/exterior temperature. However, if an indoor-outdoor temperature difference exists (which is likely) the interior static pressure may be determined by calculating the airflow through each opening as a function of the interior pressure, adding all these airflow rates together, setting the sum equal to zero, and solving for the interior pressure [18]. To solve for the interior pressure at a particular location in this way would require copious information about the locations of each opening, the wind pressures (p_w) at each location, and the relationship between the airflow rate and the pressure at each opening, which is rather difficult over a large building area. Also, if there is a temperature difference between the outside and inside of a building then a gradient (Δp_s) is imposed on the pressure difference. This added gradient confuses calculations even more adding another parameter ($p_{i,r}$) called the "interior static pressure at some reference height." More information about calculations such as these can be found in supplemental ASHRAE publications. To determine the pressure differences across the building envelope and the corresponding air exchange rates, building-specific information about the exterior pressure distribution due to wind and the location of and the airflow rate/pressure difference relationship for every opening in the building shell are needed. These inputs are difficult to obtain for any given building, which makes such a determination unrealistic even for the most advanced modeling software [18].

(2) Driving Mechanism - Stack Effect

Temperature differences between outdoor and indoor air cause small density differences (and therefore pressure differences) that drive infiltration. This is referred to as the "stack effect." During the winter months (heating season), warmer inside air rises and flows out of a building near the roof line. This air is replaced by the colder, outside air entering the building near the base or foundation. This is shown graphically in Figure 4.3. On the other hand, during the summer (cooling season) the flow directions are reversed and cooler air exits the building near the foundation and warmer enters the building nearer the roof line. The rate of air infiltration is generally lower in the cooling season (summer months) because the temperature differences between the inside and outside spaces are smaller. As can be seen in Figure 4.3, there is a height measured from the floor at which the interior and exterior pressures are equal and this height (H_{NPL}) is called the "Neutral Pressure Level" [20].

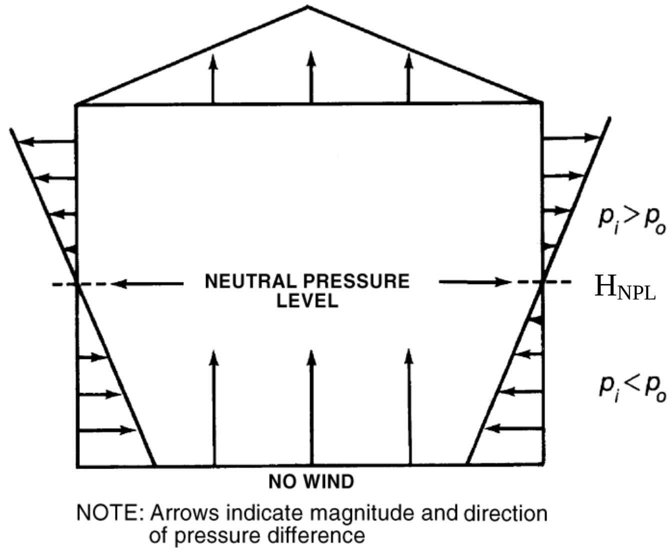

Figure 4.3: Pressure Differences Caused by Stack Effect in Heating Season [18]

The pressure difference caused by this stack effect at any particular height (H) is given by:

$$\Delta p_s = (\rho_o - \rho_i)g(H - H_{NPL}) = \rho_i g(H - H_{NPL})(T_i - T_o)/T_o$$

The pressure difference due to stack effect (Δp_s) is given in units of Pascals, the outside air density (ρ_o) has units of kg/m^3 and the indoor air density (ρ_i) is taken to be essentially constant at about 1.2 kg/m^3, the gravitational constant (g) is 9.81 m/s^2, the particular height (H) for the measurement and the height of the neutral pressure level (H_{NPL}) are both measured in meters, and the absolute indoor temperature (T_i) and the absolute outdoor temperature (T_o) have units of Kelvin.

The location of the Neutral Pressure Level (H_{NPL}) at zero wind speed is a structurally-dependent parameter. The height of the NPL depends on the vertical distribution of openings in the building shell, the resistance of the openings to airflow, and the resistance to vertical airflow within the building. If the building envelope openings are uniformly distributed vertically, they have the same resistance to airflow, and there is no internal resistance to airflow, the NPL is at the "mid-height" of the building. Internal building features such as stairwells, elevator shafts, utility ducts, chimneys, vents, windows, and mechanical supply and exhaust systems complicate the analysis of the NPL location. Likewise, added external wind conditions can alter the location of the NPL making it a difficult value to compute. Available data on the NPL in various kinds of buildings is limited [20].

Sometimes used as a "rule of thumb," a useful estimate is that the pressure difference induced in a building by the stack effect is 0.04 Pa/K*m, neglecting any resistance to airflow within a structure [18]. Precise stack effect pressure differences require building and environment specific information and are difficult/time consuming to determine.

(3) Driving Mechanism - Mechanical Systems

Operating mechanical equipment such as ventilation/exhaust systems and vented combustion devices affect pressure differences across the building envelope. The interior static pressure adjusts such that the airflows through all openings in the building envelope plus equipment-induced airflows balance to zero. These mechanical equipment pressure differences are unpredictable unless the location of each opening in the building envelope and the relationship between pressure difference and the airflow rate for each opening is known [18]. The interaction between mechanical ventilation system operation and envelope air-tightness has been discussed in other reports for low-rise buildings (Nylund 1980) and for office buildings (Tamura and Wilson 1966, 1967b; Persily and Grot 1985a).

The pressure differences caused by each driving mechanism (wind, stack, and mechanical systems) are related to the airflow through the building envelope by what is called a "leakage function." Background and theoretical materials relevant to leakage functions may be found in Hopkins and Hansford (1974), Etheridge (1977), Kronvall (1980a), and Chastain et al. (1987). Leakage functions come from incompressible flow theory and the Bernoulli equation, but each function is different based on the geometry of the opening and whether the pressure difference is driven by wind or thermal forces. Airflow rates from each driving force are calculated separately and combined using the square-root of the sum of the squares approach:

$$Q_{ws} = [(Q_w)^2 + (Q_s)^2]^{(1/2)}$$

This equation shows the combination of infiltration airflow for an envelope opening subject to wind and stack driving mechanisms. The infiltration airflow from both wind and stack effect (Q_{ws}), the infiltration airflow from the wind effects alone (Q_w), and the infiltration airflow from the stack effect alone (Q_s) are all volumetric airflow rates and as such have units such as m^3/s. Combing airflow rates in this manor for each driving mechanism is time consuming and difficult requiring specific building information and specific leakage functions for various types of building openings and driving mechanisms. Due to this fact, procedures using simplified air flow models will be discussed in later sections of this chapter.

4.1.3 Air Leakage

Despite the fact that the terms "infiltration" and "air leakage" are sometimes used interchangeably, they are separate, though related, values. As previously defined, infiltration is the rate of uncontrolled air exchange through unintentional openings that occur under a given set of conditions. On the other hand, air leakage is defined as a measure of the "air-tightness" of the building shell. The greater the air leakage area (A_L) of a building, the greater the infiltration rate will be (weather, exposure, and building geometry being equal). The air leakage area of a building is a physical, measurable characteristic of a building that depends on the building design, construction, and deterioration over time. This area is sometimes called the "Equivalent" or "Effective Air Leakage Area" (ELA) and has units of cm^2 [18]. The air leakage area for a building can be converted into an air-tightness rating which is a commonly used value for builders. Air-tightness is just one factor in determining a buildings air exchange rate (infiltration), but it is a useful value for comparing one building to another and determining the effectiveness of "air-tightening" retrofits.

Dickerhoff et al. (1982) and Harrje and Born (1982) studied the air leakage of individual building components and systems, and their findings were summarized as percentages of "whole-building air leakage area" associated with various building components. This information is shown in Table 4.1.

Table 4.1: Percentage of Air Leakage Area by Building Components [18]

Component	**Mean Percentage**	Range of Percentage
Walls	**35%**	18 - 50%
Ceiling	**18%**	3 - 30%
Heating System	**18%**	3 - 28%
Windows and Doors	**15%**	6 - 22%
Fireplaces	**12%**	0 - 30%
Vents	**5%**	2 - 12%

According to the mean percentage of air leakage area for most buildings, 35% air leakage area (the most by category) is associated with the walls of the structure; more specifically with envelope penetrations (plumbing and electrical), cracks due to poor construction that widen over time, and loosely constructed wall joints. A complete breakdown of these values and what contributes most to the leakage areas in each category can be found in the "Ventilation and Infiltration" section of the ASHRAE Fundamentals Handbook 1997 [18].

Continuing research has been done to study air leakage areas of buildings. From this, a relatively new procedure was created to determine the air leakage area of a building based on the size, quantity, and positioning of various typical building components [20]. The "building air leakage area" (A_c) is based on combining the effects (leakage areas) of individual building components. Separate component leakage areas are shown in Table 4.2 for a variety of building features at a pressure of 4 Pa. Table 4.2 shows only a sample of the various building component leakage areas available and a complete listing can be found Appendix D at the end of this report. These values in are in terms of air leakage area "per unit component." Per unit component means the values are shown as either per component (number of components), per unit surface area, or per unit length crack or sash, whichever is appropriate [18]. Looking up each building component and multiplying the component leakage area by the appropriate "unit component" gives the total leakage area (cm^2) of that building component. Summing all the component leakage areas of a building envelope, the building leakage area (A_c) can be determined for use in calculations. This value is sometimes synonymous with air leakage area (A_L); however, the air leakage area is actually a measured (not estimate from tables) value. Later sections of this report use the two terms interchangeably.

Table 4.2: Sample of Component Effective Air Leakage Areas (Residential) [18]

Component Type	Units (See Notes)	Best Estimate	Mini-mum	Maxi-mum
Ceiling				
General	cm^2/m^2	1.8	0.79	2.8
Drop	cm^2/m^2	0.19	0.046	0.19
Ceiling penetrations				
Whole-house fans	cm^2 ea	20	1.6	21
Recessed lights	cm^2 ea	10	1.5	21
Ceiling/Flue vent	cm^2 ea	31	28	31
Surface-mounted lights	cm^2 ea	0.82		
Chimney	cm^2 ea	29	21	36
Crawl space				
General (area for exposed wall)	cm^2/m^2	10	8	17
200 mm by 400 mm vents	cm^2 ea	129		
Door frame				
General	cm^2 ea	12	2.4	25
Masonry, not caulked	cm^2/m^2	5	1.7	5
Masonry, caulked	cm^2/m^2	1	0.3	1
Wood, not caulked	cm^2/m^2	1.7	0.6	1.7
Wood, caulked	cm^2/m^2	0.3	0.1	0.3
Threshold	cm^2/lmc	2	1.2	24
Doors				
Attic/crawl space, not weather-stripped	cm^2 ea	30	10	37
Attic/crawl space, weather-stripped	cm^2 ea	18	8	18.5
Attic fold down, not weather-stripped	cm^2 ea	44	23	86
Attic fold down, weather-stripped	cm^2 ea	22	14	43
Double, not weather-stripped	cm^2/m^2	11	7	22
Double, weather-stripped	cm^2/m^2	8	3	23
General, average	cm^2/lmc	0.31	0.23	0.45
Storm (difference between with and without	cm^2 ea	6	3	6.2
Single, not weather-stripped	cm^2 ea	21	12	53

Single, weather-stripped	cm^2 ea	12	4	27
Electrical outlets/Switches				
No gaskets	cm^2 ea	2.5	0.5	6.2
With gaskets	cm^2 ea	0.15	0.08	3.5
Furnace				
Sealed (or no) combustion	cm^2 ea	0	0	0
Retention head or stack damper	cm^2 ea	30	20	30
Floors over crawl spaces				
General	cm^2/m^2	2.2	0.4	4.9
Without ductwork in crawl space	cm^2/m^2	1.98		
With ductwork in crawl space	cm^2/m^2	2.25		
Fireplace				
With damper closed	cm^2/m^2	43	10	92
With damper open	cm^2/m^2	350	145	380
Piping/Plumbing/Wiring penetrations				
Uncaulked	cm^2 ea	6	2	24
Caulked	cm^2 ea	2	1	2
Vents				
Bathroom with damper closed	cm^2 ea	10	2.5	20
Dryer with damper	cm^2 ea	3	2.9	7
Kitchen with damper open	cm^2 ea	40	14	72
Walls (exterior)				
Cast-in-place concrete	cm^2/m^2	0.5	0.049	1.8
Clay brick cavity wall, finished	cm^2/m^2	0.68	0.05	2.3
Low-density concrete block, unfinished	cm^2/m^2	3.5	1.3	4
Low-density concrete block, painted	cm^2/m^2	1.1	0.52	1.1
High-density concrete block, unfinished	cm^2/m^2	0.25		
Continuous air infiltration barrier	cm^2/m^2	0.15	0.055	0.21
Window framing				
Masonry, uncaulked	cm^2/m^2	6.5	5.7	10.3
Masonry, caulked	cm^2/m^2	1.3	1.1	2.1
Wood, uncaulked	cm^2/m^2	1.7	1.5	2.7
Wood, caulked	cm^2/m^2	0.3	0.3	0.5
Windows				
Awning, not weather-stripped	cm^2/m^2	1.6	0.8	2.4
Awning, weather-stripped	cm^2/m^2	0.8	0.4	1.2
Casement, weather-stripped	cm^2/lmc	0.24	0.1	3
Casement, not weather-stripped	cm^2/lmc	0.28		
Double-hung, not weather-stripped	cm^2/lmc	2.5	0.86	6.1

Double-hung, weather-stripped	cm^2/lmc	0.65	0.2	1.9
Jalousie	cm^2/louver	3.38		
Lumped	cm^2/lms	0.471	0.009	2.06

Note: Air Leakage areas are based on values found in literature. The effective air leakage area (in square centimeter) is based on a pressure difference of 4 Pa and Cd = 1. Abbreviations: m^2 = gross area in square meters. Ea = each. Lmc = linear meter of crack. lms = linear meter of sash. A complete listing of Air Leakage Areas is found in Appendix D.

4.1.4 Measuring Infiltration

The most reliable and accurate way to determine a building's air exchange rate is to measure the value. Tracer gas measurement tests use an inert or non-reactive gas to label the indoor air and measure the rate at which this gas leaves (dissipates within) a building. This value is related to the building's air exchange rate. Tracer gas measurement procedures are considered the most accurate way of determining the air exchange rate of a building, but they are somewhat expensive and time consuming tests. For most instances, it is sufficient, or preferable, to measure the air leakage of a building with pressurization testing [18]. Fan pressurization tests are quick and relatively inexpensive. These tests characterize building envelope air-tightness independent of the outside weather conditions. The most popular fan pressurization test is called the "blower door" test. In this test, a large fan/blower is mounted in a door (or window) and this fan induces a large, roughly uniform, pressure difference across the building shell (CGSB 1986, ASTM StandardE 779). The airflow required to maintain this pressure difference is then measured. The "leakier" the building envelope, the more airflow is necessary to induce a specific indoor-outdoor pressure difference. The airflow rate is usually measured multiple times at a series of pressure difference ranging from 10 – 75 Pa. Testing in this way is the easiest, most direct manor of determining a building's infiltration characteristics.

4.1.5 Controlling Infiltration

It is easier to mitigate air leakage in new construction than to "tighten" an existing structure [22]. For new construction, it is paramount to have a continuous air infiltration retarder. A continuous retarder is one of the most effective means of reducing air leakage through walls, around windows, door frames, and at joints between major building features [18]. A continuous air infiltration retarder can also act as a continuous vapor retarder; this is called an "air-vapor retarder." Many products have been developed to act as air-vapor retarders. Companies such as DuPont Chemicals have developed strong, light-weight, polymer sheets that can be installed as a continuous barrier around a structure. These barriers can be installed on the inside or outside of the wall framing of the building. If the air-vapor barrier is installed on the outside of the wall frame it must have a vapor permeance rating high enough to allow moisture to escape (diffuse) from the wall/insulation. However, if the air-vapor barrier is installed on the inside of the wall frame, care must be taken to properly seal the barrier despite working around penetrations such as electrical outlets and light switches, plumping penetrations, at ceiling-wall and wall-wall joints, and other interior building features.

For existing buildings, the prospect of reducing air leakage is much more labor intensive. First, the air leakage sites throughout the structure must be located. As discussed previously, air leakage in a building can be traced to a wide range of unexpected/unobvious building components and construction defects. A variety of techniques and procedures developed to locate leakage sites in a building envelope are described in ASTM Standard E 1186. Once leakage sites have been located, they can be repaired/mitigated with materials and techniques appropriate to the size and location of the leak. Harrje et al. (1979), Diamond et al. (1982), and Energy Resource Center (1982) include information on air-tightening existing residential structures. Depending on the extent of leakage, the effort put forth to mitigate this leakage, and the experience of those performing the work, residential buildings can be "tightened" anywhere from 5% to more than 50% [18].

The Consumer Energy Center, a department within the California Energy Commission, provides some easy methods for reducing the air infiltration of a home. The CEC recommends "weatherizing" the windows and doors of a home, and examining the heating/cooling system ductwork and vents throughout the home. "Weatherizing" is a catch-all term for making the window/door less susceptible to weather conditions and air infiltration. Two methods for "weatherizing" are to use caulking and weather-stripping material to seal any possible space for air to leak into the building space. Millions of doors across the country have little or no weather-stripping. Since most doors have a space, sometimes as much as a quarter inch or more, between the bottom of the door and the floor, large amounts of air can flow in and out of the house. For a typical 36 inch entry door, a quarter-inch small crack can leak as much air as a nine square inch hole in a wall. It is estimated that up to 11% of the air leaks in a building are around the doors [23]. Weather-stripping for doors (and windows) comes in many forms, and can be made up of a combination of materials such as wood, rubber, vinyl, metal and foam and some types work better for different types of doors. Caulking is a silicone based sealant used to close up small cracks and seams in solid materials. Eventually, all homes need fresh caulking to fill gaps and cracks that may appear in walls and where different types of materials are joined. Checking and repairing caulk should be a maintenance project every one-two years, it not only air-tightens a home, but it also prevents moisture and even insects from entering the building envelope. Weather-stripping and caulking is probably the least expensive, simplest, and most effective way to cut down on wasted energy due to air infiltration.

Another recommendation from the Consumer Energy Center is to examine the home's ductwork and ventilation setup. Think of the HVAC ductwork system as huge hose, delivering hot air instead of water into the home. Mostly out of sight, ducts can leak for years without being detected. Ductwork can become torn or crushed and flattened or old duct tape can dry up and fall off over time, allowing junctions and splices to open, spilling heated/cooled air into the attic or unconditioned crawlspace under the flooring. According to field research performed by the California Energy Commission, you can save roughly 10% of the heating bill by preventing leaky ductwork. Leaky ducts waste heated and cooled air even before it arrives inside a carefully weather-stripped building envelope.

4.2 Infiltration Simplified Models – LBNL Model

As discussed previously, it is straightforward to calculate the air exchange rate of a given building if (1) the location and leakage function for every opening in the building envelope are known, (2) the wind pressure coefficients over the entire building envelope for a given time throughout the year are known, and (3) any mechanical ventilation airflow rates are known. Generally speaking these inputs are unavailable for most buildings except very simple structures or extremely well studied buildings. Therefore, much work has been done to provide accurate models for air infiltration. Several procedures have been developed to calculate building air exchange rates that are based on physical models of the building interior as a "single zone." Single zone approximations are to be used for buildings that have low internal resistance to airflow (like this test home). These models are not likely to return accurate results for large, multi-zone buildings (such as high-rise or commercial structures). Single zone models have been developed by the Institute of Gas Technology (IGT), the Building Research Establishment, and the Lawrence Berkeley National Laboratory (LBNL) [18].

The last model is referred to as the "LBNL model" and is widely used as a basis for residential air exchange calculations. The LBNL model originally was designed to use building pressurization test data results to characterize home air leakage through the "effective leakage area" (A_L) at a 4 Pa test pressure, but later was modified to use the calculated "building air leakage area" ("A_c" Discussed in the Air Leakage Section of this report). The LBNL model takes into account outside wind speed and temperature as well as certain building parameters called the "Stack Coefficient" (C_s), and the "Wind Coefficient" (C_w).

The Stack Coefficient (referring to the "stack effect" as an infiltration driving mechanism) is a simple value to determine. The various values of the Stack Coefficient are shown in Table 4.3 for various building heights (building stories / levels). For the LBNL model, house heights of one-, two-, and three-story buildings are taken as 2.5, 5.0, and 7.5 meters respectively. The Stack Coefficient has units of $(L/s)^2/[(cm^4)*K]$.

Determining the LBNL model Wind Coefficient (C_w) is a two step process. First, a building "Local Shielding Class" must be determined. The Local Shielding Class is based on the surroundings of the building in question. Various peripheral obstacles such as trees, adjacent buildings and solid fences play a role in distorting the incident wind on the exterior of a building and the Local Shielding Class takes these objects into account.

Table 4.4 shows the various Local Shielding Classes for residential homes. Local Shielding Class 4 is taken as the “typical suburban” setting while class 5 is taken as a “typical downtown” setting. Once a shielding class is known, a Wind Coefficient can be determined. The Wind Coefficient is a function of both the Local Shielding Class and the building height (stories/levels). Typical Wind Coefficient values are shown in Table 4.5 for various combinations of shielding class and building heights. The Wind Coefficient has units of $(L/s)^2/[(cm^4)*(m/s)^2]$.

Table 4.3: Stack Coefficient C_s

	House Height (Stories)		
	One	Two	Three
Stack Coefficient	0.000145	0.00029	0.000435

Table 4.4: Local Shielding Classes

Class	Description
1	No obstructions or local shielding
2	Light local shielding; few obstructions, few trees, or small shed
3	Moderate local shielding; some obstructions within two house heights, thick hedge, solid fence, or one neighboring house
4	Heavy shielding; obstructions around most of perimeter, buildings or trees within 10 m in most directions; typical suburban shielding
5	Very heavy shielding; large obstructions surrounding perimeter within two house heights; typical downtown shielding

Table 4.5: Wind Coefficient C_w

Shielding Class	House Height (stories)		
	One	Two	Three
1	0.000319	0.00042	0.000494
2	0.000246	0.000325	0.000382
3	0.000174	0.000231	0.000271
4	0.000104	0.000137	0.000161
5	0.000032	0.000042	0.000049

Once the Stack Coefficient, Wind Coefficient, inside temperature conditions, outside weather conditions (wind speed and outside temperature), and effective air leakage area (or calculated building air leakage area) for a particular building are known, the airflow rate into (or out of) that building can be calculated using the LBNL model equation:

$$Q = (A_L/1000) * [C_s\Delta t + C_w V^2]^{(1/2)}$$

The airflow rate (Q) has units of m^3/s, the Stack Coefficient (C_s) has dimensionalized units of $(L/s)^2/[(cm^4)*K]$, the Wind Coefficient (C_w) has dimensionalized units of $(L/s)^2/[(cm^4)*(m/s)^2]$, the average outside wind speed (V) at a given instant in time has units of m/s, and the average indoor-outdoor temperature different (Δt) for a given instant in time is measured in units of Kelvin. The building leakage area (A_L) is typically a measured value having units of cm^2, but a calculated effective air leakage area (ELA) value or building air leakage area (A_c) value can be used interchangeably [18].

As discussed in the "Basics Concepts" section of this report, the air exchange rate (I) of the building is obtained by dividing the air flow rate (Q from above) by the building volume (V). If the time interval in the calculation is for 1 hour (typical for weather station data) then this air exchange rate becomes the often used Air Changes per Hour (ACH) value. A calculation such as this gives the amount of outside air that is entering or leaving the building in question. This allows an estimate of the HVAC energy (power) that will be required to condition the “infiltrating” outside air to acceptable inside comfort levels.

The predictive accuracy of the LBNL model can be very good. The LBNL model can be as accurate as +/- 7% for weekly value and +/- 20% for “short term” calculations when the building parameters are well known (Sherman and Modera 1986).

4.3 Infiltration Energy Loads

“Outdoor air introduced into a building constitutes a large part of the total space-conditioning (heating, cooling, humidification, and dehumidification) load, which is one reason to limit air exchange rates in buildings to the minimum required. Air exchange typically represents 20% – 40% of a shell-dominated building’s thermal load [18].” Basically, high infiltration (and exfiltration) rates can contribute significantly to the heating and cooling load of a building and referring back to the DOE 2006 study, heating and cooling account for about 42% (28% heat, 14% cool) of a residential building’s total energy end use [5].

Air exchange (infiltration and ventilation) increases a building’s energy load in three ways: increased sensible loads, increased latent loads, and decreased envelope performance [18].

The first way air exchange increases a building’s energy load is that the incoming, outside air must be cooled or heated to match the inside prescribed temperature of the conditioned space. This is called the “sensible” heating or cooling load, and the rate of energy consumed by this sensible heating/cooling is:

$$q_s = Q*\rho*c_p*\Delta t$$

For this equation, the sensible heating/cooling load (q_s) has units of Watts, the airflow rate (Q) has units of m^3/s, the air density (ρ) is assumed to be a constant value of 1.2 kg/m^3, the specific heat of the air (c_p) is likewise assumed constant with a value of 1,000 J/(kg*K), and the indoor-outdoor temperature difference (Δt) is measured in degrees Kelvin or Celsius.

Secondly, air exchange increases the energy load of a building by influencing the moisture content of the air inside the conditioned space. This is particularly important in some locations during the summer when the outdoor air is very humid and must be dehumidified for comfortable inside air conditions. Also, in the winter time when the relative humidity of the indoor air is below 30%, humidification may be needed for occupant comfort [3]. Energy used to influence the moisture content of air is termed the "latent" space load, and the rate of energy consumed by this process is given by:

$$q_l = Q*\rho*h_{fg}*\Delta W$$

For this equation, the latent space load (q_l) has units of Watts, the airflow rate (Q) and air density (ρ) remain the same as the sensible heating equation, the latent heat of vapor at the current air temperature (h_{fg}) was assumed to a constant $2.34x10^6$ J/kg value, and ΔW is the humidity ratio of the indoor air ($\acute{\omega}_{in}$) minus the humidity ratio of the outdoor air ($\acute{\omega}_{out}$) which has units of mass water / unit mass dry air or kg/kg.

Finally, air exchange can increase a building's energy load by decreasing the thermal performance characteristics of the envelope insulation system. "Air flowing through and around the insulation can raise heat transfer rates above designed rates. The effect of such air flow on insulation system performance is difficult to quantify but should be considered. Airflow within the insulation system can also decrease the system's performance due to moisture condensation in and on the insulation [18]."

Since air exchange increases the sensible and latent heating/cooling load of a building space (along with the understated effects on envelope insulation performance), it is important to minimize the unintentional air exchange (infiltration) of a building/space.

4.4 Baseline Simulation Procedure

For a medium sized, residential home like the Chattanooga, TN house under investigation, the Lawrence Berkeley National Laboratory "LBNL" simplified model of infiltration is quite appropriate. This house is essentially one-story, has an open floor plan with few internal walls (resistances to airflow); none of which are insulated, and the smaller home footprint lends well to a "single-zone" approximation. As discussed previously, the LBNL model requires minimal input information, but to determine the home airflow rate (Q) and the subsequent air exchange rate (I) for this building the outside wind speed, outdoor-indoor air temperature difference, Stack Coefficient, Wind Coefficient, and building effective air leakage area (ELA) must be known. Once these values are known throughout an entire year, the air exchange rate can be modeled through the simple application of the LBNL equation. This was done using a self-made, simple MatLAB® computer code.

The outside wind speed and ambient air temperature values throughout the typical year can be taken directly from a Typical Meteorological Year (TMY3) data sheet provided by the National Weather Service. To determine the outdoor-indoor temperature difference (Δt) an indoor design temperature must be assumed. This was taken to be the temperature the home thermostat would be set to throughout the year. For simplicity, a summer design temperature was assumed for the "summer" months and a separate winter design temperature was assumed for the remaining "winter" months. The summer design temperature was assumed to be 72˚F (22.2˚C) for each hour from mid-April to late-November. On the other hand, the winter design temperature was assumed to be 68˚F (20˚C) each hour from late-November back to mid-April. Together with the known, outside ambient temperature the outdoor-indoor temperature difference for each hour of a typical year could be calculated.

The Stack and Wind Coefficients for this subject house were determined from Tables 4.3 – 4.5 presented in the "simplified models" section of this chapter. The Stack Coefficient was taken to be 0.00029 ((L/s)^2/(cm^4*K)) because despite being what most would call a "single story home" the unusually high ceilings (+20 feet in some locations) of the home would easily be enough for two-stories (and there is one small room upstairs that counts as a second level). So from the outside perspective, this home appears two-stories tall. The local shielding class was chosen for this home to be level 3. This is because one neighboring house and local shielding (wooded area) surround most of the house within two house heights. This local shielding class corresponds to a Wind Coefficient of 0.000231 ((L/s)^2/[cm^4*(m/s)^2]) for a two-story home.

The last piece of information needed for the LBNL air infiltration model is the effective leakage area (ELA) of the home. As stated previously, this can be a measured value (A_L), or this value can be estimated taking into account various building components and the typical leakage areas associated with each of those components (building air leakage area A_c). The ELA for this home was calculated using the various component leakage areas shown previously in Table 4.2 and in the Appendix (D**)** at the end of this report. Copious measuring and cataloging of each building component was performed for each room of the test house. The calculated ELA for a single room of the test home (Living Room) is shown in Table 4.6 as a representative sample. A complete listing of individual building components in every room of the test home and the overall, total ELA calculations for the test house under investigation is shown in Appendix E at the end of this report.

Table 4.6: Sample Calculated Leakage Area for the Living Room of the Test Home

Measured Values:		**Metric Unit Conversion:**		**A(L) cm^2 / Unit (Table 4.2)**	**A(L)**
Exterior Walls (ft^2):	135	Exterior Walls (m^2):	12.542	0.15	1.881
Ceiling (ft^2):	314.5	Ceiling (m^2):	29.217	1.8	52.591
Outlets (#):	11	Outlets (#):	11	2.5	27.5
Vents (#):	1	Vents (#):	1	5	5.0
Recessed Lights (#):	16	Recessed Lights (#):	16	10	160.0
Regular Lights (#):	2	Regular Lights (#):	2	0.82	1.64
Window Frame (ft^2):	48	Window Frame (m^2):	4.459	0.3	1.338
Window LMC (ft):	50	Window LMC (m):	15.24	0.24	3.658
Door Frame (ft^2):	0	Door Frame (m^2):	0	0.3	0.0
				ELA (cm^2)	**253.607**

As can be seen from Table 4.6, measurements of all relevant leakage components (exterior wall area, ceiling area, window frame area, window linear meter of crack (LMC), and door frame area) were measured for the living room and the number of recessed lights, electrical outlets/switches and vents were counted. This information (left column) was converted into metric units and multiplied by the component leakage areas per unit (A(L) per Unit from Table 4.2), and the total component leakage areas (A(L)) were summed to estimate the total effective leakage area (ELA) of the living room. For the living room of the subject house this value was determined to be 253.607 cm^2. This procedure was followed for every room of the test home, and this information can be found in Appendix E of this report.

Summing the effective leakage areas of each room in the test house, the total building leakage area was determined to be 1,498.94 cm^2. During the measurement process the volume of the home was also estimated to be about 736.24 m^3.

With all the input values known for the LBNL model, a simple MatLAB® computer code was generated to determine the building airflow rate for each hour of a typical year, and dividing this airflow value by the total building volume the infiltration (air exchange rate) was determined for each hour of a typical year. Since the calculation step increment was 1 hour, this value is known as the building air changes per hour or ACH. The computer code for this simulation can be found in Appendix F of this report under the title "ACHcalc.m." Once the amount of air entering/leaving the test house (Q) was determined, calculations were done to establish the amount of cooling and or heating loads the test home HVAC system would have to manage based on the equations discussed in the "Infiltration Energy Loads" section of this chapter (sensible and latent loads). Utilizing the HVAC energy equations discussed in the previous chapters of this report (Chapter 2 section 2) an estimation of the energy (power) required to mitigate heating/cooling loads due to infiltration were calculated.

First, all estimations/calculations were performed on the test house under investigation "as-is." This will be known as the Baseline Energy Simulation and all energy savings seen from any energy efficient upgrades will be compared to this case.

4.4.1 Infiltration Baseline Energy Simulation

According to the LBNL model equation and simulation procedure discussed in the last section, the average airflow rate of air entering/leaving the test house for each month of a typical year is shown in Figure 4.4. During January and December the rate of air infiltrating the test house is the greatest. According to the LBNL model an average rate of 451.58 m^3/hr of air will enter the test house in the month of January, and an average rate of 451.08 m^3/hr of air will infiltrate the building envelope in December. The lowest monthly average rate of air infiltration is seen in August. The LBNL model predicts that only 239.9 m^3/hr of air will infiltrate the test house in this month; that is nearly half (47%) of the January average airflow rate.

The hourly volumetric flow rate (Q) of air into the space/home is related to commonly used Air Exchange Rate per Hour (ACH) of the house through the volume of the interior of the building. Figure 4.5 shows the LBNL estimated average ACH values for this test house over each month of a typical year. The greatest monthly ACH average value for the test house was calculated to be 0.6134 air changes per hour in January. The average ACH for December (0.6127 air changes per hour) was also very close to the January value. This comes from the large temperature difference and wind conditions associated of these harsher winter months. The lowest average ACH values were found in August and September (0.335 and 0.353 air changes per hour respectively). These months have the least amount of air infiltration based on the smaller temperature differences between the outside air and the indoor design (thermostat) temperature. From this model, the annual average air exchange value for this house was determined to be 0.48 air changes per hour. Referring back to literature in the “Air Exchange Rate” section of this chapter, a building with an ACH of 0.48 is right around the median ACH value seen in newer construction (Figure 4.1). Despite the relatively low average monthly ACH values (0.4795 – 0.6134 air changes per hour) seen in Figure 4.5, the hourly range of air infiltration can vary greatly. Figure 4.6 is the same bar chart as Figure 4.5 but the ranges of hourly ACH values (highest and lowest) for each month are shown.

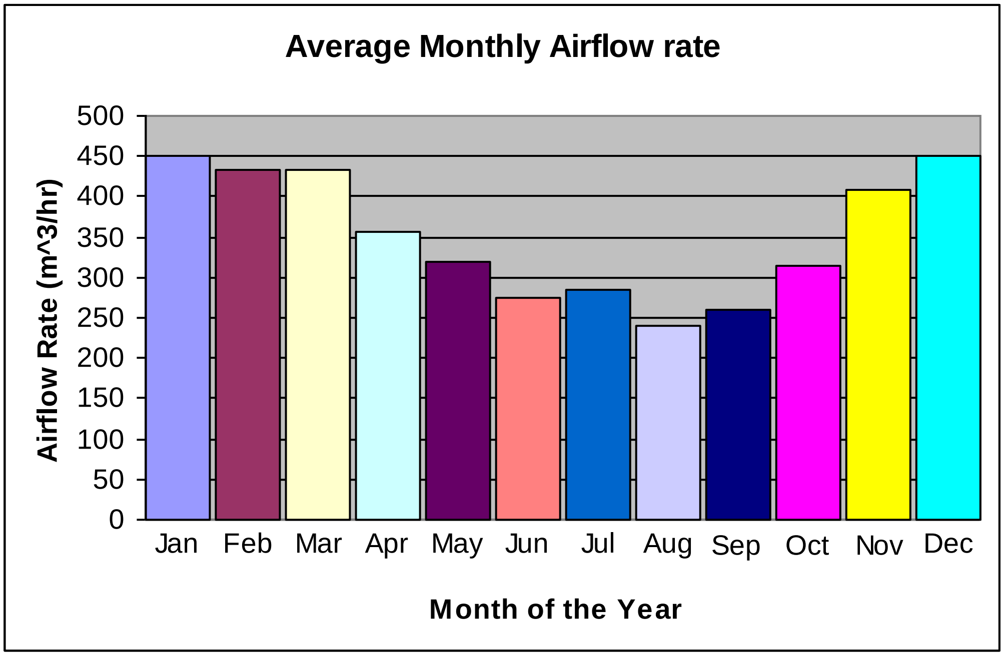

Figure 4.4: Average Monthly Airflow Rate (Q) into/out of the Test House

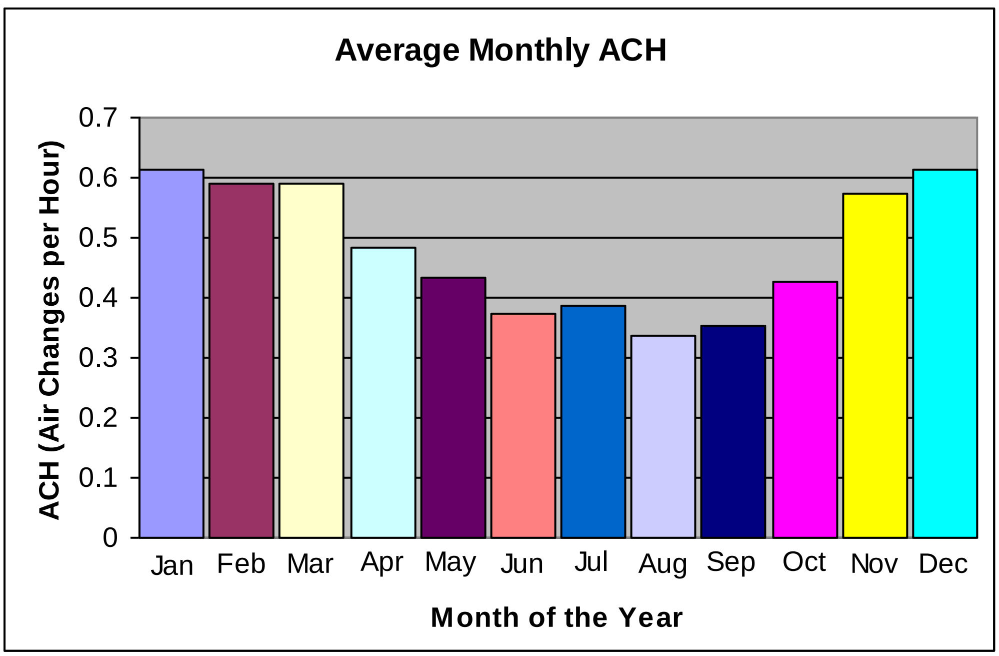

Figure 4.5: Home Average Monthly ACH

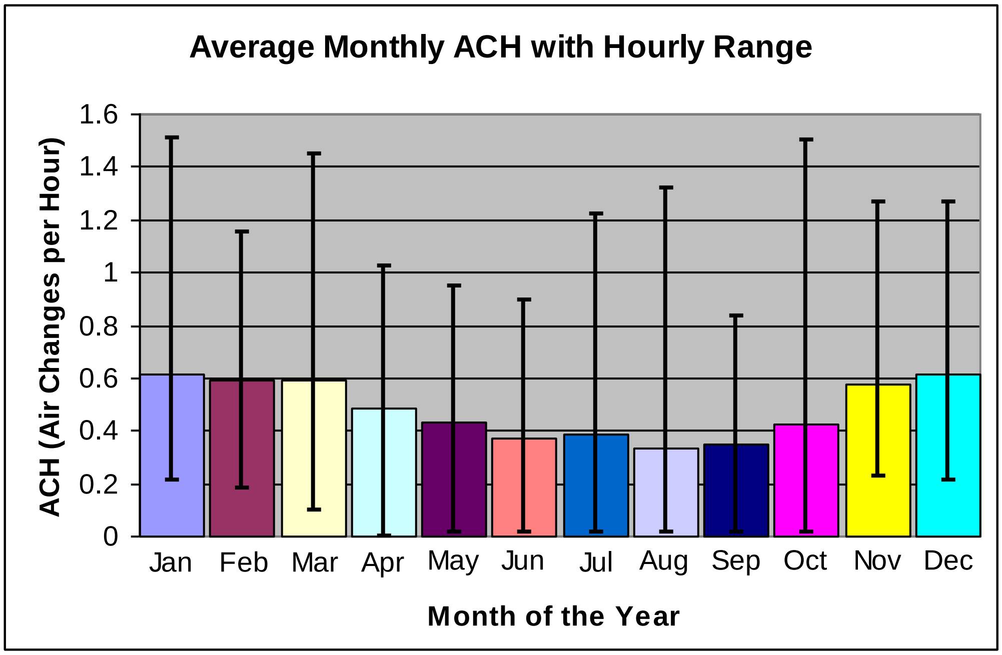

Figure 4.6: Average Monthly ACH values with Data Range for Test house

The range of hourly ACH values in each month (Figure 4.6) reveals some interesting trends. For one, the average monthly ACH values can be much less than the maximum hourly air exchange rate. For instance, the average January ACH value was determined to be 0.6134 air changes per hour**,** but the maximum ACH for a given hour can be as high as 1.5075 air changes per hour**.** This value is 60% greater than the average monthly value. Another fascinating observation is found in the month of August. As mentioned above, August has the lowest average ACH value over the entire month (0.335 air changes per hour), but August also has the fourth highest maximum ACH hourly value (~1.32 ACH). This shows how periods of high outside wind conditions can significantly increase the infiltration of a building if only for a short period of time.

According to the LBNL model, nearly 3,092,184 m^3 of air will infiltrate this test house over the course of a typical year. This unintentional air exchange will greatly increase the heating/cooling loads of the home. To estimate the impact of this air infiltration on the home's heating and cooling loads the sensible and latent thermal loads due to infiltration were calculated. The sensible load was straightforward to calculate using the TMY3 weather data and newly calculated airflow rates throughout a typical year. From these values the sensible heating/cooling load generated by air infiltrating the building envelope was determined to be 10,014.81 kWh (34,171,934 Btu) per year. The latent load calculations required knowledge of the humidity ratio difference (ΔW) between the outside environment and the indoor conditioned space. Once again we made use of the assumed indoor design (thermostat) temperature for the summer (72˚F) and winter (68˚F) and assumed a "comfortable indoor relative humidity would be about 50%" (per ASHRAE recommendations). Using the dry-bulb temperature, dew-point temperature, relative humidity, and pressure values provided in the TMY3 data set, the humidity ratio for both the indoor and outdoor air were calculated using an approximation used by the National Weather Service for humidity calculations in surface observations (Bolton 1980). Once the humidity ratio difference (indoor minus outdoor) throughout the year was determined, the latent thermal load due to the air infiltration of the building was found to be 9,471.94 kWh (32,319,585 Btu) per year. Therefore, the total thermal load due to heating, cooling, humidifying, and dehumidifying created by air infiltration in this house was calculated to be 19,486.75 kWh (66,491,519 Btu) per year. A breakdown of monthly thermal loads generated due to air infiltration across the building envelope for this test home is shown in Figure 4.7.

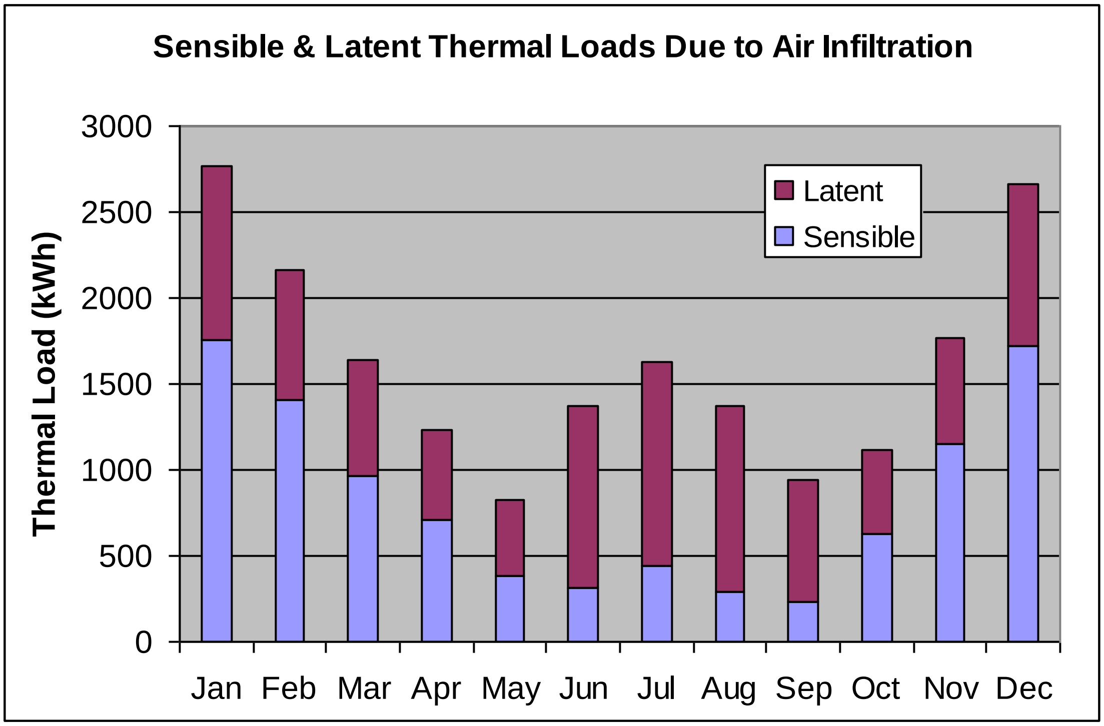

Figure 4.7: Breakdown of Monthly Thermal Loads due to Air Infiltration

As can be seen in Figure 4.7, thermal loads due to infiltration are greatest in the cold winter months such as December, January, and February. These months have high sensible thermal loads because the air that will infiltrate the building is very cold compared to the inside design temperature. In January alone, a sensible thermal load of 1,760.71 kWh (6,007,789 Btu) was seen with a latent load of 1,001.53 kWh (3,417,361 Btu). Mild "spring" and "fall" months such as April, May, September, and October displayed smaller infiltration induced thermal loads because not only is infiltration generally less in those months (see Figure 4.4) but the outside air temperature of those months is much closer to designed inside thermostat temperature. The highest monthly latent load was July, which is attributed to the highly humid outside summer conditions.

The thermal loads due to infiltration shown in Figure 4.7 are lumped together irrespective of whether the load is a heating or cooling load. During winter months cold, dry outside air will infiltrate the home and the HVAC system will have to heat (sensible load) this outside air to the desired inside temperature and add moisture (latent) if the inside air becomes too dry (if the HVAC can provide such as function otherwise other devices such as portable humidifiers will need to be used). On the other hand, during summer months, hot, humid air will infiltrate the building and this air must be cooled (sensible load) to the desired indoor temperature and excess moisture (latent load) must be removed for comfortable living. This of course requires the home split system heat pump to operate in different modes (heating mode or cooling mode) depending on the outside conditions and time of the year. Different heat pump modes require different compressor energy consumption relationships (why the heat pump equations in Chapter 2 are broken down into heating and cooling modes). Therefore, to accurately estimate HVAC power consumption due to infiltration induced thermal loads, the various thermal loads shown in Figure 4.7 must be broken down into heating and cooling loads throughout the year. Since the simulation is based on hour-by-hour calculations, it was easy to establish a “go, no-go” check system to determine if the infiltration thermal load would require heating or cooling. At each hour, the outside temperature condition was checked and compared to the inside thermostat temperature. If the outside air (air that will be infiltrating the building) was lower than the inside thermostat temperature, the thermal load was classified as a “heating” load, but if the outside temperature was greater than the inside thermostat temperature the thermal load was classified as a “cooling” load. Once the thermal loads were separated into heating and cooling, the appropriate HVAC equations for compressor power consumption were used. Care was taken when establishing HVAC “heating” loads because once the outside air temperature drops below 32 ˚F the auxiliary gas-fired furnace takes over heating responsibilities. So one more check was used to determine if the outside air temperature was indeed below the auxiliary heating threshold, and if so, the thermal load was classified as a “gas heating” load and gas-furnace information was used to determine energy/utility information.

The power consumption required by the home HVAC system to mitigate the heating and cooling loads due to air infiltration is shown month-by-month is Figure 4.8. During the winter months of January and February the heat pump compressor consumes the most electricity about 590 kWh and 560 kWh respectively. July represents the most power consumption for cooling purposes consuming about 460 kWh. According to this simulation, the test home under investigation can expect to consume nearly 5,020 kWh of electricity annually to mitigate the heating and cooling loads created by air infiltration.

