ABSTRACT

Title of Document: ANALYSES OF RESIDENTIAL BUILDING ENERGY SYSTEMS THROUGH TRANSIENT SIMULATION

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This thesis examines the performance of residential buildings and the energy systems contained within those buildings by simulating them in the TRaNsient SYstems Simulation (TRNSYS) program. After matching a building's floorplan to that of house local to the College Park area, national and local building surveys were consulted to produce a prototype of the average Maryland home. This home was simulated with ordinary insulation levels, heating, ventilation, and air conditioning (HVAC) equipment, and appliances. Various construction characteristics, including wall insulation, thermostat set points, HVAC equipment, and appliance efficiency were varied to examine the effects of each individual change upon the final annual energy consumption of the building, and in doing so, the value of retrofitting each characteristic was explored. Finally, the most effective energy-saving strategies were combined to model a low-energy home, in order to explore the possibility of refitting an existing home to become a net-zero site energy building. Sensitivity study results were listed, and a net-zero-energy building was successfully simulated.

Analyses of Building Energy System Alternatives through Transient Simulation

By

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Dedication

This thesis is dedicated to the good people of the CEEE. Paraphrasing the words of a colleague, who said it better than I could hope to myself; their energetic enthusiasm, professional dedication, and matchless moral fortitude leave me confident that the future of the engineering profession is in good hands, and whose sheer aptitude leaves me no doubt that the current engineering crises of the world have met their match.

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1. Introduction

The United States of America has, as of late, experienced a wake-up call of massive proportions regarding the health of the environment. For years, since the beginning of the Industrial Revolution, pollution and energy consumption had always been a secondary topic. In the past decades, however, the environment has become an increasingly important issue in the eyes of Americans. An annual Gallup poll finds that Americans have considered the protection of the environment more important than the economy for the past seven years (2002-2008) [1]. A major focus of this new environmental concern has been global warming, and perhaps more specifically, carbon emissions, as a result of a slew of scientific reports finding adverse trends in the global climate, including, most famously, those released by the United Nations Environment Programme's Intergovernmental Panel on Climate Change. This specific concern has begun to pervade the public arena, both in the cinema, where such films as *The Day After Tomorrow* and *An Inconvenient Truth* have enjoyed widespread, mainstream attention, and in daily life, where attention to global warming has increasingly become part of advertising campaigns for numerous everyday products.

As a result of the new strength of this fixation, political forces have begun to engage more intently with the environment as an issue, with the 2009 stimulus package dedicating approximately 55 billion dollars to promoting environmental protection procedures and energy-saving measures [2]. A large part of this money, approximately 24 billion, has been devoted to building new homes and refitting old homes to decrease overall energy consumption as well as strain on the electrical grid. Such measures have included rewarding tax credits and loan guarantees to homeowners who have purchased renewable energy technology and energy-efficient appliances, renovating and modernizing public housing units, and funding technological research with the aim of improving efficiency and bringing down prices at the point-of-sale.

The focus on building energy efficiency is understandable, considering that in the United States buildings utilize more energy than any other sector of the economy, consuming approximately 40% of its energy and 76% of its electricity annually [3,4]. Residential buildings alone account for approximately 22% of the nation's energy consumption [5], and as such, the improvement of energy efficiency in residential buildings has been approached with particular interest; however, significant challenges lie in the way of making progress in that area. In a search to increase the share of electricity generated from renewable sources and to reduce consumption overall, individual houses present great potential for reducing nationwide energy consumption because of recent technological improvements, and also provide a means through which to generate on-site renewable energy, mainly through the use of their rooftops for solar energy collection, rather than to use remotely-generated grid power.

1.1 Acceptance of Energy Efficient Technologies

After a gradual rise in energy prices since the beginning of the war in Iraq, and a particularly jarring spike in the price of gasoline in 2005, alternative sources of energy and energy efficiency began to gain more and more attention by the media, politicians, and as a result, the average American consumer [6]. However, many energy-efficient technology choices have not yet been absorbed into the mainstream of residential building attributes, despite the fact that many such energy-saving devices have been shown to be wise long-term financial investments. A number of economic and sociological studies have investigated the phenomena preventing green technology from being accepted by the free market and by the general public.

The penetration of energy efficient technology into the residential sector depends a great deal upon the confidence level of the average American consumer in their viability as reliable and cost-saving devices. Wuestenhagen writes that three main factors will determine the ability of renewable technology to break into the mainstream: sociopolitical acceptance, community acceptance, and market acceptance.[7] While the concept of moving away from fossil fuels to cheaper and infinite energy sources (temporally speaking) like sunlight has been met with great enthusiasm by the general public of America, he says that individual citizens have to grow to trust these technological innovations before they can be used in a widespread manner, and the market must in turn see this trust and individual acceptance as a representation of a potential customer base before they will produce large-enough quantities of these technologies.

Coombs recognizes a variety of obstacles to widespread adoption of energy-saving technology [8]. Among these are the strength of incumbent technologies, such as the large amount of sociopolitical power resting with the fossil-fuel industry, the lack of existent support systems (for sake of clarity one might consider the absence of hydrogen fuel pumps at many gas stations), and lack of communication of the public's need for the product. Among his recommendations for overcoming such obstacles are passing favorable legislation to nurture the growth of the relatively young and fragile technology's market share, which as mentioned previously, is being undergone, and to communicate clearly to the potential customer base the benefits of the technology can provide them as individuals.