That is 25.9% of the current average annual electricity consumed by this home. The heating and cooling thermal loads (and HVAC power consumption) represented in these figures are purely from air infiltration and do not represent total building loads or power consumption. That is why a small amount of red "heating" load/power consumption is seen in hot, summer months such as June and July. During cool, summer nights the outside air in Chattanooga sometimes falls before the thermostat design temperature. Therefore, according to this model this air which infiltrates the home at this time will be seen as a load that must be heated. In all actuality this is not the case. Other building loads such as occupant heat gain, lighting heat gain, appliances heat gain, and heat gain/loss due to heat transfer with the outside environment all play a role in the total building HVAC load, and these factors will change the "borderline" loads seen here due to small temperature differences near the inside design temperature. For example, during July the heat gain from the lights, occupants, heat gain from the environment, and appliances will make sure no small borderline heating HVAC loads will exist because larger, HVAC cooling loads will be present and the net load will undoubtedly require cooling. These borderline loads are small in nature and will not influence the overall estimations of energy savings in this section significantly. The combined effects of building heating/cooling loads are examined much more closely in the Whole Building Energy Simulation chapter later in this report.

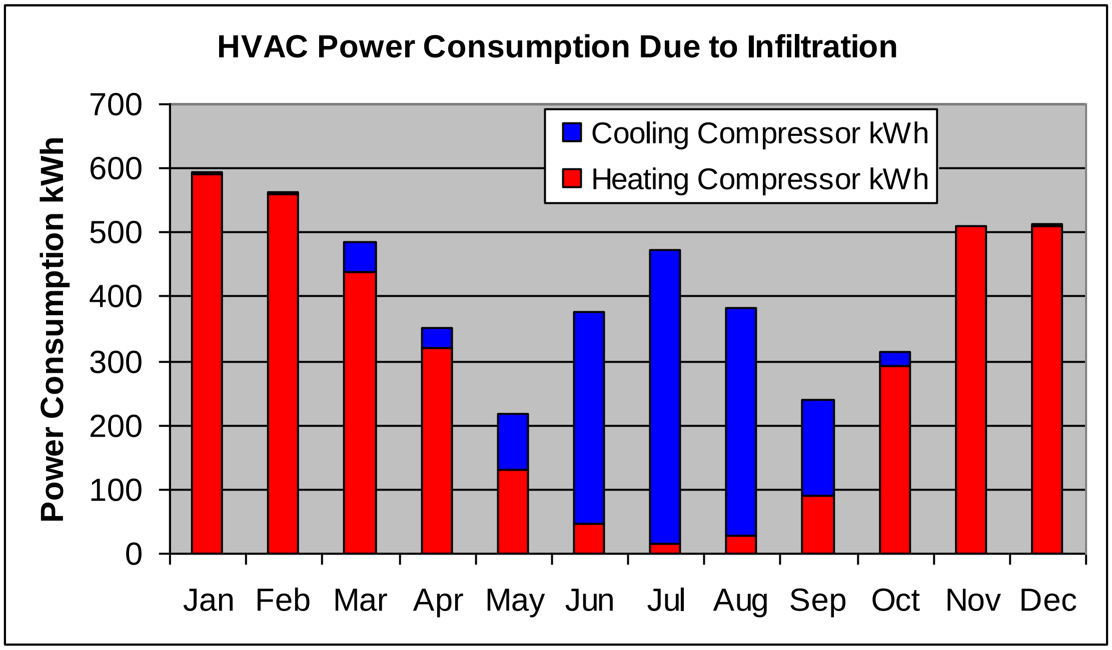

Figure 4.8: Heating and Cooling HVAC Power Consumption Due to Infiltration

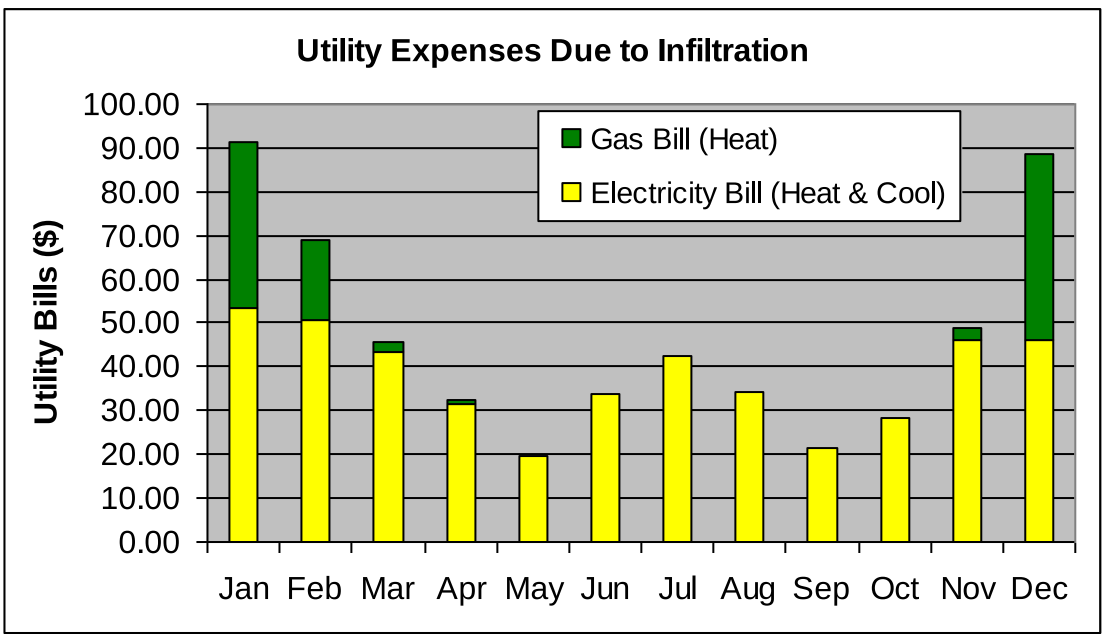

Figure 4.9: Utility Expenses Due to Infiltration

Monthly expected utility expenses to heat and cool the infiltrating air are shown in Figure 4.9. The “electricity bill” is not the total expenditure on electricity for the month but only the price for the amount of power that the HVAC system will consume to mitigate the heating and cooling loads due to infiltration alone. Likewise, the “gas bill” shown is not the total gas bill (the home also has a gas hot water heater that consumes a great deal of gas) but just the price for the amount of gas that will be consumed to heat the infiltrating air when the outside air temperature drops below the auxiliary heating threshold. According to this simulation, the test home under investigation can expect to pay nearly $556 annually for electricity and gas to merely mitigate the heating and cooling loads created by air infiltration. This accounts for about 23.5% of the average annual utility expenditures of this house.

4.5 Energy Efficient Upgrades for Infiltration Mitigation

Making “energy efficient upgrades” to mitigate air infiltration is of course a misnomer; it would be more appropriate to say “green” or “sustainable” weatherization upgrades to reduce the impact air infiltration has on HVAC power consumption. To understand the best weatherization upgrades and their impacts, an in-home energy audit was scheduled to assess possible areas of improvement. Currently, the Volunteer Energy Cooperative (local utilities provider) has partnered with the Tennessee Valley Authority (Green Power Switch Initiative) to provide free, in-home energy evaluations to residents seeking to understand what it means to be more energy efficient. A trained evaluator checks inside, outside, under, and over the house for areas where the home owner can improve house design/features to conserve energy or become more energy efficient. Once the evaluation is completed, the evaluator generates a list of recommended design improvements and suggests qualified, trustworthy contractors to perform each task. If the home owner chooses to use the suggested contractors to make the recommended home improvements (totaling over $150) then a rebate for up to 50% of the total cost of work (up to $500 on eligible upgrades) will be issued to the home owner once the VEC energy evaluator returns and makes sure the work was completed to VEC standards. Only certain eligible improvements qualify for the rebate including: replacement windows, storm windows, ventilation duct repair or replacement, glass or door replacement, heat pump replacement or "tune-up," attic insulation, static insulation, air sealing, caulking, and weather stripping. More information is available through TVA and VEC about this program.

The VEC in-home energy audit revealed several "air sealing" projects that would reduce the amount of air infiltrating the test house and limit the heating/cooling losses associated with the duct system of this home. These auditor approved upgrades together with the Consumer Energy Center recommendations applicable to this home (taken from the "Controlling Infiltration" section of this chapter) are listed in Table 4.7.

The most notable improvements for air infiltration mitigation were the recommendations to install an air-vapor barrier in floored attic space, weather strip garage and attic doors, air seal plumbing/piping envelope penetrations (envelope penetrations in the kitchen, laundry room, and main bathroom large enough that even outside light could even be seen), caulk exterior window frames (if new windows are not installed), install thresholds/door sweeps under front and garage doors, and install air sealing gaskets under electrical switch covers and around ceiling recessed light fixtures. Other recommendations were made based on the duct system of the house and these improvements will contribute more to stopping heating/cooling system losses rather than mitigating the heating/cooling loads due to infiltration.

Table 4.7: Energy Audit and CEC Recommended Upgrades

1	Install Air-Vapor barrier in floored attic to prevent airflow into upstairs
2	Caulk / seal connecting HVAC ducts under the floor to conditioned space or use duct glue (Mastic Glue) (10)
3	Install ventilation register gaskets or seal with Mastic glue (10)
4	Air seal 3 plumbing/piping penetrations in the building envelope (3)
5	Caulk exterior window frames
6	Weather-strip perimeter of garage door entrance
7	Install threshold under garage door entrance (1)
8	Install floor sweep under front door (1)
9	Weather-strip perimeter of attic door entrance
10	Install electrical outlet / light switch gaskets (70)
11	Upgrade recessed lighting gaskets and caulk around ceiling lights (15)
12	Use air duct glue (Mastic) instead of duct tape for duct work connections in the crawl space of the house (duct tape deteriorates and fails to seal)

Based on recommendations from the in-home energy auditors, the CEC, and ASHRAE literature it was estimated that making the home design improvements discussed in Table 4.7 could “air tightened” this home by about 15%. To represent these savings in energy simulations, a 15% reduction in the home effective leakage area (ELA reduced from 1,498.94 cm^2 to 1,274.10 cm^2) was assumed and the LBNL model and calculations were repeated for comparison purposes. Materials to implement the above recommendations were estimated to cost at most $200 based on local home improvement store pricing. Due to the nature of the design improvements it was reasonable to assume no contractor would be required to complete the projects and therefore the total cost would be the same as the material cost.

4.6 Infiltration Mitigation Energy Efficient Simulation / Results / Savings Estimates

According to the LBNL model equation and simulation procedure discussed previously, a 15% reduction in home leakage area will correspond to a 15% reduction in air infiltration (airflow rate and ACH) over the course of a year. This will in turn reduce thermal loads (sensible and latent), HVAC power consumption, and utility expenses. For comparison purposes most of the same information presented in the “Baseline Energy Simulation” section of this chapter will likewise be reported in this section recognizing that all values end up being approximately 15% reductions of the baseline test scenario.

After completing the proposed infiltration upgrades, the average airflow rate of air infiltrating the test house for each month of a typical year is shown in Figure 4.10. According to the LBNL model an average rate of 383.84 m^3/hr of air will enter the test house in the month of January (most), and an average rate of 383.42 m^3/hr of air will infiltrate the building envelope in December (second most). Figure 4.11 shows the LBNL estimated new average ACH values for the upgraded test house over each month of a typical year. The greatest monthly ACH average value for the test house was calculated to be 0.521 air changes per hour in January. The lowest average ACH values were found in August and September (0.285 and 0.30 air changes per hour respectively). From this model, the upgraded annual average air exchange value for this house was determined to be 0.408 air changes per hour. Figure 4.12 is the same bar chart as Figure

4.11 but the ranges of hourly ACH values (highest and lowest) for each hour of the month are shown.

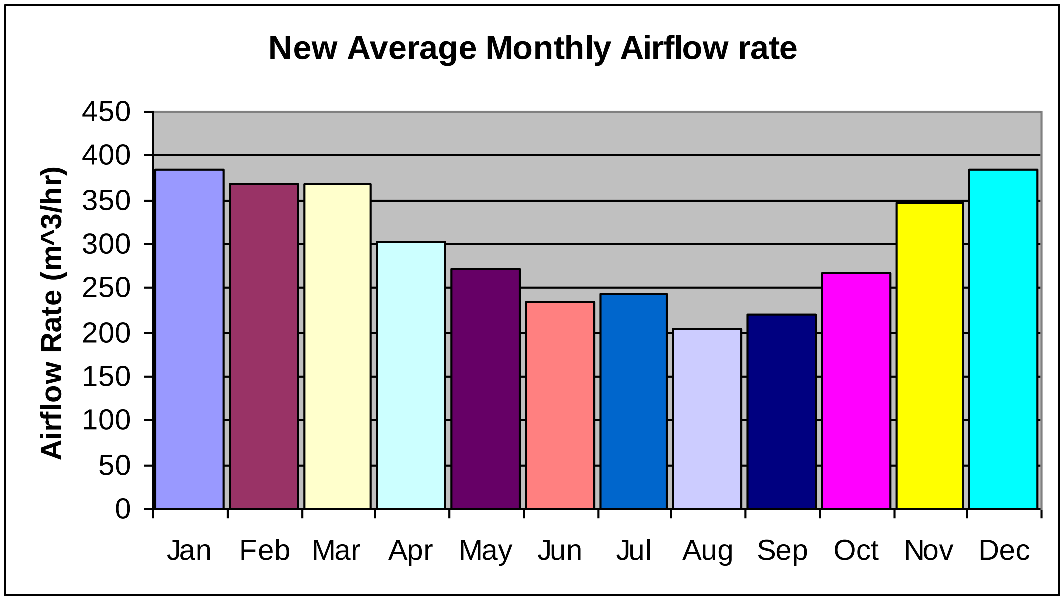

Figure 4.10: New Average Monthly Airflow Rate (Q) into/out of the Test House

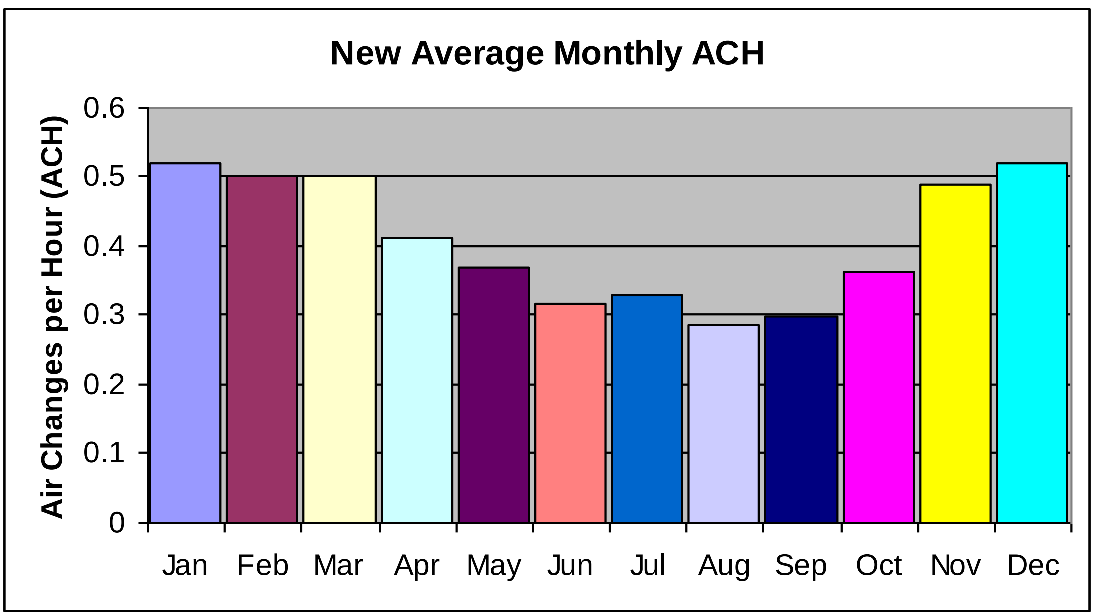

Figure 4.11: New Home Average Monthly ACH

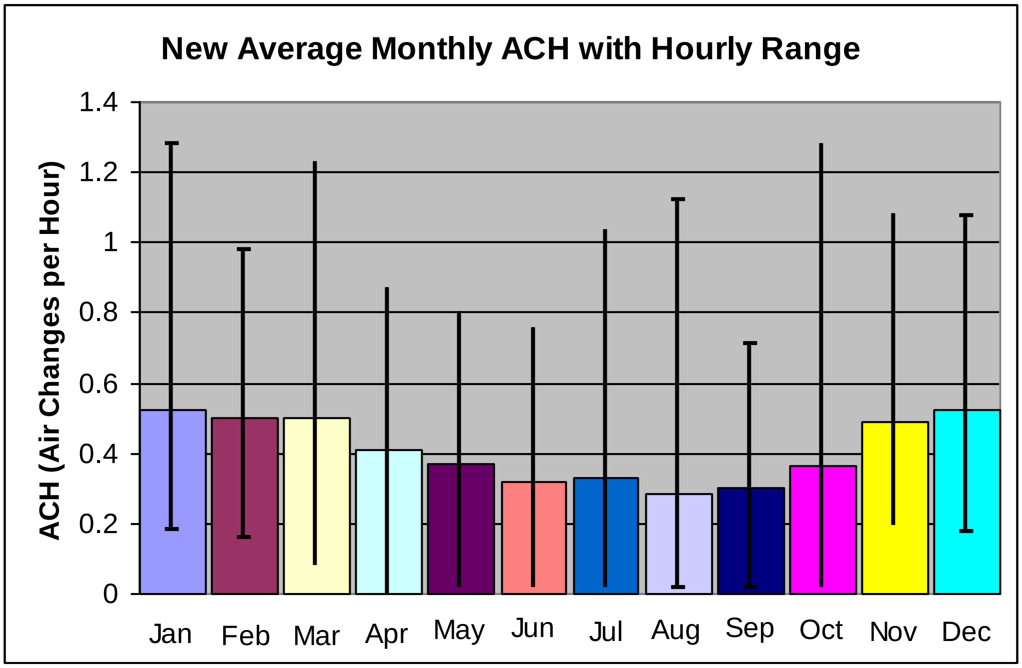

Figure 4.12: New Average Monthly ACH values with Data Range for Test house

According to the LBNL model, nearly 2,628,356 m^3 of air will infiltrate the upgraded test house over the course of a typical year. The sensible heating/cooling load generated by this air infiltrating the building envelope was determined to be 8,512.59 kWh (29,046,149 Btu) per year. The latent thermal load due to the air infiltration of the building was found to be 8,051.15 kWh (27,471,651 Btu) per year. Therefore, the total thermal load due to heating, cooling, humidifying, and dehumidifying created by air infiltration in this house was calculated to be 16,563.74 kWh (56,517,791 Btu) per year. A breakdown of monthly thermal loads generated due to air infiltration across the building envelope for this home is shown in Figure 4.13.

The power consumption required by the home HVAC system to mitigate the heating and cooling loads due to air infiltration is shown month-by-month is Figure 4.14. According to this simulation, the upgraded test home under investigation can expect to consume nearly 4,267 kWh of electricity annually (about 22% of current annual electricity consumption) to mitigate the heating and cooling loads created by air infiltration. That means approximately 753 kWh of power per year would be saved due to the weatherizing and air sealing upgrades described in Table 4.7.

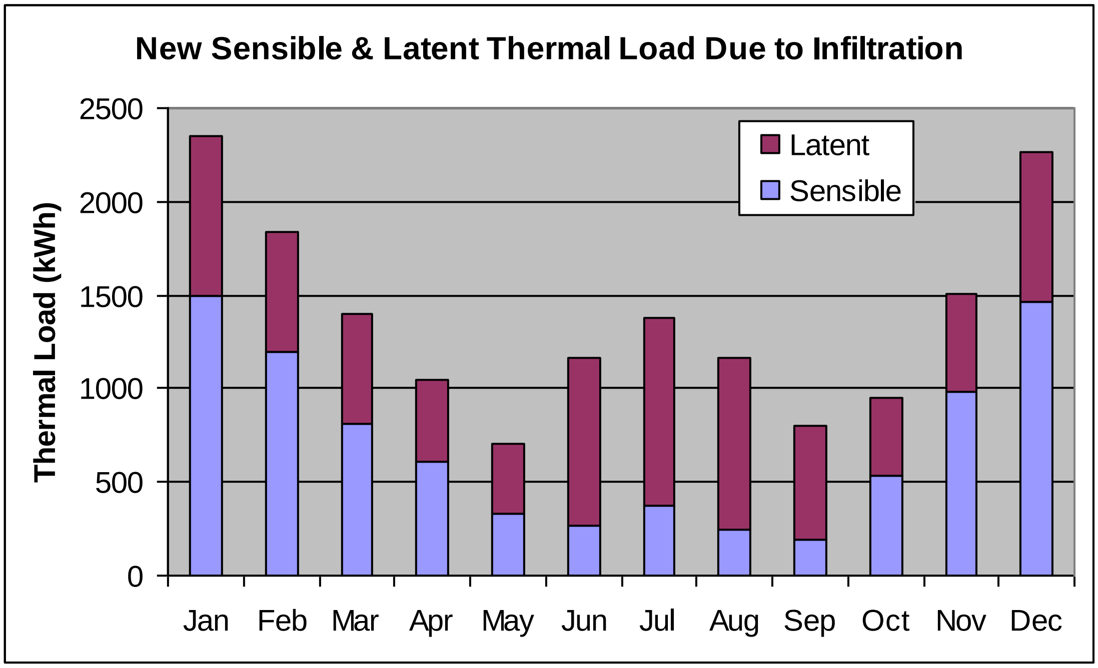

Figure 4.13: Breakdown of New Monthly Thermal Loads due to Air Infiltration

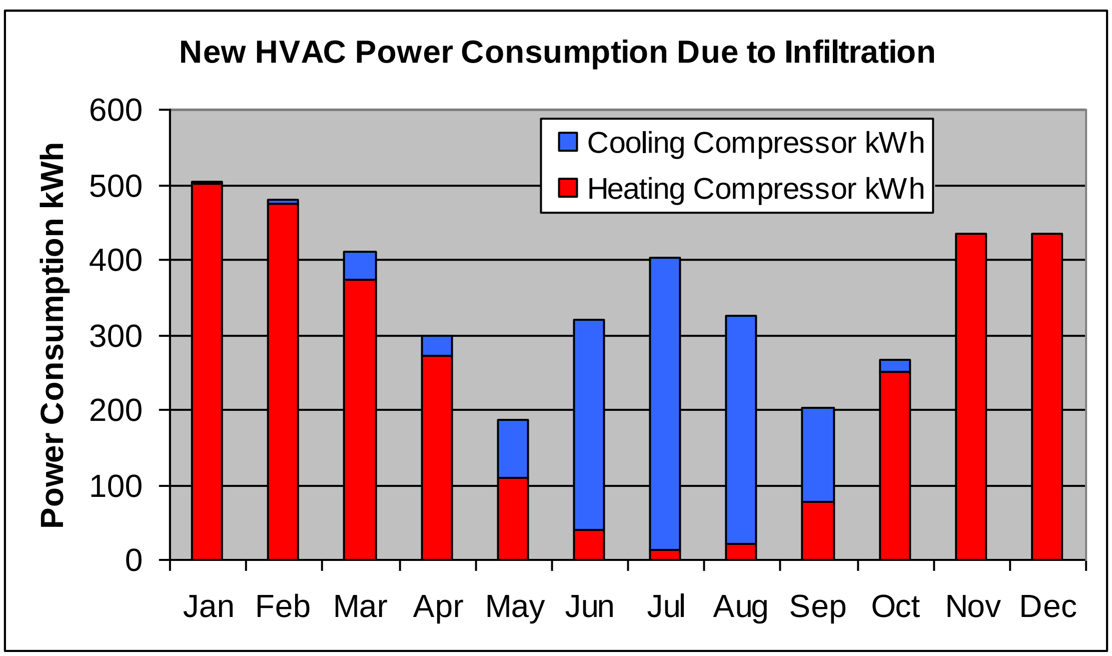

Figure 4.14: New Heating and Cooling HVAC Power Consumption Due to Infiltration

New monthly expected utility expenses to heat and cool the infiltrating air are shown in Figure 4.15. The "electricity bill" is not the total expenditure on electricity for the month but only for amount of power that the HVAC system will consume to mitigate the heating and cooling loads due to infiltration alone. Likewise, the "gas bill" shown is not the total gas bill (the home also has a gas hot water heater that consumes a great deal of gas) but just the price for the amount of gas that will be consumed to heat the infiltrating air when the outside air temperature drops below the auxiliary heating threshold (32 ˚F). According to this simulation, the upgraded test home under investigation can expect to pay $472.60 annually for electricity and gas to merely mitigate the heating and cooling loads created by air infiltration. This would represent an $83.40 savings from the baseline test scenario.

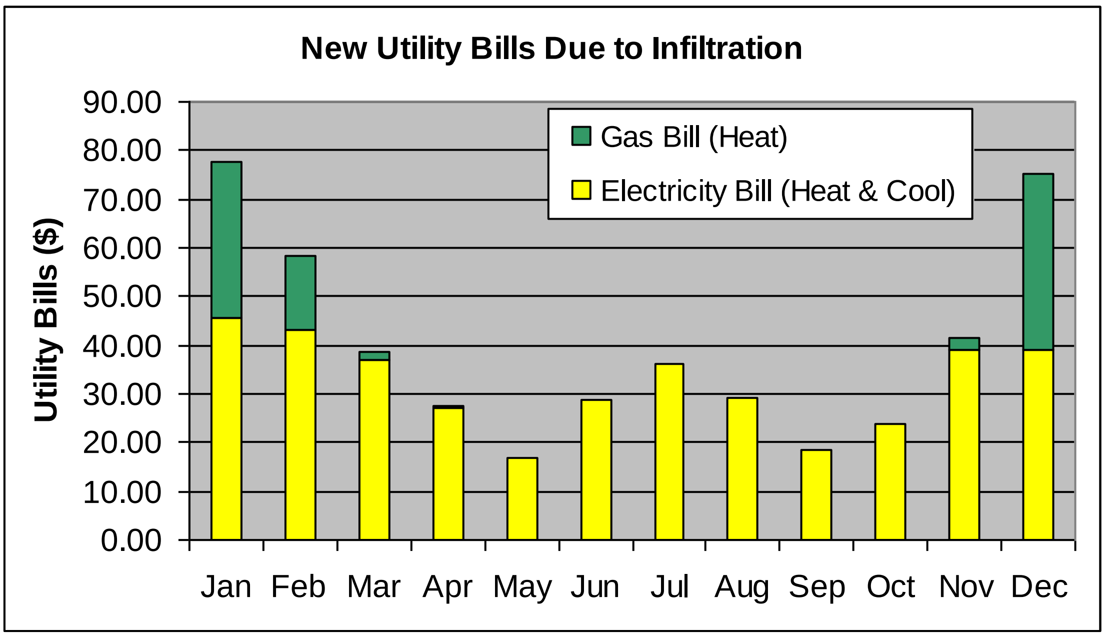

Figure 4.15: New Utility Expenses Due to Infiltration

4.7 Brief Remarks on Infiltration

Sealing leakage areas around a home can be a relatively inexpensive, easy way for a home owner to see immediate energy savings. Important infiltration simulation results and potential savings from this chapter are shown in Table 4.8. According to these simulations an annual electrical power savings of 753 kWh (consumption from 5,020 kWh to 4,267 kWh) could be seen by simply making the home improvements shown in Table 4.7 consisting of mostly caulking and weather stripping home leakage areas. Also, the home owners can expect to annually conserve 14.77 Therms of natural gas due to decreased heating loads imposed by infiltration. These two utility savings equate to $83.40 savings each year on utility expenditures. These savings are based on current rates and any increase in electricity or gas rates will provide even more monetary savings. The home improvements recommendations listed should cost no more than $200.00 to complete. This equals a simple payback period of 2.4 years at the longest. This is a very manageable payback period considering the initial investment is relatively small compared to most home energy efficient projects.

Table 4.8: Simulation Results and Savings from Infiltration Mitigation Upgrades

	Baseline	**Upgraded**	**Savings**
Effective Leakage Area (cm^2)	1,498.94	1,274.10	\
Annual Total Volume of Air Infiltrating House (m^3)	3,092,184	2,628,356	463,828
Annual Average Air Changes per Hour (ACH)	0.48	0.408	0.072
Annual Total Thermal Load due to Infiltration (kWh)	19,486.75	16,563.74	2,923.01
Annual HVAC Power Consumption to Heat & Cool Infiltration (kWh)	5,020	4,267	**753**
Annual Gas Consumption to Heat Infiltration (Therms)	98.45	83.68	14.77
Annual Expenditure to Heat & Cool Infiltration ($)	$556.00	$472.60	**$83.40**

Chapter 5

Advanced Insulation

According to the Department of Energy approximately 42% of the total energy consumed by a residential building in the United States in 2006 was dedicated to managing heating and cooling loads [5]. This was by far the largest energy consumption end-use of a residential building, and other studies have shown that this value can be anywhere from 50 – 70% of the total building energy use [24]. Therefore, it is important to reduce the heating and cooling load of a building by making sure heat gain in the summer and heat loss in the winter are kept to a minimum. Insulation plays a pivotal role in minimizing heat gain and loss through the building envelope (walls, roof, and floor). The transfer of heat energy occurs because of fundamental, natural laws. Heat transfer occurs because a temperature difference exists between the conditioned, inside space and the outside environment. Since most structural materials used in building construction such as wood, steel, and concrete easily transfer heat, insulations must be utilized to stop or at least slow down the transfer of heat from/to the conditioned building space. “In buildings such as residences, the internal energy (heat) gains are almost insignificant compared with the heat losses and gains through the building envelope. For these buildings, the heating and cooling requirements are roughly proportional to the difference between the indoor and outdoor temperature difference” which drives heat transfer [25]. Installing new, advanced insulating materials or simply adding more insulation to existing systems is seen as a first, basic step towards energy efficiency and significant energy savings can be realized.

5.1 Insulation Basic Concepts and Terminology

Thermal insulations are materials that impede the flow of heat energy by conduction, convection, and/or radiative heat transfer modes. Thermal insulations come in various physical structures and forms. Insulations can be particulate, fibrous, made into sheets, blocks, or films, monolithic, open cells, closed cells, or a composite system made of several types of insulations mechanically or chemically bonded together. For energy efficient homes, insulations primarily are used to conserve energy by reducing the heat loss or gain of structures (walls, floor, and the roof), piping, ducts, equipment, etc. Insulation also can reduce temperature variations within a conditioned space increasing personal comfort. Some secondary functions of certain insulations include: adding structural strength to walls, ceilings or floor sections, impeding water vapor transmission and air infiltration, providing support for surface finishes such as exterior siding, and aiding in the reduction noise and vibrations as well as mold and mildew growth.

5.1.1 Insulation Composition and Physical Form

Thermal insulations can generally be separated into three categories with respect to material composition: inorganic fibrous, organic fibrous, and metallic organic membranes. Inorganic, fibrous or cellular insulations are materials like glass, wool, rock, or slag, calcium silicate, bonded perlite, and ceramic products. Organic fibrous insulations such as cellulose, cotton, wood, pulp, cane, or synthetic fibers, and organic cellular insulations such as cork, foamed rubber, polystyrene, polyurethane, and other polymers are the most commonly used insulation in construction and structural applications. Metallic or metalized reflective membranes or films are used more in specialty applications where smooth finish surfaces face and air, gas-filled, or evacuated (vacuum) space [25].

Insulations for industrial and building applications come in many different physical forms. Loose-fill insulations consist of powders, fibers, granules, or nodules that are generally poured or blown via compressed air into walls or other cavities. Insulating cement is a loose insulating material that is mixed with water or another binder until a “mud” like mixture is achieved. Insulating cement can then be blown or spread into place and once dry will form a rigid surface covering irregular spaces. Flexible and semi-rigid insulations consist of organic and inorganic materials (with or without binders) with varying degrees of compressibility and flexibility. Insulations such as these are sold in sheets or rolls and are available as a “blanket,” “batt,” or “felt.” These insulations are most common in traditional residential construction. Rigid insulations are available in rectangular blocks, boards, or sheets which are pre-formed to standard sizes during the manufacturing process. Formed-in-place insulations are available as liquid components or expandable pellets that can be poured, sprayed, or frothed into place to form rigid or semi-rigid foam layers. Spray/blown in loose-fill or formed-in-place insulations are gaining popularity with contractors due to ease and speed of installation. Reflective and accessory materials are also forms of insulation but applications are limited in the residential construction field [25].

5.1.2 Insulation Thermal Properties

Analogies between heat transfer and electricity are standard in many engineering courses. Heat energy "flows" through materials much like electricity flows through materials, and as such, many correlations and terms share similar meanings when discussing heat transfer and electricity. For example, "conductivity" is a term that shares similar meaning between the two disciplines. The thermal conductivity (k) of a material is the "time rate of heat flow through a unit area of homogenous material in a direction perpendicular to isothermal planes, induced by a temperature gradient." Basically, just like in terms of electricity, highly heat conductive materials transfer heat more readily than materials which are less conductive (insulators) [24].

As described previously, the primary function of thermal insulation is to resist the flow of heat energy by conduction, convection, and/or radiative heat transfer modes. Thermal resistance is a measure of the effectiveness at which a material retards (resists) heat flow. A material with a high thermal resistance is an effective insulator; however, if a material has a low thermal resistance (high thermal conductance) then the material will readily transfer heat and is a poor candidate for insulating purposes. The thermal resistance of a material is known as the "R-value." The academic definition of the R-value is "under steady state conditions (not varying with time), the mean temperature difference between two defined surfaces of material or construction that induces unit heat flow through a unit area." Thermal resistance (R-value) has units of m^2*K/W or $hr*ft^2*^\circ F$ / Btu [25]. R-values for a wide range of building materials are published in various academic, research resources, and design handbooks/manuals.

Thermal resistance and electrical resistance are dealt with in the same manor when it comes to evaluating structures of composite (multiple) materials such as the insulating systems found in walls, ceilings, and floors. If materials are “stacked” one of top of the other (a single row) they are said to be in “series.” Just like series resistors in electrical component design, the effective thermal resistance (R_{Eff}) of a series of insulators is the numerical sum of each individual material thermal resistance represented by:

$$R_{Eff} = R_1 + R_2 + R_3 + \ldots + R_n$$

In many installations, insulating materials are arranged so that heat flows in parallel paths of different conductances. If no heat flows between lateral paths (called thermal bridging) then the materials are said to be in “parallel.” The effective thermal resistance (R_{Eff}) of insulators in parallel is given by:

$$R_{Eff} = [(1 / R_1) + (1 / R_2) + (1 / R_3) + \ldots + (1 / R_n)]^{-1}$$

Thermal resistance can be resistance to heat flow due to one of the three modes of heat transfer (conduction, convection, or radiation). Therefore, equations for evaluating resistance will change accordingly. For heat transfer due to conduction (materials physically touching one another) thermal resistance is represented by:

$$R_{conduction} = L / k*A$$

In this equation L is the length of the material in the direction of heat transfer (seen as the material thickness in most cases), k is the thermal conductivity of the material, and A is the cross sectional area of the material perpendicular to the direction of heat transfer.

For heat transfer due to convection (heat transfer by fluid) thermal resistance is represented by:

$$R_{convection} = 1 / h*A$$

In this equation h is a parameter called the convection heat transfer coefficient and A is the area of the material which is contacted by the fluid.

Lastly, for heat transfer due to radiation (energy emitted by a material) thermal resistance is represented by:

$$R_{radiation} = 1 / h_r*A$$

In this equation h_r is the linearized radiation heat transfer coefficient and is a function of the material surface temperature and a nearby surrounding temperature.

The thermal transmittance (U-factor) of a material is the "time rate of heat flow per unit area under steady conditions from the fluid on the warm side of a barrier to the fluid on the cold side, per unit temperature difference between the two fluids." The U-factor has units of W/ (m^2*K) or Btu/ (hr*ft^2*°F) and is merely the reciprocal of the R-value of a material (U = 1/R). The U-factor is sometimes called the overall coefficient of heat transfer. In building practice, the heat transfer "fluid" described in the formal definition of the U-factor is simply air [25].

Calculating the U-factor for a composite wall, such as a home exterior wall, roof, or floor is an important task for this section of energy calculations. The easiest way to determine the overall coefficient of heat transfer for a wood-framed wall with cavity insulation (typical wall construction) is to sum all the thermal resistances in each heat transfer "parallel path" (through the studs or through the cavity) and weight each path by the percentage of area found in the wall construction. For a typical residential wall with studs constructed with their centers separated by 16 inches (common building term 16" O.C.) it is estimated that the stud heat transfer path represent 15% of the total wall area (area in which heat transfer is occurring from outside to inside or vice versa), and that 85% of the total wall area is the cavity section of the wall [28]. Therefore, the overall coefficient of heat transfer for a 16" O.C. residential wall is given by:

$$U_{wall} = 0.15*U_{studs} + 0.85*U_{cavity}$$

The overall coefficients of heat transfer for the studs and cavity (U_{studs} and U_{cavity} respectively) can be determined by applying the appropriate thermal resistance combinations (series and parallel paths) described above. A detailed explanation of this process will be described later in this chapter.

Once the thermal resistance or the overall coefficient of heat transfer for a material (or a composite of materials) are known the heat that will be transferred through that medium per rate of time is given by the equation:

$$q = U*A*\Delta T$$

In this equation ΔT is the overall temperature difference, U is the overall heat transfer coefficient of the materials, and A is the cross sectional area of the material perpendicular to the direction of heat transfer. The rate of heat transfer through the medium (q) has units of Btu/hr or Watts. This equation can be used to determine the rate of heat transfer that will be transferred to or from the conditioned space of a building (through the walls, roof, floor, etc) given the composition of the insulating system and the inside/outside temperature conditions.

5.1.3 Standard Insulation R-values

Traditionally, batt and roll (most popular insulation with contractors) insulation is sold in thicknesses that correspond to whole values of thermal resistance (R-value). Thermal resistance values of R-11, R-13, R-19, R-30, and R-38 are common insulations used in residential building applications. Table 5.1 catalogues commercially available batt, roll, rigid sheathing, and blow-in insulation options from local Chattanooga home improvement stores. Pertinent manufacturer data for each insulation option includes insulation thickness (based on a set R-value), insulation coverage area (square feet), and price. From these specifications, the R-value per inch thickness and price per square foot of coverage was calculated as a way to compare various insulation options. As can be seen from Table 5.1, batt and roll insulation R-values per inch of material thickness range from 2.92 to 5.43 (average 3.49) while the price for area of coverage ranges from 0.23 to 1.00 $\$/ft^2$ (average 0.56 $\$/ft^2$). For rigid sheathing insulation options, the R-value per inch thickness ranges from 3.87 to 6.4 (average 4.58) and the price for area of coverage ranges from 0.29 to 2.38 $\$/ft^2$ (average 1.10 $\$/ft^2$).

Table 5.1: Local Commercially Available Insulation Options

		Thickness (inch)	R-Value	R-value per inch Thickness	Cover (ft^2)	Price ($)	$ / ft^2
Rolls / Batt	Johns Manville Fiberglass Insulation	3.5	11	3.14	88.12	30.61	0.35
	Johns Manville Fiberglass Insulation	3.5	13	3.71	40	10.12	0.25
	Johns Manville Fiberglass Insulation	3.5	13	3.71	40	18.33	0.46
	Johns Manville Fiberglass Insulation	3.5	13	3.71	40	12	0.30
	Johns Manville Fiberglass Insulation	3.5	13	3.71	106	47.63	0.45
	Johns Manville Fiberglass Insulation	3.5	13	3.71	106	39.87	0.38
	Johns Manville BATT	3.5	15	4.29	103.97	82.11	0.79
	Johns Manville BATT	3.5	15	4.29	103.97	78.36	0.75
	Johns Manville Fiberglass Insulation	3.5	19	5.43	87	68.63	0.79
	Johns Manville Fiberglass Insulation	6.5	19	2.92	87.18	48.96	0.56
	Johns Manville Fiberglass Insulation	6.5	19	2.92	133.68	75.07	0.56
	Johns Manville Fiberglass Insulation	6.5	19	2.92	48.96	11.28	0.23
	Johns Manville Fiberglass Insulation	6.5	19	2.92	87	46.77	0.54
	Johns Manville Fiberglass Insulation	6.5	19	2.92	133.68	67.97	0.51
	Johns Free Fiberglass Insulation	10.25	30	2.93	31.25	15.87	0.51
	Johns Manville Fiberglass Insulation	10.25	30	2.93	88	73.66	0.84
	Johns Manville Fiberglass Insulation	10.25	30	2.93	58.66	49.08	0.84
	Johns Manville Cathedral Batt	8.25	30	3.64	86.62	86.24	1.00
Rigid / Sheathing	Pactiv 1/4" x 48" x 50"	0.25	1	4	16.667	39.6	2.38
	3/4" x 8' x 4' Insulated Sheathing	0.75	2.9	3.87	32	12.98	0.41
	1/2" x 8' x 4' Insulated Sheathing	0.5	2.17	4.34	32	9.98	0.31
	Perma "R" Products 3/4" x 4' x 1'	0.75	2.9	3.87	4	9.23	2.31
	Rmax 1/2" x 8' x 4' Polyisocyanurate	0.5	3.2	6.4	32	9.25	0.29
	Pactiv 2" x 4' x 8' Square Edge	2	10	5	32	29.97	0.94
Blow-In	GreenFiber 2.2 Cu. Ft. Natural Fiber	4.33	13	~ 3.00	6.10	9.15	1.50
	GreenFiber 2.2 Cu. Ft. Natural Fiber	5	15	~ 3.00	5.28	9.15	1.73
	GreenFiber 2.2 Cu. Ft. Natural Fiber	6.33	19	~ 3.00	4.17	9.15	2.19
	GreenFiber 2.2 Cu. Ft. Natural Fiber	7.12	22	3.09	3.71	9.15	2.47
	GreenFiber 2.2 Cu. Ft. Natural Fiber	11.97	38	3.17	2.21	9.15	4.15
	GreenFiber 2.2 Cu. Ft. Natural Fiber	16.67	50	~ 3.00	1.58	9.15	5.78
	GreenFiber 2.2 Cu. Ft. Natural Fiber	20	60	~ 3.00	1.32	9.15	6.93

The values in Table 5.1 for blow-in insulation are approximate, calculated values. The GreenFiber® blow-in insulation is sold by the volume of insulation material (2.2 cubic feet in this case). Manufacturer information lists the thickness of material which corresponds to the R-22 and R-38 thermal resistance levels as 7.12 and 11.97 inches respectively. With the total volume and thickness known, an area of coverage could be calculated. For other R-values listed an approximate value of 3.0 R-value per inch of insulation thickness was assumed (based on the R-22 and R-38 information) and coverage areas were calculated.

5.1.4 Building Insulation Standards

Building insulation standards depend on several factors. Local climate, building type and construction, type of heating system and cooling system, etc all play a role in determining the proper insulating R-values throughout a structure. Oak Ridge National Laboratory (U.S. Department of Energy) provides an on-line insulation calculator that recommends various levels of insulation throughout a home by taking into account geographic location (ZIP code input) and heating system. The calculator can provide recommendations for upgrading existing structures, or give detailed insulation design instructions for new constructions. Table 5.2 shows ORNL insulation recommendations for Wood-framed, new construction and/or existing structures, with a gas furnace or heat pump heating system (similar to this test house). The insulation calculated returns more information for new constructions including information for insulating basements, foundations, crawls spaces, etc which is not shown in Table 5.2. The heating system does play a role in determining the R-value in various locations throughout the structure. As can be seen in Table 5.2, when a building uses a gas furnace heating system the ORNL insulation recommendations increase in the floor, crawl spaces, and insulative sheathing categories. Likewise, new construction insulation recommendations for the attic and wall sheathing are increased for a building that will use a gas furnace heating system. Generally speaking, insulation recommendations for new constructions will be slightly higher than for existing structures because insulation is easiest to install when the structure is open and under construction and because a concerted effort has been started to make new constructions as energy efficient as possible for future energy savings.

Table 5.2: ORNL Insulation Recommendations

		Gas Furnace R-Value	Heat Pump R-Value
Existing Building	Attic	38	38
	Wood Frame Wall Cavity	13 [1]	13 [1]
	Floor	25 [2]	13 [2]
	Crawls Space Wall	25 [3]	13 [3]
	Basement Wall Interior	11	11
	Insulative Sheathing on Empty Wall	5	5
	Insulative Sheathing to R-11 Wall	5	0
New Construction	Attic	49	38
	Cathedral ceiling	38	38
	Floor	25 [2]	25 [2]
	Wall sheathing	5	\
	Wall cavity	15	15
	OVE wall cavity	21	21
	Concrete or masonry wall	15.6	15.6
	Band joist	30	30

Notes:
1. Blow insulation into any un-insulated exterior wall cavity
2. Over unheated, un-insulated space
3. Crawl space walls are only insulated if the crawl space is un-vented and the floor above the crawl space is un-insulated.

5.1.5 Advanced Insulations

An exciting area of insulation research is being conducted in the study of a materials called "aerogels." Aerogels are manufactured materials with the lowest bulk density of any known porous solid. They are derived from a gel in which the liquid component of the gel has been replaced with a gas. This results in an extremely low-density solid with a high thermal resistance. Some specialty insulation companies are now producing aerogel products that can be used for building insulation. Aspen Aerogels makes an aerogel blanket called Spaceloft® (re-branded in the U.K. as SpaceTherm®), and Thermablok™ produces narrow strips of aerogel that may be a more cost-effective way of utilizing aerogel insulation without breaking the bank. A typical aerogel insulation blanket has a thermal conductivity of 0.091 Btu-in/hr*ft^2*°F corresponding to an R-value of more than R-10 per inch thickness of material (roll / batt no more than 5.43 R-value per inch). That is nearly double the insulation value of the best insulations boards currently available [26].

Aspen Aerogel's Spaceloft® insulation is a 57-inch wide roll of aerogel material available in 0.20 in and 0.40 in thicknesses (about R-2 and R-4 respectively). Spaceloft® is a useful product for insulating existing walls in retrofit situations where it is important to minimize the amount of floor area lost to building up wall insulation. SpaceTherm® is a re-branded form of Spaceloft insulation. Predominantly found in the U.K. SpaceTherm® insulation comes pre fabricated between either plaster or face-board (dry-wall) sheets. A 0.78 inch thick 4 x 4 ft sheet of insulation with dry wall attached sells for around \$3.34 / ft^2. SpaceTherm® sheets have thermal resistance values of about R5. Therefore, despite having excellent insulating properties aerogel insulations such as SpaceTherm® are rather expensive to install.

Thermablok™ manufactures aerogel in 1-1/2" wide strips rather than broad sheets. In stud wall construction, the cavity between the studs is filled with insulation, but the studs themselves can conduct heat/cold, a process known as "thermal bridging," which reduces the overall thermal performance of the wall. By covering the walls studs with ¼" thick strips of aerogel insulation (equating to R-2.5) before installing the interior drywall or exterior sheathing is applied, the thermal bridging is mitigated and the thermal performance of the wall can increase by 30% or more [26]. Thermablok™ strips have been used in the Solar Decathlon (collegiate energy efficient building contest) house from the California College of the Arts and the University of Santa Clara, California. The suggested retail price for Thermablock™ insulating tape is $1.99/ft.

5.2 Insulation Simulation Procedure

Energy simulations for the advanced insulation and advanced windows chapters of this report make use of a building load and energy requirement computer program created by University of Tennessee at Chattanooga engineering professor Prakash Dhamshala. The program entitled “Transient Analysis of Building Loads and Energy Requirements” or TABLER for short, uses information about the local climate, local utility rates, building orientation, design, and construction, operational equipment, lighting conditions, heating and cooling systems, number of occupants, and day-to-day operations of the building in question to estimate the energy requirements of that structure. TABLER then has the ability to re-run the simulations with upgrades such as solar power systems, wind turbines, energy recovery units, building design changes, etc to estimate energy savings. TABLER calculates peak cooling and heating loads for HVAC sizing and breaks down energy consumption and utility expenditures monthly with easy to follow bar and pie chart outputs. TABLER was originally designed for commercial building energy simulations, but can be applied to residential applications with some minor changes. Residential lighting requirements, variable infiltration rates, and window over-hangs are some conditions that could not be input into the TABLER program but each of these conditions and their energy simulations are addressed in separate chapters of this report.

5.2.1 TABLER - Transfer Function Method

TABLER uses the Transfer Function Method (TFM) to estimate hourly building heating/cooling loads. The Transfer Function Method estimates heating/cooling loads as the building’s response to thermal storage effects of solar energy, heat transfer to/from conditioned space and outside environment, occupants, lights, and the equipment of the building. The temperature of the space, the temperature of the environment outside, the solar heat transfer rate, heat energy from occupants, equipment, lighting, and others factors are referred to as driving terms. The TFM calculates the response of a system by making the following assumptions:

(1) Discrete time steps: all functions of time are represented as a series of values at regular time steps (hourly in this case).
(2) Linearity: the response of a system is a linear function of the driving terms and of the state of the system.
(3) Causality: the response at time t can depend only on the past, not on the future.

The TFM applies a series of weighting factors, or Conduction Transfer Function (CTF) coefficients to the various exterior opaque surfaces and to the differences between the “sol-air” temperature (derived temperature of the outside air that in the absence of all radiation effects would give the same heat gain into a surface as would be the combination of convective and solar radiative heat transfer normally) and the inside space temperature to determine the space heat gain with the appropriate reflection of the thermal inertias of such surfaces. These CTF coefficients relate an output function at a given time to the value of one or more driving functions at a given time and the time immediately preceding. The TFM also applies a second series of weighting factors know as Room Transfer Functions (RTF) to heat gain and cooling load values from all load elements that have radiant components. The purpose is to account for the thermal storage effect in converting heat gain to HVAC system cooling load within the building. RTF coefficients relate specifically to the special geometry, configuration, mass, and other characteristics of the defined space in order to reflect weighted variations in the thermal storage effect on a time basis rather than a straight-line average. Both CTF and RTF coefficients are highly dependent on the building materials/construction and are tabulated values [27]. Therefore, utilizing climatic data (solar radiation, temperature, wind, etc), inside temperature data, CTF coefficients, and building specific information, the heat gain through the structure is determined for each of the of the year and this heat is added to internal gains at each hour from heat sources such as people, lights, and equipment. This heat gain is transformed into HVAC heating/cooling load after using RTF coefficients that take into account thermal storage effects that are very specific to each structure under investigation. The Transfer Function Method is a very powerful transient energy simulating method allowing the combination of numerous loads and heat sources.

5.2.2 Modeling Test Home Insulation in TABLER

Several program inputs pertaining to building location, orientation, size, construction, energy loads, temperature controls, etc are required by TABLER for accurate simulations. Since this chapter only focuses on the possible energy savings due to insulation upgrades, many of the TABLER inputs such as lighting, infiltration, and window areas (for solar heat gain through the windows) will be set for the time being to zero. First, the building location must be selected so the program can import the proper climatic data including typical weather conditions such as solar radiation, outside ambient air temperature, wind speeds, etc. TABLER has information for 18 cities across the country including Chattanooga, TN already built into the user interface. Next, the building orientation must be input so correct building surface (walls, roof, windows) incident radiation values can be determined. The "front" facing wall of this home point due north (back wall faces south) so the program is already setup for this building orientation; otherwise, an angle of inclination between the normal of the north wall and true geographic north must be input. The average building height of this home was input as 15 feet (not all of the walls are perfect squares with a constant height, but 15ft is an approximation). The simulation indoor design temperatures (thermostat settings) were input as 68 ˚F for the winter and 72 ˚F for the summer (same as infiltration simulations). All renewable energy systems were turned off for this simulation (no wind turbines, no solar panels, etc.) The last information needed for simulation pertains to the wall and insulation systems under investigation.

Wall construction and insulation composition information was used to determine the overall coefficient of heat transfer (U-factor) for the north, south, east, and west facing exterior walls along with the floor and roof structures. This will allow the program to calculate the amount of heat gain/loss through the solid structures of the building envelope using the Conduction Transfer Function (CTF) coefficients for various materials. Materials used in the construction of various walls and the thermal properties associated with each material were determined from home construction plans or physical observation. Following the equations established in the "Insulation Thermal Properties" section of this chapter the U-factor for each wall was determined. Materials and U-factor calculations for the test home exterior walls are shown in Table 5.3. The overall coefficient of heat transfer for the exterior walls was determined to be 0.069 Btu / $hr*ft^2*°F$ (total wall R-value of about 14.5 $hr*ft^2*°F$ / Btu).

Materials and U-factor calculations for the test home flooring structure are shown in Table 5.4. The overall coefficient of heat transfer for the floor was determined to be 0.047 Btu / $hr*ft^2*°F$ (total floor R-value of about 21.4 $hr*ft^2*°F$ / Btu).

Table 5.3: Exterior Wall U-Factor Calculations

Exterior Wall Components	R-Value Studs	R-Value Cavity
Outside Air Film	0.17	0.17
1/2" Cedar Siding	0.80	0.80
1" Foam Board Insulation with Vapor Barrier	2.90	2.90
2" x 4" (3.5") Wall Studs	4.38	\
Insulation (R-11 ~ 3.5")	\	11.00
1/2" Dry Wall	0.45	0.45
Inside Air Film	0.68	0.68
Total Wall Component R-Value	9.38	16.00
Total Wall Component U-Value [1/R]	0.1066	0.0625
15 % for 16" O.C. Studs + Additional Support Studs	15%	85%
Wall R-Value [1 / ((Ustuds x %) + (Ucavity x %))]	14.468	
Wall U-Value [1/R]	**0.069**	

Table 5.4: Floor U-Factor Calculations

Floor Components	R-Value Studs	R-Value Cavity
Outside Air Film	0.17	0.17
2" x 10" (9.5") Floor Joist	11.875	\
Insulation (R-19 ~9.5")	\	19.00
3/4" Plywood	0.93	0.93
Carpet with Fibrous Pad	2.08	2.08
Interior Air Film	0.68	0.68
Total Wall Component R-Value	15.74	22.86
Total Wall Component U-Value [1/R]	0.0636	0.0437
15 % for 16" O.C. Studs + Additional Support Studs	15%	85%
Wall R-Value [1 / ((Ustuds x %) + (Ucavity x %))]	21.406	
Wall U-Value [1/R]	**0.047**	

Determining the U-factor for the ceiling of the test home was slightly more complicated than the exterior walls or floor structures. The test home has two different ceiling insulation systems; one over the main living space and another over the smaller bedroom areas where an attic separates the actual roof line from the ceiling in each room. To combine the two different ceiling insulation systems an effective ceiling U-factor will be calculated as the weighted average (based on ceiling area) of the two separate ceiling U-factors. First, the U-factor for the main living space (1,362 ft^2 ceiling area) was determined following the same procedure as the walls and floor structures. This information is shown in Table 5.5. The U-factor for this sloped ceiling insulation system was determined to be 0.035 Btu / $hr*ft^2*^\circ F$ (R-value of about 28.3 $hr*ft^2*^\circ F$ / Btu). Next, the U-factor for the ceiling-attic-roof insulation system over the smaller bedroom areas (764 ft^2 ceiling area) was determined. Much research has gone into the study of heat loss from attic structures including the effects of heat transfer due to radiation. For an un-vented (still air) attic the total thermal resistance is given by the equation:

$$R_{total} = R_{ceiling} + R_{roof} * (A_{ceiling} / A_{roof})$$

In this equation $A_{ceiling}$ and A_{roof} are the ceiling and roof areas over the smaller bedroom section of the test house.

The thermal resistance of the sloped roof section over the attic space in the bedroom section of the test house was determined to be 2.137 hr*ft^2*°F /Btu. The materials list and R-value calculations for this are shown in Table 5.6.

The thermal resistance of the horizontal ceiling section under the attic space in the bedroom section of the test house was determined to be 25.78 hr*ft^2*°F /Btu and the materials for this section are shown in Table 5.7.

Table 5.5: Main Room Ceiling U-Factor Calculations

Ceiling 1 (Main Room) Components	R-Value Studs	R-Value Cavity
Outside Air Film	0.17	0.17
Asphalt Roof Shingles	0.44	0.44
1/2" Plywood with Vapor Barrier	0.63	0.63
2" x 12" (11.5") Ceiling Joist	14.38	\
Insulation (R-30 ~11.5")	\	30.00
1/2" Dry Wall	0.45	0.45
Interior Sloped Ceiling Air Film	0.63	0.63
Total Wall Component R-Value	16.70	32.32
Total Wall Component U-Value [1/R]	0.0599	0.0309
15 % for 16" O.C. Studs + Additional Support Studs	15%	85%
Wall R-Value [1 / ((Ustuds x %) + (Ucavity x %))]	28.341	
Wall U-Value [1/R]	**0.035**	

Table 5.6: Bedroom Roof R-Value Calculations

Bedroom Roof Components	R-Value Studs	R-Value Cavity
Outside Air Film	0.17	0.17
Asphalt Roof Shingles	0.44	0.44
1/2" Plywood with Vapor Barrier	0.63	0.63
2" x 8" (7.5") 16" O.C Roof Joist	9.375	\
Interior Sloped Attic Air Film	0.63	0.63
Total Wall Component R-Value	11.25	1.87
Total Wall Component U-Value [1/R]	0.0889	0.5348
15 % for 16" O.C. Studs + Additional Support Studs	15%	85%
Wall R-Value [1 / ((Ustuds x %) + (Ucavity x %))]	**2.137**	
Wall U-Value [1/R]	0.468	

Table 5.7: Bedroom Ceiling R-Value Calculations

Bedroom Ceiling Components	R-Value Studs	R-Value Cavity
Attic Air Film	0.68	0.68
2" x 6" (5.5") Ceiling Joist	6.88	\
Insulation (R-38 ~12")	\	38.00
1/2" Dry Wall	0.45	0.45
Interior Ceiling Air Film	0.61	0.61
Total Wall Component R-Value	8.62	39.74
Total Wall Component U-Value [1/R]	0.1160	0.0252
15 % for 16" O.C. Studs + Additional Support Studs	15%	85%
Wall R-Value [1 / ((Ustuds x %) + (Ucavity x %))]	**25.780**	
Wall U-Value [1/R]	0.039	

With $R_{ceiling}$ and R_{roof} both known, the total ceiling-attic-roof effective thermal resistance over the bedrooms can be determined. The area of the ceiling over the bedroom section of the test home was measured to be 764 ft^2 while the area of the sloped roof over the bedroom section of the home was measured to be 942.99 ft^2. With this information the total thermal resistance of the bedroom ceiling-attic-roof was determined to be 27.51 $hr*ft^2*°F$ /Btu which corresponds to an over coefficient of heat transfer of 0.0363 Btu / $hr*ft^2*°F$.

Now, with both the U-factor of the main living area sloped roof and the bedroom sections of the test house known, a weighted average of the two can be determined and this U-factor value will be input into TABLER as the over, effective coefficient of heat transfer. As stated previously, 1,362 ft^2 of indoor ceiling area is in the main living space (U-mainceiling 0.035) and only 764 ft^2 of indoor ceiling area is located in the bedroom section (U-bedceiling 0.0363). Therefore, an effective U-factor corresponding to the total ceiling area of 2,126 ft^2 would be 0.035 Btu / $hr*ft^2*°F$, and this value will be input for the roof (ceiling) U-factor in the TABLER simulation software.

The last bit of information TABLER needs pertaining to the building exterior structure is the size (square footage) of each exterior surface. These measurements were obtained from building designs or physical measurement and are shown in Table 5.8 with their respective calculated U-factors. Note that TABLER was originally designed for commercial structures, and as such, TABLER has about 40 built in composite wall structures with U-factors to choose from that are typical of commercial construction; however, each of the U-factors displayed in Table 5.8 are found in various TABLER options. With this information, TABLER is prepared to conduct the insulation baseline energy simulation.

Table 5.8: TABLER Solid Envelope Inputs for Insulation Energy Simulations

	U-Factor (Btu / hr*ft^2*°F)	Solid Wall Area (ft^2)
North Wall	0.069	470.26
South Wall	0.069	345
West Wall	0.069	492
East Wall	0.069	475.5
Roof	0.035	2,126
Floor	0.047	2,003

5.3 Baseline Simulation of Insulation System

According to TABLER baseline energy simulation results about 10,512.16 kWh (35,868,951 Btu) of heating/cooling load is annually added to the indoor, conditioned space of this test home from heat that is transmitted through the roof, floor, and exterior wall insulating systems. A monthly breakdown of these space heating and cooling loads is shown in Figure 5.1. As can be seen in the figure, the additional space loads due to heat transfer through building insulation systems are dominated by heating loads. In fact, nearly 89% of these annual added space loads will be heating. Of course, heating loads will be greatest in the colder months such as January, February, November, and December. Somewhat surprising was how little added space cooling load was returned by these simulations. July, August, June, and May were the months with the most added space cooling load (804,055, 401,471, 339,102, and 25,557 Btu respectively) but the added space load in these months still paled in comparison to other months with high added heating loads.

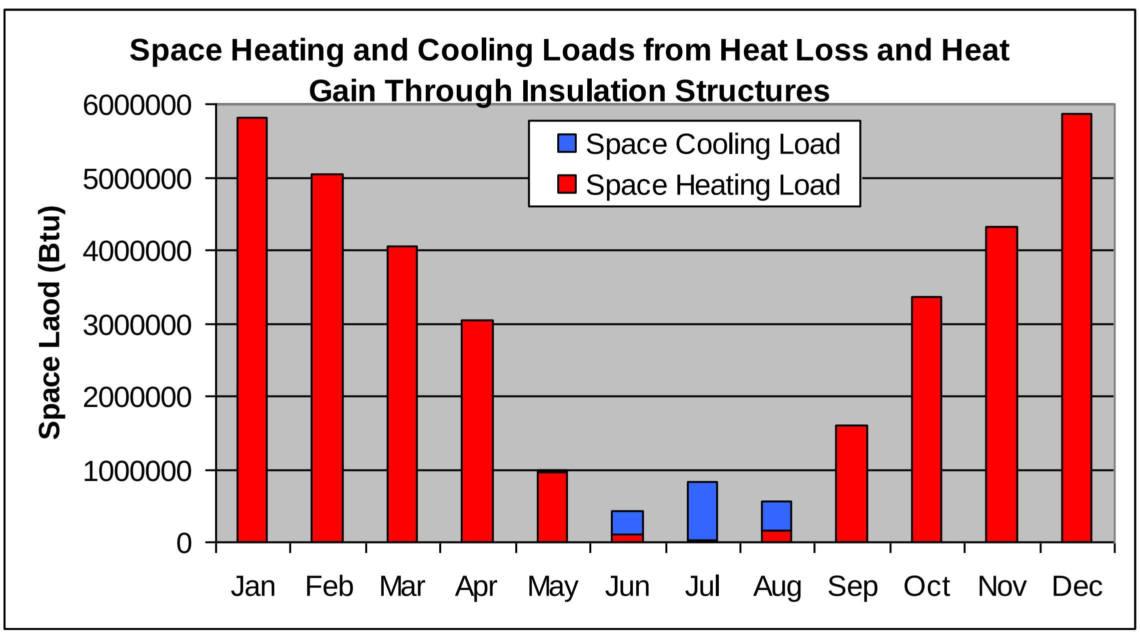

Figure 5.1: Monthly Heating and Cooling Loads through Insulation Systems

The added space heating and cooling loads in Figure 5.1 result in heat that must be added or removed from the inside, conditioned space. This requires some type of energy consumption by the home HVAC system in the form of either electricity consumed by the home heat pump, or the use of natural gas heating by the auxiliary heating system. Utilizing the HVAC system equations of Chapter 2, the energy requirements to remove the simulated thermal loads that are transmitted through the home insulation systems were determined. According to these simulations the home heat pump compressor would annually consume 2,417.31 kWh of electricity to mitigate added space heating loads, and the heat pump compressor would also annually consume 128.33 kWh of electricity to remove the added space cooling loads. Also, 48.8 Therms of natural gas would be consumed to mitigate some of the heating loads during certain cold periods of the year. All told, 2,545.645 kWh of total electricity will be consumption annually (13% of the home annual average consumption) that is purely allocated to mitigating the space loads that come through the insulated structures, and 48.8 Therms of natural gas will likewise be needed for heating these added loads. This equates to an annual utility expenditure on electricity of $242.76 and $51.12 on natural gas. Therefore, annually the home owners spend $280.93 to heat and cool the indoor, space loads that are transmitted through the home insulation systems. A breakdown of these monthly utility expenditures is shown in Figure 5.3.

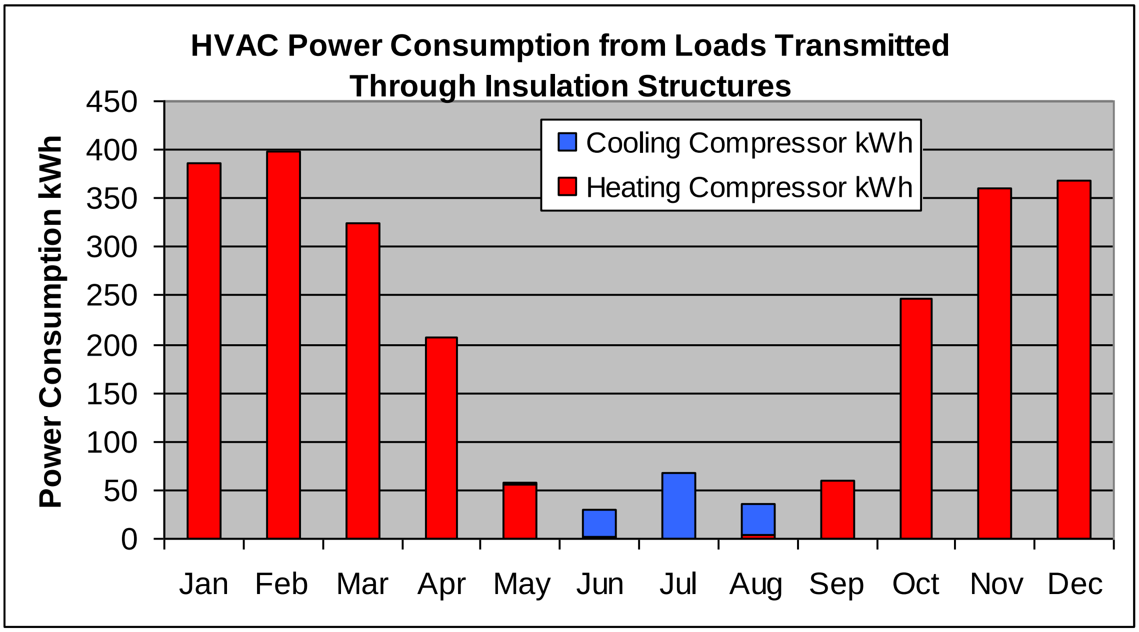

Figure 5.2: Monthly HVAC Power Consumption from Heating and Cooling Loads Transmitted through Insulation Systems

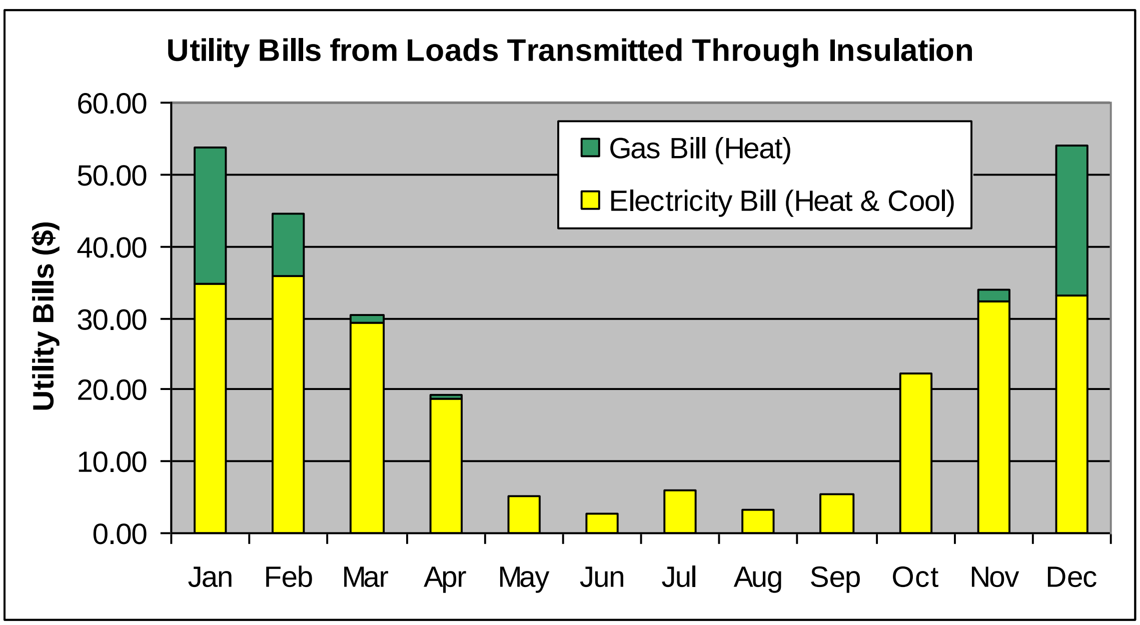

Figure 5.3: Monthly Utility Expenses from Heating and Cooling Loads Transmitted through Insulation Systems

5.4 Energy Efficient Insulation Upgrades

Energy efficient upgrades for insulating systems can be made in many ways. For one, standard, commercially available insulations can be utilized in easy to access building spaces such as attics and crawl spaces to bolster critical thermal resistances. This is seen as a relatively inexpensive, simple upgrade to the current insulation scenario. On the other hand, complete over-hauls and upgrades to an entire insulating system require the costly and time consuming removal of building materials such as interior dry-wall, exterior siding, and exterior siding. New insulation must then be purchased and installed properly. Then the building materials must of course be re-installed and returned to original finished conditions which can drive the cost of up significantly. Therefore, it is important to understand the potential energy saving benefits of varying degrees of upgraded insulating systems and properly "weigh" the benefits against the ever increasing installation and construction costs.

To evaluate various insulation upgrade options, different insulation scenarios are separated into project categories that involve no construction or minor-to-major construction. For the most part, insulation upgrade effectiveness will be measured through energy simulations (TABLER) individually (and then collectively with other upgrades) in each category. Energy simulation savings will be compared against the estimated upgrade investment which is based on the cost of materials and labor. Labor costs will be estimated from previous home improvement projects that required similar time, labor, and skills.

5.4.1 Insulation Upgrades – No Construction

Insulation upgrades with no construction is the most limiting upgrade scenario. Cavity insulation inside the roof and walls is sealed away by dry-wall and other interior-exterior finishes, and no real upgrades can be performed. However, two areas of the home can be accessed with no demolition; the (1) flooring insulation and the (2) attic insulation over the bedrooms.

(1) The home HVAC system and distribution duct system is located under the floor of the home in what amounts to an un-conditioned "crawl space" (the ceiling height

is near 5 feet in some locations no real crawling involved). The ceiling of this crawl space is the exposed flooring insulation system for the home above. Currently about 9 inches of cavity insulation with a thermal resistance of R-19 lies in between the 2" x 10" floor joists. According to the ORNL recommendations discussed in the "Building Insulation Standards" section of this chapter, flooring insulation of R-25 is recommended for not only existing building upgrades, but also for new building construction standards. Therefore, upgrading the flooring insulation to R-25 is the first insulation upgrade that can be relatively easily done since the insulation is exposed and easily changed. Insulation with R-25 values is not readily sold at local home improvement stores in this area. Two layers of R-13 insulation can be installed in-line (series) to correspond to an R-26 value but it turns out to be less expensive just to install a single layer of R-30 insulation instead. R-30 fiberglass, faced insulation can be purchased for as little as 0.51 $\$/ft^2$ (no tax). The total floor area is 2,003 ft^2 including the space occupied by the floor joist. Subtracting out floor joist area it is estimated that 1,764 ft^2 of insulation will be required for this project and this corresponds to a material cost of about $1,000 (after Tennessee sales tax and minor miscellaneous expenses). No labor cost will be required for this project, simple mounting procedures can be learned at local hardware stores and the mounting brackets used to hold the existing insulation in place may still be used. After this insulation upgrade the U-factor of the floor will be lowered to 0.035 Btu / hr*ft2*˚F (from 0.047).

(2) The second area of the home that can be accessed with no demolition is the attic over the bedroom areas (closet ceiling access). The current attic insulation in the bedroom ceilings has an insulating value of R-38. According to ORNL this is an acceptable attic insulation value for existing buildings. Of course, ORNL is anticipating a home structure where the attic spans most if not all of the roof-line and is the last line of insulation before the conditioned space and the roof structure. This is not the case for the test home under investigation in this report. Only 36% of the ceiling area of this home has an attic with R-38 insulation separating the roof structure from the conditioned space while the other 64% has lower insulation values (R-30) located within the pitched roof structure (roof structure and ceiling structure connected). ORNL recommends attic

insulation of R-49 for new construction projects and since simulations do not cost money, attic insulation upgrades to R-49 over the bedroom areas of the home will be simulated and the energy savings discussed. The simplest way to increase R-38 fiberglass attic insulation to an R-49 value is to cover the attic floor with new, R-11 fiberglass insulation. This will be acceptable since this attic is not used for storage and is not accessed regularly. The R-11 insulation will be placed over the ceiling joist and current attic insulation so the entire area of 764 ft^2 will be covered. R-11 fiberglass insulation can be purchased locally for 0.35 $\$/ft^2$. Once again, no labor costs will be needed for a simple project such as this. Therefore the total cost to upgrade the attic insulation from R-38 to R-49 will be about $300. After this attic insulation, the U-factor of the roof will be lowered to 0.034 Btu / hr*ft2*°F (from 0.035).

5.4.2 Insulation Upgrades – Minor-to-Major Construction

Minor construction insulating projects are not particularly quick and easy or inexpensive, but are also not major over-hauls of the building structure. Projects like these include adding rigid sheathing insulation either on the interior or exterior of the structure or adding dry-wall mounted advanced insulation systems such as SpacethermF® or Aspen Aerogel's Spaceloft® insulations. In order to bring the current home insulation system up to ORNL proper insulation recommendations, two areas of minor construction insulation upgrades will be discussed and simulated to understand the possible energy savings.

(3) ORNL recommends for both existing and new construction buildings that R-5 rigid sheathing insulation be installed on wall structures that typically hold R-11 cavity insulation. The exterior of the test home is finished with over-lapped cedar wood siding, and under this siding rigid sheathing insulation was first installed. The R-value of this insulating sheathing is R-2.9 according to manufacturer's information. To meet the ORNL recommendations the sheathing insulation must be upgraded. This can either be done by replacing the existing exterior sheathing insulation system under the exterior wood siding, or by adding sheathing insulation to the interior finish of the exterior wall structures. The cumulative effect on the total R-value of the wall structure will be the

same whether the sheathing is added on the exterior or interior and this theory was supported with quick, total wall R-value calculations. Rigid sheathing insulation with a thermal resistance of R-2.17 is commercially available in 0.5 inch thick sheets that can cover $32ft^2$ of wall area (8' x 4' sheet) for $9.98 each. This sheathing can be added on the interior of the wall structure to provide a total wall sheathing insulation value of R-5.7. Installation of this sheathing will not be as easy or as economical as the last section of insulation upgrades. This sheathing insulation can be installed on top of the existing dry-wall finish of the home, but for a professional look more dry-wall would have to be installed over the rigid sheathing. This would be the easiest interior installation approach but would add about 1 inch of wall thickness and would require work to re-install light switches, electrical outlets, and other current dry-wall penetrations. At this point it would make more sense to remove the existing dry-wall before hand to minimize the changes and if that is the case the wall cavity insulation should be upgraded at the same time to maximize energy savings. The other option for upgrading the rigid sheathing insulation system is to replace the exterior rigid sheathing under the exterior siding. This would be very costly unless exterior siding work was already planned or repairs are needed. Therefore, the most economical, and easiest in terms of construction way to upgrade this insulation is to simply add interior sheathing insulation to the wall structures using an advanced insulation system. SpaceThermF® is an advanced insulation system mounted with dry-wall (face board) already attached. This insulation system has an R-5 insulation value and is only 0.78 inches thick. This would make SpaceThermF® the easiest insulation to install of the interior of the test home wall structures to meet ORNL recommendations. The interior wall area of the building walls that connect directly to the outside environment that has dry-wall mounted is about 1,000 ft^2. SpaceThermF® insulation for this area would cost about $3,340 for this area and hiring a professional to dry-wall would cost another 1,000 dollars for installation. Therefore, the total installed cost for this project is around $4,400. Adding this R-5 insulation would bring the wall U-factor down to 0.06 Btu / hr*ft2*˚F (from 0.069).

Major insulation upgrade construction projects are projects that would require basically a complete over-haul of the current insulation systems. This would require opening up the wall and roof structures of the home. A project like this would require a large investment and the use of contractors.

(4) A major construction project would open up exterior walls and replace the existing R-11 wall cavity insulation with the ORNL new construction recommended R-15 insulation. This could be done utilizing new, Spaceloft® Aerogel insulation which already comes in 0.40 inch rolls corresponding to R-4 insulation (existing R11 + R4 = R-15, or utilizing standard insulations. This major construction project would also upgrade the current exterior sheathing insulation by removing the exterior wood siding and installing R-5 rigid sheathing insulation. The cost of this major construction project would be in the ball-park of $9,000 ($2,090 for 2,000 ft^2 of R-5 sheathing labor costing $5,000 to install and $869 for 1,000 ft^2 of R-15 cavity insulation costing $1,000 in labor to install). After these upgrades the wall U-factor would be lowered to 0.052 Btu / hr*ft2*˚F (from 0.069).

(5) As a simulation of special interest, total wall R-values will be calculated assuming that the wall studs will be lined with ¼" thick, advanced insulation Thermablok™ strips (R-2.5) and possible energy savings will be investigated. Studies have shown that lining the studs can significantly decrease the heat transfer due to "thermal bridging" while decreasing the cost of advanced insulation systems. If the exterior wall wood studs were lined with this insulting tape, the wall U-factor would be lowered to 0.066 Btu / hr*ft2*˚F (from 0.069). The exact length of stud coverage is difficult to estimate, but based on architectural drawings and home measurements it is estimated that 1,000 ft of insulating tape will be need. This will cost about $2,000 for the material alone and construction costs to open the walls up would cost a significant amount (total project cost to install this tape will be discussed next when it is added to another insulation upgrade project).

(6) Lastly, the combined effects of these separate insulation upgrades will be simulated. The cost for a project of this magnitude is difficult to estimate but based on previous project estimation and previous home improvement projects, the total cost to achieve these upgrades will be upwards of $15,200. A breakdown of these construction cost is shown in Table 5.9.

A review of the energy efficient insulation upgrades discussed above is shown in Table 5.10. Six simulation sets will be performed with the post-upgrade U-factors for the walls, roof, and floor being updated in TABLER when necessary.

Table 5.9: Major Construction Project Cost Breakdown

	Materials ($)	Labor ($)
Floor 1,764ft2 R25	1,940.40	1,000.00
Attic 764ft2 R49	300.00	\
Sheathing 2,000ft2 R5	2,090.00	5,000.00
Thermablok™ Stud Tape	2,000.00	1,000.00
Wall Cavity 1,000ft2 R15	869.00	1,000.00
	7,200.00	8,000.00
Total Cost:	**$15,200**	

Table 5.10: Review of Test Home Insulation Upgrades

	Upgraded U-Factor	Cost
(1) Floor R-30 Insulation	$U_{floor} = 0.035$	$1,000
(2) Bedroom Attic R-49 Insulation	$U_{roof} = 0.034$	$300
(3) Wall SpaceThermF R-5 Interior Sheathing	$U_{wall} = 0.06$	$4,400
(4) Wall Cavity R-15 and Sheathing R-5	$U_{wall} = 0.052$	$9,000
(5) Thermablok™ Stud Insulating Tape	$U_{wall} = 0.066$	$2,000
(6) Combination: R-30 Floor, R-49 Attic, R-5 Sheathing, R-15 Cavity, Thermablok™ Stud Tape	$U_{floor} = 0.035$ $U_{roof} = 0.034$ $U_{Total\text{-}wall} = 0.047$	$15,200

5.5 Energy Efficient Insulation Simulation Results

Each of the six energy efficient insulation upgrades discussed previously were simulated by re-running the hourly building load simulation in TABLER. From these simulations, the total annual space load (both heating load and cooling), peak heating load, peak cooling load, HVAC power consumption to remove the building space loads, natural gas consumption (for certain heating requirements), and the total utility cost (both electricity and gas consumption) were determined for each of the six simulation sets. These simulation results are shown in Table 5.11.

As can be seen in the table, upgrading the flooring insulation from R-19 to R-30 had very little impact on the heating and cooling requirements of this test home. Less than 1 kWh of electricity consumption by the HVAC system each year was saved by upgrading the floor insulation. Upgrading the attic insulating system shows more promise for energy conservation. According to these simulations, the HVAC system will consume about 48 kWh of electricity less when the attic insulation was upgraded from R-38 to R-49. As mentioned previously, the attic space of this structure is only a small portion of the total ceiling area and if the attic area actually covered the entire ceiling area, these savings would be considerably more.

Table 5.11: Insulation Upgrade Simulation Results

	Annual Space Load Heat + Cool (Btu)	Peak Heat (Tons)	Peak Cool (Tons)	HVAC (kWh)	Gas (Therms)	Utility Cost
Original Insulation	35868951	0.9216	0.2	2545.65	48.80	280.74
						Utility Save
(1) Floor R-30	35866425	0.922	0.2	2545.540	48.790	$0.02
(2) Bedroom Attic R-49	35184962.93	0.912	0.2	2497.175	47.863	$5.36
(3) SpaceThermF R-5 Sheathing	32918917	0.847	0.2	2355.106	44.964	$21.21
(4) Wall Cavity R-15 and Sheathing R-5	30766902	0.780	0.19	2200.542	41.710	$39.00
(5) Thermablok™ Stud Tape	34792882.47	0.895	0.2	2469.281	47.336	$8.42
(6) Combination of All	30754277	0.729	0.24	2210.428	42.636	$37.14

The greatest simulated energy savings came from the upgraded wall sheathing and cavity insulation set (set #4). Upgrading the wall sheathing from R-2.9 to R-5 (either by adding exterior or interior sheathing insulation) and upgrading the wall cavity insulation from R-11 to R-15 saved the HVAC system of the home 345 kWh of electricity per year. These power savings (along with about 7 Therms of natural gas conservation) would correspond to annual utility savings of $39. A breakdown of the monthly space heating and cooling loads for this insulation upgrade simulation set is shown in Figure 5.4.

Interestingly in these simulations, the most expensive insulation upgrades to implement (set #6), which provided the highest R-values, returned energy savings less than the strictly wall upgrades in set #4 (most savings). The increase in space loads causing a decrease in overall energy savings was due to elevated summer time, cooling loads. In fact, according to TABLER, the peak space cooling load increased from 0.2 Tons to 0.24 Tons from the original insulation simulation due to moderate temperature periods when heat inside the home was "held-in" by the enhanced insulation setup. Note that these heating/cooling loads and "Peak" heating/cooling are not the total building loads, but just the loads from heat that is transferred through the insulation systems alone.

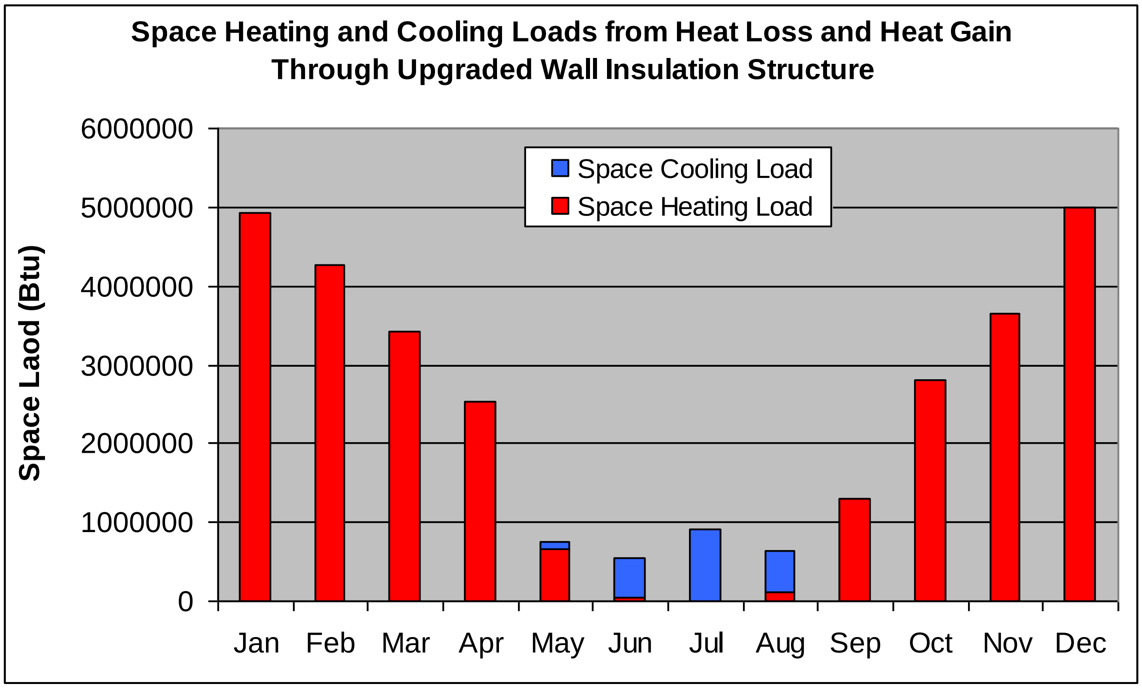

Figure 5.4: New Space Heating and Cooling Loads from Heat Loss and Heat Gain Through Upgraded Wall Insulation Structure (R-5 Sheathing and R-15 Cavity)

5.6 Brief Remarks on Insulation

Upgrading the insulating structures of a building will reduce the heating and cooling loads due to heat gain/loss through the walls, roof, and floor of a building. This will in turn reduce the energy consumption of the HVAC systems saving energy and money. Six simulation sets were each simulated using the building load estimation software TABLER and the energy (and money) savings of each set were examined to show the variation of possible savings. Table 5.12 is a review of simulation results from this chapter. The payback periods (excluding flooring insulation results) based on individual upgrade energy savings range from 56 years to 409 years. It is obvious the greatest potential for return on investment with insulation upgrades comes from attic insulation improvements. For a home that has an attic covering most of the ceiling area (not like this test home), the potential savings and return on investment for upgraded attic insulation will be much better than these simulations show. The greatest annual energy savings came from installing R-5 wall sheathing insulation and upgrading the wall cavity insulation to R-15 as recommended by ORNL. These improvements annually saved 345 kWh of HVAC electricity consumption and 7 Therms of natural gas, totaling $39 utility savings each year. Recent research has showed similar results to this simulation; unless there is a glaring deficiency in the insulation systems of a home, the energy savings seen from insulation upgrades are small compared to other energy efficient upgrade options.

Table 5.12: Review of Insulation Simulations and Savings

	Annual Space Load (Btu)	HVAC Consumption (kWh)	Gas Consumption (Therms)	Utility Cost ($)		
Original Insulation	35,868,951	2,545.65	48.8	280.74		
(Upgrades)				**Utility Save**	Install Cost	Payback (Yrs)
Floor R-30	35,866,425	2,545.54	48.79	$0.02	$1,000	50,000
Bedroom Attic R-49	35,184,962.93	2,497.17	47.86	$5.355	$300	56
R-5 Wall Sheathing	32,918,917	2,355.11	44.96	$21.21	$4,400	207
Wall Cavity R-15 and Sheathing R-5	30,766,902	2,200.54	41.71	$39	$9,000	231
Thermablok^{TM} StudTape	34,792,882.47	2,469.28	47.34	$8.42	$2,000	237
Combination of All	30,754,277	2,210.43	42.64	$37.14	$15,200	409

Chapter 6

Advanced Windows

Windows provide less resistance to heat flow than walls, ceilings, and floors in a typical home. Even though windows comprise a relatively small area of the building envelope, they are the area of greatest heat loss/gain and can be one of the most prominent sites of air leakage. Windows can account for as much as 25% - 30% of the heat loss in a home [38]. This increases energy use, utility costs, and decreases inside thermal comfort. Window replacements have been the number one energy conservation project for homeowners recently. Government tax credits for energy efficient home improvements have provided the extra incentive for homeowners to invest in new windows leading to more energy efficient homes and less energy consumption.

6.1 Windows Basic Concepts and Terminology

Windows provide heat transfer to (or from) a home in several ways. For one, loose fitting windows allow air to infiltrate/exfiltrate the home. These losses are associated with the frame of the window, poor installation and sizing, or structural changes to the window/frame over the life of the home (shifting and settling of a home over time). To combat these losses, advanced windows have begun making use of composite materials, such as fiberglass, for the window frame instead of the classic wood materials. These composite materials can be manufactured to ensure a secure fit allowing little air leakage to the outside environment.

The most noticeable way windows transfer heat is by conduction-convection interactions with the environment. Heat will transfer by conduction-convection through either the window frame that houses/supports the window glass, or through the actual window glass panes themselves [39]. The thermal resistance (R-value) and over coefficient of heat transfer (U-factor) of each material are utilized here in the same manner as discussed in the previous chapter. The higher the R-value of the window system the less apt the system will be to transfer heat when an indoor-outdoor temperature difference exists according to the equation:

$$q = U*A*\Delta T$$

To slow heat transfer through a window's frame, composite materials such as fiberglass or Vinyl are used as window frame "shells" where highly thermal resistant insulating materials can be inserted to prevent heat transfer. Insulating frames like these provide much better thermal resistance than aluminum or metal window frames and are slightly more thermally resistance than traditional solid wooden frames.

Several advancements have helped address the concern of heat transfer through the pane (glass) region of a window. The first of these is installing windows with "double-panes." Double-paned windows have two layers of glass separated by a small region of space. This space acts as an insulator between the two layers of glass and this nearly doubles the thermal resistance of the pane region of a window. Many companies have experimented with adding even more panes of glass, and each successive layer does add to the total thermal resistance of the window but with diminishing effect and increased cost. No more than 3 layers of panes are typically available on the market today. Also, advanced windows make use of inert gases, such as Argon and Krypton to fill the space between each pane of glass. The heat transfer across these inert gases is less than if the void was allowed to fill with air [38].

Another often overlooked source of heat gain from windows is solar heat gain. Solar radiation passes through the glass region of windows, and this radiation can significantly add to the space cooling load inside a building. In the winter time, these heating effects can be a helpful heating element for a building. Many buildings are designed with this winter heating effect in mind and it is classified as a "passive solar" application. However, this solar heat gain can be detrimental in the hot summer months when building cooling loads are already one of the highest energy consumers. Many residential buildings combat the summer solar heat gain by designing/constructing window over-hangs. These over-hangs block the sun's radiation from striking the windows in the summer but allow radiation penetration in the winter because the sun is at a higher solar altitude angle during the summer months (lower in the winter sinking below the "shade line" created by the window over-hang).

The solar heat gain coefficient (SHGC) refers to the fraction of solar radiation that passes through a window assembly and warms the interior living space of a building.

The SHGC is expressed as a number between 0 and 1 with a low SHGC meaning a lower amount of solar heat radiates through the structure. The “shade coefficient” is a measure of the ability of a window or skylight to transmit solar heat, relative to the ability of a 3 mm (1/8-inch) clear, single pane of glass. The shading coefficient is being phased out in favor of the solar heat gain coefficient, and is approximately equal to the SHGC multiplied by 1.15 [35].

To combat solar heat gain effects, advanced windows are generally coated with solar resistive coatings. Many different types of coatings, sometimes referred to as “tinting,” are available with SHGC values near 0. These coatings can block almost all solar radiation but also block a majority of the light from entering the house. Window coatings must therefore walk the line between solar radiation resistance and appropriate light transmittance [39]. Solar coatings are commercially available for application on existing windows from companies such as 3M and GILA at local home improvement stores. The application process is relatively simply and does not require any type of training.

Manufacturer reported values called the “Full Frame R-value” are becoming standard in the window market. The full frame R-value is analogous to the overall thermal resistance value of the entire advanced window system. The full frame R-value takes into account the type of glass glazing material, number of air chambers created by multiple layers of suspended film or glass panes, what type of gas (if any) is used to fill the air spaces, thermal resistance of the frame and spacer materials, and air “tightness” of the window [41]. The reciprocal of the full frame R-value is likewise known as the full frame U-factor. Typical full frame values of single and double pane windows along with the criteria for windows to be certified as “Energy Star®” are shown in Table 6.1.

Table 6.1: Full Frame R-values and U-factors for Typical Windows [39]

	Full Frame R-value	Full Frame U-factor
Energy Star®	3.33 - 1.67	0.30 - 0.60
Double Pane	2.04	0.49
Single Pane	1.03	~1.00

6.2 Advanced Windows

SeriousWindows™ is one of the companies supplying the advanced window revolution. SeriousWindows™ provides help taking advantage of the government Tax Credits to finance efficient windows with full frame R-values ranging from R-5.1 – R-11.1. Initial costs can be substantial for installing new windows, but depending on the outside climate, window manufactures claim the initial capital cost can be recovered in less than 10 years for any location in the United States. Many homes with older windows can expect to recoup the initial investment in less than 5 years by cutting a home's heating and cooling load by approximately 30% [41]. SeriousWindows™ has over one hundred advanced window systems to choose from with full frame U-factors ranging from 0.09 to 0.34. Table 6.2 shows a sample of the advanced window options available from SeriousWindows™ dealers nationwide. These windows are some of the best thermally performing windows available but can be extremely costly (cost for window replacement in the test house will be estimated in later sections). According to the manufacture, the most economical SeriousWindows™ window option is the 725 Series. Of course SeriousWindows™ is not the only provider of energy efficient windows, and local window installers have large catalogues of energy efficient windows to choose from.

There is also a growing market for solar coatings ("tinting") for residential applications. 3M (manufacture most known for developing adhesive products) has developed sun control window films that are available for installation on new and existing windows. The highest rated coatings come from the "prestige series." The performance characteristics of some 3M window films are shown in Table 6.3. Solar coatings can be a cost effective way to cut down on solar heat gain through existing windows without having to invest a large amount in whole replacement windows.