As an immature industry, renewable energy systems are expensive to produce, and their high costs have prevented widespread adoption, but compounding the problem of prohibitive cost is the fact that the energy systems remain unnervingly novel and foreign to many American consumers. To combat this unfamiliarity, the government, particularly the Department of Energy and many state governments, have pursued a variety of campaigns dedicated to informing the general public of the environmental and financial benefits of making energy-saving building modifications. However, despite the campaigns and the fact that many renewable technologies present cost-saving opportunities, many current energy-efficient technologies remain untapped by the mainstream of American residential buildings. This thesis serves to provide a method by which the merits and disadvantages of these technologies can be understood.

1.2 Value of Retrofit

The retrofitting of currently standing buildings is challenging, but it is a necessary task if the energy consumption of the nation's buildings is to be decreased. Studies of the service lives of residential buildings estimate that the average lifespan of a house is as much as 90 years, and some last much longer [9,10]. This would suggest that the building codes dictating the quality of new-construction buildings will not reach the whole of the U.S. building stock only very gradually. Thus, although designing new residences to be energy efficient is indeed a key part of ensuring an energy efficient future, the above service life estimations suggest that relying on solely those new designs would not be sufficient to counteract the rapidly-moving climatic changes reported by the IPCC, and that retrofit plays a very important role in reducing energy consumption and pollutant emissions in a timely manner.

1.3 Simulation

As the speed of computer processors continues to grow, simulation has become an increasingly accessible and powerful tool in the building research community, and has been adopted because of its ability to estimate real-life conditions without the expense of "hard" resources and funds. Numerous programs, varying in levels of specificity and breadth of scope, have been developed. TRNSYS is one of the many tools for building energy analysis [11]. Developed by the

University of Wisconsin at Madison, the program was originally designed to simulate the transient performance of a solar hot water system, but has expanded in scope to simulate the performance of many types of energy systems. TRNSYS' main, and, generally considered, most promising feature is its modularity, and the flexibility that comes with such an approach. Given the wide variety of layouts of household HVAC, hot water, and controls systems, TRNSYS is particularly well-suited due to its ability to allow for the creation of new components, which allows for the exploration of new technologies far more easily than in less flexible software. The particular strength of TRNSYS in evaluating complex thermal systems such as a modern home is reiterated in past studies comparing each major competitor software program in the thermal simulation community [12]. Also, although TRNSYS' base code was not altered in this simulation, TRNSYS' code is also highly modifiable, being written in FORTRAN, a common engineering programming language. The value of using TRNSYS and the decision-making process used for purchasing TRNSYS instead of any other software package has been explained in a past CEEE thesis [13].

2. Literature Review

2.1. Simulation of Residences

There have been numerous studies concerning simulation of low-energy residences. Many of these have been feasibility studies, conducted in order to verify expectations of building energy performance within a given climate, or to test specific, new-construction buildings' expected energy consumption levels.

The main focus of much simulation has been in the building of new energy-efficient and zero-energy houses. Such examples may be seen in the work of Tse (2007) [14], who used TRNSYS as a tool to determine the design of a new set of net-zero-energy townhomes in the Toronto area. Another study made use of TRNSYS to simulate the feasibility of constructing a new low-rise home in the Netherlands which would meet zero-net-energy status [15]. Another investigates the possibility of constructing such a home in the cold and windy weather of Newfoundland [16].

The program created and the simulations performed during the course of this thesis undoubtedly are of some value for designing new residential buildings with superior energy performance. However, the main focus is not on new construction, but rather on retrofits, and providing data regarding the effects of possible modifications on building energy consumption and human comfort.

2.2. Retrofit Simulation

The concept of using simulation software to model retrofit savings has indeed been used previously in academic studies, although not in a widespread manner. Despite the existence of the already mentioned studies, retrofit analysis studies have not been widely performed on single-family residences. Most research has been done on specific buildings of large energy consumption. There are logical reasons for this pattern. Truly accurate building models require an exhaustively detailed survey of such things as a building's particular geometry, its behavior with respect to infiltration, and many times these involved processes yield no results that can be transferred over to other buildings, which each have their own set of idiosyncrasies. Thus large scale projects are routinely the only situations in which the potential immediate savings in energy consumption are worth the effort of creating such a detailed simulation. A study at Texas A&M University in 1991 utilized simulation software to study the effect of retrofitting a laboratory with a variable air volume HVAC system instead of the dual duct constant volume system it had, which involved simulating two buildings, of equal size, layout, and envelope, and examining the energy used by each system to condition this standard load [17]. Another study by NIST uses TRNSYS to explore the effect of air-tightness upon an office building's energy consumption [18].

Only one paper found in this literature review has attempted to explore the importance of a wide range of residential building attributes as is done in this thesis. It was performed by Verbeeck and Hens, with the intention of determining the most cost-effective available envelope and HVAC system option [19]. Verbeeck and Hens conducted an analysis of real buildings in Belgium, and engaged in simplified building simulations by use of calculation procedures developed by the Belgian Laboratory of Building Physics. The simulation mentioned, however, was not a transient simulation, instead compiling annual estimates to create one building net energy consumption level. In addition to providing a transient evaluation of building performance, this thesis intends to explore further characteristics of the building, including building controls, and to allow for the simulation of additional space conditioning and water heating system layouts.

As Verbeeck notes, the majority of building simulation projects are undertaken in order to explore one option of improving a building's energy efficiency, rather than comparing the effectiveness of an array of options. While many separate studies have investigated individual energy-saving modifications, this thesis intends to compare the various options on a single home, providing more consistency than to compare different modifications effects on different building layouts. This thesis will examine a wide variety of building characteristics to demonstrate each characteristic's importance to the building's annual energy consumption. Each characteristic has been investigated to some extent previously and therefore the history surrounding the study of each will be presented along with that series of simulations.

3. Objectives

The objectives of this thesis are threefold. First, the thesis investigates the importance of many building characteristics in determining the final annual energy consumption of a building by undergoing a sensitivity analysis, in order to shed light on which aspects of a building's construction are most deserving of attention when retrofitting a house for energy savings. In doing so, it explores the feasibility of various building energy systems for use in the vicinity of College Park, MD, by comparing the effects of some of the many options for space-conditioning, water heating, insulation, and appliances on the total annual energy performance of a College Park area home.

Second, the model is meant to provide a realistic building model on which to simulate future CEEE projects. The model is currently being used to provide a check for the sufficiency of capacity in the CEEE's experimental combined heating and power unit. Future potential projects could be first simulated on the building model before being attached to an actual building, to ensure the ability of a system to meet a building's conditioning requirements by providing a theoretical estimation of actual building system performance.

Third, the program has been designed to act as the first step towards a program, which, in the future, could allow homeowners to simulate their own house's annual energy consumption, and to compare, for example, the costs and benefits of installing different space-conditioning systems. The personalized analysis would then allow the homeowner to estimate the energy savings he or she might achieve by making energy-efficient modifications to his or her building. The program has been designed such that a number of common building modifications can be selected and compared to a baseline home to provide such data.

4. Simulation Tool Development

The building analysis tool is based on a variety of components, each of which performs calculations to simulate the behavior of a certain aspect of the building's operation. The following section will present an overview of the methods used in creating the simulation program, including assumptions made and the mathematical equations inherent to the operation of certain important components. Figure 1 Displays the Simulation's overall structure. Each arrow indicates an information flow from one component to another, for example, the "weather macro" component outputs outdoor temperature data, which is then inputted into the "Building Models" component to provide the temperature for heat transfer calculations. The notable components, which will be described in further detail, are:

- The "Building Models," which contain information concerning the layout of the buildings simulated in this thesis, and, accordingly, their heat and humidity transfer characteristics
- The "Weather Macro," which contains data concerning the building's local environment
- The "HVAC Macro," which contains information concerning the operation of the buildings' Heating, Ventilation, and Air Conditioning (HVAC) systems,
- The "Energy Macro," which sums and arranges total energy consumption data over the entire year

- The “PV Macro”, which receives insolation data from the Weather Macro and simulates photvoltaic conversion of light into electrical energy
- The “Hot Water Macro,” which receives hot water demand data from an Excel spreadsheet and calculates the energy required by a water-heating system to meet those demands.

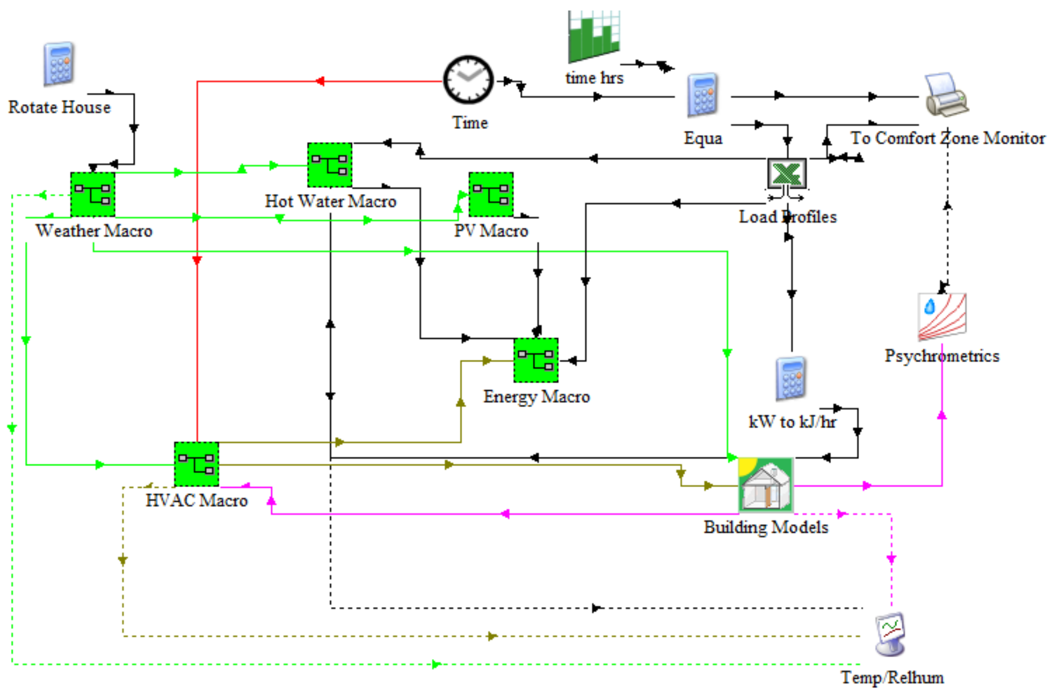


Figure 1: Overall Simulation Structure

4.1. Building

4.1.1 TRNBUILD

The building model is constructed within the sister program to TRNSYS, TRNBUILD. TRNBUILD models the building by simulating each thermal zone, in this case, basically each room of the house, as a single node, rather than modeling any geometrical shape. Properties are therefore uniform throughout each thermal zone, which is an important consideration when evaluating the attainable level of certainty. Two important balance equations exist for each point in this nodal structure: the energy balance and the humidity balance. All equations in Section 4.1.1 were drawn from the TRNBUILD manual.

4.1.1.1 Heat Flows

For each timestep TRNBUILD performs the following balance:

$$Q_{internal} = Q_{conv,surface} + Q_{conv,infiltration} + Q_{conv,ventilation} + Q_{conv,adj\ space} + Q_{conv,internal} + Q_{rad,solar} \quad (1)$$

Where $Q_{internal}$ is total heat flux into the thermal zone, and is comprised of surface convection from walls $Q_{conv,surface}$, convective heat gains as a result of infiltration $Q_{conv,infiltration}$, convective gains occurring from airflows from adjacent zones $Q_{conv,adj\ space}$, heat gains created within the zone, and radiative gains $Q_{rad,solar}$.