Table 6.2: Sample of Various SeriousWindows™ Advanced Windows [41]

	Style	U-Factor	R-Value	SHGC	Glazing	Gas
300	Awning	0.27	3.7	0.18	Dual Pane	Ar
300	Double Hung	0.29	3.4	0.21	Dual Pane	Ar
301	Double Hung	0.30	3.3	0.21	Dual Pane	Ar
501	2 section Sliding	0.22	4.5	0.29	Dual, 1 Low SHG	Ar
501	Double Hung	0.2	5	0.26	Dual, 1 Low SHG	Kr
501	Awning	0.21	4.8	0.24	Dual, 1 Low SHG	Ar/Kr
501	Casement	0.18	5.6	0.25	Dual, 1 High SHG	Kr
501	Fixed Picture	0.25	4	0.22	Dual Pane	Ar
501	Fixed Picture	0.18	5.6	0.29	Dual, 1 Low SHG	Ar/Kr
600	Fixed Picture	0.17	5.9	0.28	Dual, 1 Low SHG	Kr
600	Casement	0.27	3.7	0.18	Dual Pane	Ar/Kr
600	Double Hung	0.29	3.4	0.19	Dual Pane	Kr
600	Double Hung	0.2	5	0.25	Dual, 1 Low SHG	Ar
600	2 section Sliding	0.23	4.3	0.25	Dual, 1 Low SHG	Kr
725	Fixed Picture	0.2	5	0.5	Dual, 1 High SHG	Ar
725	Casement	0.18	5.6	0.21	Dual, 1 Low SHG	Ar
725	Awning	0.22	4.5	0.39	Dual, 1 High SHG	Kr
725	Double Hung	0.19	5.3	0.22	Dual, 1 Low SHG	Kr
725	Horizontal Slide	0.23	4.3	0.44	Dual, 1 High SHG	Ar
725	Single Hung	0.18	5.6	0.23	Dual, 1 Low SHG	Kr
925	Fixed Picture	0.11	9.1	0.22	Dual, 2 Low SHG	Kr
925	Fixed Picture	0.14	7.1	0.42	Dual, 2 High SHG	Kr
925	Casement	0.15	6.7	0.17	Dual, 2 Low SHG	Kr
1125	Fixed Picture	0.09	11.1	0.26	Dual, 3 Low SHG	Kr
1125	Casement	0.13	7.7	0.2	Dual, 3 Low SHG	Kr

Table 6.3: 3M Window Sun Coating Performance Characteristics 42]

	Single Pane Clear	Single Pane Tinted	Double Pane Clear	Double Pane Tinted
Visible Light Transmitted	90%	27%	81%	24%
Total Solar Energy Rejection	14%	59%	25%	60%
Solar Heat Gain Coefficient	1.03	0.41	0.90	0.4
Solar Heat Reduction	13%	34%	15%	21%
UV Light Rejected	23%	99%	25%	99%
Shading Coefficient	0.90	0.47	0.87	0.46

6.3 Importance of Southern Window Over-Hangs

In the northern hemisphere the sun rises in the east and sets in the west following a southern path. This means that southern facing windows are exposed to solar radiation during most daylight hours. As mentioned previously, home designs for years have taken advantage of this fact by utilizing southern facing windows as a "passive" solar design feature. In the colder winter months the sun radiates into a home through the southern windows and helps heat the interior space. This same principle hold true during the hot summer months when heat inside the conditioned space is unwanted. To illustrate the effects of southern facing windows on the building heating and cooling load, a simple solar heat gain simulation was conducted and the importance of window over-hangs for southern facing glass features will be discussed.

In this simulation, the solar heat gain through 200ft^2 of southern facing, double-paned, clear glass (just like the test home under investigation) was examined throughout a typical year. Only southern windows are discussed in this section since solar heat gain from southern windows accounts for most of the total window solar heat gain (70 – 94% throughout the year according to these simulations). Sustainable Design® in Seattle, Washington provides window solar heat gain calculators for various window characteristics which follow standard procedures set out in the Residential Cooling and Heating Load Calculations chapter (chapter 27) of the ASHRAE 1997 Fundamentals Handbook. This procedure makes use of the Window Glass Load Factor (GLF) which can be found in ASHRAE tables, the window Solar Heat Gain Coefficient (SHGC) which depends on the window glass type and design, the local ground radiation reflectance, the window orientation and size, and the solar radiation data at a given global position (latitude). The solar heat gain through these southern facing windows is shown in Figure 6.1 for each month of the year. As can be seen in the figure, the solar heat gain through these windows is greatest in the winter months of January, February, November, and December when solar heat gain is a welcomed phenomenon (1,785 - 1,560 kWh heat gain). While solar heat gain is less in the summer months, all of this heat gain is un-wanted inside the conditioned space.

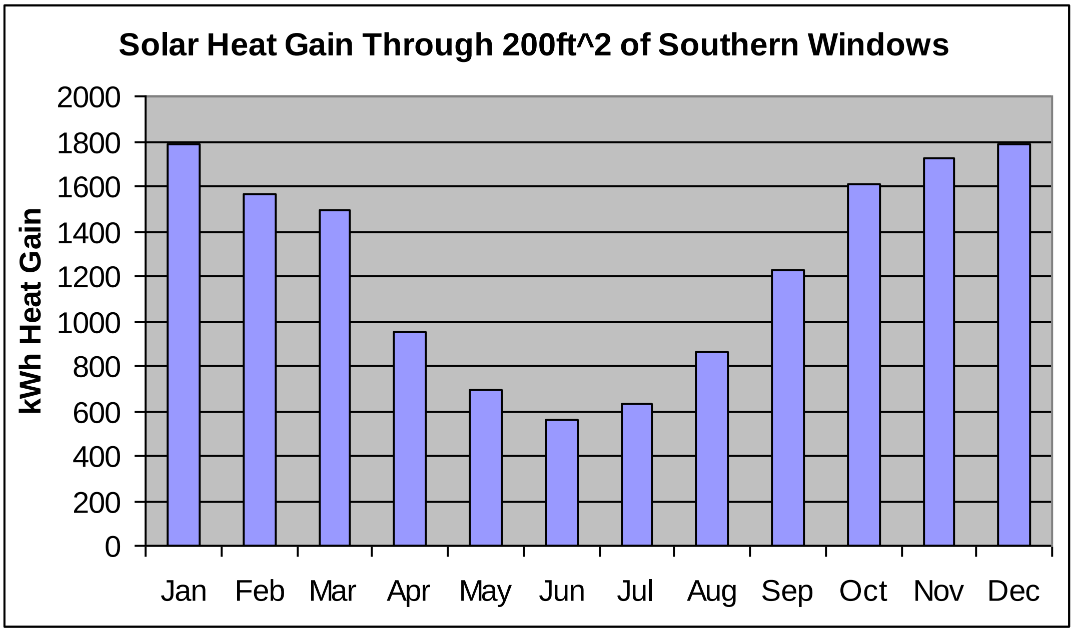

Figure 6.1: Solar Heat Gain through Southern Windows

The best way to mitigate summer solar heat gain through southern facing glass is to prevent the solar radiation from even contacting the glass panes during this time. This is accomplished by strategically designed window over-hangs. As mentioned in chapter 2 of this report, this test home has deep, pitched window/door over-hangs running along the entire length of the south building face. Over-hangs are effective because they take advantage of sun position information such as the solar "altitude angle." The altitude angle gives the relative position of the sun in the sky at a given location and a given point in time. During the hot, summer months the sun is higher in the sky. During the cold, winter months the sun is lower in the sky. Over-hangs mitigate the un-wanted summer heating loads from solar heat gain in the summer by blocking the higher-angled sun but still allow winter solar heat gain because the sun has a lower "altitude" angle during these months.

Several on-line resources are available to assist with proper over-hang design. Sustainable Design® in Seattle, Washington provides online sun position calculators, over-hang simulators, and a heat gain calculator to help understand the performance of different over-hang designs. Sustainable Design's online "Over-hang Annual Analysis" tool was used to understand the potential shading savings the test home southern over-hangs provide. General geometrical information for a typical window "pitched" over-hang on the test home were input into the Sustainable Design® analysis tool. This information is shown in Figure 6.2 and is adjustable for "pitched" over-hangs of any size and position as well as for flat (straight, horizontal) over-hangs of any size. The online tool uses calculated sun positioning data and geometry to estimate the glass area that will be shaded by the over-hang throughout the year. Results are given in tabular form as the average percent of the sun that is incident on the glass surface throughout the day. The results for a typical southern over-hang on this test home are shown in Table 6.4. As can be seen in Table 6.4, these southern over-hangs block 100% of the direct sun during the spring/summer months of April, May, June, July, and August. During September the sun is mostly blocked from the windows with the highest percentage of sun reaching the glass being 8% in the 11:00am – 1:00pm hours. Ideally, over-hangs would be designed to allow 100% of the sun to reach the window surfaces during winter months but that is not the case with this geometry.

It is important to understand that shading the window from 100% of the direct, incident solar radiation (like in the April – August months of this simulation) does not mean there is zero solar heat gain into the building space through these windows. ASHRAE says that "shaded glass is considered the same as north-facing glass" [35]. This means there is still solar heat gain through the windows from reflected and diffuse radiation, but these gains are much less than if the windows were not shaded from the direct sun. Therefore, to understand potential over-hang shade savings, the solar heat gain simulation must be re-run with the 200ft^2 of windows facing north. This simulates the solar heat gain through the southern facing windows during the months of the year when the sun is 110% blocked by the over-hangs. To simulate the months of the year when only a portion of the direct sun shines on the southern windows (1% – 99% in Table 6.4), a "shade percentage" is used to take the percent of shade savings seen between a southern un-shaded window (first simulation), and a southern completely shaded window (second simulation also known as a "North facing window"). For example, at noon (12:00pm) in mid-March, only 26% (Table 6.4) of direct sun radiation is incident on the southern facing windows with these over-hangs. That is like saying

74% of the window is "shaded" and has the solar heat gain like a northern facing window at that same time.

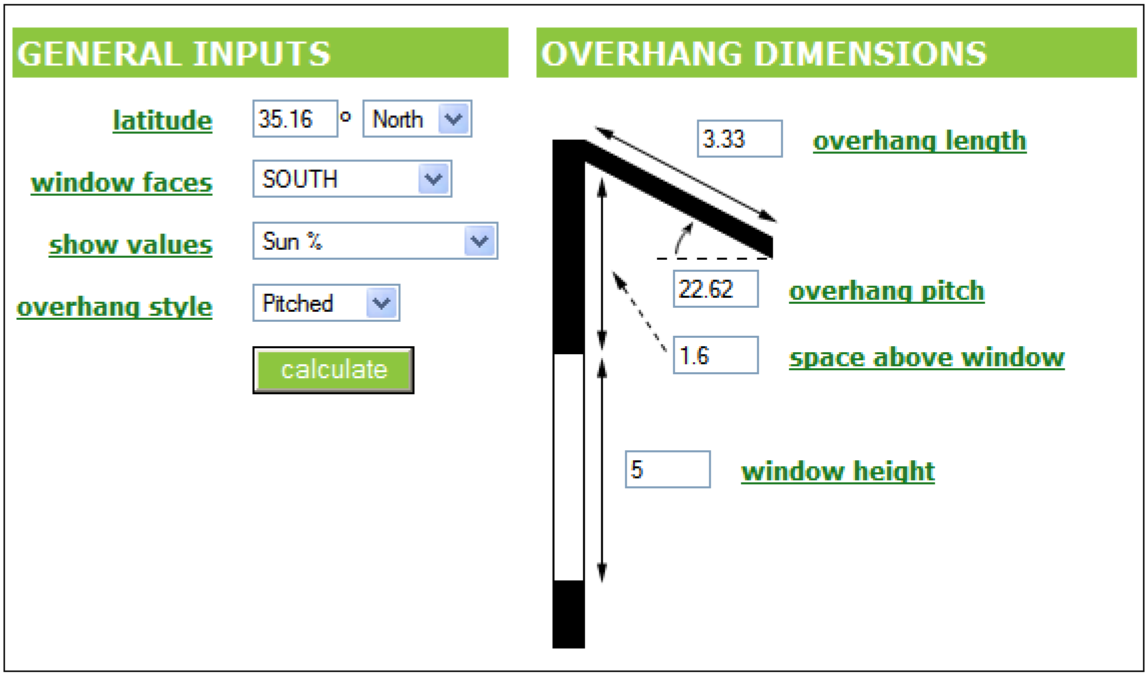

Figure 6.2: Sustainable Design's Over-hang Annual Analysis Online Tool Inputs

Table 6.4: Sustainable Design's Over-hang Annual Analysis Online Tool Results for Typical Pitched Southern Over-hang. Percentage of Direct Sun Incident on these Windows

MORNING						AFTERNOON						
	6:00	7:00	8:00	9:00	10:00	11:00	12:00	1:00	2:00	3:00	4:00	5:00	6:00
Jan			87%	76%	70%	66%	65%	66%	70%	76%	87%		
Feb		92%	70%	60%	54%	52%	51%	52%	54%	60%	70%	91%	
Mar		42%	32%	29%	27%	26%	26%	26%	27%	28%	31%	41%	
Apr		0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	
May			0%	0%	0%	0%	0%	0%	0%	0%	0%		
Jun				0%	0%	0%	0%	0%	0%	0%			
Jul				0%	0%	0%	0%	0%	0%	0%			
Aug			0%	0%	0%	0%	0%	0%	0%	0%	0%		
Sep		0%	0%	3%	6%	8%	8%	8%	7%	4%	0%	0%	
Oct		78%	58%	49%	45%	43%	42%	43%	45%	49%	58%	78%	
Nov		100%	83%	71%	65%	62%	61%	62%	65%	72%	83%	100%	
Dec			91%	80%	73%	70%	69%	70%	73%	80%	91%		
	6:00	7:00	8:00	9:00	10:00	11:00	12:00	1:00	2:00	3:00	4:00	5:00	6:00

Therefore, with 74% of the window area acting like a northern facing window, the inside space will see 74% of the potential shade savings of substituting a northern facing window at that specific time. This procedure was done for each month of the year to estimate the annual benefits of the test home southern window over-hangs. The southern window solar heat gain with and without over-hangs for this test home is shown in Figure 6.3.

As can be seen in the figure, the solar heat gain through the southern facing windows was reduced throughout the entire year when the shading effect of the over-hangs was introduced into the simulation. Even in the winter months when solar heat gain is typically desired, the heat gain was reduced due to some window shading that occurs towards mid-day hours. The most savings (reduced air conditioning requirements) will be realized in April, September, August, and May. From the months of April to September these southern over-hangs will reduce the interior space solar heat gain through the south facing windows 2,414.5 kWh (8238743 Btu). Once again the HVAC equations from chapter 2 and the local climactic data for each hour of a typical year were used to determine the power and money savings associated with these southern over-hangs. If all of the summer solar heat gain that was blocked by the southern over-hangs was seen by the conditioned space as a cooling load, the electricity consumed by the home HVAC equipment to remove this unwanted summer solar heat gain would be approximately 440 kWh, costing the home owner about $40.00. A breakdown of this HVAC power consumption for each summer month is shown in Figure 6.4.

The best window over-hangs strive to reduce solar heat gain in the summer but minimize the reduction of winter time solar heat gain. Sustainable Designs® provides over-hang design recommendations based on geographic location (latitude), climate type, and window/glass size that attempt to maximize over-hang effectiveness. Over-hang recommendations for a window of 5 units (could be feet or meters) are shown in Table 6.5. These recommendations can be recalculated for a window of any size online. The most effective over-hang designs block most if not all of the sun from March 21st at 12:00 pm – September 21st at 12:00pm (the Spring and Fall Equinox) and allow maximum sun exposure during the remaining months (October to February).

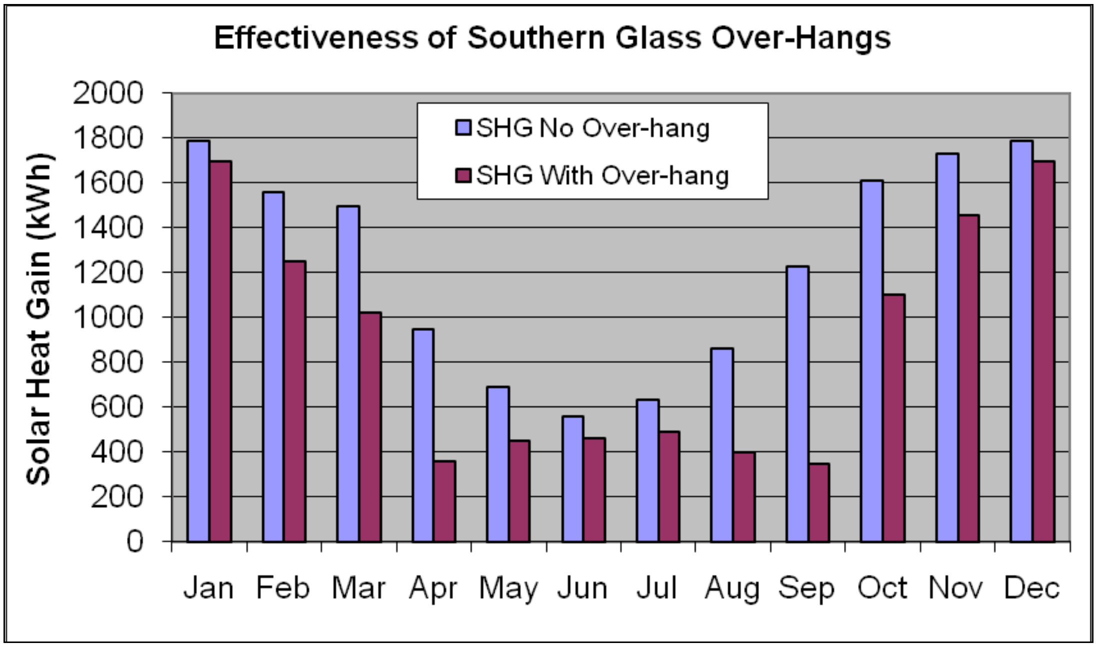

Figure 6.3: Southern Window Solar Heat Gain with and without Window Over-hangs

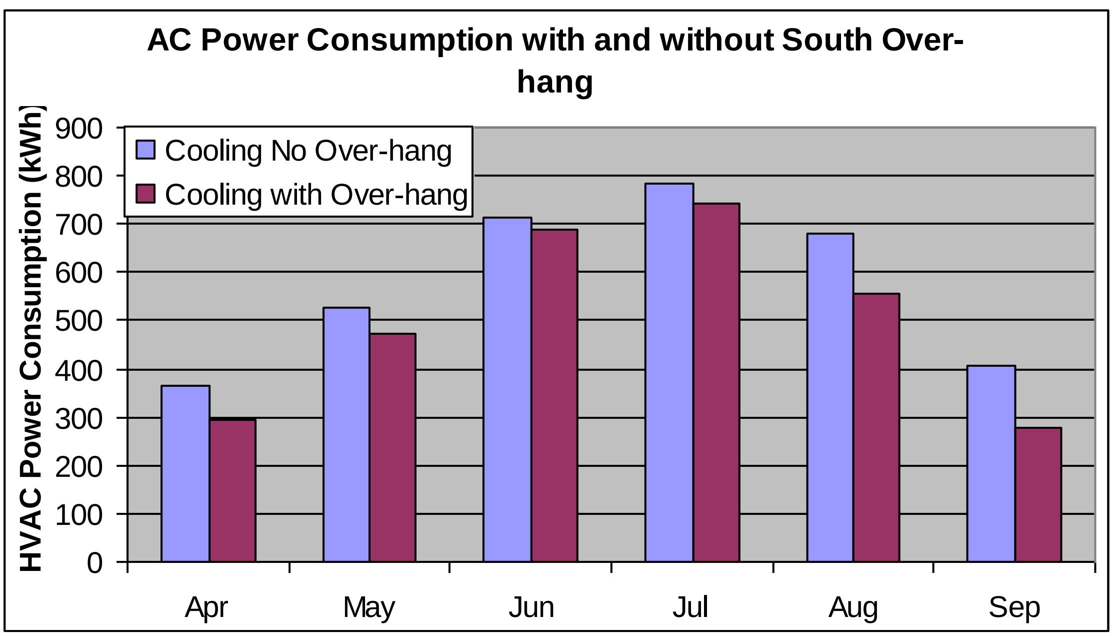

Figure 6.4: HVAC Power Consumption to Remove the Difference in Solar Heat Gain with and without Southern Window Over-hangs

Table 6.5: Over-hang Design Recommendations for Chattanooga

Window Height: 5 units				
		CLIMATE TYPE		
		Warm	Mixed	Cool
Latitude	24°	depth: 1.5 height: 0.5	depth: 1.5 height: 2.5	N/A
	28°	depth: 2.0 height: 0.5	depth: 1.5 height: 2.5	N/A
	32°	depth: 2.5 height: 0.5	depth: 2.0 height: 2.0	N/A
	36°	depth: 3.0 height: 0.5	depth: 2.5 height: 1.8	depth: 1.5 height: 1.5
	40°	depth: 3.5 height: 0.5	depth: 3.0 height: 1.5	depth: 2.0 height: 1.5
	44°	N/A	depth: 3.5 height: 1.5	depth: 2.5 height: 1.5
	48°	N/A	depth: 4.0 height: 1.3	depth: 3.0 height: 1.5

6.4 Window Baseline Energy Simulation

The test home baseline energy simulation for energy efficient window upgrades was generated using both the TABLER software and home HVAC system performance equations from Chapter 2. The current test home windows are double paned (2 window panes separated by air spaces U-factor = 0.67) with standard, clear glass (shade coefficient 0.87) with southern over-hangs. Unfortunately, TABLER does not take into account window over-hangs (that is why a whole section of this chapter was devoted to showing the importance of window over-hangs and their potential savings). The window areas for each building face (north, south, east, and west), the shade coefficients, and the U-factors for each set of windows in this baseline, "as-is" simulation are shown in Table 6.6. TABLER was used to generate new heating and cooling loads when taking into account these home windows. The heating and cooling loads of the test house under investigation assuming no windows (just insulated walls) were presented in the preceding chapter on Advanced Insulation, and for comparison sake, the resulting loads of both the current insulation and current window simulations are shown in Figure 6.5.

As can be seen in Figure 6.5, the heating loads in each winter, spring, and fall month were reduced significantly from the "original heat load" (insulated walls alone); however, the building cooling loads were likewise increased each month especially in the summer. The electricity required by the HVAC equipment to remove the space heating and cooling loads that are transmitted through the insulation structures and the current home windows are shown in Figure 6.6. The utility expenses (electricity and natural gas) expected to mitigate the heating/cooling loads transmitted through the insulation structures and the current home windows are shown in Figure 6.7.

Table 6.6: Actual Test Home Window Information

	Area (ft^2)	U-Factor ($Btu/hr*ft^2*°F$)	Shade Coefficient
South	200	0.67	0.87
North	35	0.67	0.87
East	17	0.67	0.87
West	18	0.67	0.87

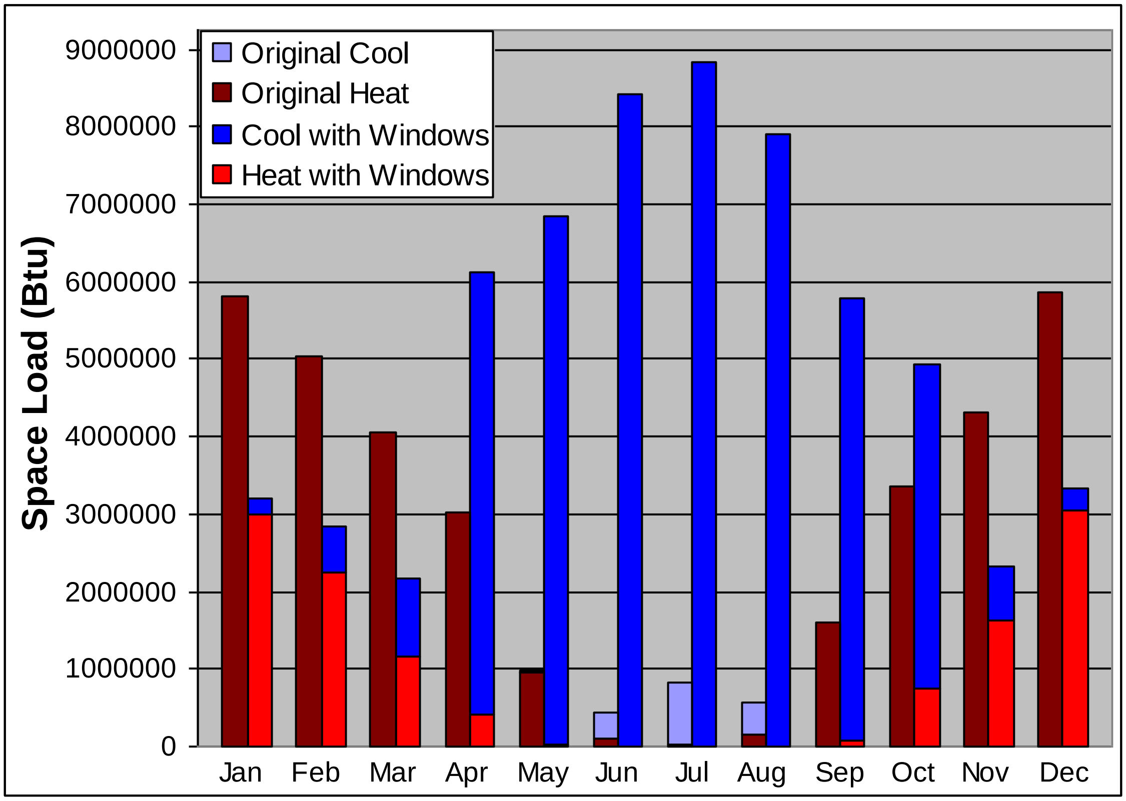

Figure 6.5: Comparison of Heating/Cooling Loads with and without Windows

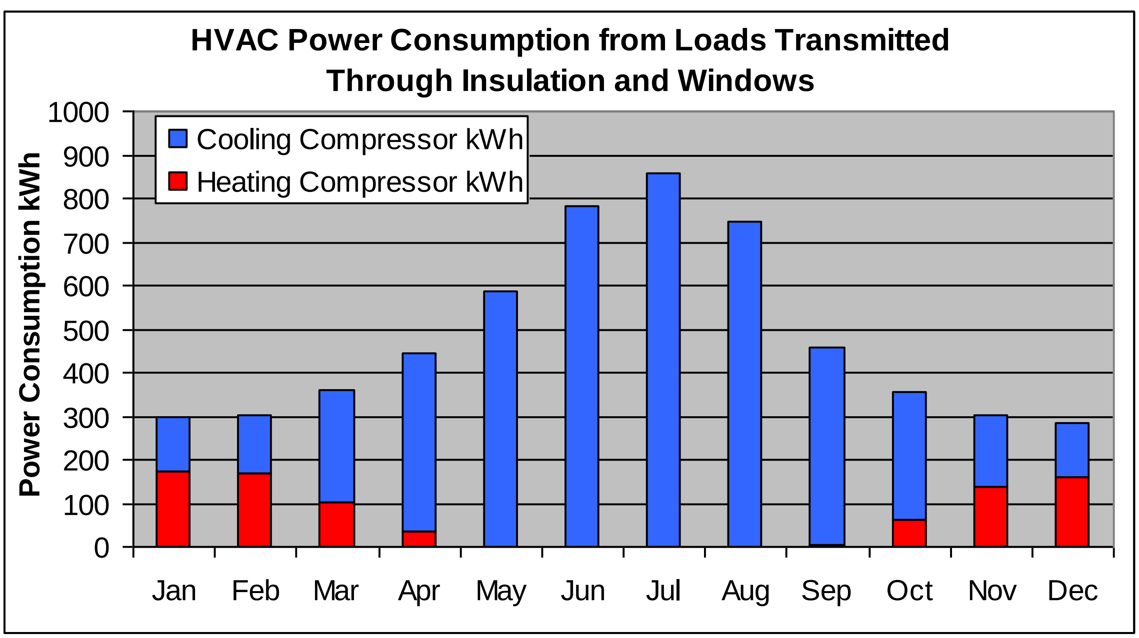

Figure 6.6: Baseline HVAC Power Consumption for Heating/Cooling Loads through Insulation and Windows

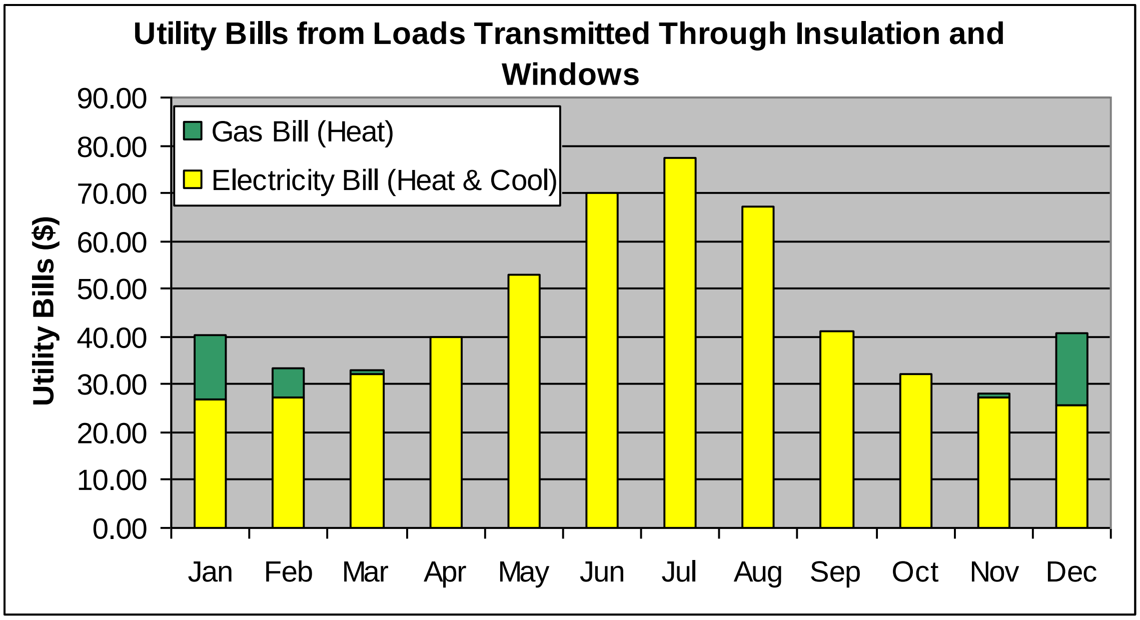

Figure 6.7: Baseline Utility Expenses for Heating/Cooling Loads through Insulation and Windows

As can be seen in previous 3 figures, the advantageous reduced winter heating loads are far out-shadowed by the considerably large induced summer cooling loads in May, June, July, and August. Over a typical year, a home with these characteristics (original insulation properties and current window designs) would consume 839.48 kWh of electricity in heat pump heating mode to meet the added heating loads. This was a reduction of 1,577.83 kWh from the simulation scenario where no windows were installed (insulation alone). This is the passive solar design that builders have utilized for years to reduce winter heating requirements. Likewise, the reduction in natural gas consumption to heat the home in the winter time was reduced 14 Therms from 48.8 to 34.8 Therms with these windows. The introduction of these windows would save the test home $156.66 annually on heating requirements during the winter time. However, over a typical year, a home with these characteristics (original insulation properties and current window designs) would consume 4,934.18 kWh of electricity in heat pump cooling mode to remove the unwanted cooling loads. This was an increase of 4,806 kWh from the simulation scenario where no windows were installed (insulation alone). It is important to remember that some of these summer heating loads will be mitigated by window over-hangs especially those coming from southern facing windows (the majority in this test home). Therefore, the total energy consumed by the home HVAC system to mitigate the heating and cooling loads that are transmitted through the current insulating and window systems is 5,774 kWh and 35 Therms of natural gas. At the current utility rates this would amount to $556.10 in annual utility expenditures. Cooling loads of the scale seen above is why energy efficient window upgrades have become so popular in recent years with homeowners.

6.5 Window Energy Efficient Upgrades

Energy efficient window upgrade simulations in this work were two-fold. First (Test 1), new windows with lower U-factors were chosen to mitigate the conduction-convection heat gains and losses through the windows themselves. Following SeriousWindows™ recommendations, the 725 Series, double pane, low SHG model (one of the top sellers due to price and performance) was chosen as the test home upgrade. According to SeriousWindows™ data, the energy efficient window upgrades will be input into TABLER using the information shown in Table 6.7, and the energy simulations were re-evaluated. The cost to replace windows on a home can vary greatly depending on the contractor, but for these simulations, an estimate of $8,125 to replace the 25 windows on this test home was given (note several tax rebates are available which will cut down on this price).

The second (Test 2) energy efficient simulation for window upgrades was to examine the effectiveness of "after-market" solar coatings that could be applied directly to the current home windows. This obviously will not change the U-factor of the window frames and glass panes, but this method will substantially reduces the implementation cost for upgrading the home windows while still reaping some of the benefits of solar heat gain control. The solar coatings to be examined are the CM40 series coatings from 3M. The performance characteristics of these coatings when applied to a standard, double-paned window (like current windows in this test home) are shown for TABLER input in Table 6.8. Coatings such as these can be applied by the homeowner at little to no installation cost, but 3M recommends using a trained, trusted installer such as the Energy

Control Group in Chattanooga, TN. The cost for covering the 270 ft^2 of home window area will be around $400 through the Energy Control Group.

Table 6.7: SeriousWindows™ Energy Efficient Test Home Window Upgrades Test 1

	Area (ft^2)	U-Factor (Btu/hr*ft^2*°F)	Shade Coefficient
South	200	0.18	0.21
North	35	0.18	0.21
East	17	0.18	0.21
West	18	0.18	0.21

Table 6.8: 3M CM40 Window Coatings Upgrade Test 2

	Area (ft^2)	U-Factor (Btu/hr*ft^2*°F)	Shade Coefficient
South	200	0.67	0.46
North	35	0.67	0.46
East	17	0.67	0.46
West	18	0.67	0.46

6.6. Energy Efficient Window Upgrade Energy Simulation

The heating and cooling loads seen by the conditioned space, the HVAC power requirements to mitigate these loads, and the expected home utility expenses concurrent with these energy requirements will be estimated using the TABLER software for the performance characteristics of each simulation test in the preceding section.

6.6.1 Test 1: SeriousWindowsTM 725 Series Window Upgrades

A comparison of the HVAC power consumption required to mitigate the heating and cooling loads seen inside the test home with the "old," (current) window performance characteristics and the "new," energy efficient window performance characteristics (Test 1) is shown in Figure 6.8. As can be seen in Figure 6.8, the total HVAC power consumption after installing the new, energy efficient SeriousWindows™ only decreased slightly in the winter months (December, January, and February) but the energy savings seen throughout the rest of the year compared to the baseline simulation were significant. With these window upgrades, every month from March to November saw a reduction in cooling loads. Summer cooling loads were reduced nearly 80% in the months of August and May.

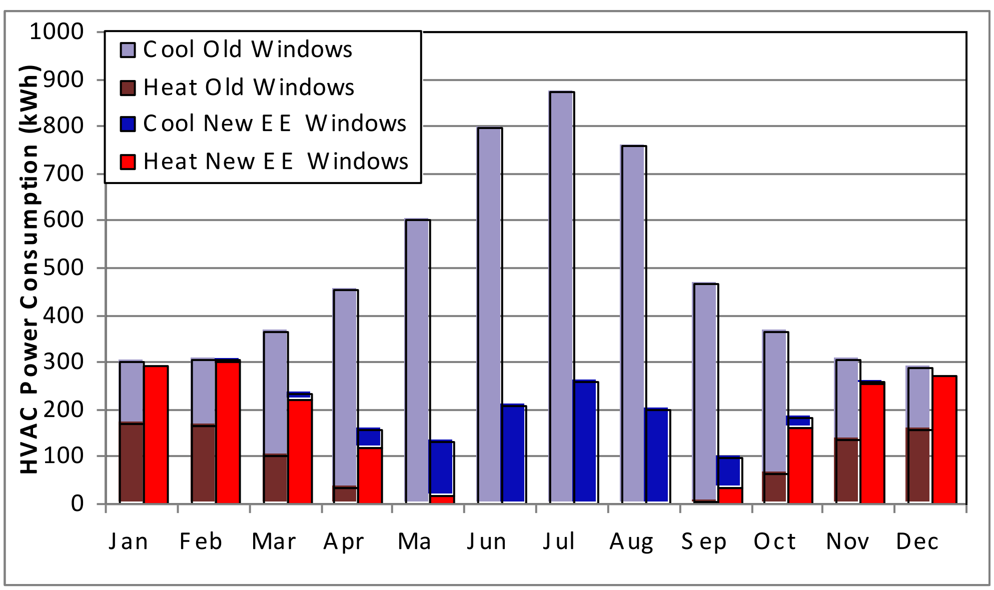

Figure 6.8: HVAC Power Consumption with New, Energy Efficient Windows Compared to Baseline Consumption for Heating/Cooling loads seen through the Windows and Insulation

With the installation of these energy efficient windows, the HVAC power consumption due to heating loads actually increased to nearly 1,674 kWh from the baseline simulation. This is because these new windows have a lower SHGC which allows less solar heat gain in the winter. On the other hand, the HVAC power consumption due to cooling loads decreased nearly 82% down to 925 kWh. This 4,131 kWh reduction in power needs for cooling requirements will more than make up for the 848.58 kWh increase in HVAC heating mode power consumption (plus some extra gas heating during cold winter times). All told, the total annual HVAC power consumption to mitigate the heating and cooling loads seen through the current insulation conditions and new, energy efficient SeriousWindows™ 725 series window upgrades would be 2,600 kWh. This is a 55% reduction (from 5,774 kWh to 2,600 kWh which is a 3,174 kWh reduction) in HVAC power consumption (just from loads attributed to the home's insulation and window structures) over the baseline energy simulation. Also, the energy efficient simulation revealed that 44 Therms of natural gas annually would be required by the HVAC auxiliary heating mode during the winter. This was an increase of 9 Therms over the baseline simulation. The monthly expected utility expenses for mitigating the heating and cooling loads that are transmitted through the insulation and window structures after upgrading the home windows are shown in Figure 6.9.

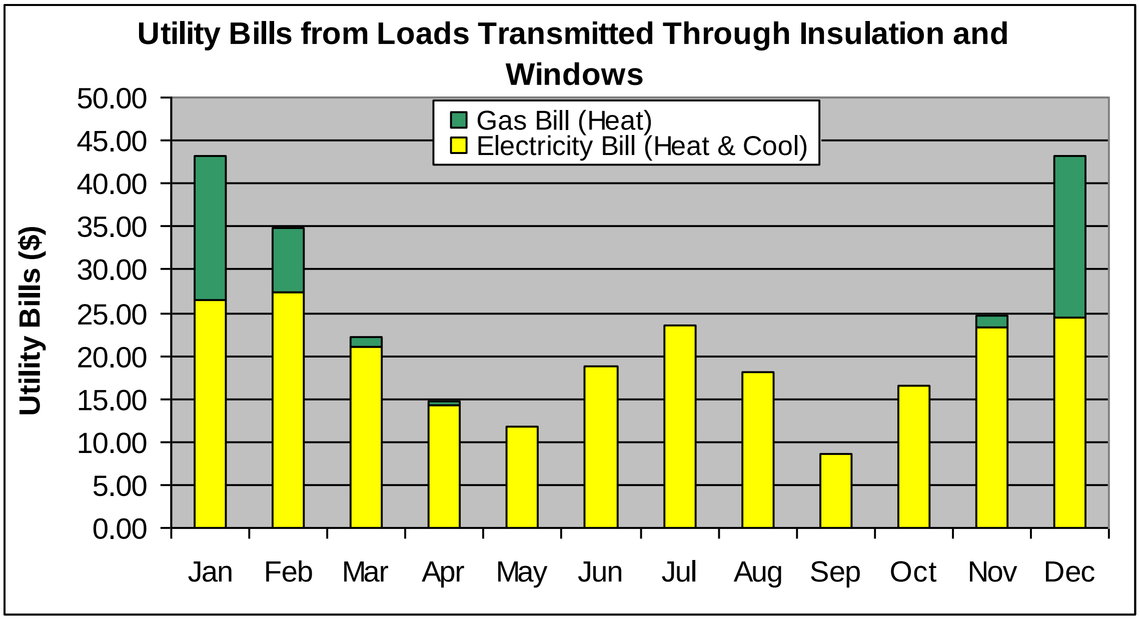

Figure 6.9: Utility Expenses for Heating/Cooling Loads through Insulation and Upgraded Windows

Over the course of a year, this test home would to spend $280.00 for the energy (electricity and natural gas) required to alleviate the heating and cooling loads coming through the insulation and updated window structures. Compared to the baseline (current) window simulation, the home could expect to save $277 annually on the utilities to heat and cool these space loads. Referring back to the $8,125 (less rebates) installation cost to implement these new windows, a payback period of 29.4 years will be seen from these savings simulations. Note that replacing windows have other added energy savings advantages. For example installing new windows and insuring proper size and fit will cut down on infiltrating air (refer back to Chapter 4).

6.6.2 Test 2: 3M CM40 Solar Coatings Applied to Current Test Home Windows

A comparison of the HVAC power consumption required to mitigate the heating and cooling loads seen inside the test home with the “old” (current) window performance characteristics and the “new” window performance characteristics with 3M CM40 solar coatings installed over-top of the original window system (Test 2) is shown in Figure 6.10. As can be seen in Figure 6.10, the total HVAC power consumption after installing the 3M window coatings decreased in every month of the year.

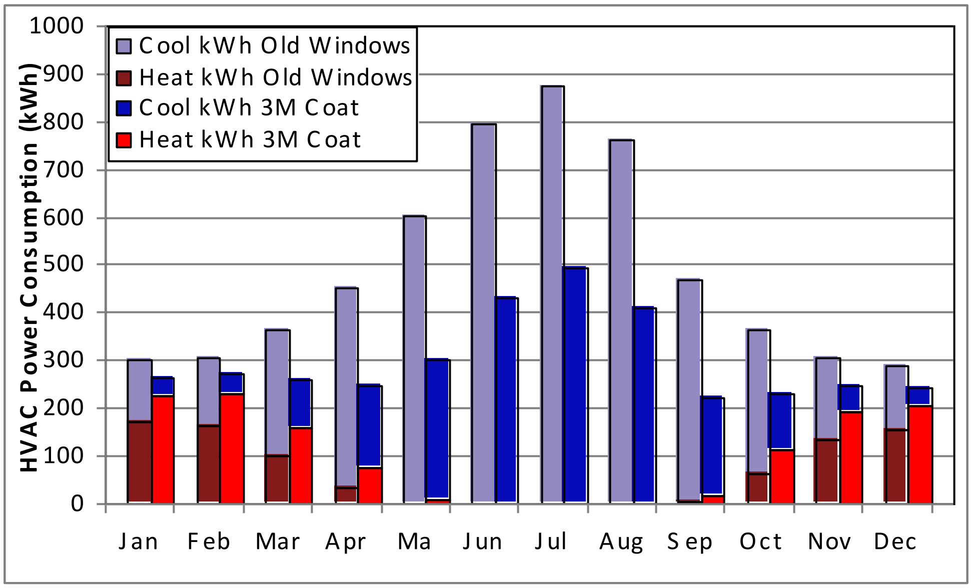

Figure 6.10: HVAC Power Consumption with 3M Solar Coatings Compared to Baseline Consumption for Heating/Cooling loads seen through the Windows and Insulation

The savings seen in the winter time (December, January, and February) were slightly more pronounced than the savings seen from the previous window simulation because the current windows coated with 3M CM40 solar coatings allow more solar heat gain than the complete window replacements in Test 1. Despite the significant decreases in HVAC cooling mode power consumption seen in Figure 6.10, the HVAC cooling mode power consumption in the summer time will be significantly higher than the previous simulation with complete, advanced window replacements.

With the application of the 3M solar coatings to the original windows, the annual HVAC power consumption due to heating loads actually increased nearly 48% to 1,222 kWh from the baseline case. This is because these coated windows have a lower SHGC which allows less solar heat gain in the winter. On the other hand, the annual HVAC power consumption due to cooling loads decreased nearly 52% down to 2,392 kWh. This 2,664 kWh reduction in power needs for cooling requirements will more than make up for the 397 kWh increase in HVAC heating mode power consumption (plus some extra gas heating during cold winter times). All told, the total annual HVAC power consumption to mitigate the heating and cooling loads seen through the current insulation conditions and 3M CM40 coated windows would be 3,614 kWh. This is a

37.4% reduction (from 5,774 kWh to 3,614 kWh which is 2,159 kWh reduction) in HVAC power consumption (just from loads attributed to the home's insulation and window structures) over the baseline energy simulation. Also, the 3M coating simulation revealed that 38 Therms of natural gas annually would be required by the HVAC auxiliary heating mode during the winter. This was only an increase of 4.0 Therms over the baseline simulation. The monthly expected utility expenses for mitigating the heating and cooling loads that are transmitted through the insulation and window structures after coating the home windows is shown in Figure 6.11.

Over the course of a year, this test home would to spend $366 annually for the energy (electricity and natural gas) required to alleviate the heating and cooling loads coming through the insulation and coated windows. Compared to the baseline (current) window simulation, a home could expect to save $191 annually on the utilities to heat and cool these space loads. Referring back to the $400 coating installation cost to implement the solar coating upgrades, a payback period of 2.1 years will be seen from these savings simulations.

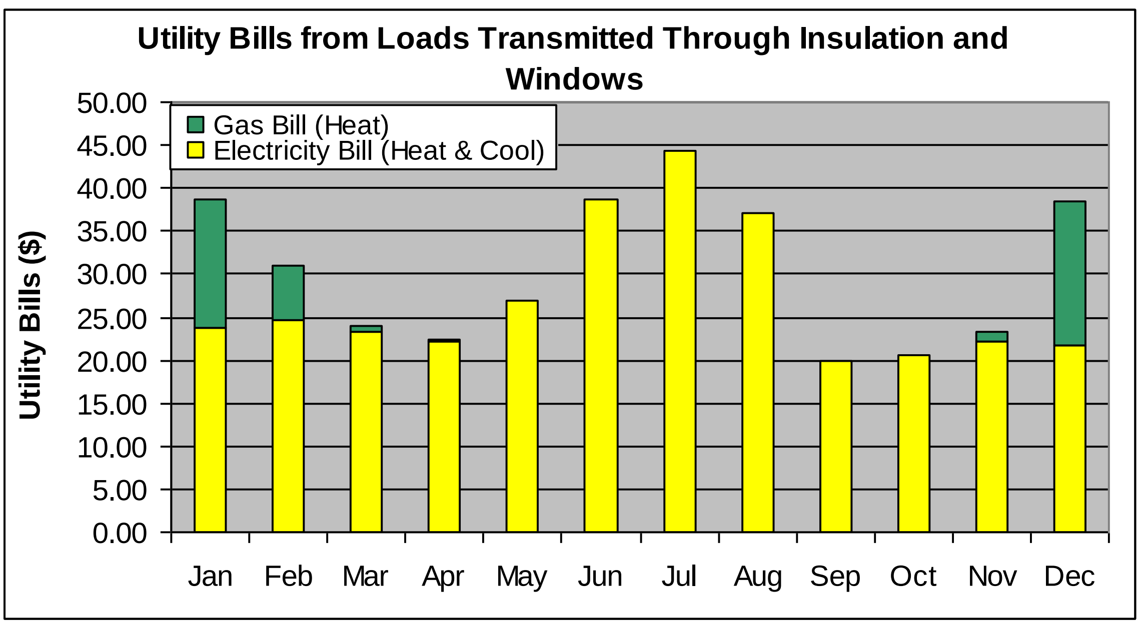

Figure 6.11: Utility Expenses for Heating/Cooling Loads through Insulation and Current Windows with 3M CM40 Solar Coatings

6.7. Brief Remarks on Windows

Using TABLER and window performance characteristics two energy efficient window upgrade simulations were performed and compared to the baseline simulation which represented the test home's current window systems. A review of the simulation results in shown in Table 6.9.

The first simulation was for a complete window replacement study. In this simulation all of the windows in the home were replaced by SeriousWindows™ 725 series energy efficient windows. With these new windows, the total (annual) HVAC power consumption to remove the heating/cooling loads attributed to the windows and insulation (walls and windows) was reduced by 3,174 kWh. The total utility savings (electricity and natural gas) over the course of a year would be $277 when these windows are installed. Despite these savings, the high installation cost ($8,125) of the window replacements revealed a payback on investment of 29.4 years.

The second simulation investigated applying "after-market" 3M CM40 solar coatings onto the current home window systems. These coatings reduced the summer heat gains tremendously, but also reduced some of the positive winter passive solar heating designs of the home. With these new solar coatings, the total (annual) HVAC power consumption to remove the heating/cooling loads attributed to the coated windows and insulation (walls and windows) was reduced 2,159 kWh. The total utility savings (electricity and natural gas) over the course of a year would be $191 when these coatings are applied. The payback on this investment ($400) would be about 2.1 years.