4.1.1.2. Thermal Capacitance Values

A very important part of a TRNBUILD design lies in the determination of the thermal capacitance of each thermal zone, since this value determines the zone's ability to retain heat, and also the amount of energy introduction needed from the HVAC system to raise the temperature to the desired set point, as is denoted by the following equation:

$$T_{i,\tau} = T_{i,\tau-1} + \frac{\overline{\dot{Q}_{\Delta\tau}}}{\rho V C_p} \tag{2}$$

An entirely empty zone would have a thermal capacitance of approximately 1.2 times its volume because it would be full of air. When the room is filled with objects, this number is much more difficult to estimate, because the amount of furniture, types of material in the pieces of furniture, and other factors must be determined to make any accurate calculation of thermal capacitance. TESS, the leading group of experts on TRNSYS building simulations, recommends a thermal capacitance value of 6 to 12 times the volume of the room as a rule of thumb when evaluating TRNSYS thermal zones [20]. This guideline was followed in the development of the building model by estimating each capacitance at 7.5 times the volume of the space, excepting the basement and attic, which were modeled with capacitances 3 times their volumes, since those spaces presumably would have less furniture, etc within them.

4.1.1.3 Humidity flows

TRNBUILD is designed to use either of two models of humidity transfer: a buffer-storage model and a more simplified capacitance model. The buffer-storage method makes use of three variables to quantify the ability of the zone node to hold humidity, the storage ability of the contents within the zone (deep storage), and the storage ability of the walls surrounding the zone (surface storage). The capacitance model reduces these variables to one coefficient of humidity capacitance, similar to a thermal capacitance. In this model, the capacitance method was used. In future versions, when further detail is proposed as to the contents of each zone (furniture, etc), the buffer-storage method could prove to be useful, but since little such detail is known about furniture in this simulation of a hypothetical building, the capacitance method was chosen.

The capacitance method works as follows: a humidity capacitance ratio C, is multiplied by the mass of air to produce a total moisture capacity for the room. The humidity capacitance ratio was determined by consulting values recommended by the creators of TRNSYS for rooms in residential buildings, and set at the value of 5 [21]. .

$$M_{eff} = C * m_{air} \tag{3}$$

The moisture addition rate is then calculated similar to the heat transfer mechanism:

$$M_{eff,i} * \frac{\partial \omega_i}{\partial t} = m_{inf} * (\omega_a - \omega_i) + \sum^{vents} (m_{vent,i} * (\omega_v - \omega_i)) + \omega_g$$

$$+ \sum^{surf} (m_{adj} * (\omega_j - \omega_i)) \quad (4)$$

Where ω_a is the ambient humidity ratio, ω_i is the zone's humidity ratio, $m_{vent,i}$ is the mass flow rate of ventilation, ω_v is the humidity ratio of ventilated air, ω_g is humidity produced within the zone, m_{adj} is the mass flow rate of coupled air flows from adjacent zones, and ω_j is the humidity ratio of a particular adjacent zone.

4.1.1.4 Relationship Between Thermal Energy and Humidity

TRNBUILD models humidity entirely separately from thermal energy. Using a mass balance based on absolute humidity values, the water content of the room is calculated at each time step, and in conjunction with the temperature levels determined by the heat equations, other psychrometric values are calculated, including relative humidity. In this particular simulation, TRNBUILD does not deal with, for example, the use of furnace heat to evaporate water in a humidifier.

Those are done externally to TRNBUILD by components in the HVAC macro. These HVAC components run on performance maps, which, given a set of return temperatures, return humidities, and outdoor temperatures, outputs a particular sensible heat factor of heat removal (that is, sensible energy removed divided by total (sensible and latent) energy removed), energy consumption, and set of conditions for the supply air. Thus thermodynamic equations are not used to determine conversion of sensible energy into latent energy. Instead, tabulated observed output values of HVAC equipment are used.

4.1.2 Building Layout & Floor Area

The building's dimensions are modeled upon a sample two-story, detached residential building in the College Park area. The layout of the building is somewhat simplified. It consists of a bottom floor of four rooms, each 308 square feet (11x14), or 28.61 m^2 (designated as a living room, a dining room, a kitchen, and an entertainment room; and a top floor of two rooms, each of 716 square feet (57.22 m^2). The total amount of finished floor space is 2464 square feet (228.91 m^2).

This square footage is slightly smaller than the national average floor area for new, detached, single-family residential buildings, which was 2519 square feet, according to census data compiled in 2008, and slightly smaller than the mean floor area for the Southern census region (in which Maryland is included), which was 2564 square feet [22]. The median floor area for new single family homes, in the nation and in the South respectively, were 2215 and 2312 square feet. The great difference in these mean and median values results from the large number of small, lower-class residences and the comparatively small number of significantly larger, high-income housing. It should be noted, however, that the average floor space has steadily increased over the past three decades, as can be seen in Figure 2. Thus, its similarity in size to 2008's new houses prove that the sample house geometry by no means represents a house out of the mainstream. However, the fact that the average size of a new home is almost 50% larger than those built only 25 years ago allows the assumption that it is slightly above average. Furthermore, a Census report from 2001 estimated that the average age of a U.S. house was 32 years [23]. This statistic, if still true for today, would make the average floor area of existing homes nearer 1800 sq ft, making the modeled building significantly larger than average when compared to all existent homes rather than just newly constructed homes. The point of relative size is important when comparing each house with average energy consumption data, since, logically, a larger-than-normal home will consume larger-than normal amounts of energy. This relative size is important when comparing house properties, such as heating consumption, to tabulated average values.