Table 6.9: Review of Advanced Window Simulation Results

	HVAC Power Consumption				
	kWh Heat	kWh Cool	Total kWh	kWh Save	Gas Heat
Baseline (Current) Windows	825.71	5,056.40	5,773.66	\	34.8 Therm
New EE Windows	1,674.29	924.94	2,600	3,173.66	43.5 Therm
3M Solar Coatings	1,222.39	2,392.08	3,614.47	2,159.19	38.4 Therm
	Utility Expense				
	Electricity $	Total $	Save $	Investment Payback	
Baseline (Current) Windows	519.63	556.10	\	\	
New EE Windows	234.00	279.50	276.60	29.4 Years	
3M Solar Coatings	325.30	365.51	190.60	2.1 Years	

A breakdown of the HVAC power consumption into heating and cooling loads for each energy efficient window upgrade (and the baseline simulation) is shown in Figure 6.12. As can be seen from the figure, both upgrades did little to help the winter time heating loads, but both simulations greatly decreased summer cooling loads. The most savings came from the complete energy efficient window upgrades. Figure 6.13 shows the expected total utility expenditures (HVAC electricity and natural gas heating) to mitigate the heating and cooling loads seen through the windows and walls of this test home for each simulation set. Once again, the complete window replacements saved more money on utilities but both upgrades showed utility savings from the baseline simulation.

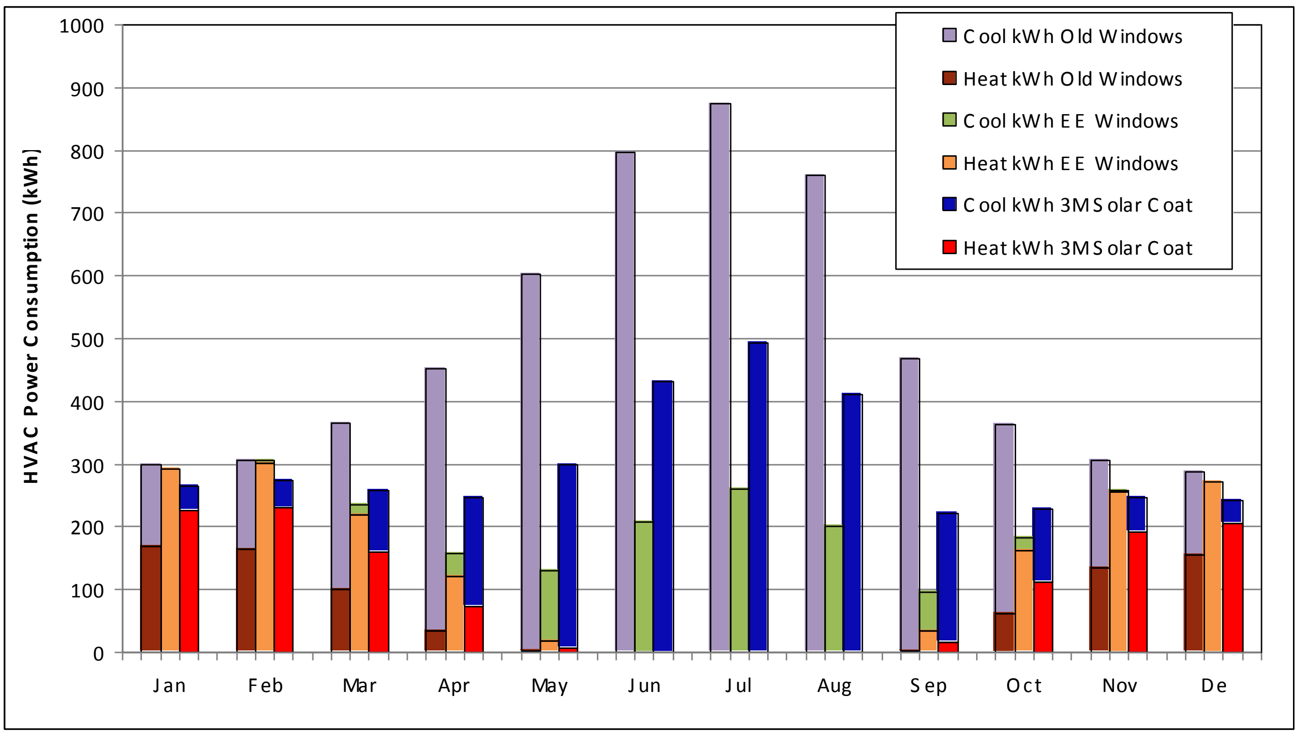

Figure 6.12: Breakdown of the HVAC Power Consumption for the Heating/Cooling Loads Attributed to Heat Gain Through the Windows and Walls

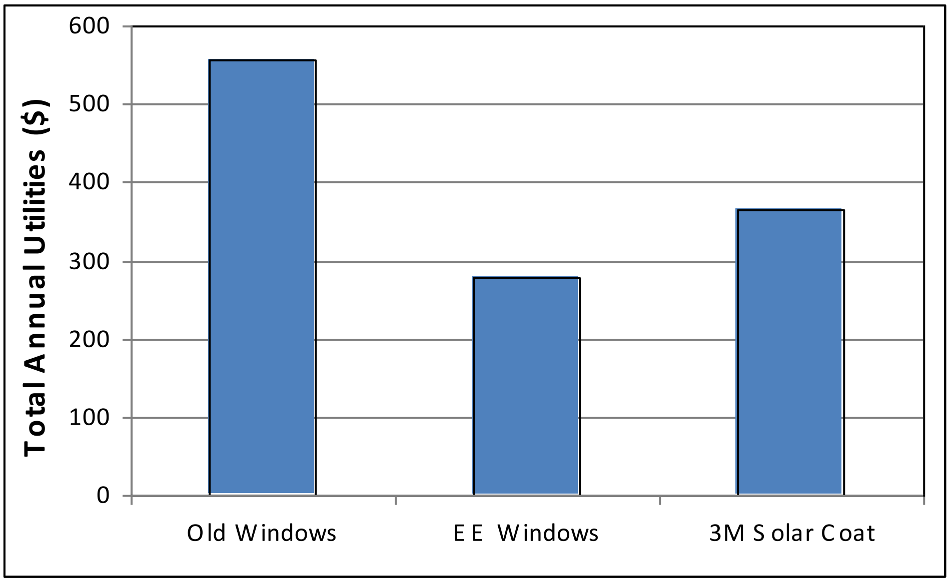

Figure 6.13: Expected Total Annual Utility Expenses to Mitigate the Heating/Cooling Loads Attributed to Heat Gain Through the Windows and Walls

The next generation of advanced windows called "electrochromic" windows are presently under investigation at the National Renewable Energy Laboratory (NREL) in Golden, Colorado. These windows can be darkened or lightened electronically. A small voltage applied to the windows will cause them to darken; while reversing the voltage causes them to lighten. This capability allows for the automatic control of the amount of light and heat that pass through the windows, thereby presenting an opportunity for the windows to be used as active, energy-saving devices. Further research should be made into the application of these windows in residential structures to take advantage of clear window winter heat gain, and dark window solar heat rejection in the summer.

Chapter 7
Plug Loads – Appliances and Electronics

A growing area of energy management research and energy efficiency work is being done to understand the power consumption from electronic devices and residential appliances. According to the 2006 DOE energy end-use study, approximately 23% of all residential energy consumption is used by electronic devices or appliances. Of this, 1% is used for computers, 9% for electronics, 8% for refrigeration, and 5% for cooking by stoves, ovens, microwaves, etc [5]. Energy for these devices represents an increasingly large portion of a building's energy-use "pie" because the number and variety of electrical devices increase constantly with the introduction of the newest television, audio-video, and personal computing models. Most plug loads are not included in ASHRAE 90.1 building standards and are typically not addressed by any building codes [29]. This chapter is dedicated to understanding the energy consumption of common residential electronics and appliances, investigating the potential savings of energy efficient products such as EnergyStar® registered equipment, and discussing new energy management techniques that can mitigate un-wanted (or un-known) electricity consumption.

7.1 Plug Load Basic Concepts and Terminology

When discussing electricity consumption of electronics and appliances researchers have developed a "catch-all" term that describes the overall energy consumption of these devices. A "plug load" (PL) is the energy consumed by any electronic device that is plugged into a building electrical socket. Plug loads are not related to general lighting, heating, ventilation, cooling, and water heating loads, and typically do not provide comfort to the occupants [29]. Many appliances (such as stoves, ranges, and dishwashers) are not actually plugged into an electrical socket but are hardwired directly into the electrical distribution system of the building. The consumption of these devices can still be lumped into the category of plug loads or just referred to as an appliance load. A special division of a building's plug load is called the "vampire" or "phantom" load. A vampire or phantom load is the amount of energy a device consumes when in standby mode or when the device is switched off (de-powered/de-active). When a device is in standby mode or switched off the power being consumed generally serves little to no purpose for the overall mission of the device and can be a waste of electricity. Vampire loads fall into three general categories: electronic controls such as remote controls or electronic power switches, internal/external clocks and other always-on components, and direct-current power supplies for DC devices that have power transformers. Some appliances such as a microwave oven can draw more than one type of phantom load (electronic touch pad always active, internal and display clock illuminated, etc) [30]. Electronic devices such as computers, digital television cable boxes, internet modems, video recorders, cordless phones, and home alarm systems are notorious "vampires" consuming electricity when not in operation. Appliances such as clothes washing machines, clothes dryers, dishwashers, microwaves, and stoves/ovens are not only high energy consumers when in operation, but are also high energy consumers when de-activated. All of these loads (active plug loads and phantom loads) add up over the course of a typical year and account for a significant portion of power consumption.

Mitigating plug and vampire loads is a two-fold process. First, installing newer, energy efficient electronics and appliances such as EnergyStar® products will cut down on plug loads while the device is in operation and in standby mode; however, most of these devices will still draw some power when de-activated or turned off completely (albeit less than current models). Therefore, to fully mitigate phantom loads a power management strategy must be employed to prioritize the distribution of electricity throughout a building to essential devices that truly need power at all times only [29]. For residential buildings, this means cutting the power supplies to devices that are turned off and do not need constant power such as televisions, computers, dishwashers, clothes washers, clothes dryers, etc. This has been accomplished for years by plugging devices into "power strips" which can easily shut off the power supply to each tethered device with the flip of a switch. More recently, separate "branch" home electrical circuits have been incorporated into building designs that allows the power to be cut off to certain areas of the building at the flip of a master switch which may be under the control of some type of occupancy sensor or other automated control measure. Obviously, devices that require constant power such as television recorders (if they are programmed to record at a set time), home alarm systems, alarm clocks, and refrigerators will need to have a constant power supply to assure proper performance and must be on separate electrical circuits from these so called “kill switches.”

7.2 EnergyStar® Products

EnergyStar® is a joint program of the U.S. Environmental Protection Agency (EPA) and the U.S. Department of Energy designed to help consumers save money and protect the environment through the identification of energy efficient products and practices. The program started in 1992 and EnergyStar Results are already evident. In 2009 Americans saved (through EnergyStar® rated devices) enough energy to avoid greenhouse gas emissions equivalent to those from 30 million cars while saving nearly $17 billion on utility bills [31]. The EnergyStar program identifies energy efficient products for both residential and commercial (business) applications ranging from appliances such as refrigerators, washing machines, dishwashers, etc, to computer and electronic equipment, to heating and cooling systems, to lighting, to water heating systems. A brief discussion of what it means to be an EnergyStar® rated product for residential energy consuming devices is presented next.

7.2.1 EnergyStar® Clothes Washer

Clothes washers originally qualified for the EnergyStar label in May, 1997 and the current specifications were set January 1, 2001. Clothes washers that have earned the EnergyStar® rating are 37% more efficient than non-qualified models that simply meet the federal minimum standard for energy efficiency [31]. Only front and top loading clothes washers with capacities greater than 1.6 ft^3 are eligible to earn EnergyStar® ratings. The efficiency of clothes washers are determined based on two factors: the Modified Energy Factor (MEF) and the Water Factor (WF).

The Modified Energy Factor (MEF) is the quotient of the capacity of the clothes container (C) divided by the total clothes washer energy consumption per cycle. The total clothes washer energy consumption per cycle is the sum of the machine electrical energy consumption (M), the hot water energy consumption (E), and the energy required for removal of the remaining moisture in the wash load (D). The higher the MEF value, the more efficient the clothes washer. The MEF has units of ft^3/kWh/cycle. The equation for the MEF is given by:

$$MEF = C / (M + E + D)$$

The Water Factor (WF) is the present water performance metric that allows the comparison of clothes washer water consumption independent of clothes washer capacity. The WF is the quotient of the total per-cycle water consumption (Q) divided by the capacity of the clothes washer (C). The lower the value, the more water efficient the clothes washer. The Water Factor has units of gallons per cycle per cubic foot and is determined by the equation:

$$WF = Q / C$$

Based on the MEF and WF, the requirements for a clothes washing machine to be EnergyStar® rated are shown in Table 7.1.

Table 7.1: Energy Star Requirements for Clothes Washing Machines [31]

ENERGY STAR top and front loading	MEF >= 2.0 WF <= 6.0
Federal Standard top and front loading	MEF >= 1.26 WF <= 9.5

7.2.2 EnergyStar® Dishwasher

Dishwashers originally qualified for the EnergyStar® label in June, 1996 and current model specifications were set August 11, 2009. New, more aggressive federal minimum specifications for dishwashers were recently updated January 1. 2010. Dishwashers that have earned the EnergyStar® rating are 10% more efficient than non-qualified models that simply meet the federal minimum standard [31]. Dishwashers can be separated into two size based categories called "Standard" and "Compact" models. Each size has different EnergyStar® requirements. Dishwasher EnergyStar® qualification is based on specific energy consumption and water consumption levels. The maximum energy consumption is measured in kWh/year and the maximum water consumption is measured in gallons/cycle. The criteria for defining the two size categories for dishwasher models and the EnergyStar® ratings are shown in Table 7.2.

Dishwasher manufacturers must self-test their equipment according to the new DOE test procedure defined in 10 CFR 430, Subpart B, Appendix C. This test procedure establishes a separate test for soil-sensing machines. Included in the final rule was a decision to add standby energy consumption to the annual energy and cost calculation. The average wash cycles per year has been set as 215 cycles per year in the test rules. Therefore, the maximum energy consumption (kWh/year) EnergyStar® criteria seen in Table 7.2 takes into account the energy required for 215 wash cycles per year and the standby power consumption during the rest of the time when the dishwasher is idle.

If the dishwasher operating in a residence was made before 1994 the EPA estimates that the homeowner pays $40 extra each year on utilities than if an EnergyStar® washer was used. Also, a dishwasher built before 1994 wastes more than 10 gallons of water per cycle compared to owning a new EnergyStar® qualified model. If an EnergyStar® dishwasher was used instead the homeowner could save enough water each week to wash 3 loads of laundry in an EnergyStar® qualified clothes washer [31].

Table 7.2: EnergyStar® Specifications for Dishwashers [31]

Equipment	Capacity	EnergyStar	Federal Standards (Jan. 2010)
Standard Size	>= 8 place settings + 6 serving pieces	<= 324 kWh/year <= 5.8 gallons/cycle	<= 355 kWh/year <= 6.5 gallons/cycle
Compact Size	< 8 place settings + 6 serving pieces	<= 234 kWh/year <= 4.0 gallons/cycle	<=260 kWh/year <= 4.5 gallons/cycle

7.2.3 EnergyStar® Refrigerators and Freezers

Refrigerators originally qualified for the EnergyStar label in June, 1996 and current model specifications were set January 1, 2003. Refrigerators that have earned the EnergyStar® rating are 20% more efficient than non-qualified models that simply meet the federal minimum standard [31]. In January, 2003 the EnergyStar® criteria for refrigerators expanded to include all sizes and configurations (based on volume) of refrigerators and freezers. This expansion allowed EnergyStar® qualifications for previously ineligible products like chest freezers, upright freezers, manual defrost freezers and refrigerators, single door refrigerators, and compact refrigerators and freezers. The EnergyStar® qualifications for refrigerators based on model volume are shown in Table 7.3.

The minimum federal standards to which EnergyStar® refrigerators are compared are dictated by the National Appliance Energy Conservation Act (NAECA). The federal standard varies depending on the size (volume), configuration (side-by-side, top freezer, bottom freezer, single door refrigerator and freezer, single door refrigerator only, chest freezer, upright freezer, etc), whether the model has automatic or manual defrost, and whether the model has through-the-door ice and water service. The refrigerator or freezer volume is based on the "Adjusted Volume" (AV) of the device and for refrigerators the AV can be calculated from:

$$AV = (\text{Refrigerator Volume}) + 1.63*(\text{Freezer Volume})$$

Choosing a new, EnergyStar qualified refrigerator rather than a non-qualified model can cut your energy bills by $165 over the lifetime the refrigerator. If a home still has a 1980's era refrigerator, replacing it with an EnergyStar® qualified model can save over $100 each year on utility bills [31].

Table 7.3: EnergyStar® Specifications for Refrigerators and Freezers [31]

Equipment	Volume	Criteria
Full Size Refrigerators	7.75 cubic feet or greater	At least 20% more energy efficient than the minimum federal government standard (NAECA)
Full Size Freezers	7.75 cubic feet or greater	At least 10% more energy efficient than the minimum federal government standard (NAECA)
Compact Refrigerators & Freezers	Less than 7.75 cubic feet and 36 inches or less in height	At least 20% more energy efficient than the minimum federal government standard (NAECA)

7.2.4 EnergyStar® Televisions

Televisions originally qualified for the EnergyStar® Label in 1998. EnergyStar® has ratings for televisions from standard TVs, to HD-ready TVs, to the largest flat-screen plasma TVs. There are two sets of television EnergyStar® specifications, one current specification (version 4.1 effective May, 2010) and one future specification (version 5.1 effective May, 2012). Current EnergyStar® qualified televisions use about 40% less energy than standard units. All EnergyStar® rated televisions must consume 1 watt or less in standby mode but power requirements when the device is powered on vary according to screen area and whether the unit is non-high, high, or full-high definition. Also, external power supplies (EPS) packaged with televisions must meet separate EnergyStar® requirements [31]. EnergyStar® ON power (active) requirements for televisions to be certified as EnergyStar® efficient are shown in Table 7.4 for viewable screen areas in English units. Newer television models have several modes of operation including a Data Acquisition Mode (DAM) where the device communicates with service providers and an Automatic Brightness Control (ABC) feature for even more energy savings. EnergyStar® addresses power consumption for various new television modes and features on their website. Televisions using an external power supply (EPS) must meet the level V performance requirements under the International Efficiency Marking Protocol (IEMP) and be labeled as such on packaging information.

Table 7.4: EnergyStar® Requirements for Televisions Based on Viewable Screen Area [31]

Version 4.1 - May 1, 2010	**Max ON Power in Watts (Area in^2)**
A < 275 square inches A >= 275 square inches	$P_{max} = 0.190 * A + 5$ $P_{max} = 0.120 * A + 25$
Version 5.1 - May 1, 2012	**Max ON Power in Watts (Area in^2)**
A < 275 square inches 275 <= A <= 1068 square inches A > 1068 square inches	$P_{max} = 0.130 * A + 5$ $P_{max} = 0.084 * A + 18$ $P_{max} = 108$

7.2.5 EnergyStar® Computers and Monitors

Computers originally qualified for EnergyStar® ratings in June, 1992. The most recent power supply and power management EnergyStar® requirements for computers became effective July, 2009 (Version 5.0). EnergyStar® Version 5.0 products must meet stringent total energy consumption (TEC) requirements for estimated annual energy consumption. These requirements ensure energy savings when the computers are being used and performing a range of tasks, as well as when they are turned off or into a low power mode. EnergyStar® qualified computers must also have efficient internal or external power supplies. An EnergyStar® qualified computer meeting the newest EnergyStar® specifications will use between 30% and 65% less energy depending on how it is used [31]. How the computer is used refers to “power management” computer settings. EnergyStar® power management features place computers (CPU, hard drive, monitor, etc) into a low-power “sleep mode” after a designated period of inactivity. Simply hitting a key on the keyboard or moving the mouse awakens the computer in a matter of seconds. EnergyStar® power supply and power management requirements for computers are shown in Table 7.5.

Computers are most always accompanied by a monitor to display processed information. Many new television sets break the mold of traditional television design and are considered monitors because the input that is displayed may come from different sources such as a computer. A monitor is defined as a “commercially-available, electronic product with a display screen and its associated electronics encased in a single housing that is capable of displaying output information from a computer or one or more inputs, such as VGA, DVI, and/or IEEE 1394" [31].

Monitors usually rely on a cathode-ray tube (CRT), liquid crystal display (LCD), or other display devices. Monitors can contribute greatly to the power consumption of a desktop computer setup. Like computers, monitors have three basic modes of operation: ON (active) mode where an image is rendered on the display, sleep mode where the power state of the monitor is reduced by displaying a blank screen when the computer is not in operation, and OFF (de-active) mode which is the lowest power consumption mode that is still connected to the electrical source of the building. EnergyStar® requirements for all three modes of operation for monitors are shown in Table 7.6. In this table Y is the power consumption expressed in Watts (rounded up to the nearest whole number) and X is the number of mega-pixels of the monitor display in decimal form.

If all computers sold in the United States met EnergyStar® requirements, the savings in energy costs would be more than $1.5 billion each year, reducing greenhouse gas emissions equivalent to those from 2 million vehicles [31].

Table 7.5: EnergyStar Computer Specifications [31]

Power Supply	**Internal power supplies:** 85% minimum efficiency at 50% of rated output and 82% minimum efficiency at 20% and 100% of rated output, with Power Factor > 0.9 at 100% of rated output for power supplies with >= 75W output or **External power supplies:** either ENERGY STAR qualified or meet the no-load and active mode efficiency levels provided in the ENERGY STAR Program Requirements for Single Voltage External Ac-Ac and Ac-Dc Power Supplies, Version 2.0.
Power Management	**Monitor Sleep Mode:** within 15 minutes of user inactivity **System Sleep Mode:** within 30 minutes of user inactivity **Wake On LAN and Wake Management features** (for some systems)

Table 7.6: EnergyStar Monitor Specifications [31]

	On Mode	Sleep Mode	Off Mode
Tier 1 Maximum Allowable Power Consumption (January 2005):	Y = 38*X + 30	<= 4 watts	<= 2 watts
Tier 2 Maximum Allowable Power Consumption (January 2006):	If X < 1 : Y = 23 If X > 1 : Y = 28*X	<= 2 watts	<= 1 watt

7.3 Test House Plug Loads and Appliance Loads

Electronics and appliances draw some of the most difficult energy loads to estimate for a residential building because the amount of power they require depends so much on knowledge of user preferences and operation. The power consumption of computers, televisions, dishwashers, clothes washing machines, clothes dryers, etc depend not just on the model/electrical efficiency of the device, but also on the amount of time the device is operated which is controlled solely by the occupants operating them. A home that uses an outdoor clothes line to dry clothes draws no power for a clothes dryer, while the clothes dryer in another home could be the top energy consuming appliance or electronic device in that building over the course of a typical year. Since plug and appliance loads can vary so widely, it is best practice to actually measure the amount of power being consumed by various devices inside the particular building of interest to gain an understanding of the typical power consumption. To do this, a P3 International power meter called a "Kill-A-Watt" meter was utilized to measure the power consumption of various electronic and appliance devices in the residential test home. The P3 International power meter fits into a standard 120V electrical outlet and the device being measured plugs into the front of the meter drawing power through the measurement system. The power meter displays the instantaneous power being drawn (Watts), the voltage, amperage, frequency, the time since the device was plugged in, and the total kWh of power consumed during that time frame on a small digital display. For devices that do not draw a constant amount of power such as computers, refrigerators, and washing machines, an average power could be determined by using the total power consumption matched with the time interval of operation when appropriate. For greater understanding of the active and phantom power loads the power meter was used to measure the power consumption of each device during different modes of operation (where applicable) like when the device is in active/ON mode, standby/dormant mode, and powered OFF/de-active mode. The results of these measurements are shown in Table 7.7 for various measureable electronics and appliances.

Table 7.7: Power Measurements of Test House Electronics and Appliances

		In Use		Dormant		Powered Off	
		Power (W)	(kWh/Hr)	Power (W)	(kWh/Hr)	Power (W)	(kWh/Hr)
Desk	°Main Computer	120	0.12	105	0.105	3	0.003
	oCable Modem	9	0.009			9	0.009
	oPrinter	10	0.01	2	0.002	2	0.002
	oCordless Phone	4	0.004				
Upstairs	*Upstairs Computer	112.5	0.1125	89	0.089	6	0.006
	*Laptop Computer	26.1	0.0261	1	0.001	0.574	0.000574
	*Cell Phone Charger	2	0.002	0.714	0.000714		
	oCordless Phone	3	0.003				
	*Alarm Clock	2	0.002				
	*Paper Shredder	140	0.14	0	0	0	0
	*TV (20" Tube)	56	0.056			5	0.005
	oDigital Cable Box	3	0.003				
	*Sowing Machine	90	0.09	0	0	0	0
	*VCR	11	0.011	7	0.007	6.5	0.0065
Living Room	*TV Power Strip	6	0.006	6	0.006	6	0.006
	*TV (56" DLP)	189	0.189	186	0.186	1	0.001
	oDVR	46	0.046	46	0.046	42	0.042
	*DVD	24	0.024	20	0.02	1	0.001
	*Game System	14	0.014	13	0.013	2	0.002
	*Video8 Player	10	0.01	10	0.01	4	0.004
	oCordless Phone	3	0.003				
	*Elliptical Machine	7	0.007			0	0
Kitchen	oRefrigerator	112.4	0.117				
	*Mixer	35	0.035			0	0
	*Microwave	2000	2			2	0.002
	*Washing Machine	368.18	0.3681			0	0
Bed	*TV (32” LCD)	46	0.046			1	0.001
	oDigital Cable Box	3	0.003				
	oAlarm Clock	2	0.002				
	oAlarm System	15	0.015				

°Device Stays Turned ON at all Time. *Device Stays Plugged in but Turns OFF at times.

Several high-use appliances such as the stove/oven, dishwasher, and clothes dryer could not be measured by this power meter because they were either hard-wired into the home electrical system or the voltage/wattage was too high for this meter to measure.

As can be seen from the power measurements in Table 7.7, the top energy consumers during operation (average power) are the microwave (2000+ W), clothes washing machine (368 W), living room television (189 W), refrigerator (112.4 W), and personal computers 120W and 112.5W). Typically, the greatest energy consuming devices in a residential building are the large appliances like the refrigerator, clothes washing machine, clothes dryer, stove/oven, and dishwasher. As mentioned previously certain large appliances could not be measured and the energy consumption of these devices will be estimated from research literature later in this chapter.

As can be seen from the power measurements, the top energy consumers while the device were in the standby/dormant operational mode are the two computers (105 W and 89 W) and living room television (186 W). The top energy consumers while the device were in the OFF/de-active operational mode (still plugged in) are the cable modem (9 W), computer (6 W), VCR (6.5 W), and DVR (42 W) (Digital Video Recorder which is also the digital cable box for the main television set).

With the power consumption in each operational mode for each device known, annual power consumption estimations can be made based on the approximate hours each device will be in each operation mode for a given year. This estimation is simple for devices that stay ON or OFF all the time, but can be more difficult for devices that change from one operational mode to the next frequently. The rate of power consumption (kWh/hr), estimated hours of operation for each mode in a given year, calculated annual energy consumption, and calculated annual electricity expenditure (using a rate of $0.09/kWh) for each device is shown in Table 7.8. At the bottom of the "Total Annual" table columns are the summed annual totals for all of the measured electronics for a typical year. From these results, over 3,828 kWh of electricity will be consumed by these measured electronic devices over the course of a typical year. This would correspond to an expenditure of about $345. The main consumers were determined to be the computer (946 kWh), living room television (558 kWh), and refrigerator (1,024 kWh). The power consumption of the refrigerator is an extremely low estimation and the reason for this will be discussed in a later section of this chapter.

Table 7.8: Total Annual Power Consumption and Expenditure Estimation

	In Use		**Dormant**		**Power OFF**		Total Annual	Total Annual
	(kWh/Hr)	Hrs	(kWh/Hr)	Hrs	(kWh/Hr)	Hrs	kWh/yr	$/yr
Main Computer	0.12	4200	0.105	4200	0.003	360	946.08	85.15
Cable Modem	0.009	8760			0.009	0	78.84	7.10
Printer	0.01	5	0.002	8400	0.002	355	17.56	1.58
Cordless Phone	0.004	8760					35.04	3.15
Upstairs Computer	0.1125	12	0.089	10	0.006	8738	54.67	4.92
Laptop	0.0261	120	0.001	120	0.00057	8520	8.14	0.73
Cell Phone Charger	0.002	2920	0.00071	5840			10.01	0.90
Cordless Phone	0.003	8760					26.28	2.37
Alarm Clock	0.002	8760					17.52	1.58
Paper Shredder	0.14	1	0	0	0	0	0.14	0.01
TV (20" Tube)	0.056	730			0.005	8030	81.03	7.29
Digital Cable Box	0.003	8760					26.28	2.37
Sowing Machine	0.09	5	0	0	0	8755	0.45	0.04
VCR	0.011	0	0.007	0	0.0065	8760	56.94	5.12
TV Power Strip	0.006	8760	0.006	0	0.006	0	52.56	4.73
TV (56" DLP)	0.189	2920	0.186	5	0.001	5835	558.65	50.28
DVR	0.046	2920	0.046	580	0.042	5260	381.92	34.37
DVD	0.024	24	0.02	5	0.001	8731	9.41	0.85
Game System	0.014	5	0.013	1	0.002	8754	17.59	1.58
Video8 Player	0.01	0	0.01	0	0.004	8760	35.04	3.15
Cordless Phone	0.003	8760					26.28	2.37
Elliptical Machine	0.007	12			0	8748	0.08	0.01
Refrigerator	0.117	8760					1024.92	92.24
Mixer	0.035	48			0	8712	1.68	0.15
Microwave	2	17			0.002	8743	51.49	4.63
Washing Machine	0.3681	300			0	8560	110.43	9.94
TV	0.046	365			0.001	7495	24.29	2.19
Digital Cable Box	0.003	8760					26.28	2.37
Alarm Clock	0.002	8760					17.52	1.58
Alarm System	0.015	8760					131.40	11.83
							3,828.51	**344.57**

The total annual power consumption (kWh/yr) and total annual electricity expenditure ($/yr) values for each electronic device/appliance in Table 7.8 are the total values for all modes of operation (on, standby, and off). For a greater understanding of the possible phantom (vampire) power loads associated with these electronic devices a breakdown of the standby and OFF/de-active power consumption and the utility expense associated with that power consumption are shown in Table 7.9. These values are part of the total values seen in the previous table (Table 7.8). The standby consumption of each device is power that is being consumed when the device is not in operation but is still powered on (like the "screen saver" computer mode, or the cellular phone charger that is plugged in with no phone attached, or the video recorder sitting powered on, etc). The OFF/de-active consumption of each device is the power that is being consumed when the device is turned off completely but still plugged in (like a shutdown computer or powered off television).

As can be seen from Table 7.9 the total vampire load from these measured electronics was estimated to be 960 kWh annually which would cost the home owner about $86 each year. Not all of this total vampire load could have been prevented. Devices will change into standby mode when users leave them idle for too long. This does not mean the user wanted to necessarily shutdown the device just that something else took priority for the time being. It is not reasonable to cut the power to devices just because they enter into standby mode, but certainly some of the standby power consumption can be mitigated using a proper power management system. Most of the time electronics are left on for long periods of time (like overnight) and enter into standby mode for long periods of time. Learning to turn these devices off when they will sit for long periods of time will cut down greatly on the standby power consumption. According to Table 7.9 over 491 kWh annually of power is consumed by devices sitting in standby operational mode. This would correspond to $44 each year. The major standby power consumers are the computer (441 kWh), DVR (26.68 kWh), and printer (16.8 kWh). The computer is one example where standby power consumption can be significantly reduced by following a power management procedure. Easily over half of the computer standby energy consumption (220+ kWh) is because the computer is left on overnight instead of shutting down the system. This wasted power would be saved.

Table 7.9: Annual Vampire Electronic Loads Broken Down into Standby and OFF Modes

		Standby kWh/Yr	Standby $/Yr	OFF kWh/Yr	OFF $/Yr	Total Vampire kWh/Yr	Total Vampire $/Yr
Desk	Main Computer	441.00	39.69	1.08	0.10	442.08	39.79
	Cable Modem	0.00	0.00	0.00	0.00	0.00	0.00
	Printer	16.80	1.51	0.71	0.06	17.51	1.58
	Cordless Phone	0.00	0.00	0.00	0.00	0.00	0.00
Upstairs	Upstairs Computer	0.89	0.08	52.43	4.72	53.32	4.80
	Laptop	0.12	0.01	4.89	0.44	5.01	0.45
	Cell Phone Charger	4.17	0.38	0.00	0.00	4.17	0.38
	Cordless Phone	0.00	0.00	0.00	0.00	0.00	0.00
	Alarm Clock	0.00	0.00	0.00	0.00	0.00	0.00
	Paper Shredder	0.00	0.00	0.00	0.00	0.00	0.00
	TV (20" Tube)	0.00	0.00	40.15	3.61	40.15	3.61
	Digital Cable Box	0.00	0.00	0.00	0.00	0.00	0.00
	Sowing Machine	0.00	0.00	0.00	0.00	0.00	0.00
	VCR	0.00	0.00	56.94	5.12	56.94	5.12
Living Room	TV Power Strip	0.00	0.00	0.00	0.00	0.00	0.00
	TV (56" DLP)	0.93	0.08	5.84	0.53	6.77	0.61
	DVR	26.68	2.40	220.92	19.88	247.60	22.28
	DVD	0.10	0.01	8.73	0.79	8.83	0.79
	Game System	0.01	0.00	17.51	1.58	17.52	1.58
	Video8 Player	0.00	0.00	35.04	3.15	35.04	3.15
	Cordless Phone	0.00	0.00	0.00	0.00	0.00	0.00
	Elliptical Machine	0.00	0.00	0.00	0.00	0.00	0.00
Kitchen	Refrigerator	0.00	0.00	0.00	0.00	0.00	0.00
	Mixer	0.00	0.00	0.00	0.00	0.00	0.00
	Microwave	0.00	0.00	17.49	1.57	17.49	1.57
	Washing Machine	0.00	0.00	0.00	0.00	0.00	0.00
Bed	TV	0.00	0.00	7.50	0.67	7.50	0.67
	Digital Cable Box	0.00	0.00	0.00	0.00	0.00	0.00
	Alarm Clock	0.00	0.00	0.00	0.00	0.00	0.00
	Alarm System	0.00	0.00	0.00	0.00	0.00	0.00
		490.70	44.16	469.21	42.23	**959.92**	**86.39**

On the other hand, the power consumption by these electronic devices that occurs when the devices are powered off could completely be avoided all together. The power consumed by these electronic devices when they are turned off still totaled 469 kWh annually which would cost the home owner

each year. Cutting the power supply to each device (master kill-switch or power strip) once they are already turned off could potentially save all of this power.

As can be gathered from these results, major energy savings can be seen in home plug loads if proper power management procedures and smart electronic setup procedures are used. Connecting all the electronics that do not constantly need power to master power strips, cutting the power when these devices are powered off, and shutting devices down instead of letting them run in standby mode could realistically save around 644.18 kWh of power consumption each year (that is to save ~50% of standby power and ~85% of OFF power consumption). This would correspond to about 3.5% of the current home average annual electricity consumption and would save about $58 annually. These savings would require little to no upfront investment like other energy efficient upgrades and do not take into account replacing any appliance or electronics.

7.4 Major Appliances

Major appliances such as refrigerators, dishwashers, clothes washers, clothes dryers, and cooking appliance like the stove/oven can account for a significant portion of residential power consumption (or energy consumption in terms of electricity and natural gas appliances combined together). Some of these major power consuming appliances were briefly discussed in the preceding sections of this chapter, but several chief appliances could not be measured using the P3 International power meter. Therefore, a closer look at these major consuming appliances is warranted.

7.4.1 Refrigerator

As mentioned previously, according to the 2006 DOE energy end-use study, 8% of a residential building's total energy consumption was used for refrigeration purposes. This test home operates a 1998 Whirlpool (Maytag) MSD2756AEW side by side, 2-door, 26.5 ft^3, refrigerator-freezer combination machine. The power consumption of this home's refrigerator was listed in the power consumption measurements shown in Table 7.8 as 0.117 kWh/Hr. This was determined from power measurements made over a 24 hour period (March 14th 2011) which showed the refrigerator consumed a total of 2.81 kWh of electricity. Since the refrigerator operates 24 hours a day for the entire year (8,760 hours), the annual total energy consumption was determined to be 1,024.92 kWh which would cost the home owner about $92.24 each year. The validity of this estimation will be discussed momentarily. The maximum amperage was listed as 7.2 Amps and the voltage was listed as 115 Volts on the interior of the refrigerator door. Multiplying these two values gives a possible max power usage of 828 Watts, but during normal operation power readings did not reach this maximum value. When in standard operation, this refrigerator cycles between a "cooling" and "dormant" phase. During the cooling phase the refrigerator is removing heat from inside the refrigeration compartment and the power fluctuates between 185 Watts and 160 Watts. The length of the cooling phase depends on factors such was how much warm air entered the cooling space in the previous few minutes. The cooling cycle ranged anywhere from 35 to 10 minutes over the 24 hours of observation. The refrigerator dormant phase showed little power fluctuation drawing a constant 2 Watts of power between cooling cycles. The refrigerator was also consuming different amounts of power to perform tasks such as indoor lighting when the doors were open and ice/water dispensing through the door. The average power being drawn by the refrigerator over the 24 hours of observation was determined to be 112 Watts based on hourly power measurements. The average measured hourly power being drawn by the refrigerator over the 24 hour measurement period is shown in Figure 7.1 and the total power consumption (kWh) of the refrigerator for that same time period is shown in Figure 7.2. Figure 7.1 shows the fluctuation of power during each hourly measurement of the refrigerator. The data points in this figure are the average instantaneous powers being drawn over the time interval (1 hour). The figure shows a large increase in the power requirement immediately following high use times such as 8:00am – 10:00am (breakfast) and 7:00pn – 9:00pm (dinner). According to Figure 7.2

despite these "short-lived" power increases, the rate of total energy consumption does not vary much over the course of the day.

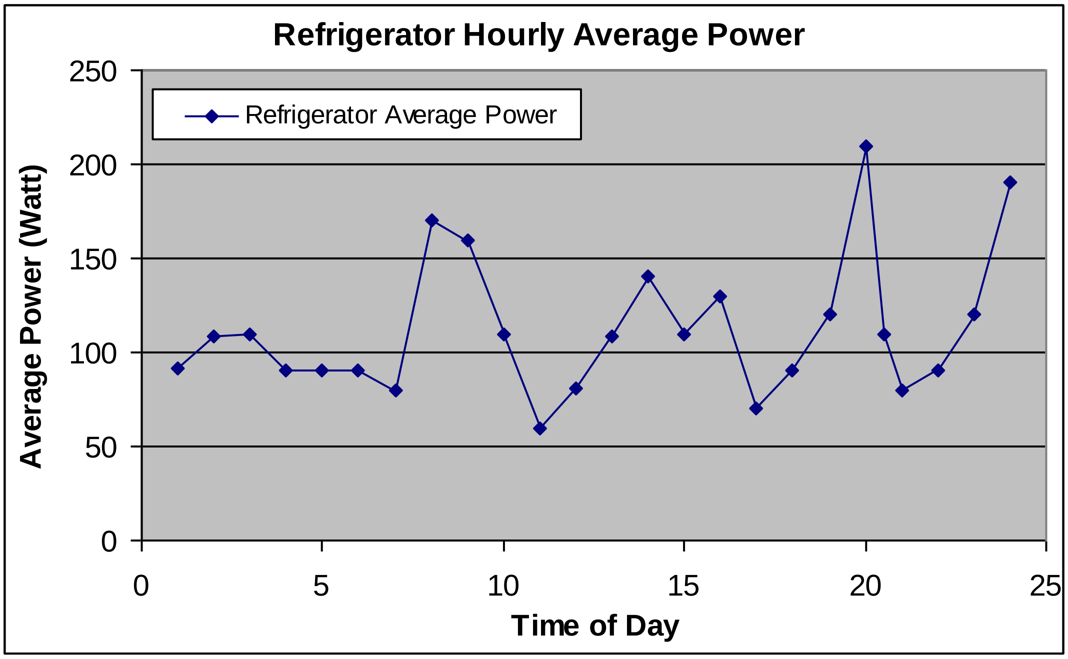

Figure 7.1: Average Measured Hourly 26.5 ft^3 Refrigerator Power Usage

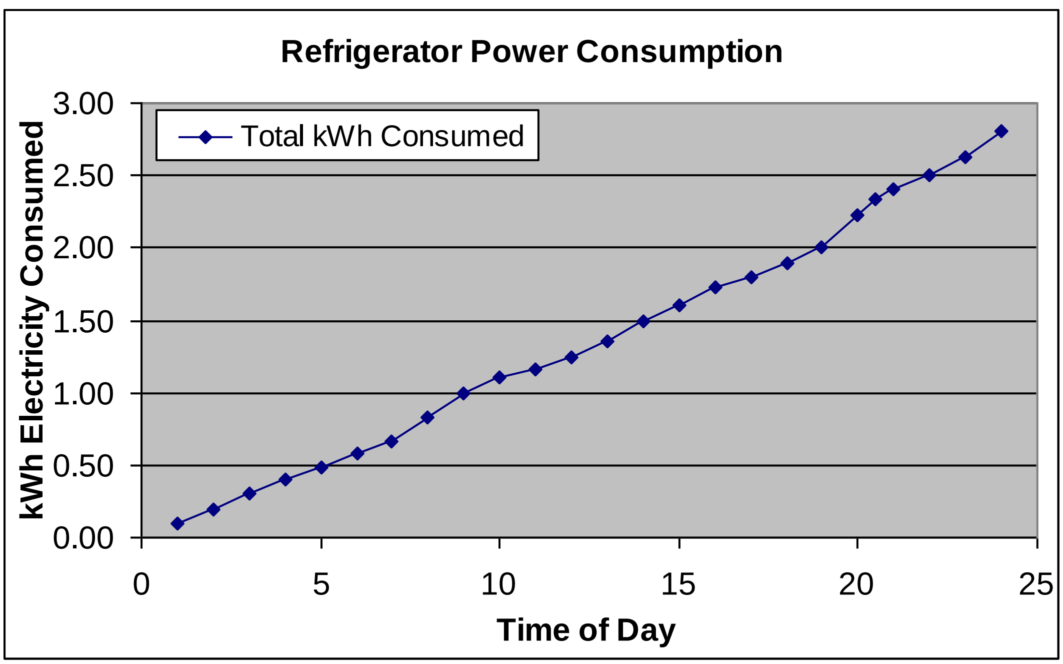

Figure 7.2: Measured Refrigerator Power Consumption

The total annual power consumption value (estimated in Table 7.8 as 1,024.92 kWh a year) is a low estimation of the annual refrigerator energy use. This is because the power requirements of a refrigerator are not constant throughout a typical year. According to the "Geoexchange Project" the energy consumption of a residential refrigerator is much greater in the warm summer months than in the cold and moderate winter, spring, and fall months because the warm air that infiltrates the refrigeration space is warmer in the summer months [33]. This was determined during a similar measurement procedure using a simple power meter to determine the energy savings associated with the installation of a new, energy efficient refrigerator at the Geoexchange project site. The results of this study are shown below in Figure 7.3. Ignoring the difference between the new and old refrigerators, the trend shows a large increase in power consumption (kWh) from June to August. The exact data values were not given for this figure, but just by reading the plot, the power consumption in July is about 55% higher than the power consumption in March. March 14th is when the power measurements were made for this test house refrigerator. It is difficult to quantifiably determine the expected increase in power consumption of the test home's refrigerator that would occur during the summer time, but the trend is clear, the annual refrigerator power consumption will be much greater than the estimated value seen in the above tables.

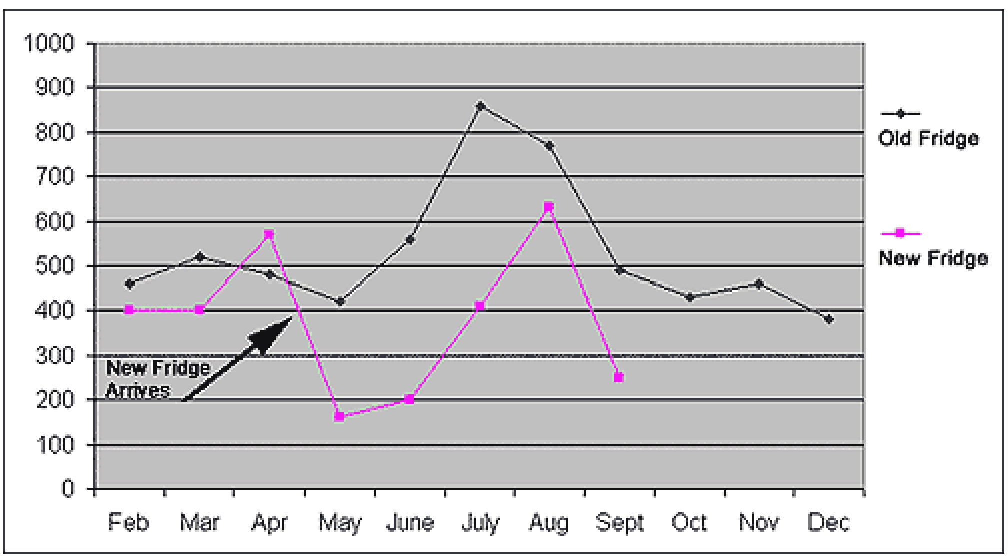

Figure 7.3: Geoexchange Graph of Power Consumption (kWh) Old and New Refrigerator [33]

Using an online calculator provided by EnergyStar®, the annual power consumption of a 1998, side-by-side, 25+ cubic foot, comparable refrigerator was estimated to be 1,252 kWh. This is a 227.08 kWh increase from the estimation made from the March 14th measurements. This increase seems very reasonable following the trend seen in the Geoexchange Project results figure. The EnergyStar® online calculator also provides a comparison for a new, energy efficient refrigerator of comparable size. According to the calculator, a comparable EnergyStar® refrigerator would only consume around 600 kWh a year, which is an annual reduction of 652 kWh (47.9%) to the current model. This would save the home owner around $59 a year (annual payment drops from $112 to $54) in electricity expenditures. The cost for an EnergyStar® refrigerator of comparable size and features at local distributors ranges from $700 – $2,000. This would give a simple payback period based on energy savings alone from 11 – 33 years.

7.4.2 Clothes Dryer

A clothes dryer can account for a staggering 12% of electricity use in a typical household [32]. Most dryers are connected to a 240 volt electrical outlet and tend to be the largest power drawing appliances in a home. This test home operates a Kenmore 4392065 electric clothes dryer. Since the dryer uses a 240 volt outlet the P3 International power meter could not be used to measure actual power consumption. According to the online source "Mr. Electricity," a typical electric clothes dryer operates for about 45 minutes per load of clothes and consumes approximately 3.3 kWh of electricity for that single load [32]. Consulting the home owners, it was determined that this home operates the dryer for about 7 cycles per week or 364 loads per year. That equates to around 1,201 kWh ($108 at the typical $0.09/kWh rate) of power annually for clothes drying alone.

Unfortunately, "EnergyStar® does not label clothes dryers because most dryers use similar amounts of energy, which means there is little difference in the energy use between models" [31]. Despite the fact that there are no significantly "energy efficient" dryer models, a home owner can still see energy savings in this area. EnergyStar® and other resources provide several steps/procedures for conserving energy when it comes to drying clothes. The following are 5 of the most common ways to conserve power when it comes to drying clothes.

(1) Use other drying techniques besides the dryer. The simple fact is that mechanical clothes dryers simply are not necessary. Clothes can be dried by hanging them up either inside the home or outside on a clothes line. This idea may seem old fashioned, but it is gaining popularity around the world and even in the United States. According to a 2009 Pew Research study “fewer people believe that clothes dryers are a necessity vs. a few years ago.” TipthePlanet.com has a large collection of resources pertaining to clothes drying techniques including clever products like the retractable clothes line. The best part about hanging clothes up to air-dry is that 100% of the energy consumption from the mechanical clothes dryer is conserved (~1200 kWh) [31].