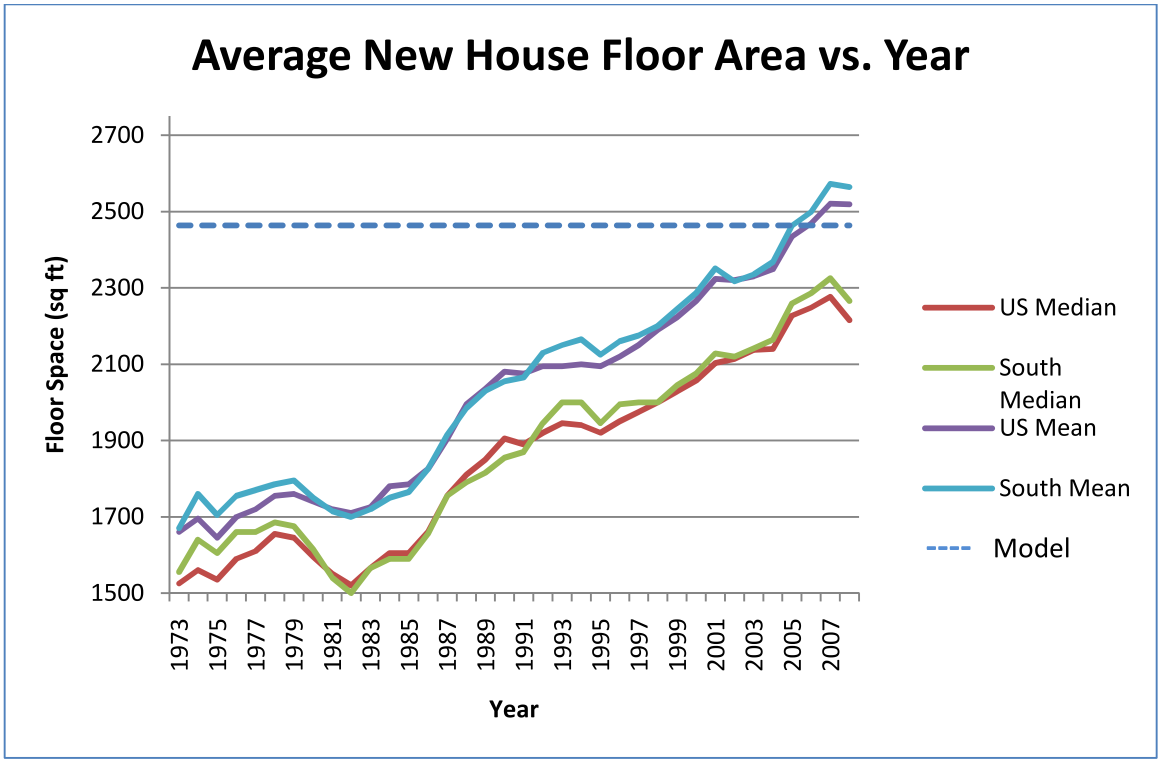


Figure 2: Average New House Floor Area vs. Year. Data taken from a 2008 U.S. Census Bureau Report [24].

The ceilings of each finished zone are modeled to be the standard height of 8 feet (2.5 m). Thus the total conditioned volume is 19712 cubic feet, or equivalently 558 cubic meters. There is also an unconditioned basement of 1432 square feet and 7 ft (2.13 m) high walls, assumed to be surrounded on all sides by earth, and an unconditioned attic, of the same square footage as the basement but with a pitched ceiling, rising at a grade of 36 degrees to a middle height of 10.7 ft (3.26 m). The grade of the roof was determined by consulting generally accepted building construction guidelines, which define "normal" roof slopes as those between 30 and 45 degrees from the horizontal [25]. The roof has an area of 1377 sq ft (128 m^2), half of which is later assumed to be available for either solar photovoltaic or thermal collectors. This roof square footage assumes zero overhang. Overhang areas were considered to be negligible in the thermal analysis of the building in all things other than shading from radiative heat transfer. Although conduction from these areas will occur, the level of such was assumed to be negligible. An overview of the building's major characteristics can be seen in Table 1.

Building	
Floor Area	2464 sq ft (228.91m^2)
Conditioned air volume	19712 cu ft (558 m2
Ceiling height	8 ft (2.5 m)
Length	22 ft (6.7 m)
Width	48 ft (14.6 m)
Total height (incl bsmt)	42.7 ft (13.0 m) 50.7 ft (15.45 m)

Table 1: Building Characteristics

4.1.3. Low-Energy Building Model

TRNSYS only allows one Type56 component (building model) in each simulation, so in order to simulate both a baseline house and a modified house, the abovementioned set of rooms was duplicated to create a second house that was identical in size but whose energy systems and insulation materials could be modified to allow the exhibition of energy consumption differences achieved by changes in appliances and envelope construction. It should be noted that two entirely separate systems were not created. In order to reduce the number of computations made in each time step, the buildings were assumed to share certain qualities. In particular, the water systems and the setback schedules were shared. The effects of these assumptions will be discussed at a later point in the thesis.

4.1.4. Fenestration

Windows are a necessary feature in a building: they provide visual comfort by offering views of the outdoors; they provide natural lighting, a source of heat, and a means of natural ventilation of the building. However, in many cases windows are a source of strain on the energy efficiency of buildings. They are consistently the weak point in a building's thermal envelope. Windows are routinely the source of much infiltration into a building, since in most cases in residential buildings they are meant to be opened and therefore cannot be perfectly sealed to the rest of the wall. Windows are also a major example of what is called "cold-bridging," or, more accurately, thermal bridging, which occurs when a highly conductive material reaches from the inside of the envelope to the outside, providing a path for high rates of heat transfer from the interior of the building to the exterior, or vice versa.

Because of windows' inherent negative effects on the energy performance of a building's envelope, certain limits have been placed upon the amount of glazed surfaces in buildings. The building code for new residential buildings in the State of Maryland conforms to the IRC and IECC [26], which uses a 15% window area to wall area ratio as its standard for recommending window performance [27]. Thus a 15% ratio was modeled in the building. Each external wall on the main floor was modeled as having 15% of its area taken up by windows. No data was found concerning an average window-to-wall ratio, thus this building was used as the baseline. However, since many buildings must not follow this code since they were built previous to the year 2009, when the code was put into law, and therefore the majority of Maryland houses could have a window-wall ratio greater than this value.

In the baseline model, the windows were modeled as double-pane windows of U-value U-.35, in accordance with regulations set by the 2009 IECC, which limited U-values to that number. Each baseline window was modeled as clear glass, meaning that no material properties had been altered in order to restrict wavelengths of light outside the visible spectrum from entering the building, as is done in the case of shaded or low-emissivity (low-e) windows.

4.1.5. Insulation

The interior walls of the baseline building, that is, those separating rooms from other rooms, were constructed of the same material in both building models. More specifically, they were constructed of 2x4, 16 inches on center frame construction, with gypsum drywall. The frame construction of the house was simulated in TRNBUILD by producing two simulated walls for each actual wall, both consisting of gypsum board on their exteriors, one containing 3.5 inches of air space, and another containing 3.5 inches of wood. The areas of these two sub-walls are then modified to imitate the existence of one, whole, studded wall. These walls were all constructed to be 8 ft (~2.5m) tall, as is standard in residential building construction.

As for exterior walls, in the baseline model, the walls exhibit the same frame construction as the interior walls, but with fiberglass batt insulation filling the void rather than air. This form of insulation is termed “cavity insulation,” and is subject to thermal bridging since the wood, of much higher conductivity than the fiberglass, provides a less resistive path for heat to progress across the building envelope. This effect is mimicked by creating the two sections of wall. The outside of these walls then have a brick face. Overall this configuration produces an insulation level of R-12.5.

The basement is surrounded by concrete walls and a concrete floor, both of insulation value R-10. These insulation values are in accordance with the recommendations of the IECC. These IECC Guidelines are generally in accordance with ASHRAE Standards 62.2 and 90.2, respectively, "Ventilation and Indoor Air Quality," and "Energy Efficient Design of Low-Rise Residential Buildings."

	Base	2009 IECC
Exterior Walls	R-12.5	R-13
Basement	R-10	R-10
Ceilings (Attic)	R-33	R-38
First floor	R-17	R-19
Windows, Doors	U-.35	U-0.35 (R-2.86)
Infiltration	.454 average	7 ACH50 (~.44 ACH)

Table 2: Insulation Levels

4.1.6. Infiltration

The default infiltration model in TRNBUILD simply uses a constant rate of air exchange with the outside. It employs the units of air-changes per hour, meaning the number of times the volume of air in a room is replaced by air from the outside in one hour. Infiltration is caused by three main phenomena:

- Temperature differences across the building envelope
- Wind velocity
- Pressurization caused by fans

Given the first two causes, which are highly variable throughout the year, a constant infiltration rate would not be an accurate model of reality. Therefore, a calculator was put in place to determine the expected amount of infiltration through the building's envelope at each time step, the development of which will be discussed in the following section.

Infiltration is routinely measured by a "blower door test" during which a fan pumps air into the envelope of the building, and air-change rate is measured by computing the difference between the actual pressure inside the building and the ideal pressure which would exist in a perfectly-sealed building. This measurement is typically performed by pressurizing the building to 50 Pa above atmospheric pressure, and the measured infiltration rate is recorded in ACH50, or “air changes per hour at 50 Pa.” In the past, a rule of thumb has been used to estimate the level of infiltration at normal pressure levels, namely

ACH=ACH50/20 [28]

This equation yields reasonable results [28], but it neglects the fact that infiltration rates change depending on external weather conditions, and being developed by Princeton University, was correlated to only a few houses in New Jersey, and thus does not allow for variation in climate. An attempt at achieving a more accurate average ACH rating was undertaken by Sherman (1987) [29] which allowed for differences in housing construction. This equation, for the region of Washington DC, yields the equation

ACH=ACH50/16 [29]

The IECC has set standards for the infiltration rate into buildings. As mentioned above in Table 2, the blower-door test must find a new home to have a rating of 7 ACH50. Sherman’s estimate approximates to a .4375 ACH constant infiltration rate in the home.

However, more specific equations have been created to allow for the transient nature of the infiltration phenomenon. The ASHRAE Handbook of Fundamentals provides equations that detail the causes of infiltration, and these equations were included in the building simulation construction to more accurately model the home’s thermal conditions on an hour-by-hour basis [30]. These ASHRAE equations, which calculate stack effect and wind effect infiltration, will be listed and explained in the following paragraphs.

4.1.6.1. Stack effect

This form of infiltration results simply because of density differences caused by temperature variations. The ASHRAE Handbook makes use of the following method of estimating stack infiltration:

$$P = P_o * g * \frac{(T_i - T_o)}{T_i} * H \tag{5}$$

Where P is pressure difference across the envelope, P_o is the density of outside air, T_i is the indoor temperature, T_o is the outdoor temperature, and H is the height of a leak above a plane of neutral buoyancy.

4.1.6.2 Wind Effect

The magnitude of wind velocity causes short-term but relatively high magnitude pressure differences across the envelope of a building. The ASHRAE Handbook recommends modeling these pressure differences as such:

$$P = \rho_o \frac{U^2}{2} * s^2 * C_d \tag{6}$$

Where U is the velocity of the wind, s is a shielding factor determined by the amount of cover from the wind the building receives from adjacent buildings or vegetation, and C_d is a series of coefficients describing a wall's susceptibility to infiltration at different angles of wind incidence.