(2) If the home already has natural gas service and natural gas is cheaper than electricity in the area, then a gas clothes dryer could possibly save money. “Mr. Electricity” reports that a gas dryer would consume 0.22 Therms of natural gas and 0.21 kWh of electricity (to spin the dryer drum) per load of clothes. With a local average utility rate of $1.058/Therm and $0.09/kWh the cost to dry one load of clothes with this gay dryer would come to $0.25 as compared to $0.30 for the all electric (3.3 kWh electricity) dryer. Of course these values are contingent on local utility rates but according to these numbers there is some potential savings available with natural gas dryers. Whether or not you save any money by switching to a gas dryer, energy will be saved. Power plants are only about 37% - 44% efficient at turning coal or other fuels into electricity while gas dryers are far more efficient at turning natural gas into the desired drying output. Therefore, overall energy is conserved by not have to first convert a fuel into electricity at a power plant and then utilizing that electricity to produce a drying output at a residential home [32].

(3) When replacing a clothes dryer, be sure to choose a new model that has a moisture sensor. A moisture sensor shuts off the dryer automatically when the clothes are dry. This prevents the dryer from running longer than necessary and wasting energy. According to the California Energy Commission, moisture sensors cut dryer energy use

by about 15%. A temperature sensor works almost as well as a moisture sensor and has been reported to cut energy use by about 10% [32].

(4) Using an energy efficient, front-load washing machine will reduce dryer energy consumption. Front-load clothes washers tend to leave about 7% less water in the clothes load than top-load, older washers. The less moisture left in the clothes will cut down the drying times and energy consumption of the dryer [31].

(5) Using a spin dryer will also reduce the energy consumption of a clothes dryer. A spin dryer is a separate machine that removes excess moisture from the newly washed clothes by spinning the clothes at a high rate of speed before the clothes are placed in the dryer. The spin dryer does not add heat to the clothes and consumes far less energy than the clothes dryer would [32].

7.4.3 Dishwasher

The test home dishwasher is hard-wired directly into the home's electricity system and therefore could not be measured using the P3 International power meter. The home operates a Whirlpool 940 Series "Quiet Wash Plus" dishwasher from 1995. The dishwasher specifications show the machine uses 6.7 amps for heating and 5.3 amps for the motor which totals 11 amps. At 120 Volts, that equates to 1,320 watts when the heater and motor are running simultaneously during the wash cycle. At certain times during the wash cycle only the heater will be running (drying time) and at others times only the motor will be operating to move the cleaning water around the machine (rinse time). Various resources have reported a typical dish washer from this time frame uses about 1,200 Watts on average during the entire wash cycle (about 60 minutes) [32]. Therefore, if a home operates the dishwasher for 18 wash cycles per month (equates to 216 wash cycles per year which is the EnergyStar® testing standard), the dishwasher would consume around 22 kWh per month or 264 kWh per year ($23.76 annually). Therefore, the current home dishwasher falls below the EnergyStar rating standard of <= 324 kWh/year (note: Dishwasher EnergyStar maximum power consumption values also take into account the standby power when the machine is not in operation and no calculation for the current models' standby or "phantom" load could be made). Also, EnergyStar® ratings take into account water usage per wash cycle and no information on the current dishwasher water usage could be found.

Energy efficient dishwashers that do not have heating cycles (no water heating or heated drying cycles) consume considerably less energy. These machines consume about 200 Watts during operation (43.2 kWh annual consumption). EnergyStar® dishwashers that have the same standard heating functions as traditional dishwashers can be expected to consume a similar amount of power as the current home dishwasher (assuming the standby power of the current model is not outrageous), and any real savings would have to be realized with the water saving abilities of EnergyStar® qualified model.

7.4.4 Cooking Appliances (Stove / Oven)

This test home operates a Sears Roper Nouvelle stove top range and oven combination as the primary cooking appliance. The machine is hardwired directly to the home so no power measurements could be made. According to "Mr. Electricity" electric ovens have baking elements of 2,000 Watts to 3,500 Watts with a maximum temperature of 500 degrees (Fahrenheit); however, different oven models should use approximately the same amount of energy to reach and maintain a particular temperature setting. Whether the oven is at the higher wattage rating or the lower wattage rating it is rare for the baking heating element to run continuously at the full power capacity. Generally, the heating element either runs at a lower power level or shuts off completely for a few minutes at a time to maintain a particular temperature. "The best estimate for an electric oven set to 350˚F is 2.0 kWh per hour" [32]. For comparisons sake, Table 7.10 shows a comparison of energy consumption and utility cost for various cooking methods found in a residential building. If the test home were to operate the oven for one hour, twice weekly (104 hours) the oven would consume approximately 208 kWh of electricity on cooking.

Table 7.10: Cooking Methods and Power Consumption / Cost [32]

	Temperature (˚F)	Time	Energy Used	Cost*
Electric Oven	350	1 hr.	2.0 kWh	$0.18
Gas Oven (electric ignition)	350	1 hr.	0.115 therm + 0.35 kWh	$0.15
Gas Oven (pilot)	350	1 hr.	0.112 therm	$0.12
Electric Oven Convection	325	45 min.	1.39 kWh	$0.13
Toaster Oven	350	1 hr.	0.33 kWh	$0.03
Crock-Pot	200	7 hr.	0.70 kWh	$0.06
Microwave Oven	High	15 min.	0.36 kWh	$0.03

*Utility Rates: $1.058/therm gas and $0.09/kWh electricity

Much debate has occurred through the years on whether it is more efficient to use cooking appliances that utilize electricity versus cooking appliance that operate on natural gas. EnergyStar® does not label cooking appliances such as stoves or ovens, but a quick breakdown of a natural gas and electric range/oven combination appliance is shown in Table 7.11. The utility values in the table do not match the local values used in previous calculations in this report, but the overall point will remain the same. Natural gas cooking appliances are less expensive on fuel costs when using just the stove top burners (range), but are more expensive when the appliance is used just as a traditional oven. When deciding the proper cooking appliance for a home the type of cooking most used (oven or stove top) and overall conservation goals of the home must be identified.

Table 7.11: Electric vs. Gas Cooking Appliances [32]

	Gas	**Electric**
Model	Kenmore 30" #73052	Kenmore 30" #93052
Price	$350	$360
Avg. Fuel Prices*	0.00147 ¢/Btu ($1.47/therm)	12 ¢/kWh
Burner		
Energy Use (1 hr.)	9,000 Btu	2,500 watt-hours
Yearly Cost (2 burners x 10 mins./day ea.)	**$16.11**	**$36.53**
Oven		
Energy Use (1 hr.)	18,00 Btu + 350 watt-hours	2,000 watt-hours
Yearly Cost (2 hours/week)	**$31.89**	**$24.96**
Burner + Oven		
Total Yearly Cost	**$48.00**	**$61.49**

*Prices from Sears.com in July 2006. Fuel rates are U.S. national averages in August 2009

7.5 Brief Remarks on Plug Loads

Investigation of the test home's electronic and appliance energy consumption was a two part process. First, plug load consumption measurements were conducted using a P3 International "Kill-a-Watt" power meter on electronics and select appliances (refrigerator and clothes washer) that were connected directly to electrical outlets. These values were used to estimate the annual energy consumption of these devices in the various operational modes (ON, standby, and OFF). Second, large appliances that could not be directly measured with the power meter, such as the dishwasher, clothes dryer, and stove/range, were investigated using various resources and calculators. The refrigerator power consumption was both measured and later adjusted using researched information.

According to estimations made using power meter measurements, the electronics (televisions, audio-video equipment, computers and peripherals, etc) and the plugged in appliances (refrigerator and clothes washer) of this home will consume 3,829 kWh of power annually. Of this total value, 491 kWh will be when the devices are in standby mode, and 469 kWh will be when the devices are turned OFF altogether. This is known collectively as the phantom or vampire load of the home and it totals 960 kWh ($86) annually (note this is just for the measurable, plugged-in devices). Utilizing best practices and power management techniques such as turning devices off when not in use (instead of running standby mode), and cutting the supply of power to powered-OFF devices via "kill-switches" or power strips, it was estimated that about 50% of the standby power load and about 85% of the OFF power load could be saved by these home owners. This corresponds to an annual savings of 644 kWh or $58 for little to no investment cost. These power savings are 3.5% of the home's current average annual electricity consumption. Greater conservation gains could be realized if more stringent power management strategies are adopted and energy efficient electronics (televisions, computers, etc) are utilized.

Upon further research, it was determined that the refrigerator consumption estimation from the power measurements would be an under-estimation for the whole year since refrigerator power consumption increases during warmer months. Online calculations showed a refrigerator of comparable size, make, model, and age would consume 1,252 kWh annually (227.08 kWh more than the previous estimation). If an EnergyStar® rated refrigerator was used instead, the home owner could save 652 kWh ($59) of annual power consumption.

Research for the un-measurable, large appliances showed that a clothes dryer of comparable size and age consumes about 1,201 kWh ($108 annually). Since little progress has been made in the field of energy efficient clothes dryers, several strategies and procedures can be used to mitigate some of this power consumption like hanging clothes up to dry or partially removing some of the moisture before placing clothes in the dryer. Research revealed that the test home dishwasher consumes about 264 kWh annually which is similar to newer, EnergyStar® rated dishwashers, although some models that do not have heating cycles can save significant power. Lastly, research showed that over the course of a typical year an electric oven/range consumes approximately 512.4 kWh (208 kWh for the oven and 304.4 kWh for the electric range "burners") of power. Depending on utility rates monetary savings can be available for homes that use natural gas cooking appliances. A review of the pertinent consumption, expenditure, and savings values from this chapter are shown in Table 7.12.

The DOE 2006 residential energy end-use study showed that 23% of all residential energy consumption is used by electronic devices or appliances. Of this, 1% is used for computers, 9% for electronics, 8% for refrigeration, and 5% for cooking by stoves, ovens, microwaves, etc [5]. Plug loads are only expected to rise in the future with the introduction of newer technologies that will require more energy to perform. Therefore, a great deal of time and money has been dedicated to researching strategies to reduce building plug (electronic) and process (appliance) loads.

Table 7.12: Review of Plug Loads -Electronics and Appliance Important Information

Estimated Plug Loads (Electronics and Refrigerator / Clothes Washer Measurements)		
	Annual Power Consumed	Utility Expenditure
Total Annual Plug Load	3,828.51 kWh	$344.57
Standby Plug Load	490.7 kWh	$44.16
OFF Plug Load	469.21 kWh	$42.23
Total Phantom (Standby+OFF)	959.92 kWh	$86.39
Save ~50% Standby and ~85% OFF	**644.18 kWh**	**$57.98**
Appliance Annual Consumption From Research		
Refrigerator	1,252 kWh	$112.68
Clothes Dryer	1,201 kWh	$108.10
Dishwasher	264 kWh	$23.76
Electric Stove/Oven/Range	512.4 kWh	$46.12
Total Home Appliance and Electronics Load		
Electronics + Dryer + Dishwasher + Stove/Oven + Refrigerator Change	**6,033 kWh**	**$542.97**
Energy Efficient Options		
EnergyStar Refrigerator	600 kWh	$54.00
No Heat Dishwasher	43.2 kWh	$3.89

Chapter 8

Total Building Energy Simulation

The preceding chapters of this report focused on analyzing individually the energy consumption of this home from lighting, electronics and appliances, and the HVAC systems to mitigate space heating/cooling loads that come from envelope air infiltration, internal heat generation from lighting, and heat gain/loss through windows and insulation systems. The individual energy simulations will now be combined into a total building energy simulation utilizing the TABLER software and HVAC performance information. The TABLER software uses a transient calculation method that takes into account space energy storage effects and is seen as a much more accurate representation of how the total home energy varies hourly throughout the year. To accomplish this simulation, some information from the previous chapters will be input into the TABLER interface in such a way as to match the energy consumption from the individual simulations over the course of year (since some TABLER inputs are geared towards commercial buildings and do not accommodate residential applications easily).

For example, the energy requirements for lighting must be input into TABLER on a Watt per Square Foot basis for typical work hours (8am – 5pm), typical night hours (5pm – 8am), and weekend/holiday times. TABLER assumes regimented lighting "ON – OFF" schedules based on a typical working environment with the light being spread out over the entire floor area. Of course, this is not how lights are operated in a residential building. Lighting requirements during the day vary greatly as discussed in Chapter 3 of this report. Therefore, to match the individual lighting simulation, an equation was setup to approximately distribute the known (Chapter 3 simulated) lighting requirements into an appropriate TABLER schedule. From this, an "effective" lighting wattage was calculated for each of the three TABLER time frames and each was divided by the floor area to match the TABLER input units. The end result (after running a TABLER simulation) is a TABLER generated annual lighting power consumption that matches the individual lighting simulation of Chapter 3 even if there is not actually a constant light power usage per square foot in the home during each time frame. The same procedure was used for the appliance and electronic plug-loads. The total annual energy consumption determined from simulations in Chapter 7 of this report was "forced" into TABLER as a "total effective equipment wattage" (kilowatts) for each of the three time frames (work, night, and weekend/holiday) even if it is not a constant plug-load for each time frame. The end result is an annual equipment energy requirement output from TABLER that matches the individual electronic and appliance simulations in Chapter 7.

On top of this, the average annual ACH (0.48 air changes per hour) found in Chapter 4 was input into the TABLER interface and the required ventilation was set to zero. The wall, roof, floor, and window compositions (areas and U-values) were also input into TABLER for a baseline, current home energy simulation. All other TABLER setting remained the same as previous baseline simulations. A review of all the TABLER inputs for the baseline, whole building energy simulation is shown in Table 8.1.

Table 8.1: TABLER Inputs for Baseline, Whole Building Energy Simulation

Location	Chattanooga (2)		
Zones	1		
Angle of Incl.	0		
Building Height	15ft		
Infiltration	0.48 ACH		
Ventilation	0 CFM		
Economizer	OFF		
Energy Recovery	OFF		
DOAS	OFF		
DCV sys	OFF		
TIAC	OFF		
	Work (8am-5pm)	Night (5pm-8am)	Weekend/Holiday
# of Occupants	1	3	3
Lighting	0.09985 W/ft^2	0.29955 W/ft^2	0.269596 W/ft^2
Equipment	0.4 kW	0.8 kW	0.8 kW
	Summer	Winter	
Thermostat	72 (no setback)	68 (no setback)	
Wind Turbines	OFF		
Solar Panel	OFF		
	U-factor	Area (ft^2)	Shade Coeff.
North Wall	0.069	470.26	\
South Wall	0.069	345	\
West Wall	0.069	492	\
East Wall	0.069	475.5	\
Roof	0.035	2126	\
Floor	0.047	2003	\
North Windows	0.67	35	0.87
South Windows	0.67	200	0.87
West Windows	0.67	18	0.87
East Windows	0.67	17	0.87
Elec Power Cost	9 c/kWh		
Elec Demand Cost	0		
Gas Cost	1.058 $/Therm		

8.1. Baseline Total Building Energy Simulation

With the TABLER inputs listed in the previous section (and the help of HVAC performance equations in Chapter 2), a whole building, baseline energy simulation was conducted. This is a rough estimate of the current state (energy usage) of the test home. This simulation will only give general insight about what aspects of the home are consuming the most energy since some energy consuming devices were not accounted for in the simulation (gas hot water heater, various electronics that could not be/were not measured, rough estimates on appliance and electronic usage, etc). Therefore, this is not an accurate, complete, total building simulation of annual energy consumption, but it will be a great approximation for energy savings and should come somewhat close to expected utility electricity usage values (less accurate on natural gas consumption). The results of the whole building, baseline energy simulation are shown in Table 8.2. Graphically, a breakdown of electricity usage by end-use for this baseline simulation is shown in Figure 8.1. Also, the baseline breakdown of the utility costs associated with this energy usage is shown in Figure 8.2. As can be seen in the table and figures, the total annual electricity consumption from the HVAC equipment, the home lighting, and the electronics/appliances simulated for the home's current state was determined to be 19,153 kWh. This value is 1.2% less than the average electricity consumption calculated from home utility records in Chapter 2. This was to be expected since not all electricity consuming home devices were addressed in this simulation.

Table 8.2: Baseline Total Building Energy Simulation Results

	kWh	Cost ($)
Heat Pump Cooling	6,872.44	618.52
Heat Pump Heating	1,106.22	99.56
Lighting	4,456.67	401.10
Electronics/Appliances	5,658.44	509.26
HVAC Equipment	1,059	95.33
	19,152.99	1,723.77
	Therms	Cost ($)
Gas Heat	202.48	214.22
Total Utility Cost ($)		1,937.99

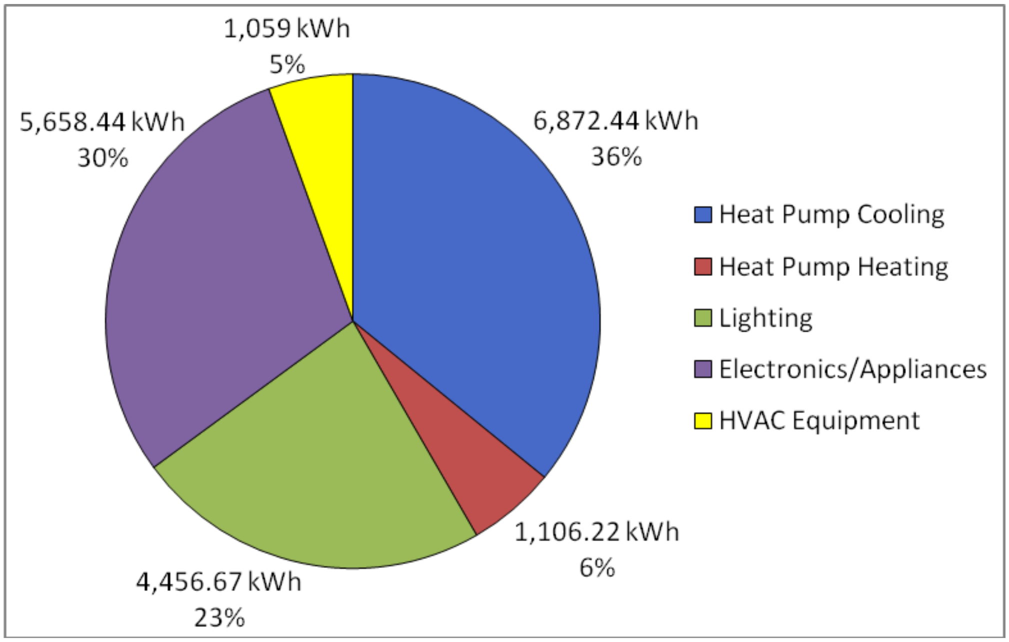

Figure 8.1: Baseline Electricity Consumption Breakdown by End-Use

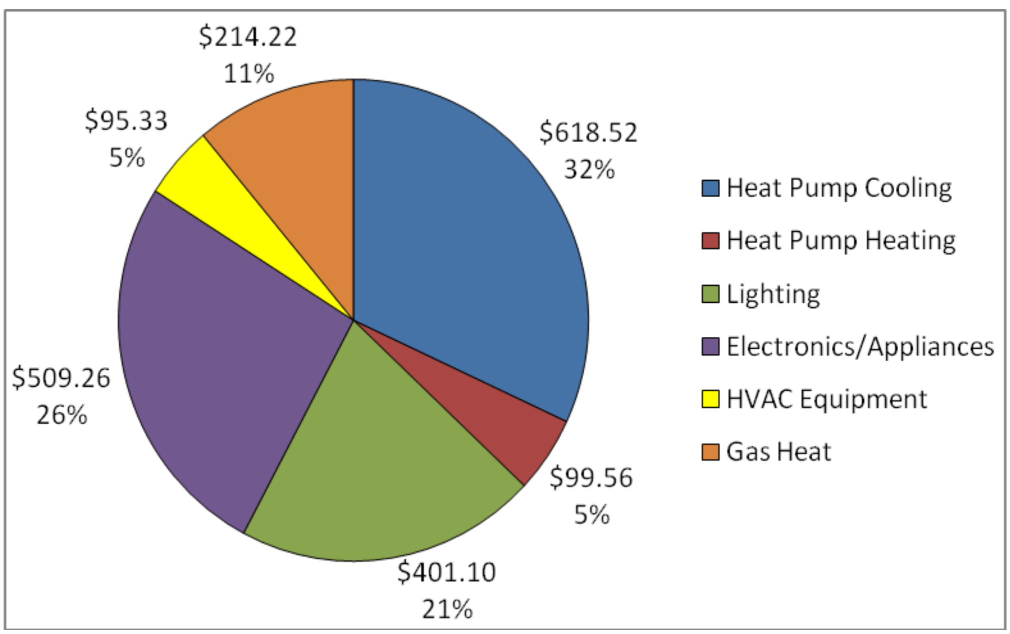

Figure 8.2: Baseline Utility Expenditures by End-Use

According to these simulations, the total annual utility expenditures from the HVAC equipment, natural gas used for space heating, home lighting, and electronics/appliances simulated for the test home's current state was determined to be $1,938 ($1,724 for electricity and $214.22 for gas heating). This value is 18.1% ($428) less than the average, annual utility expenditures calculated from home utility records in Chapter 2. This is due to the fact that electricity consumption in this simulation is slightly less than actual averages and there was no natural gas estimates for hot water heating (DOE estimates 13% of total home energy is used for heating water). Remember, the DOE 2006 End-Use study described in Chapter 1 gives percentages of energy end-uses based on the total energy consumption of the house (electricity + gas) and these percentages will differ from the percentages shown in Figure 8.1 and Figure 8.2 which only have part of the energy consumption totals. Based on research (electricity consumption percentages) the values returned from the TABLER whole building baseline simulation are excellent estimates for a residential building such as this test home.

8.2. Total Building Energy Efficient Upgrades

The next two sections explain and simulate the combined effects of the various energy efficient upgrades described in the preceding chapters of this report. Two separate energy efficient, whole building simulations will be performed and the results will be compared to the baseline, whole building simulation. Two separate simulations were chosen because of the variations in energy efficient upgrades described in each individual chapter. The first simulation will be seen as a "best-case" scenario for energy savings. This simulation will examine the combination of the "most energy efficient" upgrades described in each chapter. Of course, further energy savings can be realized from more study and application of energy efficient upgrades; therefore, this is not truly the "best"/most energy savings that this test house could ever see, but rather it is the best of the options investigated previously in this report. These upgrades are usually (not always) the more expensive upgrades to implement and the cost versus savings will be examined. The second simulation will be seen as the implementation of a "cost-effective" upgrade system that is chosen to return appreciable energy savings while not burdening the home owner with the substantial upfront investment that would be needed for the best case scenario.

8.2.1 Best-Case Energy Simulation with Most Effective Energy Efficient Upgrades

The best-case energy simulation investigates the cumulative energy savings from implementing the “most efficient” system upgrades. The upgrades for this simulation included installing the LED light bulbs ($4,054) described in Chapter 3, applying the infiltration mitigation techniques ($200) from Chapter 4, upgrading the insulating systems ($15,200 for upgrading floor, attic, wall cavity, stud-tape, and wall sheathing insulations) from Chapter 5, installing the energy efficient advanced windows ($8,125) from Chapter 6, operating a new, EnergyStar® refrigerator ($2,000), and implementing a new power management system (~$0) discussed in Chapter 7. The total initial investment to implement these upgrades would be about $29,579. After making these upgrades, the performance characteristics of the various power end-uses that will be input into TABLER for this first energy efficient, whole building simulation are shown in Table 8.2. Once again, the lighting and equipment inputs are the distributed power requirements found in the individual simulations in each of the associated chapters, and the wall/window performance characteristics come from the appropriate simulations in each dedicated chapter.

With these inputs, the whole building energy simulation was re-evaluated using TABLER (and Chapter 2 HVAC equations) and the results of this “best-case” energy simulation are shown in Table 8.3.

Table 8.2: TABLER Inputs for Best Case Energy Efficient Whole Building Simulation

Location	Chattanooga (2)		
Zones	1		
Angle of Incl.	0		
Building Height	15ft		
Infiltration	**0.408 ACH**		
Ventilation	0 CFM		
Economizer	OFF		
Energy Recovery	OFF		
DOAS	OFF		
DCV sys	OFF		
TIAC	OFF		
	Work (8am-5pm)	Night (5pm-8am)	Weekend/Holiday
# of Occupants	1	3	3
LED Lighting	**0.02496 W/ft^2**	**0.0399 W/ft^2**	**0.0515 W/ft^2**
Reduced Equipment	**0.3646 kW**	**0.6 kW**	**0.62 kW**
	Summer	Winter	
Thermostat	72 (no setback)	68 (no setback)	
Wind Turbines	OFF		
Solar Panel	OFF		
	U-factor	Area (ft^2)	Shade Coeff.
EE North Wall	**0.047**	470.26	\
EE South Wall	**0.047**	345	\
EE West Wall	**0.047**	492	\
EE East Wall	**0.047**	475.5	\
EE Roof	**0.034**	2126	\
EE Floor	**0.035**	2003	\
EE North Windows	**0.18**	35	**0.21**
EE South Windows	**0.18**	200	**0.21**
EE West Windows	**0.18**	18	**0.21**
EE East Windows	**0.18**	17	**0.21**
Elec Power Cost	9 c/kWh		
Elec Demand Cost	0		
Gas Cost	1.058 $/Therm		

Table 8.3: Best Case Energy Efficient Total Building Simulation Results

	kWh	Cost ($)
Heat Pump Cooling	3,866.67	348
Heat Pump Heating	2,597.56	233.78
Lighting	666.67	60.00
Electronics/Appliances	4,655.56	419
HVAC Equipment	1,567	141.00
	13,353.11	1,201.78
	Therms	Cost ($)
Gas Heat	206.276	218.24
Total Utility Cost ($)		1,420.02

As can be seen from Table 8.3, the total annnual electricity consumption of the test home after the installation/implementation of the afore mentioned energy efficicent upgrades was estimated to be 13,353 kWh. This represents a 30.3% reduction in annual electricity consumption over the baseline simulation. In other words, this test home would consume about 5,800 kWh of electricity less each year if these energy efficient upgrades were made. A breakdown of the electricity savings of each home end-use compared to the baseline simulation is shown in Figure 8.3. The simulation reveals that energy consumption actually increased for the heat pump heating mode operation of the HVAC system, and this in turn required more energy to operate the secondary HVAC devices (pumps, fans, etc). This was mostly due to two factors: (1) the winter time solar heating gains were somewhat mitigated by the energy efficient windows and (2) the winter internal heat gains from lighting, electronics, and appliances were also decreased by the other energy efficient measures. The greatest energy savings were seen in the lighting and cooling (Heat Pump Cooling mode) end-uses. The lighting energy requirements fell right in-line with the individual savings estmates in Chapter 3 with a slight increase in energy usage that was attributed to the way TABLER distributes lighting requirements over the "weekend/holiday" time frame. The difference between TABLER and the simulation in Chapter 3 was less than $10 in annual electricity expenditure.

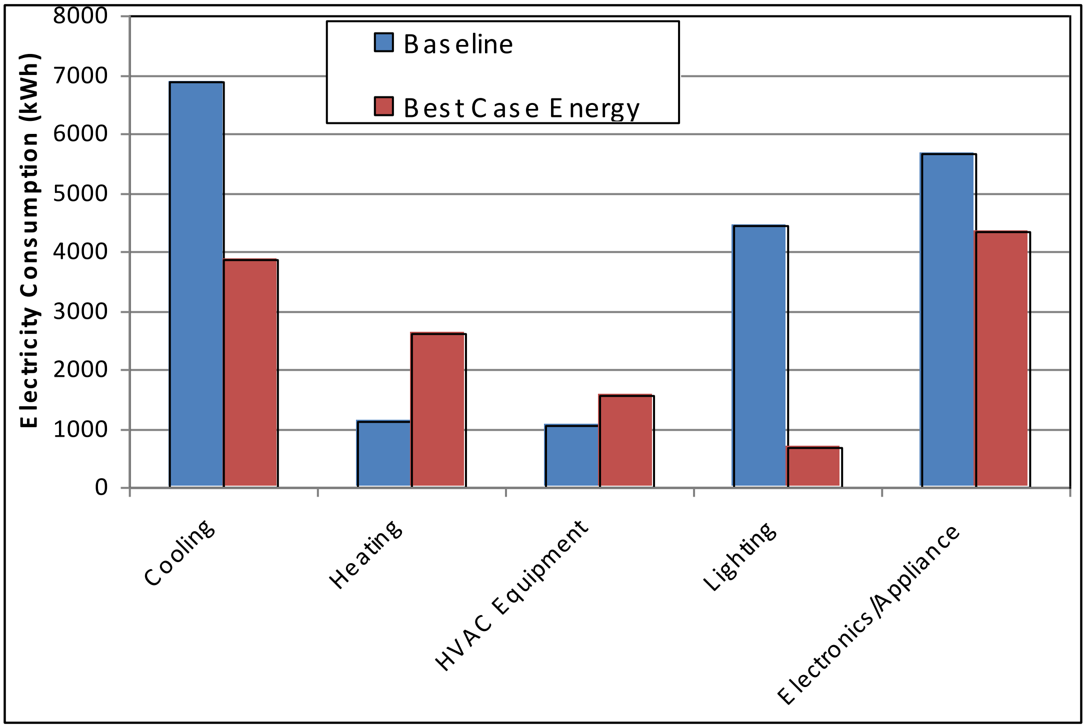

Figure 8.3: Electricity Savings of Best Case Energy Efficient Upgrades

Graphically, a breakdown of electricity usage by end-use for this best-case energy efficient simulation is shown in Figure 8.4. Also, the breakdown of utility costs associated with this energy usage is shown in Figure 8.5.

According to these simulations, the total annual utility expenditures from the HVAC equipment, natural gas used for space heating, home lighting, and electronics/appliances simulated for the test home with best-case energy efficient upgrades was determined to be $1,420 ($1,202 for electricity and $218 for gas heating). This value is 26.7% ($518) less than the baseline expenditures. Since the installation/implementation of these upgrades cost about $29,579, the payback period with these utility savings is near 57 years.

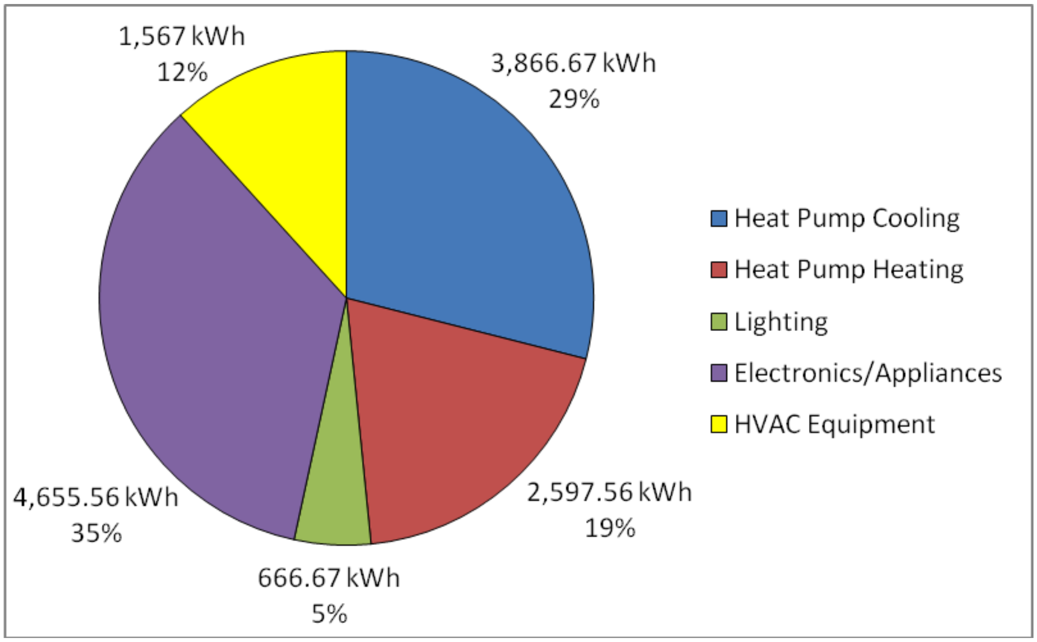

Figure 8.4: Best-Case Electricity Consumption Breakdown by End-Use

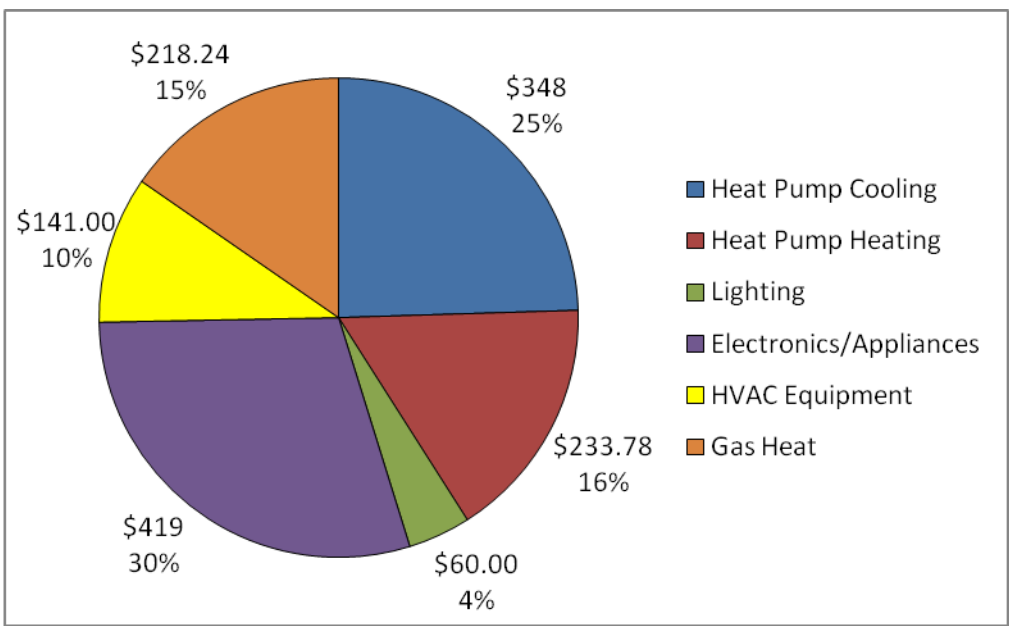

Figure 8.5: Best-Case Estimated Utility Expenditures by End-Use

8.2.2 "Cost Effective" Energy Simulation for Energy Efficient Upgrades

The "Cost Effective" energy simulation investigates the cumulative energy savings from implementing not necessarily the "most efficient" system upgrades, but upgrades that showed appreciable energy savings while still remaining fairly affordable. The upgrades for this simulation included installing the CFL light bulbs ($377) described in Chapter 3, applying the infiltration mitigation techniques ($200) from Chapter 4, upgrading the insulating systems ($9,000 for upgrading wall cavity and wall sheathing insulation) from Chapter 5, installing the 3M CM40 solar window coatings ($400) from Chapter 6, and implementing the new power management system (~$0) discussed in Chapter 7. The total initial investment to implement these upgrades would be about $9,977. Note that 90% of the total investment comes from costly insulation upgrades. After making these upgrades, the performance characteristics of the various power end-uses that will be input into TABLER for this cost effective, energy efficient, whole building simulation are shown in Table 8.3. Once again, the lighting and equipment inputs are the distributed power requirements found in the individual simulations in each of the associated chapters, and the wall/window performance characteristics come from the appropriate simulations in each dedicated chapter.

With these inputs, the whole building energy simulation was re-evaluated using TABLER (and Chapter 2 HVAC equations) and the results of this "cost effective" energy simulation are shown in Table 8.4.

Table 8.3: TABLER Inputs for Cost Effective Energy Efficient Upgrades Simulation

Location	Chattanooga (2)		
Zones	1		
Angle of Incl.	0		
Building Height	15ft		
Infiltration	**0.408 ACH**		
Ventilation	0 CFM		
Economizer	OFF		
Energy Recovery	OFF		
DOAS	OFF		
DCV sys	OFF		
TIAC	OFF		
	Work (8am-5pm)	Night (5pm-8am)	Weekend/Holiday
# of Occupants	1	3	3
CFL Lighting	**0.0479 W/ft^2**	**0.09985 W/ft^2**	**0.07489 W/ft^2**
Reduced Equipment	**0.4 kW**	**0.68134 kW**	**0.70764 kW**
	Summer	Winter	
Thermostat	72 (no setback)	68 (no setback)	
Wind Turbines	OFF		
Solar Panel	OFF		
	U-factor	Area (ft^2)	Shade Coeff.
EE North Wall	**0.052**	470.26	\
EE South Wall	**0.052**	345	\
EE West Wall	**0.052**	492	\
EE East Wall	**0.052**	475.5	\
EE Roof	**0.035**	2126	\
EE Floor	**0.047**	2003	\
EE North Windows	**0.67**	35	**0.46**
EE South Windows	**0.67**	200	**0.46**
EE West Windows	**0.67**	18	**0.46**
EE East Windows	**0.67**	17	**0.46**
Elec Power Cost	9 c/kWh		
Elec Demand Cost	0		
Gas Cost	1.058 $/Therm		

Table 8.4: Cost Effective Energy Efficient Whole Building Simulation Results

	kWh	Cost ($)
Heat Pump Cooling	4,383.56	394.52
Heat Pump Heating	1,837.56	165.38
Lighting	1,588.89	143.00
Electronics/Appliances	5,255.56	473
HVAC Equipment	1,711	154.00
	14,776.67	1,329.9
	Therms	Cost ($)
Gas Heat	155.21739	164.22
Total Utility Cost ($)		1,494.12

As can be seen from Table 8.4, the total annnual electricity consumption of the test home after the installation/implementation of the afore mentioned cost effective upgrades was estimated to be 14,777 kWh. This represents a 22.8% reduction in annual electricity consumption over the baseline simulation. In other words, this test home would consume about 4,376 kWh of electricity less each year if these energy cost effective energy efficient upgrades were made. A breakdown of the electricity savings of each home end-use compared to the baseline simulation is shown in Figure 8.6**.** The simulation revealed the same trends as the first energy efficient simulation (inceased heating loads and the associated secondary HVAC equipment power consumption). Once again the greatest energy savings were seen in the lighting and cooling (Heat Pump Cooling mode) end-uses, and moderate savings were seen in the electronics and applaince category.

Yet again, the lighting energy requirements slight increase in energy usage over the Chapter 3 CFL simulation. This must be from the way TABLER distributes lighting requirements over the "weekend/holiday" time frame. The difference (increase) between TABLER and the simulation in Chapter 3 was right on $10 in annual electricity expenditure.

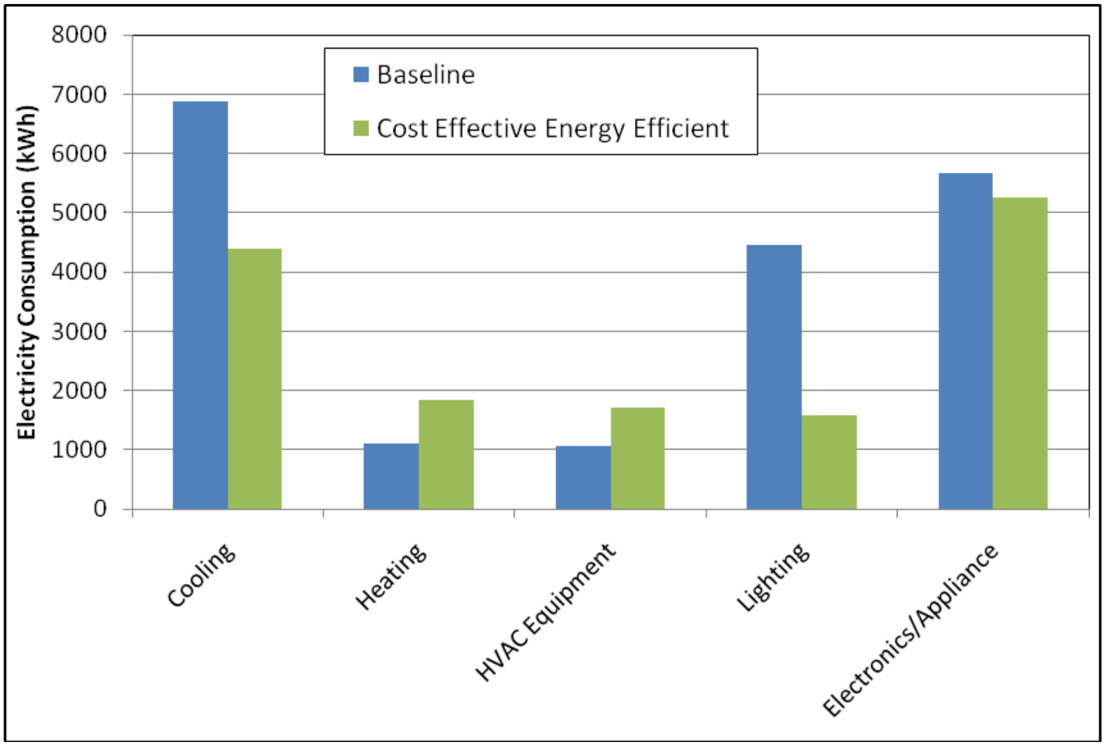

Figure 8.6: Electricity Savings of Cost Effective Energy Efficient Upgrades

Graphically, a breakdown of electricity usage by end-use for this cost effective energy efficient simulation is shown in Figure 8.7. Also, a breakdown of the utility costs associated with this energy usage is shown in Figure 8.8.

According to this simulation, the total annual utility expenditures from the HVAC equipment, natural gas used for space heating, home lighting, and electronics/appliances simulated for the test home with cost effective energy efficient upgrades was determined to be $1,494 ($1,330 for electricity and $164 for gas heating). This value is 22.9% ($444) less than the baseline expenditures. Since installation/implementation of these upgrades costs about $9,977, the payback period with these utility savings will be near 22.5 years.

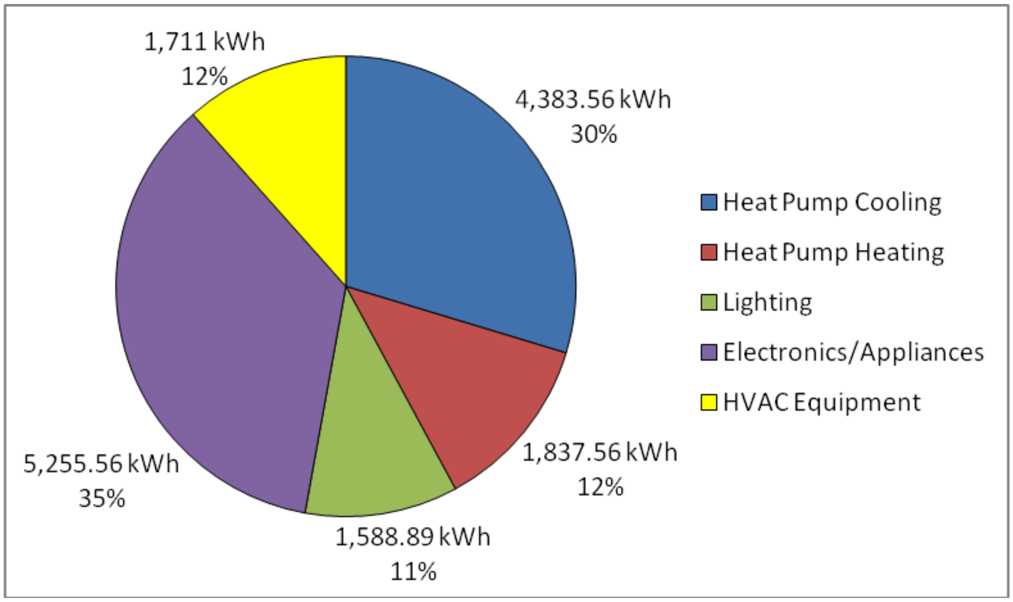

Figure 8.7: Cost Effective Electricity Consumption Breakdown by End-Use

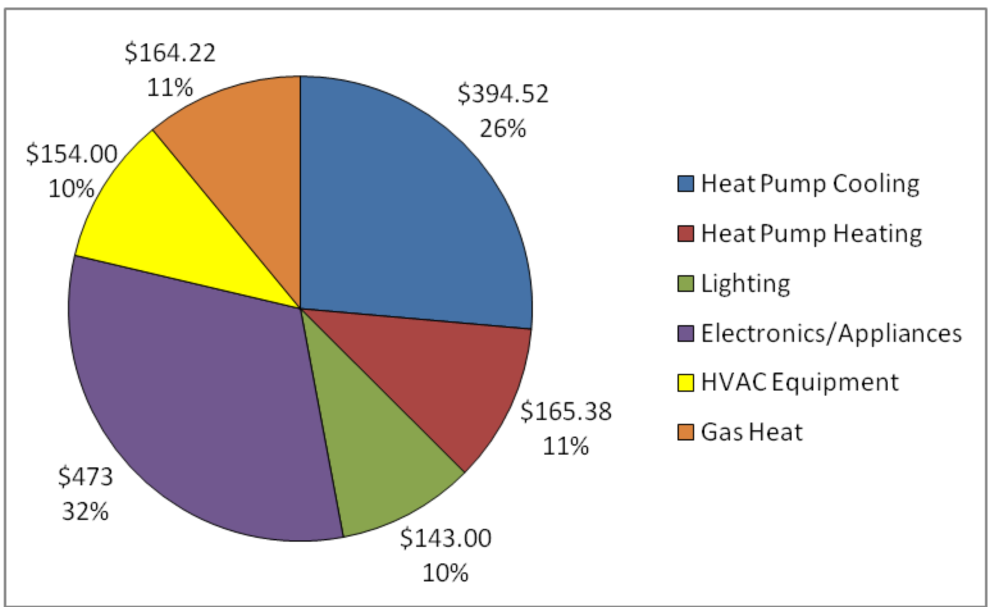

Figure 8.8: Cost Effective Estimated Utility Expenditures by End-Use

8.3. Brief Remarks on Total Building Energy Simulation

The results of each whole building, energy efficient upgrade simulation and the baseline (current home state) are shown in Table 8.5. As can be seen in the table, the various upgrades listed as “best-case” would save the most electricity (5,800 kWh) and subsequently save the most utility expenses ($517.97) over the course of a typcial year. On the other hand, the various upgrades listed as “cost effective” would only save 4,376 kWh and $444 in utility expenses over the current home setup. Despite the fact that the best case scenario annually saves 1,424 kWh more electricty over the cost effective upgrade scenario, it will only save about $74 more each year on utility expenses, because while the best-case scenario is saving more electricity, it is “trading off” and consuming more natural gas for certain heating loads at various times of the year. The high initial investement of the best case collection of upgrades makes the pay back period over twice as long when compared to the cost effective upgrade installation. A breakdown of the electricity savings in each home end-use is shown for each energy efficient upgrade simulation set in Figure 8.9.