Both of these equations were used to provide an instantaneous model for the infiltration through the walls of the building. Exact characteristics of infiltration behavior differ from building to building, since they are dependent on size, shape, and location of holes, which are in many cases not necessarily reproduced from building to building. Each leak, depending on its size and shape, acts uniquely to a certain pressure.

Thus empirical coefficients are routinely used to estimate the magnitude of infiltration in the home. This method of describing infiltration is called the K_1, K_2, K_3 method, because it makes use of three constants, one as a base constant, another as a coefficient for stack effect, and another as a coefficient for the wind effect, in the following fashion:

$$Inf = K_1 + K_2 * f(T_i, T_o) + K_3 * f(s, C_d, U) \quad [31] \qquad (7)$$

TRNBUILD models infiltration as a property of a zone rather than a property of a wall. It is inputted as an ACH value rather than any sort of volume flow rate:

$$Q_{inf} = ACH * \rho_{air} * V_{zone}(T_i - T_o) \qquad (8)$$

Therefore directionality cannot be directly modeled internally to TRNBUILD, although an external calculator of such coefficients for each surface external to the building is feasible. Whereas the windward side of a house (presumably the west face), would be more susceptible to infiltration, by using this model only a whole-house average can be estimated. Thus the directionality coefficient C_d was absorbed into the constant K_3.

Also, due to the fact that TRNBUILD's node-based structure does not recognize height, stack effects are not easily modeled as a function of location in the building. Hence the height variable H was absorbed into the constant K_2.

A module was therefore created using this method of producing instantaneous infiltration rates, and since no blower door was available, the constants were estimated to produce a mean annual infiltration rate of .454 ACH in the baseline house. In all variations of the infiltration rate a coefficient was applied to the entire equation, simultaneously increasing each K constant by the same percentage amount, and assumes that an airtight house gains resistance to each type of infiltration equally. Any other more involved form of modification would be the result of so much projection as to the size and location of various hidden leaks as to be unproductive.

4.1.7. Ventilation

The great majority of residential buildings employ no building-wide systems dedicated to ventilation. Routinely the only method of exchange with outside air is leakage through the building envelope. However, when designing a high-efficiency building, it is necessary to reduce this uncontrollable leakage to a minimum, to avoid losing heat during the winter and to avoid introducing heat and humidity during the summer.

Currently, ASHRAE standards require that the air exchange of a residential building should meet a minimum level in order to prevent health hazards caused by excessive inhalation of numerous household substances such as volatile organic compounds (VOCs) released by furniture and packaging, dust, and fumes from household cleaners. However, by rejecting conditioned air, unconditioned air must be introduced to fill its place, and this unconditioned air must be conditioned in order to maintain comfort levels, placing extra loads upon the building's climate control systems.

ASHRAE Standard 62.2 requires that whole-house ventilation levels should adhere to the following equation:

$$V = .01 * A_{floor} + 7.5 * (N_{br} + 1) - inf^{+} \quad [32] \qquad (9)$$

Where V is the air exchange with the outdoors in cfm, A_{floor} is the floor area in m^2 and N_{br} is the number of bedrooms, and $inf^{+}$is the infiltration when above the default value of $.02 * A_{floor}$ (.15 ACH in this house). In the case of the currently simulated house, this ventilation requirement is approximately 47.14 cfm, which amounts to a building-wide ACH of .143. Thus, in order to achieve the standard for a sufficiently ventilated house, infiltration would be required to meet the following inequality:

$$Inf \geq .343 \tag{10}$$

Again, the average American home likely does not stand up to each stipulation of ASHRAE Standards, but this model assumes that both houses meet this requirement. The baseline house's infiltration profile renders any mechanical ventilation system unnecessary, since although the infiltration rate does at times drop below .343 ACH, it is only for short periods of time, on the order of two hours.

In the modified building, the ventilation system is set to activate when the coefficient applied to infiltration levels reduces infiltration by more than 10%. When the coefficient is less reductive than this, infiltration averages above the ASHRAE-designated minimum.

4.1.8. Occupancy

The purpose of residential buildings, of course, is to shelter people. And as anyone who has attended a meeting in a small room in mid-August knows, occupants of a room contribute an appreciable amount to the sensible and latent loads imposed upon a buildings climate control systems. The building houses a family of three, all of whom are assumed to essentially be at a state of rest inside the home while they are there. This produces only approximately 0.5 kW of combined sensible and latent energy gains into the surrounding area when all three persons are present, but this is a greater heat gain than from the appliance load profile at many times. Occupancy models were developed similarly to the other profiles (using the timeslots shown with the setback simulation in Table 4), assuming two occupants leave the home between 8:00 AM and 6:00 PM for a 9:00 to 5:00 work schedule, and the other occupant leaves home between the hours of 8:00 AM and 4:00 PM, as if that occupant were attending school. On weekend days the house is vacant from 1:00 PM to 5:00 PM

4. 2. Weather

The model building was simulated within a weather pattern dictated by TMY2 data collected in Sterling, VA, the TMY2 station of closest proximity to College Park. The weather location is readily changed by selecting one of the files associated with over 200 other U.S. and international weather data collection sites. This weather file contains data regarding outdoor temperature, humidity, direct and diffuse light radiation, and wind velocity and direction, as recorded at the Sterling weather station and averaged over thirty years. Figure 3 shows the Weather macro layout, in which the weather file is labeled “Weather: Sterling VA.”