Table 8.5: Whole Building Energy Efficient Upgrade Simulation Results

	Annual kWh	kWh Save	Annual Utilities	$ Save	Payback
Baseline (Current Home)	19,152.99	\	$1,937.99	\	\
Best Case Energy Efficient	13,353.11	5,799.88	$1,420.02	$517.97	57 yr
Cost Effective Energy Efficient	14,776.67	4,376.32	$1,494.12	$443.87	22.5 yr

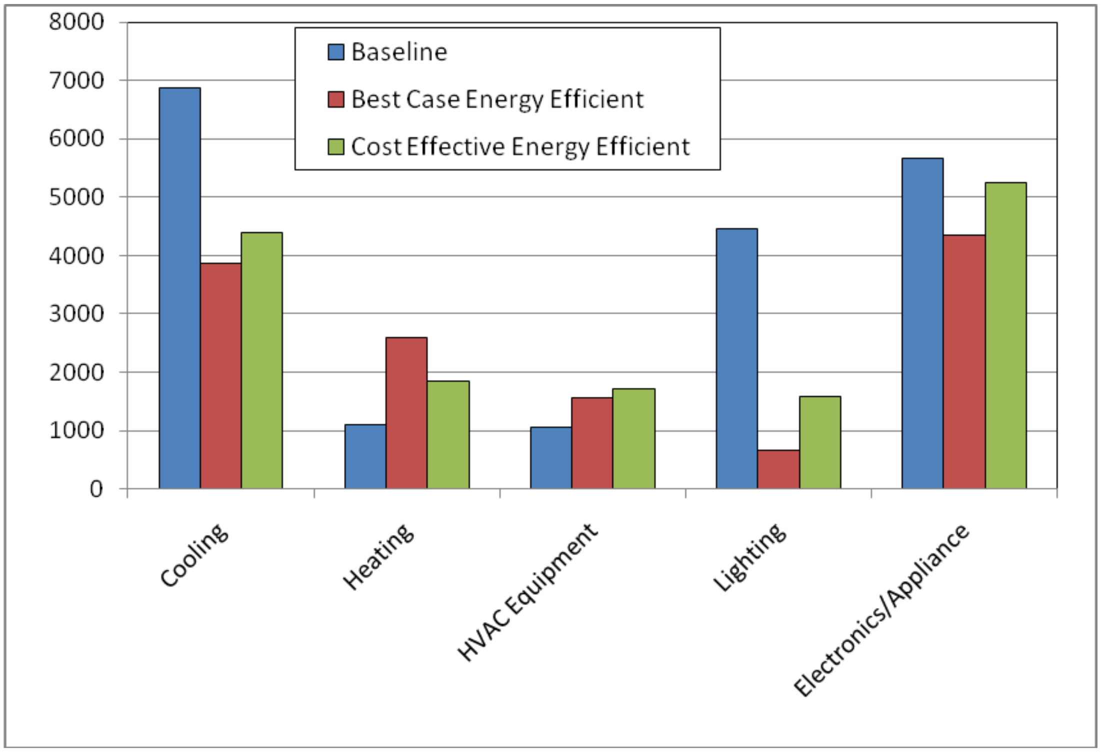

Figure 8.9: Compare Whole Building Energy Efficient Upgrades with Baseline End-Uses

An often over-looked aspect of these energy efficient upgrades is the reduction in building peak heating and cooling loads. The whole building, baseline energy simulation revealed at peak winter heating load of 3.06 Tons (1 Ton is 12,000 Btu/hr) and a peak summer cooling load of 4.26 Tons. The best-case upgrade simulation revealed a peak heating load of 2.0 Tons and a peak cooling load of 1.9 Tons, while the cost effective upgrade simulation showed a peak heating load of 2.7 Tons and a peak cooling load of 2.67 Tons. This is an important upgrade feature. Back in Chpater 2 of this report, a "quick calculation" was done online to estimate the proper sizing of the home HVAC system. The calculator estimated a peaking load of 3.3 – 3.5 Tons (assumed this was cooling capacity). As can be seen from simulations, the baseline peak cooling load is well over the estimated value and is (1.26 Tons greater) than the current HVAC peak cooling load capacity. Therefore, the HVAC system is somewhat under-sized for this home. Lessening the peak loads (like the energy efficient upgrades did) will bring the peak load down into the proper range for the currrent HVAC system. In general, if the peak heating and cooling loads can be reduced through energy efficient upgrades, the size and cost of installing or replacing an HVAC system can be reduced as well.

Chapter 9

Residential Solar Power Generation

In order to strive towards a residential zero energy building (ZEB), some type of energy generation element must be installed on location to provide the power that is utilized by all the various modes of energy consumption discussed in the previous chapters (lighting, HVAC, electronics, appliances, etc). For most residential buildings, the power generation element of choice is solar power. Solar power is a renewable energy source that has generating on-site residential power for many years. Enough solar radiation strikes the earth every day to meet the world's energy need for a whole year and countless solar power companies have been harnessing the power of the sun to generate power with photovoltaic panels (PVs), thin-film solar cells, and other solar collecting systems [43]. The solar power generation potential for the United States is measured by the National Renewable Energy Laboratory (NREL) located in Golden, Colorado. NREL investigates the use of photovoltaic cells as-well-as concentrated solar systems across the United States. NREL reports this data in tabular form, but it is convenient to present this information as a geographical map [44]. Both of these potential solar power generation maps (photovoltaic and concentrated power systems) are shown below in Figure 9.1.

As can be seen from Figure 9.1, solar power generation potential from photovoltaic resources does exist in the Chattanooga, TN area. This chapter briefly discusses the potential residential solar generation capacities for the test house under investigation utilizing the NREL solar online calculator titled PV-Watts version 1.0.

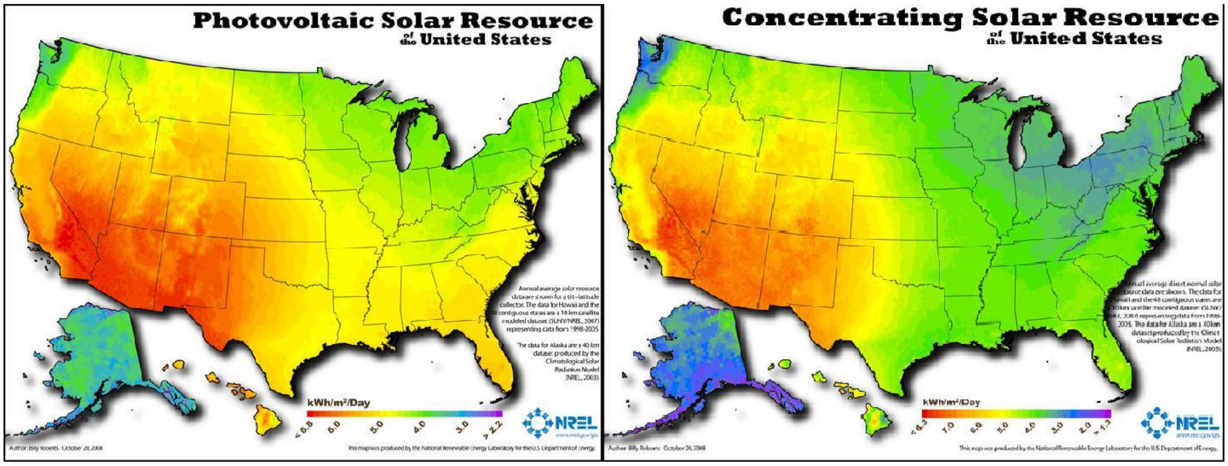

Figure 9.1: Photovoltaic and Concentrating Solar Power Resources in U.S. [44]

The most important concepts to understand for solar power generation potential are the solar radiation available for use, and solar system (PV in this case) performance characteristics.

First, to understand solar power potential generation a clear understanding of how much total solar radiation is incident upon a solar system must be known. The total solar load (I_t) incident on a surface (solar panel or collector system) is a combination of the direct radiation (I_{dir}) incident normal to the surface, the solar diffuse radiation (I_{dif}) which is radiation scattered from the surroundings and particles in the atmosphere, and the solar radiation reflected (I_{ref}) from the ground and other surfaces [45]. This total solar load available for use in power generation is given by the equation:

$$I_t = I_{dir} * \cos(\theta) + I_{dif} + I_{ref}$$

In this equation, θ is the angle of incidence between the sun and a surface (PV panel) at a given instant in time. The calculation of this angle will be discussed later in this section. Direct (sometimes called "normal") radiation (I_{dir}) is measured by most major weather stations and is a reported value in TMY data sets. On the other hand, diffuse and reflected radiation values are not measured and reported in TMY data sets since they vary with surface orientation, and these values must be determined from other measured, reported radiation values.

The diffuse radiation (I_{diff}) striking any surface can be determined by diffuse horizontal ($I_{dif,hor}$) data measurements from local weather stations by using the equation:

$$I_{diff} = I_{dif,hor} * [1 + \cos(\beta) / 2]$$

In this equation β is the angle of inclination ("tilt") of a particular surface with the local horizontal surface (tilting a surface towards the sun will be discussed later).

The reflected solar radiation (I_{ref}) that contacts a particular surface can be determined from the weather station measured global, horizontal radiation ($I_{glo,hor}$) by using the equation:

$$I_{ref} = 0.5*\rho*I_{glo,hor}*[1 - \cos(\beta)]$$

In this equation ρ is the surrounding surfaces' reflectivity which can be taken as 0.2 for normal conditions and 0.6 for areas with highly reflective surroundings such as snow covered roofs [45]. The preceding three equations can be used to determine the amount of solar radiation that will strike a particular surface such as a titled PV panel if the angle of incidence is known.

Calculating the angle of incidence (θ) between a particular surface and the sun is a slightly complicated procedure. The angle of incidence depends on the position of the sun in the sky (which depends on the time of the year and time of the day), surface orientation (tilt and angle between the south/north and the vector normal of the surface known as the "surface Azimuth"), geographic location, and other factors. Several resources are available to assist in calculating these values, but a basic procedure is presented next from resources [46] and [47].

The first step in finding the angle on incidence is to determine the sun-earth declination angle (δ). The declination angle is the angle between the earth-sun line and the equatorial plane (equator). The sun-earth declination changes with the date and is independent of the location. The declination angle can be found using the equation:

$$\sin \delta = -\sin(23.45^{\circ})*\cos[360^{\circ}(n+10) / 365.25]$$

Where “n” in this equation is the “Julian Day” counter. The Julian Day counter starts at 1 on January 1st and subsequently increases 1 unit each day until the end of the year (365 days non-leap year). The Julian Day is represented as a vector in most programming languages as:

$$n = 1:1:365$$

The Julian Day counter is also used in conjuncture with the “Equation of Time” (E_t) to establish the difference between solar noon (the time when the sun reaches the highest point in the sky) and noon (12:00pm) of the local, geographic time. The Equation of Time links local standard time (on the clock) to solar time (sun position) and is given by the equation:

$$E_t = 9.87*\sin([360^o(n-81)]/364) - 7.53*\cos([360^o(n-81)]/364) - 1.5*\sin([360^o(n-81)]/364)$$

From the Equation of Time (E_t) the solar time can be found utilizing the equation:

$$t_{sol} = t_{std} + [(L_{std} - L_{loc}) / 15^o] + (E_t / 60)$$

In this equation t_{std} is the local standard time, L_{std} is the longitude of the standard time (United States, Eastern = 75º, Central = 90º, Mountain = 105º, Pacific = 120º), L_{loc} is the longitude of the location in degrees, and E_t is the Equation of Time value from above (varies each day with “n”).

Once the solar time is known, the hour angle (ω) can be determined. The hour angle is the angular distance that the earth has rotated in a day and can be found by using the equation:

$$\omega = [360^o*(t_{sol} - 12)] / 24$$

With the hour angle known, sun positioning angles relative to the particular surface in question can be determined. First, the solar altitude angle (ά) will the found. The solar altitude angle is the vertical angle between the horizontal (horizon) and a line connecting to the sun. At sunset/sunrise the altitude is 0. The altitude angle relates to the geographic latitude of the site, the declination angle, and the hour angle through the equation:

$$\sin ά = \sin δ * \sin φ + \cos δ * \cos ω * \cos φ$$

In this equation φ is the Latitude (location relative to the equator) of the site where the surface (PV) is located.

Next, the solar zenith angle (Z) will be determined. The solar zenith angle is the angle between the sun's rays and the normal on the local horizontal plane, given by the equation:

$$\cos Z = \cos ά * \cos δ * \cos ω + \sin ά * \sin δ$$

The last intermediate angle before the angle of incidence is the solar azimuth angle (χ). The solar azimuth angle is the angle within the horizontal plane measured from true South or North. The azimuth, when in reference to the South is usually called the "bearing." If the sun is East of South, the "bearing" is positive.
The solar azimuth is given by the equation:

$$χ = (\cos δ * \sin ω) / \sin Z$$

Lastly, and most importantly, the angle on incidence (θ) can be determined from the equation:

$$\cos θ = \sin Z * \sin β * \cos(χ - ε) + \cos Z * \cos β$$

In this equation the surface azimuth (ε) is the angle made by the surface normal with the south direction ($180 - A_{zs}$). This angle can then be used to calculate the total solar energy striking a surface at a given point in time. For some clarification, the angle of incidence (θ), altitude angle (ά), surface tilt (β), and surface azimuth to the north (Azs) are shown in Figure 9.2.

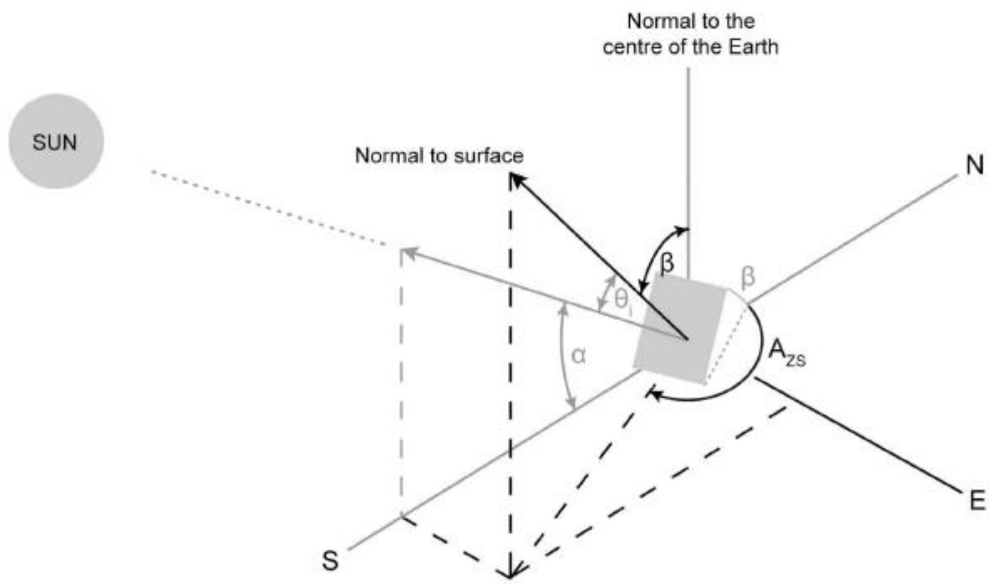

Figure 9.2: Important Solar and Orientation Angles for Solar Power generation Evaluation [46]

The second aspect of understanding solar power generation capacities is to understand the performance characteristics of solar power installations (residential sized PV systems). Most solar estimation tools do not break PV systems down and analyze individual PV cells/modules but an understanding of what happens at the single panel level is important when evaluating efficiencies and expected power production. Without going into too much detail, the performance of a PV system is contingent on the surrounding weather conditions and PV system setup. As the cell temperature of a PV panel increases the efficiency at which the panel converts sunlight into DC power decreases. Therefore understanding the expected cell temperatures throughout the year is important to estimating the power output of a PV system. The cell temperature (T_c) for a poly-crystal PV panel (the most efficient solar panels) can be determined by following the correlation [48]:

$$T_c = 0.943T_a + 0.028G_t - 1.528V_w + 4.3$$

In this equation the outside ambient air temperature (T_a) is taken from weather station data in degrees Celsius, the incident solar radiation (G_t) is the same as the total solar load

(It) previously discussed in units of kWh (or kW per a certain time frame), and the outside wind speed (V_w) taken from weather station data is measured in m/s.

Many attempts have been made to model the performance of a individual photovoltaic panel, and the most accurate results have come from studies that model the PV cell as a simple electrical circuit. From this equivalent circuit several equations were determined that model the performance (voltage and current) of a typical solar panel based on manufacture performance information.

Manufacture performance data for solar panels comes from laboratory testing under what is known as "standard test conditions" (STC). Standard test conditions means the panel is subjected to a constant 1,000 W/m^2 (E_{st}) of radiation at a particular spectral makeup while having a module temperature (T_{st}) of 25ºC. From these laboratory tests, PV manufactures report several performance values for that specific solar panel. PV manufactures list the cells maximum power output (P_{max}), open circuit voltage (V_{oc}), maximum power voltage (V_{mp}), short circuit current (I_{sc}), maximum power current (Imp), module efficiency, normal operating cell temperature NOCT, maximum power temperature coefficient, voltage temperature coefficient (β_o), and current temperature coefficient ($\acute{\alpha}_o$). These PV module performance characteristics can be used to determine the expected behavior (voltage, current, and power) output of a PV panel in operation by following the multi-step procedure described next.

First, the temperature difference (ΔT) between the current cell temperature (T_c) and the STC cell temperature (T_{st} = 25ºC) by using the equation:

$$\Delta T = T_c - T_{st}$$

Next, the change in current (ΔI) is determined by using the STC radiation level (E_{st} = 1,000 W/m^2), the temperature difference (ΔT), the current incident radiation (E_{tt} also known as I_t), the current temperature coefficient ($\acute{\alpha}_o$), and the short circuit current (I_{sc}) and following equation:

$$\Delta I = \acute{\alpha}_o * (E_{tt} / E_{st}) * \Delta T + [(E_{tt} / E_{st}) - 1\ ] * I_{sc}$$

The voltage of a solar cell at a given time can be determined by using the maximum power voltage (V_{mp}), the current and STC radiation levels (E_{tt} and E_{st} respectively in Watts/m^2), the temperature difference (ΔT), and the voltage temperature coefficient (β_o) by following equation:

$$V = V_{mp}*[1+ 0.0539*\log(E_{tt} / E_{st})] + \beta_o*\Delta T$$

Once the voltage (V) is determined, the change in voltage (ΔV) is just the difference between the voltage and the maximum power voltage (V_{mp}) given by the equation:

$$\Delta V = V - V_{mp}$$

Two panel constants (C_1 and C_2) can be determined from utilizing manufacture performance characteristics and the equations:

$$C_2 = [(V_{mp}/V_{oc}) – 1] / \ln(1 – [I_{mp} / I_{sc}])$$

and

$$C_1 = [1 – (I_{mp}/I_{sc})]*\exp[-V_{mp} / (C_2*V_{oc})]$$

Lastly, the panel current (I) can be determined by following the equation:

$$I = I_{sc}*\{1 – C_1*[\exp(V – \Delta V / C_2*V_{oc}) – 1]\} + \Delta I$$

Once both the voltage (V) and the current (I) are known for a given instant in time (based on the cell temperature and sun radiation levels at that time, and performance characteristics of the panel itself), then the DC power (P in Watts) of that particular panel under the given conditions can be determined by the equation:

$$P = V*I$$

This will not be the usable power seen from the solar panel to operate household needs because the power supplied will be DC while a conversion must take place into AC power through an inverter. Other losses and conversion processes (known as the DC-to-

AC Derate factors) will further decrease the usable power seen from the panel, and these will be discussed later.

9.1 Solar Power Generation Simulation

A MatLAB® computer code was generated to follow the procedures outlined in this chapter and estimate the power output from a residential solar system. The computer code used TMY3 data to calculate the incident solar energy on a tilted surface (PV panel), and then used the performance characteristics of a SHARP NT-175U1 175 Watt solar panel to determine the power output of the PV panel. The performance characteristics for this type of solar panel are shown in Table 9.1. This computer code is shown in Appendix G at the end of this report. The results of this program mimicked the results seen in established, heavily used online calculators such as the NREL PV-Watts Version 1.0 simulation tool, and followed closely the SHARP manufacturer testing results. According to these simulations, 4.79 kWh/m^2/day of radiation will be incident on the tilted surface (35 degree tilt angle equal to the local latitude which is the tilt of the southern facing roof on this test home) of this PV panel. The in-house computer code performs the PV performance equations in the preceding section, but is only setup to evaluate the performance of a single PV panel. Individual panels must be connected properly in series and parallel to attain a usable power output and the design of solar systems is outside the scope of this report.

Table 9.1: SHARP 175W PV Performance Characteristics

SHARP NT-175U1 PV	
Maximum Power (Pmax)	175W
Open Circuit Voltage (Voc)	44.4V
Maximum Power Voltage (Vmp)	35.4
Short Circuit Current (Isc)	5.40A
Maximum Power Current (Imp)	4.95A
Module Efficiency (%)	13.45%
Temperature Coefficient (Pmax)	-0.485
Temperature Coefficient (Voc)	-0.36
Temperature Coefficient (Isc)	0.053
Dimensions: 32" x 62" x 1.8"	

Since the calculated incident solar radiation followed NREL's PV Watts calculator, the remaining simulation and estimations will be made utilizing the online calculator PV Watts Version 1.0 for Chattanooga, TN to determine what effects the energy efficient upgrades previously simulated in this report had on the sizing of a PV solar system to make this test home a "Zero-Energy" (zero electrical energy) building.

First, PV Watts was used to simulation the power output (AC usable power) for various sized residential PV systems. The annual AC power output from the PV system was then matched to the simulated annual power consumption of this test home for each whole building energy simulation. This information is shown in Figure 9.3.

As can seen in the figure, for the baseline energy consumption (test home presently consumes 19,152.99 kWh according to the simulation), a PV system with a DC rating of 16 kW would be needed to offset 100% of the consumed electrical energy of the test home (rounded up to the next whole kW of solar installation). Utilizing the "rule of 10," which states that $10ft^2$ of roof area will be needed for every 10 Watts of solar power, this would mean that $1{,}600ft^2$ of roof area would be needed for this solar installation [43]. The southern-facing, un-shaded roof area of this test home was measured to be just under 1,600 ft^2. A system of this size would be pushing the limits for available roof area.

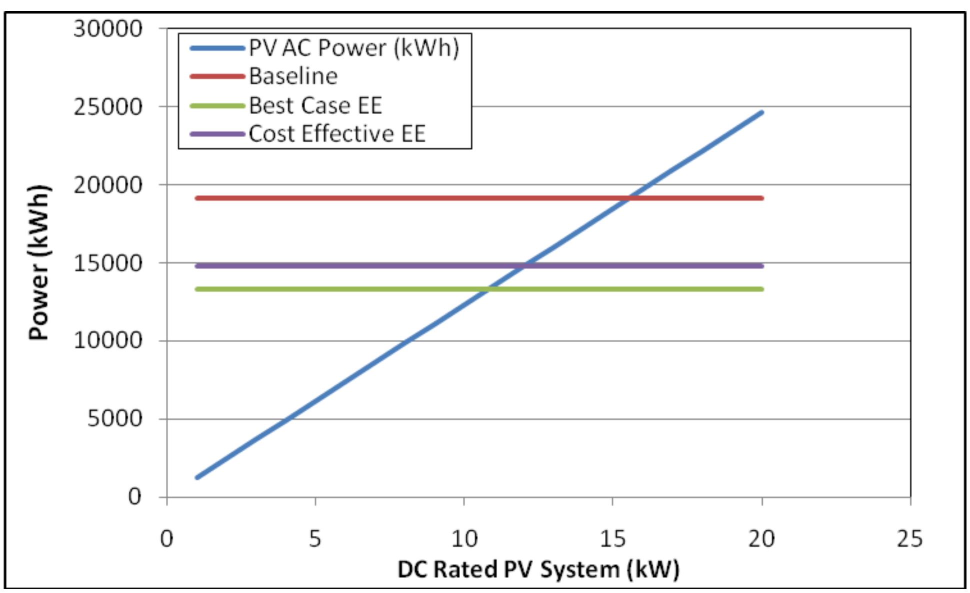

Figure 9.3: PV System Sizing Based on Home Energy Consumption Simulations

Using the average national solar installation price of $9/Watt a 16kW PV system would initially cost the homeowner $144,000. According to the DOE program "Open PV," in 2010 Tennessee's PV installation costs ranked 32nd among U.S. States with an average PV installation cost of $8.85/Watt [49]. However, to aide in solar installations, there is an un-capped 30% federal tax rebate/incentive for solar installations and a 1,000 instant rebate from the Tennessee Valley Authority which would bring the total cost for this 16kW PV system to $99,800.

As can be seen in Figure 9.3, when the best-case energy efficient upgrades are implemented, the annual test home energy consumption was simulated to be 13,353.11 kWh. To offset all of this total annual electricity consumption a PV system rated at 11 kW would need to be installed on-site. The roof area for an 11 kW system would be about 1,100 ft^2 which easily fits within the area restrictions of the southern-facing roof on this test home. An 11 kW PV system would cost about $68,300 to install using the national average cost and subtracting out possible rebates and tax incentives. This is $31,500 less than the PV system needed to cover the baseline energy needs.

Lastly, when the cost effective energy efficient upgrades are implemented on this test home, the annual home energy consumption was simulated to be 14,777 kWh. To offset all of this electricity consumption a PV system rated at 12 kW would need to be installed. The roof area for a 12 kW system would be about 1,200 ft^2 which would also easily fit within the area on the southern-facing roof. A 12 kW PV system would cost about $74,600 to install using the national average cost and subtracting rebates. This is $25,200 less than a system to cover the baseline energy needs but $6,300 more than the best case energy upgrades.

The Tennessee Valley Authority Green Power Switch™ program offers to purchase 100% of the clean, renewable solar energy from residential solar installations back from the residential homeowner at a 12 c/kWh premium over the local electricity utility rate. Therefore, if the local utility rate for electricity is 9 c/kWh, TVA will pay the homeowner 21 c/kWh of solar energy put back onto the utility's grid. This extra incentive helps decrease the long payback periods associated with the initial investment of PV systems. For example, TVA will purchase the 14,808 kWh of solar power generated by the 12 kW system described above at a premium rate of 21 c/kWh. This would amount to $3,109.68 annually from TVA. With an initial investment of $74,600 it would take nearly 24 years to payback the startup cost for this PV system.

To bring the goal of a Chattanooga zero-energy building closer to realization, the power consumption of this test home would need to be further reduced to accommodate a smaller PV installation. This would help ease the initial investment requirements from homeowners. Typically, 4 kW is the “starting point” for residential applications, and this corresponds to an annual power output (and annual home energy consumption for a zero-energy building) of about 5,000 kWh [49]. This represents a 74% reduction from this test home’s baseline energy consumption. Indeed a TVA owned zero-energy building in the nearby city of Oak Ridge, Tennessee lists a total annual energy consumption less than 5,000 kWh and this home makes extensive use of some of the energy efficient upgrades discussed in this report.

Chapter 10

Conclusions and Recommendations

The results of the preceding energy simulations in this thesis demonstrate the potential power and utility savings associated with energy efficient upgrades to a residential building's lights, infiltration mitigation, insulation, windows, and electronics/appliances.

The LED lighting set showed the most energy savings for lighting upgrades. The LED lighting conditions annually consumed 791.96 kWh/yr of electricity. This is an 82.7% electrical energy savings from the 4,568.3 kWh/yr incandescent (base-line) condition. This would reduce the annual utility cost associated with the lights from $411.17/yr to $71.28/yr. Despite showing the most energy (and money) savings, the LED lights would cost a staggering $4,054.30 to purchase and install. This makes the LED light substitutions unattractive for most home owners with a high payback period of 11.9 years. Future LED lighting techniques hold great promise for energy efficient lighting when the initial cost is reduced.

The CFL lighting set showed the least energy savings of the three simulation sets; however, the energy savings for full CFL lighting conditions over incandescents is still significant. The CFL lighting conditions annually consumed 1,479.2 kWh/yr of electricity. This is a 67.6% electrical energy savings from the 4,568.3 kWh/yr incandescent (base-line) condition. This would reduce the annual utility cost associated with the lights from $411.17/yr to $133.13/yr. The major selling feature of the CFL lighting set is the relatively inexpensive purchase and installation cost. The CFL light substitutions would only cost $376.85 to implement. This makes CFL replacements very attractive for home owners with a low payback period of only 1.35 years.

The combination set of LED and CFL bulbs shows great promise for both energy savings and cost minimization. The combination set annually consumed 994.65 kWh/yr of electricity which is a 78.2% energy savings over the base-line lighting set. This would reduce the annual utility cost associated with the lights to $89.52/yr. The combination set would cost $1,670.38 to implement, which is still a fairly large investment for most home owners. Future optimizations should be done to decide the proper mixture of CFL and

LED bulbs. This should be aimed at reducing the initial investment while maintaining the most energy savings possible. Based on the initial investment, energy savings, and payback period at this time it is recommended that an optimized combination of LED and CFL lighting upgrades should be implemented for residential applications. Buildings that require larger amounts of day-time lighting such as commercial/office complexes can make use of daylighting techniques such as sun tubes.

Sealing leakage areas around a home can be a relatively inexpensive, easy way for a home owner to see immediate energy savings. According to infiltration simulations an annual electrical power savings of 753 kWh/yr (electricity consumption from 5,020 kWh to 4,267 kWh) could be seen by simply making simple improvements consisting of mostly caulking and weather stripping home leakage areas. Also, the home owners can expect to annually conserve 14.77 Therms of natural gas due to decreased heating loads imposed by infiltration. These two utility savings equate to $83.40 savings each year on utility expenditures. These savings are based on current rates and any increase in electricity or gas rates will provide even more monetary savings. The home improvements recommendations listed should cost no more than $200.00 to complete. This equals a simple payback period of 2.4 years at the longest. Since this is a very manageable payback period considering the initial investment is relatively small compared to most home energy efficient projects, it is recommended that infiltration mitigation techniques be implemented on this residential building.

Upgrading the insulating structures of a building will reduce the heating and cooling loads due to heat gain/loss through the walls, roof, and floor of a building. This will in turn reduce the energy consumption of the HVAC systems saving energy and money. Six simulation sets were each simulated using the building load estimation software TABLER and the energy (and money) savings of each set were examined to show the variation of possible savings. The payback periods (excluding flooring insulation results) based on individual insulation upgrade energy savings range are significantly high. It was found that the greatest potential for return on investment with insulation upgrades comes from attic insulation improvements. For a home that has an attic covering most of the ceiling area (not like this test home), the potential savings and return on investment for upgraded attic insulation will be much better than these simulations show. The greatest annual energy savings came from installing R-5 wall sheathing insulation and upgrading the wall cavity insulation to R-15 as recommended by ORNL. These improvements annually saved 345 kWh/yr of HVAC electricity consumption and 7 Therms/yr of natural gas, totaling $39/yr utility savings each year. This insulation upgrade represented a mid-range investment and since the energy savings were the greatest, this insulation upgrade is recommended. Recent research has showed similar results to this simulation; unless there is a glaring deficiency in the insulation systems of a home, the energy savings seen from insulation upgrades are small compared to other energy efficient upgrade options. It should be noted that these simulations were performed for Chattanooga, TN and residential buildings in other climate zones (especially in colder regions) will see better energy savings with insulation upgrades.

Upgrading the window systems in a home has become one of the most popular home improvement projects. According to these simulations replacing the current, clear, double-paned widows by SeriousWindows™ 725 series energy efficient windows will reduce the total (annual) HVAC power consumption to remove the heating/cooling loads attributed to the windows and insulation (walls and windows) 3,173.66 kWh/yr. The total utility savings (electricity and natural gas) over the course of a year would be $276.60/yr when these windows are installed. Despite these savings, the high installation cost ($8,125) of the window replacements revealed a payback on investment of 29.4 years. However, if "after-market" 3M CM40 solar coatings were to be installed on the current home window systems, the total (annual) HVAC power consumption to remove the heating/cooling loads attributed to the coated windows and insulation (walls and windows) was reduced 2,159.19 kWh/yr. The total utility savings (electricity and natural gas) over the course of a year would be $190.60/yr when these coatings are applied. The payback on this investment ($400) would be about 2.1 years. Therefore, based on savings and investment, employing these solar coatings on the current windows appears to be a better choice for residential implementation.

The plug and process (appliance) load of a home represents a considerable amount of the overall home energy consumption. According to estimations made using power meter measurements, the electronics (televisions, audio-video equipment, computers and peripherals, etc) and the plugged in appliances (refrigerator and clothes washer) of this home will consume 3,828.51 kWh/yr of power annually. Of this total value, 490.7 kWh/yr will be when the devices are in standby mode, and 469.21 kWh/yr will be when the devices are turned OFF altogether. This is known collectively as the phantom or vampire load of the home and it totals 959.92 kWh/yr ($86.39/yr) annually (note this is just for the measurable, plugged-in devices). Utilizing best practices and power management techniques such as turning devices off when not in use (instead of running standby mode), and cutting the supply of power to powered-OFF devices via "kill-switches" or power strips, it was estimated that about 50% of the standby power load and about 85% of the OFF power load could be saved by these home owners. This corresponds to an annual savings of 644.18 kWh/yr or $57.98/yr for little to no investment cost. These power savings are 3.5% of the home's current average annual electricity consumption. Greater conservation gains could be realized if more stringent power management strategies are adopted and energy efficient electronics (televisions, computers, etc) are utilized. Since plug loads represent a significant portion of home energy, and the procedures ("upgrades") to reduce these loads are very cost effective, it is recommended that the upgrades and power management strategies discussed be implemented in this test home.

The results found in these simulations can be extended with additional consideration for commercial buildings. There is an opportunity for greater energy savings with for these building (commercial structures) because of their larger window, lighting, and plug / process loads.

This test home under investigation can be converted to a zero-energy building by installing a 16kW PV solar installation on the southern facing roof to generate the needed estimated power. This would be rather expensive for most residential customers. Optimal sizing of the PV panels, battery storage system (storing the energy for use at night time), and an appropriate contract with the local utility for "green-power" generation can yield a very attractive payback period after the aforementioned energy efficient upgrades are employed to reduce the total energy consumption of this test home.

For example, when taking into account the “best-case” energy efficient upgrades discussed in Chapter 8 of this report, only an 11kW PV system would need to be installed to completely cover the home’s annual energy consumption. This would save the homeowner substantial upfront investment.

It is recommended that energy efficiency research be continued with addition of state of the art PV panels and battery storage systems for residential buildings located in various cities in the U.S. to establish general guidelines for energy efficient upgrades suitable for different geographical/meteorological locations.

Refferences:

[1] BBC News. Copenhagen deal: Key points. 19 December 2009. http://news.bbc.co.uk/2/hi/science/nature/8422307.stm

[2] 2009 Annual Energy Review. U.S. Energy Information Administration (DOE). August 2010.

[3] Thermodynamics An Engineering Approach, Cengel, Boles. Sixth Edition. McGraw Hill, NY, NY © 2008.

[4] Electropedia, Electricity Demand. Woodbank Communications Ltd. Chester, United Kingdom © 2005.

[5] Zero Energy Commercial Buildings Consortium. 3 December 2009 Webinar. U.S. Department of Energy Energy Efficiency & Renewable Energy. commercialbuildings.energy.gov

[6] Michale Bluejay INC. ©1998-2011. Electrical consumption: Saving Energy http://michaelbluejay.com/electricity/howmuch.html

[7] United States Department of Energy. Energy Efficiency & Renewable Energy, Energy Savings, Air-Source Heat Pumps: http://www.energysavers.gov/your_home/space_heating_cooling/index.cfm/mytopic=12620

[8] Payne Heating and Cooling. Split-System Heat Pumps. Catalog No. 52PH-1210 11-04 ©2004 Payne Heating & Cooling P.O. Box 70, Indianapolis, IN 46206.

[9] York Heating and Air-Conditioning. The York brand of Johnson Controls, Inc. ©2009 Johnson Controls, Inc. 5005 York Drive, Norman, OK 73069. Latitude Series Gas Furnace Literature: Model TG9S.

[10] ConsumerReports.Org ®. Heating, Cooling, and Air: How powerful an air conditioner do you need? Online Worksheet: http://www.consumerreports.org/cro/appliances/heating-cooling-and-air/air-conditioners/sizing-worksheet/

[11] Tennessee Valley Authority: Fuel Cost Adjustment Information. February 2011. http://www.tva.gov/fuelcost/index.htm

[12] U.S. Energy Information Administration (DOE). Frequently Asked Questions – Electricity. December 22, 2010.

[13] United States Agency for International Development (US AID). Energy Conservation Building Code Tip Sheet: Building Lighting Design. Version 1.0. February 2008.

[14] *How Many Lightbulbs Does it Take to Change the World? One. And You're Looking At It*. Charles Fishman. September 2006. Fast Company. © 2010 Mansueto Ventures LLC. 7 World Trade Center, New York, NY 10007-2195.

[15] CRS Report for Congress. Energy Independence and Security Act of 2007: A Summary of Major Provisions. December 21, 2007.

[16] Energy-Efficient Lighting. Compact Fluorescent Light Bulbs, LED Lights. Eartheasy.com © 2000-2009.

[17] American Society of Heating, Refrigeration, and Air-conditioning Engineers (ASHRAE) 1997 HVAC Fundamentals Handbook. Chapter 28: Nonresidential Cooling and Heating Load Calculations.

[18] American Society of Heating, Refrigeration, and Air-conditioning Engineers (ASHRAE) 1997 HVAC Fundamentals Handbook. Chapter 25: Ventilation and Infiltration.

[19] Grot, R. A. and Clark, R. E., "Air Leakage Characteristics and Weatherization Techniques for Low Income Housing," DOE/ASHRAE Conference on Thermal Performance of Exterior Envelopes of Buildings, Florida, 1979, ASHRAE, Atlanta, GA.

[20] Tamura, G.T & Wilson A. G. 1967a "Pressure differences caused by stack effect in three high buildings". ASHRAE Transactions 73(2), pp II.1.1 – II.1.10,

[21] Colliver, D.G., W. Sun, and W.E. Murphy. 1994. Development of a building component air Leakage database. ASHRAE *Transactions* 100(1):293-305.

[22] Elmroth, A. and Levin. Air Infiltration control in Housing: A guide to international practice.
Swedish Council for Building Research, Stockholm, Sweden. 1983

[23] California Energy Commission Consumer Energy Center. © 2002 -2011. http://www.consumerenergycenter.org/

[24] Building Envelope Research Oak Ridge National Laboratory, Oak Ridge, TN. Insulation Fact Sheet 2008. http://www.ornl.gov/sci/roofs+walls/insulation/ins_01.html.

[25] American Society of Heating, Refrigeration, and Air-conditioning Engineers

(ASHRAE) 1997 HVAC Fundamentals Handbook. Chapter 22: Thermal and Moisture Control in Insulated Assemblies-Fundamentals.

[26] Jetson Green. Design-oriented site for sustainable homes, natural materials, and green technology. Boulder, Colorado. © 2010-2011. http://www.jetsongreen.com/2010/02/aerogel-ultra-thin-super-insulation.html

[27] Modern Practices in Design of Airconditioning and refrigeration systems. Prakash Dhamshala. The University of Tennessee, Chattanooga. College of Engineering 2007.

[28] American Society of Heating, Refrigeration, and Air-conditioning Engineers (ASHRAE) 1997 HVAC Fundamentals Handbook. Chapter 23: Insulated Assemblies-Applications.

[29] Reducing Plug and Process Loads for a Large Scale, Low Energy Office Building: NREL's Research Support Facility. Chad Lobato, Shanti Pless, Michael Sheppy, Paul Torcellini. National Renewable Energy Laboratory. Golden, Colorado. 2011.

[30] Managing Plug Loads. Jessica Rivas. E Source. 11 February 2009. Climate Leaders Web Conference.

[31] EnergyStar.gov. US Environmental Protection Agency (US DOE). Energy Star Product Index and Specifications.

[32] Mr. Electricity. http://michaelbluejay.com/electricity/dryers.html. ©1998-2011 Michael Bluejay, Inc. All Rights Reserved.

[33] The "Geoexchange" project (Geothermal heat pump installation). http://www.thegeoexchange.org/fridge-power-consumption/index.html

[34] Citizens Campaign for the Environment, and Home Energy 1993 and 2001. NY, White Planes. http://www.citizenscampaign.org/about.asp

[35] American Society of Heating, Refrigeration, and Air-conditioning Engineers (ASHRAE) 1997 HVAC Fundamentals Handbook. Chapter 27: Residential Cooling and Heating Load Calculations.

[36] Solartube® Documentation. Solatube Australia PO Box 3429 Tingalpa , QLD 4173. www.solatube.com.au

[37] United States Department of Energy. Energy Efficiency & Renewable Energy, Energy
Savings:
http://www.energysavers.gov/your_home/space_heating_cooling/index.cfm/mytpic=12360.

[38] United States Department of Energy. Efficient Windows.
http://www1.eere.energy.gov/consumer/tips/windows.html.

[39] Energy Codes. [39] Energy Codes. http://www.energycodes.gov/implement
efficient_windows.pdf.

[400] Energy-Efficient Lighting. Compact Fluorescent Light Bulbs, LED Lights. Eartheasy.com
© 2000-2009.

[41] SeriousWindows TM. © 2009 Serious Materials, 1250 Elko Drive, Sunnyvale, CA.
Informational pamphlets from 2009 Chattanooga Home Show.

[42] 3M United States. Residential Window Films.
http://solutions.3m.com/wps/portal/3M/en_US/Window_Film/Solutions/

[43] Tennessee Valley Authority's Energy Right Solutions. "Go Solar: Install a solar system
with help from TVA's Generation Partners." Solar Energy Pamphlet ©2010.

[44] National Renewable Energy Laboratory. Solar Maps.
http://www.nrel.gov/gis/solar.html

[45] Perez, R. "Modeling Daylight availability and Irradiance Components from Direct and
Global Irradiance." Solar Energy 1986.

[46] Appropriate Technologies. ITACA; Calculating Solar Angles
http://www.itacanet.org/eng/elec/solar/sun3.pdf

[47] Dhamshala, Prakash. Chapter 4 "Building Loads and Energy Estimating Methods."

[48] Dhamshala, Prakash. Madhu, Bhavin. "Reaching Zero Electrical Energy Building by Use of
Grid-Connected Hybrid Systems of PV panels and Wind Turbines."

[49] National Renewable Energy Laboratories (NREL). PV Watts Version 1.0: A Performance Calculator for Grid-Connected PV Systems.
http://rredc.nrel.gov/solar/calculators/PVWATTS/version1/

Appendix

Appendix A: Cooling Load Factor (CLF) for Lighting

On For	Number of Hours after Lights Turned On																							
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
	Zone Type A																							
8	0.85	0.92	0.95	0.96	0.97	0.97	0.97	0.98	0.13	0.06	0.04	0.03	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
10	0.85	0.93	0.95	0.97	0.97	0.97	0.98	0.98	0.98	0.98	0.14	0.07	0.04	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.01
12	0.86	0.93	0.96	0.97	0.97	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.14	0.07	0.04	0.03	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.02
14	0.86	0.93	0.96	0.97	0.98	0.98	0.98	0.98	0.98	0.98	0.99	0.99	0.99	0.99	0.15	0.07	0.05	0.03	0.03	0.03	0.02	0.02	0.02	0.02
16	0.87	0.94	0.96	0.97	0.98	0.98	0.98	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.15	0.08	0.05	0.04	0.03	0.03	0.03	0.02
	Zone Type B																							
8	0.75	0.85	0.9	0.93	0.94	0.95	0.95	0.96	0.23	0.12	0.08	0.05	0.04	0.04	0.03	0.03	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.01
10	0.75	0.86	0.91	0.93	0.94	0.95	0.95	0.96	0.96	0.97	0.24	0.13	0.08	0.06	0.05	0.04	0.04	0.03	0.03	0.03	0.03	0.02	0.02	0.02
12	0.76	0.86	0.91	0.93	0.95	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.24	0.14	0.09	0.07	0.05	0.05	0.04	0.04	0.03	0.03	0.03	0.03
14	0.76	0.87	0.92	0.94	0.95	0.96	0.96	0.97	0.97	0.97	0.97	0.98	0.98	0.98	0.25	0.14	0.09	0.07	0.06	0.05	0.05	0.04	0.04	0.03
16	0.77	0.88	0.92	0.95	0.96	0.96	0.97	0.97	0.97	0.98	0.98	0.98	0.98	0.98	0.98	0.99	0.25	0.15	0.1	0.07	0.06	0.05	0.05	0.04

Appendix A (Cont.): Cooling Load Factors (CLF) for Lighting

On For	Number of Hours after Lights Turned On																							
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
	Zone Type C																							
8	0.72	0.8	0.84	0.87	0.88	0.89	0.9	0.91	0.23	0.15	0.11	0.09	0.08	0.07	0.07	0.06	0.05	0.05	0.05	0.04	0.04	0.03	0.03	0.03
10	0.73	0.81	0.85	0.87	0.89	0.9	0.91	0.92	0.92	0.93	0.25	0.16	0.13	0.11	0.09	0.08	0.08	0.07	0.06	0.06	0.05	0.05	0.04	0.04
12	0.74	0.82	0.86	0.88	0.9	0.91	0.92	0.92	0.93	0.94	0.94	0.95	0.26	0.18	0.14	0.12	0.1	0.09	0.08	0.08	0.07	0.06	0.06	0.05
14	0.75	0.84	0.87	0.89	0.91	0.92	0.92	0.93	0.94	0.94	0.95	0.95	0.96	0.96	0.27	0.19	0.15	0.13	0.11	0.1	0.09	0.08	0.08	0.07
16	0.77	0.85	0.89	0.91	0.92	0.93	0.93	0.94	0.95	0.95	0.95	0.96	0.96	0.97	0.97	0.97	0.28	0.2	0.16	0.13	0.12	0.11	0.1	0.09
	Zone Type D																							
8	0.66	0.72	0.76	0.79	0.81	0.83	0.85	0.86	0.25	0.2	0.17	0.15	0.13	0.12	0.11	0.1	0.09	0.08	0.07	0.06	0.06	0.05	0.04	0.04
10	0.68	0.74	0.77	0.8	0.82	0.84	0.86	0.87	0.88	0.9	0.28	0.23	0.19	0.17	0.15	0.14	0.12	0.11	0.1	0.09	0.08	0.07	0.06	0.06
12	0.7	0.75	0.79	0.81	0.83	0.85	0.87	0.88	0.89	0.9	0.91	0.92	0.3	0.25	0.21	0.19	0.17	0.15	0.13	0.12	0.11	0.1	0.09	0.08
14	0.72	0.77	0.81	0.83	0.85	0.86	0.88	0.89	0.9	0.91	0.92	0.93	0.94	0.94	0.32	0.26	0.23	0.2	0.18	0.16	0.14	0.13	0.12	0.1
16	0.75	0.8	0.83	0.85	0.87	0.88	0.89	0.9	0.91	0.92	0.93	0.94	0.94	0.95	0.96	0.96	0.34	0.28	0.24	0.21	0.19	0.17	0.15	0.14

Appendix B: Zone Types and Zone Parameters for CLF Values

Zone Parameters				Zone Type		
No. Walls	Floor Covering	Partition Type	Inside Shade	Glass Solar	People and Equipment	Lights
1 or 2	Carpet	Gypsum	b	A	B	B
1 or 2	Carpet	Concrete block	b	B	C	C
1 or 2	Vinyl	Gypsum	Full	B	C	C
1 or 2	Vinyl	Gypsum Block	Half to None	C	C	C
1 or 2	Vinyl	Concrete Block	Full	C	D	D
1 or 2	Vinyl	Concrete	Half to None	D	D	D
3	Carpet	Gypsum	b	A	B	B
3	Carpet	Concrete Block	Full	A	B	B
3	Carpet	Concrete Block	Half to None	B	B	B
3	Vinyl	Gypsum	Full	B	C	C
3	Vinyl	Gypsum	Half to None	C	C	C
3	Vinyl	Concrete Block	Full	B	C	C
3	Vinyl	Concrete Block	Half to None	C	C	C
4	Carpet	Gypsum	b	A	B	B
4	Vinyl	Gypsum	Full	B	C	C
4	Vinyl	Gypsum	Half to None	C	C	C

Appendix C: Baseline Incandescent Home Lighting Conditions

	Light Bulb	#	Lumens ea	Total Lumens	Watts ea	Total Watts	lm/W
Living Room	Sylvania Soft White 60 Standard Bulb	2	850	1700	60	120	14.1667
	Sylvania Soft White Double Life 75	1	1055	1055	75	75	14.0667
	Sylvania 15172 BR30 Indoor Flood Light (Recessed)	7	640	4480	65	455	9.84615
Front Entry	GE 40 Decorative Pointed Display Bulb	6	455	2730	40	240	11.375
Back Entry	Energy Wise 50 Narrow Indoor Flood	3	660	1980	50	150	13.2
Dining Room	Sylvania Soft White 60 Standard Bulb	5	850	4250	60	300	14.1667
	Sylvania 15172 BR30 Indoor Flood Light (Recessed)	6	640	3840	65	390	9.84615
Fire Place	Energy Wise 50 Narrow Indoor Flood	2	660	1320	50	100	13.2
Desk	Sylvania Soft White 60 Standard Bulb	1	850	850	60	60	14.1667
Kitchen	GE 40 Decorative Pointed Display Bulb	6	455	2730	40	240	11.375
Laundry	Sylvania Soft White 60 Standard Bulb	2	850	1700	60	120	14.1667
Garage	Sylvania Soft White 60 Standard Bulb	2	850	1700	60	120	14.1667
Stairs	Sylvania Soft White 60 Standard Bulb	1	850	850	60	60	14.1667
My Bath	Sylvania Soft White 60 Standard Bulb	2	850	1700	60	120	14.1667
	Linear Fluorescent 40W T12 Commercial	2	2000	4000	40	80	50
Hall	Sylvania Soft White 60 Standard Bulb	2	850	1700	60	120	14.1667
Bed 1	Sylvania Soft White 60 Standard Bulb	4	850	3400	60	240	14.1667
Bed 2	Sylvania Soft White 60 Standard Bulb	3	850	2550	60	180	14.1667
	Sylvania Soft White 60 Standard Bulb	1	850	850	60	60	14.1667
Bed 3	Sylvania Soft White 60 Standard Bulb	5	850	4250	60	300	14.1667
	Sylvania Soft White 60 Standard Bulb	2	850	1700	60	120	14.1667
	Linear Fluorescent 40W T12 Commercial	2	2000	4000	40	80	50
Bath 2	GE 40 Decorative Pointed Display Bulb	6	455	2730	40	240	11.375
My Bed	Sylvania Soft White 60 Standard Bulb	4	850	3400	60	240	14.1667
Back Deck	SLI Lighting 150 Outdoor Flood Light	6	1730	10380	150	900	11.5333
Front Outside	SLI Lighting 150 Outdoor Flood Light	4	1730	6920	150	600	11.5333
	GE 40 Decorative Pointed Display Bulb	3	455	1365	40	120	11.375
				78130	In-Out lm	**5830**	In-Out W
				57765	In Only lm	**4090**	In Only W

Appendix C (Cont.): CFL Home Lighting Replacement Bulbs

	Light Bulb	#	Lumens ea	Total Lumens	Watts ea	Total Watts	lm/W
Living Room	Lumacoil Energy Saving Regular CFL	2	900	1800	13	26	69.2308
	Bright Effects 20 Regular CFL	1	1250	1250	20	20	62.5
	EcoSmart 14 Indoor Flood (Recessed) CFL	7	640	4480	14	98	45.7143
Front Entry	EcoSmart 9 Regular CFL	6	470	2820	9	54	52.2222
Back Entry	GE Energy Smart Indoor Flood (Recessed) CFL	3	720	2160	15	45	48
Dining Room	Lumacoil Energy Saving Regular CFL	5	900	4500	13	65	69.2308
	EcoSmart 14 Indoor Flood (Recessed) CFL	6	640	3840	14	84	45.7143
Fire Place	GE Energy Smart Indoor Flood (Recessed) CFL	2	720	1440	15	30	48
Desk	Lumacoil Energy Saving Regular CFL	1	900	900	13	13	69.2308
Kitchen	EcoSmart 9 Regular CFL	6	470	2820	9	54	52.2222
Laundry	Lumacoil Energy Saving Regular CFL	2	900	1800	13	26	69.2308
Garage	Lumacoil Energy Saving Regular CFL	2	900	1800	13	26	69.2308
Stairs	Lumacoil Energy Saving Regular CFL	1	900	900	13	13	69.2308
My Bath	Lumacoil Energy Saving Regular CFL	2	900	1800	13	26	69.2308
	40 W Fluorescent	**2**	**2000**	**4000**	**40**	**80**	**50**
Hall	Lumacoil Energy Saving Regular CFL	2	900	1800	13	26	69.2308
Bed 1	Lumacoil Energy Saving Regular CFL	4	900	3600	13	52	69.2308
Bed 2	Lumacoil Energy Saving Regular CFL	3	900	2700	13	39	69.2308
	Lumacoil Energy Saving Regular CFL	1	900	900	13	13	69.2308
Bed 3	Lumacoil Energy Saving Regular CFL	5	900	4500	13	65	69.2308
	Lumacoil Energy Saving Regular CFL	2	900	1800	13	26	69.2308
	40 W Fluorescent	**2**	**2000**	**4000**	**40**	**80**	**50**
Bath 2	EcoSmart 9 Regular CFL	6	470	2820	9	54	52.2222
My Bed	Lumacoil Energy Saving Regular CFL	4	900	3600	13	52	69.2308
Back Deck	Bright Effects Outdoor Flood CFL	6	1300	7800	26	156	50
Front Outside	Bright Effects Outdoor Flood CFL	4	1300	5200	26	104	50
	EcoSmart 9 Regular CFL	3	470	1410	9	27	52.2222
				76440	In-Out lm	**1354**	In-Out W
				62030	In Only lm	**1067**	In Only W

Appendix C (Cont.): LED Home Lighting Replacement Bulbs

	Light Bulb	#	Lumens ea	Total Lumens	Watts ea	Total Watts	lm/W
Living Room	Philips EnduraLED Regular 60W Replacement	2	806	1612	8	16	100.75
	Philips EnduraLED Regular 60W Replacement	***1***	***806***	***806***	***8***	***8***	***100.75***
	EcoSmart 15 Indoor Flood (Recessed) LED	7	725	5075	15	105	48.3333
Front Entry	Phillips 8 Regular LED	6	450	2700	8	48	56.25
Back Entry	EcoSmart 15 Indoor Flood (Recessed) LED	3	725	2175	15	45	48.3333
Dining Room	Philips EnduraLED Regular 60W Replacement	5	806	4030	8	40	100.75
	EcoSmart 15 Indoor Flood (Recessed) LED	6	725	4350	15	90	48.3333
Fire Place	EcoSmart 15 Indoor Flood (Recessed) LED	2	725	1450	15	30	48.3333
Desk	Philips EnduraLED Regular 60W Replacement	1	806	806	8	8	100.75
Kitchen	Phillips 8 Regular LED	6	450	2700	8	48	56.25
Laundry	Philips EnduraLED Regular 60W Replacement	2	806	1612	8	16	100.75
Garage	Philips EnduraLED Regular 60W Replacement	2	806	1612	8	16	100.75
Stairs	Philips EnduraLED Regular 60W Replacement	1	806	806	8	8	100.75
My Bath	Philips EnduraLED Regular 60W Replacement	2	806	1612	8	16	100.75
	Linear Fluorescent 40W T12 Commercial	***2***	***2000***	***4000***	***40***	***80***	***50***
Hall	Philips EnduraLED Regular 60W Replacement	2	806	1612	8	16	100.75
Bed 1	Philips EnduraLED Regular 60W Replacement	4	806	3224	8	32	100.75
Bed 2	Philips EnduraLED Regular 60W Replacement	3	806	2418	8	24	100.75
	Philips EnduraLED Regular 60W Replacement	1	806	806	8	8	100.75
Bed 3	Philips EnduraLED Regular 60W Replacement	5	806	4030	8	40	100.75
	Philips EnduraLED Regular 60W Replacement	2	806	1612	8	16	100.75
	Linear Fluorescent 40W T12 Commercial	***2***	***2000***	***4000***	***40***	***80***	***50***
Bath 2	Phillips 8 Regular LED	6	450	2700	8	48	56.25
My Bed	Philips EnduraLED Regular 60W Replacement	4	806	3224	8	32	100.75
Back Deck	Phillips 16 Outdoor Flood LED	6	850	5100	16	96	53.125
Front Outside	Phillips 16 Outdoor Flood LED	4	850	3400	16	64	53.125
	Phillips 8 Regular LED	3	450	1350	8	24	56.25
				68822	In-Out lm	**1054**	In-Out W
				58972	In Only lm	**870**	In Only W

Appendix C (Cont.): LED and CFL Combination Home Lighting Replacement Bulbs

		#	Lumens ea	Total Lumens	Watts ea	Total Watts	lm/W
Living Room	Lumacoil Energy Saving Regular CFL	2	900	1800	13	26	69.2308
	Bright Effects 20 Regular CFL	***1***	1250	1250	20	20	62.5
	EcoSmart 14 Indoor Flood (Recessed) CFL	7	640	4480	14	98	45.7143
Front Entry	Phillips 8 Regular LED	6	450	2700	8	48	56.25
Back Entry	GE Energy Smart Indoor Flood (Recessed) CFL	3	720	2160	15	45	48
Dining Room	Lumacoil Energy Saving Regular CFL	5	900	4500	13	65	69.2308
	EcoSmart 14 Indoor Flood (Recessed) CFL	6	640	3840	14	84	45.7143
Fire Place	GE Energy Smart Indoor Flood (Recessed) CFL	2	720	1440	15	30	48
Desk	Philips EnduraLED Regular 60W Replacement	1	806	806	8	8	100.75
Kitchen	Phillips 8 Regular LED	6	450	2700	8	48	56.25
Laundry	Philips EnduraLED Regular 60W Replacement	2	806	1612	8	16	100.75
Garage	Lumacoil Energy Saving Regular CFL	2	900	1800	13	26	69.2308
Stairs	Lumacoil Energy Saving Regular CFL	1	900	900	13	13	69.2308
My Bath	Philips EnduraLED Regular 60W Replacement	2	806	1612	8	16	100.75
	40 W Fluorescent	***2***	**2000**	**4000**	**40**	**80**	**50**
Hall	Philips EnduraLED Regular 60W Replacement	2	806	1612	8	16	100.75
Bed 1	Lumacoil Energy Saving Regular CFL	4	900	3600	13	52	69.2308
Bed 2	Lumacoil Energy Saving Regular CFL	3	900	2700	13	39	69.2308
	Lumacoil Energy Saving Regular CFL	1	900	900	13	13	69.2308
Bed 3	Philips EnduraLED Regular 60W Replacement	5	806	4030	8	40	100.75
	Philips EnduraLED Regular 60W Replacement	2	806	1612	8	16	100.75
	40 W Fluorescent	***2***	**2000**	**4000**	**40**	**80**	**50**
Bath 2	Phillips 8 Regular LED	6	450	2700	8	48	56.25
My Bed	Philips EnduraLED Regular 60W Replacement	4	806	3224	8	32	100.75
Back Deck	Bright Effects Outdoor Flood CFL	6	1300	7800	26	156	50
Front Outside	Bright Effects Outdoor Flood CFL	4	1300	5200	26	104	50
	EcoSmart 9 Regular CFL	3	470	1410	9	27	52.2222
				74388	In-Out lm	**1246**	In-Out W
				59978	In Only lm	**959**	In Only W

Appendix D: Component Air Leakage Effective Areas

Component Type	Units (See Notes)	Best Estimate	Minimum	Maximum
Ceiling				
General	cm2/m2	1.8	0.79	2.8
Drop	cm2/m2	0.19	0.046	0.19
Ceiling penetrations				
Whole-house fans	cm2 ea	20	1.6	21
Recessed lights	cm2 ea	10	1.5	21
Ceiling/Flue vent	cm2 ea	31	28	31
Surface-mounted lights	cm2 ea	0.82		
Chimney	cm2 ea	29	21	36
Crawl space				
General (area for exposed wall)	cm2/m2	10	8	17
200 mm by 400 mm vents	cm2 ea	129		
Door frame				
General	cm2 ea	12	2.4	25
Masonry, not caulked	cm2/m2	5	1.7	5
Masonry, caulked	cm2/m2	1	0.3	1
Wood, not caulked	cm2/m2	1.7	0.6	1.7
Wood, caulked	cm2/m2	0.3	0.1	0.3
Trim	cm2/lmc	1		
Jamb	cm2/lmc	8	7	10
Threshold	cm2/lmc	2	1.2	24
Doors				
Attic/crawl space, not weather-stripped	cm2 ea	30	10	37
Attic/crawl space, weather-stripped	cm2 ea	18	8	18.5
Attic fold down, not weather-stripped	cm2 ea	44	23	86
Attic fold down, weather-stripped	cm2 ea	22	14	43
Attic fold down, with insulated box	cm2 ea	4		
Attic from unconditioned garage	cm2 ea	0	0	0
Double, not weather-stripped	cm2/m2	11	7	22
Double, weather-stripped	cm2/m2	8	3	23
Elevator (passenger)	cm2 ea	0.26	0.14	0.35

General, average	cm2/lmc	0.31	0.23	0.45
Interior (pocket, on top floor)	cm2 ea	14		
Interior (stairs)	cm2/lmc	0.9	0.25	1.5
Mail slot	cm2/lmc	4		
Sliding exterior glass patio	cm2 ea	22	3	60
Sliding exterior glass patio	cm2/m2	5.5	0.6	15
Storm (difference between with and without	cm2 ea	6	3	6.2
Single, not weather-stripped	cm2 ea	21	12	53
Single, weather-stripped	cm2 ea	12	4	27
Vestibule (subtract per each location)	cm2 ea	10		
Electrical outlets/Switches				
No gaskets	cm2 ea	2.5	0.5	6.2
With gaskets	cm2 ea	0.15	0.08	3.5
Furnace				
Sealed (or no) combustion	cm2 ea	0	0	0
Retention head or stack damper	cm2 ea	30	20	30
Retention head and stack damper	cm2 ea	24	18	30
Floors over crawl spaces				
General	cm2/m2	2.2	0.4	4.9
Without ductwork in crawl space	cm2/m2	1.98		
With ductwork in crawl space	cm2/m2	2.25		
Fireplace				
With damper closed	cm2/m2	43	10	92
With damper open	cm2/m2	350	145	380
With glass doors	cm2/m2	40	4	40
With insert and damper closed	cm2/m2	36	26	46
With insert and damper open	cm2/m2	65	40	90
Gas water heater	cm2 ea	20	15	25
Joints				
Ceiling-wall	cm2/lmc	1.5	0.16	2.5
Sole plate, floor/wall, uncaulked	cm2/lmc	4	38	5.6
Sole plate, floor/wall, caulked	cm2/lmc	0.8	0.075	1.2
Top plate, band joist	cm2/lmc	0.1	0.075	0.38
Piping/Plumbing/Wiring penetrations				
Uncaulked	cm2 ea	6	2	24
Caulked	cm2 ea	2	1	2
Vents				
Bathroom with damper closed	cm2 ea	10	2.5	20

Bathroom with damper open	cm2 ea	20	6.1	22
Dryer with damper	cm2 ea	3	2.9	7
Dryer without damper	cm2 ea	15	12	34
Kitchen with damper open	cm2 ea	40	14	72
Kitchen with damper closed	cm2 ea	5	1	7
Kitchen with tight gasket	cm2 ea	1		
Walls (exterior)				
Cast-in-place concrete	cm2/m2	0.5	0.049	1.8
Clay brick cavity wall, finished	cm2/m2	0.68	0.05	2.3
Precast concrete panel	cm2/m2	1.2	0.28	1.65
Low-density concrete block, unfinished	cm2/m2	3.5	1.3	4
Low-density concrete block, painted	cm2/m2	1.1	0.52	1.1
High-density concrete block, unfinished	cm2/m2	0.25		
Continuous air infiltration barrier	cm2/m2	0.15	0.055	0.21
Rigid sheathing	cm2/m2	0.35	0.29	0.41
Window framing				
Masonry, uncaulked	cm2/m2	6.5	5.7	10.3
Masonry, caulked	cm2/m2	1.3	1.1	2.1
Wood, uncaulked	cm2/m2	1.7	1.5	2.7
Wood, caulked	cm2/m2	0.3	0.3	0.5
Windows				
Awning, not weather-stripped	cm2/m2	1.6	0.8	2.4
Awning, weather-stripped	cm2/m2	0.8	0.4	1.2
Casement, weather-stripped	cm2/lmc	0.24	0.1	3
Casement, not weather-stripped	cm2/lmc	0.28		
Double horizontal slider, not weather-stripped	cm2/lmc	1.1	0.019	3.4
Double horizontal slider, wood, weather-stripped	cm2/lmc	0.55	0.15	1.72
Double horizontal slider, aluminum, weather-stripped	cm2/lmc	0.72	0.58	0.8
Double-hung, not weather-stripped	cm2/lmc	2.5	0.86	6.1
Double-hung, weather-stripped	cm2/lmc	0.65	0.2	1.9
Double-hung with storm, not weather-stripped	cm2/lmc	0.97	0.48	1.7
Double-hung with storm, weather-stripped	cm2/lmc	0.79	0.4	4 1
Double-hung with pressurized track, weather-stripped	cm2/lmc	0.48	0.39	0.56
Jalousie	cm2/louver	3.38		

Lumped	cm2/lms	0.471	0.009	2.06
Single horizontal slider, weather-stripped	cm2/lms	0.67	0.2	2.06
Single horizontal slider, aluminum	cm2/lms	0.8	0.27	2.06
Single horizontal slider, wood	cm2/lms	0.44	0.27	0.99
Single horizontal slider, wood clad	cm2/lms	0.64	0.54	0.81
Single-hung, weather-stripped	cm2/lms	0.87	0.62	1.24
Sill	cm2/lmc	0.21	0.139	0.212
Storm inside, heat shrink	cm2/lms	0.018	0.009	0.018
Storm inside, rigid sheet with magnetic seal	cm2/lms	0.12	0.018	0.24
Storm inside, flexible sheet with mechanical seal	cm2/lms	0.154	0.018	0.833
Storm inside, rigid sheet with mechanical seal	cm2/lms	0.4	0.045	0.833
Storm outside, pressurized track	cm2/lmc	0.528		
Storm outside, 2-track	cm2/lmc	1.23		
Storm outside, 3-track	cm2/lmc	2.46		

Note: Air Leakage areas are based on values found in literature. The effective air leakage area (in square centimeter) is based on a pressure difference of 4 Pa and Cd = 1. Abbreviations: m^2 = gross area in square meters. Ea = each. Lmc = linear metre of crack. lms = linear metre of sash

Appendix E: ELA Calculations for Whole Test House

	Measured Values:		Metric Units Needed:		A(L) cm^2 / Unit	A(L)
Living Room	Exterior Walls (ft^2):	135	Exterior Walls (m^2):	12.5415	0.15	1.881225
	Ceiling (ft^2):	314.5	Ceiling (m^2):	29.21705	1.8	52.59069
	Outlets (#):	11	Outlets (#):	11	2.5	27.5
	Vents (#):	1	Vents (#):	1	5	5
	Recessed Lights (#):	16	Recessed Lights (#):	16	10	160
	Regular Lights (#):	2	Regular Lights (#):	2	0.82	1.64
	Window Frame (ft^2):	48	Window Frame (m^2):	4.4592	0.3	1.33776
	Window LMC (ft):	50	Window LMC (m):	15.24	0.24	3.6576
	Door Frame (ft^2):	0	Door Frame (m^2):	0	0.3	0
Entry + Back	Exterior Walls (ft^2):	181	Exterior Walls (m^2):	16.8149	0.15	2.522235
	Ceiling (ft^2):	247.5	Ceiling (m^2):	22.99275	1.8	41.38695
	Outlets (#):	4	Outlets (#):	4	2.5	10
	Vents (#):	3	Vents (#):	3	5	15
	Window Frame (ft^2):	358.5	Window Frame (m^2):	33.30465	0.3	9.991395
	Window LMC (ft):	68	Window LMC (m):	20.7264	0.24	4.974336
	Door Frame (ft^2):	42	Door Frame (m^2):	3.9018	0.3	1.17054
Dinning	Exterior Walls (ft^2):	407	Exterior Walls (m^2):	37.8103	0.15	5.671545
	Ceiling (ft^2):	387	Ceiling (m^2):	35.9523	1.8	64.71414
	Outlets (#):	8	Outlets (#):	8	2.5	20
	Vents (#):	1	Vents (#):	1	5	5
	Window Frame (ft^2):	121	Window Frame (m^2):	11.2409	0.3	3.37227
	Window LMC (ft):	104	Window LMC (m):	31.6992	0.24	7.607808
	Door Frame (ft^2):	0	Door Frame (m^2):	0	0.3	0
	Chimney (#)	1	Chimney (#)	1	29	29
	Fireplace (ft^2)	18	Fireplace (m^2)	1.6722	40	66.888

Appendix E (Cont.): ELA Calculations for Whole Test House

	Measured Values:		Metric Units Needed:		A(L) cm^2 / Unit	A(L)
Kitchen	Exterior Walls (ft^2):	115	Exterior Walls (m^2):	10.6835	0.15	1.602525
	Ceiling (ft^2):	149.5	Ceiling (m^2):	13.88855	1.8	24.99939
	Outlets (#):	11	Outlets (#):	11	2.5	27.5
	Vents (#):	2	Vents (#):	2	10	20
	Window Frame (ft^2):	12.25	Window Frame (m^2):	1.138025	0.3	0.3414075
	Window LMC (ft):	16	Window LMC (m):	4.8768	0.24	1.170432
	Door Frame (ft^2):	0	Door Frame (m^2):	0	0.3	0
	Bath Plumbing (#)	2	Bath Plumbing (#)	2	2	4
Laundry	Exterior Walls (ft^2):	230	Exterior Walls (m^2):	21.367	0.15	3.20505
	Ceiling (ft^2):	112	Ceiling (m^2):	10.4048	1.8	18.72864
	Outlets (#):	6	Outlets (#):	6	2.5	15
	Vents (#):	1 Dryer	Vents (#):	1	8	8
	Window Frame (ft^2):	0	Window Frame (m^2):	0	0.3	0
	Window LMC (ft):	0	Window LMC (m):	0	0.24	0
	Door Frame (ft^2):	84	Door Frame (m^2):	7.8036	0.3	2.34108
	hot Water Heater (ft)	1	hot Water Heater (m)	0.3048	1.5	0.4572
Bath 1	Exterior Walls (ft^2):	50	Exterior Walls (m^2):	4.645	0.15	0.69675
	Ceiling (ft^2):	48	Ceiling (m^2):	4.4592	1.8	8.02656
	Outlets (#):	2	Outlets (#):	2	2.5	5
	Regular Lights (#)	2	Regular Lights (#)	2	0.82	1.64
	Vents (#):	1	Vents (#):	1	15	15
	Window Frame (ft^2):	0	Window Frame (m^2):	0	0.3	0
	Window LMC (ft):	0	Window LMC (m):	0	0.24	0
	Door Frame (ft^2):	0	Door Frame (m^2):	0	0.3	0
	Bath Plumbing (#)	2	Bath Plumbing (#)	2	2	4

Appendix E (Cont.): ELA Calculations for Whole Test House

	Measured Values:		Metric Units Needed:		A(L) cm^2 / Unit	A(L)
Bed 1	Exterior Walls (ft^2):	100	Exterior Walls (m^2):	9.29	0.15	1.3935
	Ceiling (ft^2):	110	Ceiling (m^2):	10.219	1.8	18.3942
	Outlets (#):	4	Outlets (#):	4	2.5	10
	Vents (#):	1	Vents (#):	1	5	5
	Recessed Lights (#):	0	Recessed Lights (#):	0	10	0
	Regular Lights (#):	1	Regular Lights (#):	1	0.82	0.82
	Window Frame (ft^2):	10	Window Frame (m^2):	0.929	0.3	0.2787
	Window LMC (ft):	14	Window LMC (m):	4.2672	0.24	1.024128
	Door Frame (ft^2):	0	Door Frame (m^2):	0	0.3	0
Bed 2	Exterior Walls (ft^2):	240	Exterior Walls (m^2):	22.296	0.15	3.3444
	Ceiling (ft^2):	143	Ceiling (m^2):	13.2847	1.8	23.91246
	Outlets (#):	4	Outlets (#):	4	2.5	10
	Vents (#):	1	Vents (#):	1	5	5
	Recessed Lights (#):	0	Recessed Lights (#):	0	10	0
	Regular Lights (#):	1	Regular Lights (#):	1	0.82	0.82
	Window Frame (ft^2):	10	Window Frame (m^2):	0.929	0.3	0.2787
	Window LMC (ft):	14	Window LMC (m):	4.2672	0.24	1.024128
	Door Frame (ft^2):	0	Door Frame (m^2):	0	0.3	0
Bed 3	Exterior Walls (ft^2):	400	Exterior Walls (m^2):	37.16	0.15	5.574
	Ceiling (ft^2):	375	Ceiling (m^2):	34.8375	1.8	62.7075
	Outlets (#):	13	Outlets (#):	13	2.5	32.5
	Vents (#):	2	Vents (#):	2	5	10
	Recessed Lights (#):	0	Recessed Lights (#):	0	10	0
	Regular Lights (#):	4	Regular Lights (#):	4	0.82	3.28
	Vents (#):	1 Bath	Vents (#):	1	15	15
	Window Frame (ft^2):	25	Window Frame (m^2):	2.3225	0.3	0.69675
	Window LMC (ft):	28	Window LMC (m):	8.5344	0.24	2.048256
	Door Frame (ft^2):	42	Door Frame (m^2):	3.9018	0.3	1.17054
	Plumbing (#)	4	Plumbing (#)	4	2	8

Appendix E (Cont.): ELA Calculations for Whole Test House

	Measured Values:		Metric Units Needed:		A(L) cm^2 / Unit	A(L)
Hall	Exterior Walls (ft^2):	0	Exterior Walls (m^2):	0	0.15	0
	Ceiling (ft^2):	84	Ceiling (m^2):	7.8036	1.8	14.04648
	Outlets (#):	2	Outlets (#):	2	2.5	5
	Recessed Lights (#):	0	Recessed Lights (#):	0	10	0
	Regular Lights (#):	2	Regular Lights (#):	2	0.82	1.64
	Window Frame (ft^2):	0	Window Frame (m^2):	0	0.3	0
	Window LMC (ft):	0	Window LMC (m):	0	0.24	0
	Door Frame (ft^2):	0	Door Frame (m^2):	0	0.3	0
Bed 4 (my)	Exterior Walls (ft^2):	170	Exterior Walls (m^2):	15.793	0.15	2.36895
	Ceiling (ft^2):	324	Ceiling (m^2):	30.0996	1.8	54.17928
	Outlets (#):	5	Outlets (#):	5	2.5	12.5
	Recessed Lights (#):	0	Recessed Lights (#):	0	10	0
	Regular Lights (#):	2	Regular Lights (#):	2	0.82	1.64
	Window Frame (ft^2):	12.5	Window Frame (m^2):	1.16125	0.3	0.348375
	Window LMC (ft):	14	Window LMC (m):	4.2672	0.24	1.024128
	Door Frame (ft^2):	0	Door Frame (m^2):	0	0.3	0
	AC Unit in wall!		AC Unit in wall!	1	6	6
Closet (my)	Exterior Walls (ft^2):	68	Exterior Walls (m^2):	6.3172	0.15	0.94758
	Ceiling (ft^2):	72	Ceiling (m^2):	6.6888	1.8	12.03984
	Outlets (#):	2	Outlets (#):	2	2.5	5
	Recessed Lights (#):	0	Recessed Lights (#):	0	10	0
	Regular Lights (#):	1	Regular Lights (#):	1	0.82	0.82
	Window Frame (ft^2):	0	Window Frame (m^2):	0	0.3	0
	Window LMC (ft):	0	Window LMC (m):	0	0.24	0
	Door Frame (ft^2):	17.5	Door Frame (m^2):	1.62575	0.3	0.487725

Appendix E (Cont.): ELA Calculations for Whole Test House

	Measured Values:		Metric Units Needed:		A(L) cm^2 / Unit	A(L)
Attic/Crawl	Exterior Walls (ft^2):	170	Exterior Walls (m^2):	15.793	0.15	2.36895
	Ceiling (ft^2):	198	Ceiling (m^2):	18.3942	1.8	33.10956
	Outlets (#):	0	Outlets (#):	0	2.5	0
	Recessed Lights (#):	0	Recessed Lights (#):	0	10	0
	Regular Lights (#):	1	Regular Lights (#):	1	0.82	0.82
	Window Frame (ft^2):	0	Window Frame (m^2):	0	0.3	0
	Window LMC (ft):	0	Window LMC (m):	0	0.24	0
	Door Frame (ft^2):	0	Door Frame (m^2):	0	0.3	0
	Un-insulated Roof!					

Under Floor Crawl w/ Ducts (ft^2)	2008	**Under Floor Crawl w/ Ducts (m^2)**	186.5432	2.25	419.7222
				cm^2	**1498.9459**
					ELA

Volume of House (m^3)

736.2380116

Appendix F: Air Changes per Hour Computer Code: ACHcal.m

```
% Drew Frye - Mechanical Engineer
% 11-18-2010
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% This program calculates the Air Changes per Hour (ACH) for my house in
% Chattanooga, TN throughout the a typical year using TMY3 Data from NREL
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

clc;
clear all;

% Inputs:
ELA = 1498.946; % (cm^2) - Effective Leakage Area (ELA) Calculated
Cs = 0.000290; % ((L/s)^2/(cm^4*K)) - Stack Coefficient for a Two story
Cw = 0.000231; % ((L/s)^2/(cm^4*(m/s)^2)) Wind Coefficient for a Two story house in Local Shielding
Class 3 (Typical Rural)
HouseVolume = 736.2; % (m^3)
WinterThermostatF = 68; % 68 and 72 "Thermostat Temperatures" (F)
SummerThermostatF = 72; % 68 and 72 "Thermostat Temperatures" (F)
WinterThermostatC = (5/9)*(WinterThermostatF - 32); % Convert to C
SummerThermostatC = (5/9)*(SummerThermostatF - 32); % Convert to C

% Read in Meterological Data from TMY3 File from rrdc.nrel
WeatherData = xlsread('TMY3 Chattanoga.xls'); % Master Weather Excel Sheet
AmbientTempC = WeatherData(3:8762,32); % Ambient Air Temperature C
WindSpeed = WeatherData(3:8762,47); % Ambient Wind Speed m/s
% Set inside air temperature throughout the year (Thermostat Setting) in a vector
for ii = 1:1:8760 % hours in a year (24 per day for 365 days)
  if ii < 2200 % (January to Mid April "Winter")
    Tinside(ii) = WinterThermostatC; % Degrees C
  elseif (ii >= 2200) & (ii <= 8000) % (Mid April to Late November "summer")
    Tinside(ii) = SummerThermostatC;
  else % (Late November to end of December "Winter")
    Tinside(ii) = WinterThermostatC;
  end
end
Tinsidesave = [Tinside]'; % Puts Inside air Temperature row vector into a column vector like Weather
Data
DeltaT = abs(Tinsidesave - AmbientTempC); % Absolute value of the outside and inside air temperature
Airflow = (ELA/1000)* sqrt((Cs.*DeltaT) + (Cw.*(WindSpeed).^2)); % Air Flow Rate due to Infiltration
(m^3/s)
Airflowhour = Airflow.*3600; % Infiltration air flow rate (m^3/hr)
ACH = Airflowhour / HouseVolume; % Air Changes Per Hour (ACH)
MaxACH = max(ACH)
AvgACH = sum(ACH)/8760

% End Program %
```

Appendix G: Solar Calculator Computer Code: Test_Solar_new.m

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Solar Calculations                  %
% Mechanical Engineer Drew Frye 2010   %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Program Notes: The solar Declination angle, solar Hour angle, solar Altitude angle, solar Azimuth
angle, and solar Zenith angle are calculated for a specified Latitude/Location for a 24 hour day for 365
days. From this, the angle of Incidence for a specified Photovoltaic position (Known: Tilt and PV-
Azimuth) can be determined. Using TMY3 or Annual "Solar Anywhere (tm)" Data, Solar Irradiation
Incident on a Photovoltaic Panel can be found. This can be used to examine PV characteristics such as
power output, cell temperature, and many other performance parameters.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

clc;
clear all;

% Geographical Parameters %
TiltD = 35.03; % Solar Panel Tilt from Horizon set to Latitude in Degrees
AzsD = 180; % Surface Azimuth Measured CW from Due North; South = 180
TiltR = TiltD*(pi/180); % PV Tilt from Horizon set to Latitude in Radians
AzsR = AzsD*(pi/180); % Solar Panel Azimuth Angle Measured in Radians

% Chattanooga, TN Information %
LatD = 35.03; % Chattanooga Latitude in Degrees
LatR = 35*(pi/180); % Convert to Radians
LongD = 85.20; % Chattanooga Longitude in Degrees
LongR = LongD*(pi/180); % Convert to Radians
LongEasternD = 75; % Standard Longitude for Eastern Time Zone Degrees
LongEasternR = (pi/180)*LongEasternD; % Standard Longitude for Eastern Time Zone Radians

% Solar Panel Parameters - Sharp NT-175U1 Pannels %
Voc = 44.4; % Open Circuit Voltage (V)
Vmp = 35.4; % Maximum Power Voltage (V)
Isc = 5.40; % Short Circuit Current (A)
Imp = 4.95; % Maximum Power Current (A)
Pmax = 175; % Maximum Power (W) at STC = 25C, 1 kW/m^2, AM 1.5
Pmin = 157.5; % Minimum Power (W) at STC = 25C, 1 kW/m^2, AM 1.5
EffcP = 16.20; % Encapsulated Cell Efficiency (%)
EffmP = 13.45; % Module Efficiency (%)
NOCT = 47.5; % Normal Operating Cell Temperature (C)
AP = -0.053; % Module Current (Isc) Temperature Coefficient (% / degree C)
BP = -0.36; % Module Voltage (Voc) Temperature Coefficient (% / degree C)
CP = -0.485; % Module Max Power (Pmax) Temp Coefficient (%/degree C)
PanelAreaMeter = 1.3; % Single Panel Area (m^2)
EffinverterP = 97; % Inverter Efficiency (%) (Sunny Boy)
A = AP/100; % Module Current (Isc) Temperature Coefficient (A / degree C)
B = BP/100; % Module Voltage (Voc) Temperature Coefficient (V / degree C)
```

```
C = CP/100; % Module Max Power (Pmax) Temperature Coefficient (W/degree C)
Effc = EffcP/100; % Encapsulated Cell Efficiency
Effm = EffmP/100; % Module Efficiency
Effinverter = EffinverterP/100; % Inverter Efficiency (Sunny Boy)

% Solar Irradiation Calculations %
for n = 1:1:365; % Julian Day Counter- January 1 = 1 and December 31 = 365
  Etime(n) = (9.87*sin(2*(((360*(n - 81))/364)*(pi/180)))) - (7.53*cos((((360*(n-81))/364)*(pi/180)))) -
(1.5*sin((((360*(n-81))/364)*(pi/180)))); % Equation of Time
  stepdeclR(n) = ((-1)*sin(23.45*(pi/180)))*cos(((360*(n+10))/365.25)*(pi/180));
  declR(n) = asin(stepdeclR(n)); % Declination Angle in Radians
  declD(n) = declR(n)*(180/pi); % Declination Angle in Degrees

  jj = 0; % Initialize Counter
  for ii = 1:1:24; % Hour Counter (24 Hours in a day)
    Localtime(ii) = 1 + jj; % Counts Local Time stating at 1:00 am (Like TMY3)
    Solartime(ii) = Localtime(ii) + ((LongEasternR - LongR) / (15*(pi/180))) + (Etime(n)/ 60); % Solar
time as a func of Local Time
    hourangleR(ii) = (((360*(pi/180))*(Solartime(ii) - 12)) / 24); % Solar Hour Angle in Radians

% Solar Altitude Angle Calculations:
StepAltitudeR(ii) = ((sin(declR(n))*sin(LatR)) + (cos(declR(n)).*cos(hourangleR(ii))*cos(LatR)));
AltitudeR(ii) = asin(StepAltitudeR(ii)); % Solar Altitude Angle in Radians
AltitudeD(ii) = AltitudeR(ii)*(180/pi); % Solar Altitude Angle in Degrees

% Solar Azimuth Angle Calculations:
PreStepAzimuthR(ii) = ((cos(declR(n)) * sin(hourangleR(ii))) / (cos(AltitudeR(ii))));

StephlimitR(n) = acos(tan(declR(n)) / tan(LatR)); % "hlimit" Goswami et al. (2000) finds houranlge
corresponding to sun due East/West

if LatR > declR(n) % hlimit is only valid for Latitude greater than Declination angle on that day
  hlimitR(n) = StephlimitR(n);
else
  hlimitR(n) = 0; % Otherwise hlimit is zero
end

% For Solar Azimuth Angles Greater than 90 Degrees Logic must be used to maintain an Azimuth Angle
> 90 using the hlimit %
if hourangleR(ii) > hlimitR(n)
  SolarAzimuthR(ii) = (pi - asin(PreStepAzimuthR(ii))); % Solar Azimuth Angle in Radians
elseif hourangleR(ii) < (-1)*hlimitR(n) % For Azimuth Angles less than -90 Logic must be used to get
Azimuth Angles < -90 Degrees
    SolarAzimuthR(ii) = (-1)*(pi + asin(PreStepAzimuthR(ii))); % Solar Azimuth Angle in Radians
  else
    SolarAzimuthR(ii) = asin(PreStepAzimuthR(ii)); % For -90 < Azimuth Angle < 90 Inverse Sine is
valid and no hlimit is needed
  end
```

```
SolarAzimuthD(ii) = (SolarAzimuthR(ii) * (180/pi)); % Solar Azimuth Angle in Degrees

% Solar Zenith Angle Calculations:
ZenithR(ii) = acos((cos(LatR)*cos(declR(n))*cos(hourangleR(ii))) + (sin(LatR)*sin(declR(n)))); % Solar
Zenith Angle in Radians
ZenithD(ii) = ZenithR(ii)*(180/pi); % Solar Zenith Angle in Degrees

% Solar Angle of Incidence on the Solar Panel Calculations:
StepIncidenceR(ii) = (sin(declR(n))*sin(LatR)*cos(TiltR)) +
(sin(declR(n))*cos(LatR)*sin(TiltR)*cos(AzsR)) +
(cos(declR(n))*cos(LatR)*cos(TiltR)*cos(hourangleR(ii))) -
(cos(declR(n))*sin(LatR)*sin(TiltR)*cos(AzsR)*cos(hourangleR(ii))) -
(cos(declR(n))*sin(TiltR)*sin(AzsR)*sin(hourangleR(ii)));
IncidenceR(ii) = acos(StepIncidenceR(ii)); % Angle of Incidence in Radians
IncidenceD(ii) = IncidenceR(ii)*(180/pi); % Angle of Incidence in Degrees

    % Save "ii" Loops Values
    save(ii) = ii; % Save the ii counter
    dayLocaltime(save) = Localtime; % Save 24 hours worth of Local Time for this (n) day
    daySolartime(save) = Solartime; % Save 24 hours worth of Solar Time for this (n) day
    dayhourangleR(save) = hourangleR; % Save 24 hours worth of Solar Hour Angles for this (n) day in
Radians
    dayhourangleD(save) = hourangleR*(180/pi); % Save 24 hours worth of Solar Hour Angles for this
(n) day in Degrees
    dayAltitudeRsave(save) = AltitudeR; % Save 24 hours worth of Solar Altitudes for this (n) day in
Radians
    dayAltitudeDsave(save) = AltitudeD; % Save 24 hours worth of Solar Altitudes for this (n) day in
Degrees
    daySolarAzimuthRsave(save) = SolarAzimuthR; % Save 24 hours of Solar Azimuth for this (n) day
in Radians
    daySolarAzimuthDsave(save) = SolarAzimuthD; % Save 24 hours of Solar Azimuth for this (n) day
in Degrees
    dayZenithRsave(save) = ZenithR; % Save 24 hours of Solar Zenith for this (n) day in Radians
    dayZenithDsave(save) = ZenithD; % Save 24 hours of Solar Zenith for this (n) day in Degrees
    dayIncidenceRsave(save) = IncidenceR; % Save 24 hours of Incidence Angles for this (n) day in
Radians
    dayIncidenceDsave(save) = IncidenceD; % Save 24 hours of Incidence Angles for this (n) day in
Degrees

    jj = jj + 1; % Step the counter by 1

  end % End of the ii (24 hours) loop

 % Save "n" Loop Values
 day(n) = n; % Save the Julian Day
 Localtimematrix(n,:) = dayLocaltime; % Save each 24 hours of Local time (1:00 am - "24:00" midnight)
 Solartimematrix(n,:) = daySolartime; % Save each 24 hours of Solar time (at 0 Solar time the sun is
directly overhear)
```

```
  houranglematrixR(n,:) = dayhourangleR; % Save each 24 hours of Hour Angles in Annual Solar Hour
Angle Matrix (Radians)
  houranglematrixD(n,:) = dayhourangleD; % Save each 24 hours of Hour Angles in Annual Solar Hour
Angle Matrix (Degrees)
  AltitudeRmatrix(n,:) = dayAltitudeRsave; % Save each 24 hours of Altitudes in Annual Solar Altitude
Matrix (Radians)
  AltitudeDmatrix(n,:) = dayAltitudeDsave; % Save each 24 hours of Altitudes in Annual Solar Altitude
Matrix (Degrees)
  SolarAzimuthRmatrix(n,:) = daySolarAzimuthRsave; % Save each 24 hours of Solar Azimuths in
Annual Solar Azimuth Matrix (Radians)
  SolarAzimuthDmatrix(n,:) = daySolarAzimuthDsave; % Save each 24 hours of Solar Azimuths in
Annual Solar Azimuth Matrix (Degrees)
  SolarZenithRmatrix(n,:) = dayZenithRsave; % Save each 24 hours of Solar Zenith in Annual Solar
Azimuth Matrix (Radians)
  SolarZenithDmatrix(n,:) = dayZenithDsave; % Save each 24 hours of Solar Zenith in Annual Solar
Azimuth Matrix (Degrees)
  SolarIncidenceRmatrix(n,:) = dayIncidenceRsave; % Save each 24 hours of Incidence Angles in Annual
Solar Azimuth Matrix (Radians)
  SolarIncidenceDmatrix(n,:) = dayIncidenceDsave; % Save each 24 hours of Incidence Angles in Annual
Solar Azimuth Matrix (Degrees)

end % End of the n (Julian Day) loop

% % Plot Azimuth vs Altitude for the 21st of each month and compare this to plot in Alternative Energy
System Applications pg. 137
% plot(SolarAzimuthDmatrix(21,:),AltitudeDmatrix(21,:), 'yo--' ,
SolarAzimuthDmatrix(52,:),AltitudeDmatrix(52,:), 'gx--' ,
SolarAzimuthDmatrix(80,:),AltitudeDmatrix(80,:), 'k*--' ,
SolarAzimuthDmatrix(111,:),AltitudeDmatrix(111,:), 's--' ,
SolarAzimuthDmatrix(141,:),AltitudeDmatrix(141,:), 'd--' ,
SolarAzimuthDmatrix(172,:),AltitudeDmatrix(172,:), 'v-' ,
SolarAzimuthDmatrix(202,:),AltitudeDmatrix(202,:), 'p--' ,
SolarAzimuthDmatrix(233,:),AltitudeDmatrix(233,:), 'h--' ,
SolarAzimuthDmatrix(264,:),AltitudeDmatrix(264,:) , '<--' ,
SolarAzimuthDmatrix(294,:),AltitudeDmatrix(294,:), '>--' ,
SolarAzimuthDmatrix(325,:),AltitudeDmatrix(325,:), 'r+--' ,
SolarAzimuthDmatrix(355,:),AltitudeDmatrix(355,:), 'bo-')
% xlabel('Azimuth Angle');
% ylabel('Altitude Angle');
% title(' Azimuth vs Altitude for the 21st of Each Month');
% legend('Jan', 'Feb', 'Mar', 'Apr', 'May', 'Jun', 'Jul', 'Aug', 'Sep', 'Oct', 'Nov', 'Dec');
% % Looks good! %

% Change Matrix into Column Vector like the data in TMY3
StepSolarIncidenceRvector = (SolarIncidenceRmatrix)'; % Transpose 365x24 Matrix into a 24x365
Matrix
SolarIncidenceRvector = StepSolarIncidenceRvector(:); % String out Matrix by columns (column1 on top
of column2 on top of 3 ....)
SolarIncidenceDvector = SolarIncidenceRvector*(180/pi); % Convert Solar Incidence Angles to Degrees
```

```
CosineSolarIncidenceRvector = cos(SolarIncidenceRvector); % Take cosine for Incident Solar
Calculations in Radians
CosineSolarIncidenceDvector = CosineSolarIncidenceRvector*(180/pi); % % Cosine of Incident Anlges
in Degrees

% Read in Meterological Data from TMY3 File from rrdc.nrel
WeatherData = xlsread('TMY3 Chattanoga.xls');
GHI = WeatherData(3:8762,5); % Global Horizontal Irradiance (W/m^2)
DNI = WeatherData(3:8762,8); % Direct Normal Irradiance (W/m^2)
DHI = WeatherData(3:8762,11); % Diffuse Horizontal Irradiance (W/m^2)
GHILLU = WeatherData(3:8762,14); % Global Horizontal Illuminance (lux)
DNILLU = WeatherData(3:8762,17); % Direct Normal Illuminance (lux)
DHILLU = WeatherData(3:8762,20); % Diffuse Horizontal Illuminance (lux)
AmbientTempC = WeatherData(3:8762,32); % Ambient Air Temperature C
WindSpeed = WeatherData(3:8762,47); % Ambient Wind Speed m/s

% Total Solar Incident on Surface
StepDirectRadiation = DNI.*CosineSolarIncidenceRvector; % Need tp Insert 0 for Negative Direct
Radiation values
DirectRadiation = (StepDirectRadiation > 0).*StepDirectRadiation; % Direct (beam) Radiation on
Surface Per Hour (W/m^2)
DiffuseRadiation = DHI.*((1 + cos(TiltR)) / 2); % Diffuse Radiation on Surface Per Hour (W/m^2)
ReflectedRadiation = 0.5*0.2*(1 - cos(TiltR)).*GHI; % Reflected Radiation on Surface Per Hour
(W/m^2)

TotalRadiation = DirectRadiation + DiffuseRadiation + ReflectedRadiation; % Total Solar Radiation on
Surface Per Hour (W/m^2)
AnnualTotalRadiation = sum(TotalRadiation); % Annual Total Solar Radiation on the Surface (W/m^2)
KWHAnnualTotalRadiation = (AnnualTotalRadiation/1000); % Annual Total Solar Radiation on the
Surface (kWh/m^2)

% Solar Panel System Calculations %
Tcell = ((0.943.*AmbientTempC) + (0.028.*TotalRadiation) - (1.528.*WindSpeed) + 4.3); % PV Cell
Temperature (C)
DeltaT = Tcell - 25;
DeltaI = (((A.*(TotalRadiation ./ 1000)).*DeltaT) + (((TotalRadiation ./ 1000) - 1)*Isc));
V = ((Vmp.*(1 + (0.0539.*(log10(TotalRadiation ./ 1000))))) + (B.*DeltaT)); % PV Module Voltage (V)
Division by 0 gives "NAN"
DeltaV = V - Vmp;
Ctwo = (((Vmp/Voc) - 1) / log((1 - (Imp/Isc))));
Cone = ((1 - (Imp/Isc))*(exp(((-1)*Vmp)/(Ctwo*Voc))));
I = ((Isc*(1 - (Cone*((exp((V - DeltaV)/(Ctwo*Voc)) - 1))))) + DeltaI); % PV Module Current (A)
PowerCell = (V.*I); % PV Module Power (P=VxR) (Watts)
NANs = isnan(PowerCell); % Finds the location of "NANs" (Need to remove NANs for summation)
PowerCell(NANs) = 0; % Replace "NANs" in Power Cell Vector with 0
% PowerCell(PowerCell > Pmax) = Pmax; % maximum Power cut off for each Module
AnnualPowerCell = sum(PowerCell); % Annual Power of One PV Module (Watts)
AnnualkWhPowerCell = AnnualPowerCell / 1000 % Annual Power of One PV Module (kW)
```

% 1.672E3 kW/m^2 Annual Total Radiation on Surface (line 170) gives 2173.6 kW per year.
% AnnualkWhPowerCell says 302.0366 kW. That is 13.8 % Efficiency which is what is listed as Cell Efficiency from Sharp!

```
% End Program %
```