Maryland’s climate is an effective example of one that demands a great deal from both a house’s heating and cooling system. The thirty-year average of heating degree days (HDD) was 2308 C-days. The thirty-year average of cooling degree days (CDD) as of 2006 was 861 C-day [33]. A “degree-day” is an integration over time of how often and by what magnitude ambient temperatures differ from acceptable room temperatures. Thus, although these degree-day values take no latent loads into account, it can be seen the modeled house will be most affected by heating concerns, rather than cooling.

The sky temperature component computes an effective temperature to be used in calculations of radiation heat transfer between the atmosphere and the building. The Psychrometrics Processor performs simple conversions between various indicators of humidity using the input of dry-bulb temperature and absolute humidity from the TMY2 data. The ground temperature components “Bsmt Wall Temp” and “Bsmt Floor Temp” estimate the average temperature of the soil in contact with the exteriors of the basement floor and walls. The exterior temperature of the entire basement wall was estimated to be the temperature of the outside soil at the depth of the midpoint of the height of the basement wall. The two temperature components show no connections in Figure 3 since they output data only to components outside this Weather macro.

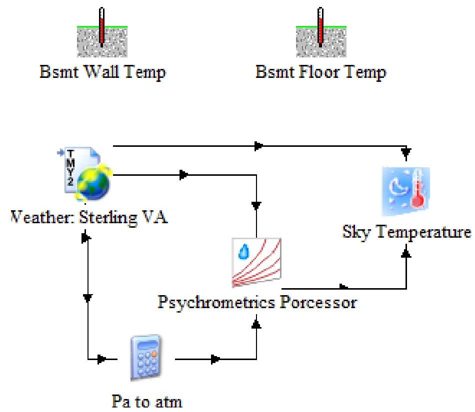


Figure 3: Weather Macro

4. 3. Building Controls

4. 3. 1. Orientation

The default orientation for the building model is the ideal one for photovoltaic collection, with the axis of the longest side of the building running perfectly east-west, and thus showing the largest possible roof area for potential use for solar panels. There is little data to support any assumption of an average orientation of a house, therefore this orientation was chosen as the default. This orientation is easily changed, however, by altering the values in the “Rotate House” component in the main, zoomed-out layer of the simulation, which simply alters the azimuth toward which each of the building’s surfaces faces. The building may be rotated from -90 degrees (facing East) to 90 degrees (facing West), but it is always assumed that all solar collection devices are attached to the half of the roof most nearly facing south.

4.3.2. Shading

At least in Maryland, houses are rarely built on flat, treeless plains, and windows are rarely perfectly unobstructed year-round. Three factors go into the shading of the house from radiation: permanent exterior shading devices, variable exterior shading devices, and interior shading devices.

4.3.2.1. Exterior Shading

The first is constant shading caused by such things as nearby buildings, high slopes, and evergreen trees, all of which reduce the exposure of the wall to ambient radiation from the initial nominal value of π steradians. This category can also include roof overhang, wingwalls, and awnings.

The second factor in shading is external, variably shading objects. The most important example of this would be deciduous trees, which provide shade from the sun’s rays in the summer but allow light through in the winter. TRNBUILD does not currently provide the ability to model a continuously changing external shading device, although it would be possible to create an equivalent TRNSYS component in the future.

These shading devices were treated solely as a method of reducing radiation striking the building's exterior walls or transmitting through glazing. In reality shading devices affect convection and infiltration losses as well. For example, a row of pine trees immediately to the west of a building provides shade upon a window, but also deflects winds, resolving pressure differences between the interior and exterior of the building, thus reducing infiltration levels, as well as reducing the wind velocity, and therefore reducing the rate of convection from and to the walls of the house. Vegetation surrounding a home also provides a relatively stationary mass of moist air which can be a boon to the indoor environment during dry winters but places extra loads upon the air-conditioning/dehumidification system in the summer. External shading devices rarely have a great effect on the u-value of windows, except in the case of adding a storm window or incorporating external shutters. In this simulation, external shading devices add no insulation to the window area of the building other than shielding from incoming radiation.

4.3.2.2. Interior Shading

The third type of shading, interior shading, is not a property of the building's environment or construction so much as it is the choice of a building's occupants.

Since a building interacts directly with humans, not only design factors into a building's performance, and its effects are therefore less predictable and more erratic. With human interaction introduced, understanding a building's performance becomes as much a psychological and biological endeavor as a technical one. Solar radiation through common, .8 SHGC windows, when fully opened, and spread across the entire modeled building, represents a 2.5 kW heating source on a hot summer day. When a set of Venetian blinds is applied to each window, this avenue of heat transfer is reduced to .6 kW, an almost 80% reduction. Thus the usage pattern of interior shading system has the potential of being a large source of energy savings.

Interior shading can be used to improve the U-value of a set of windows. Heavy curtains provide a layer of insulation than can appreciably improve the U-value of a window opening, by reducing levels of infiltration and convection at the window opening. Thus the internal shading devices have been modeled both as means of reducing the transmissivity of windows as well as means of slightly improving the insulation of the building's windows, which are routinely the greatest weakness of a building's thermal envelope. The baseline model is outfitted with Venetian blinds on its windows, which do not add appreciable thermal resistance, but when fully closed, block out 80% of light [34]. Heavy curtains provide more thermal resistance, but their effects were not explored in this particular study.

In a perfect situation, during the winter, blinds would always be open during the day, in order to benefit from natural lighting and solar heat gain, and closed after sundown. In the summer, the blinds would be open during building occupancy periods to benefit from natural light, and closed at all other times to block incoming solar radiation and to avoid placing extra loads on the air conditioning system. Studies have shown that building occupants rarely behave with such awareness, however. There are various reasons for opening or shutting blinds beyond those of energy concerns: one might shut them while taking a midafternoon nap, or to block uncomfortable glare while reading or watching television. Inevitably one might open the blinds for light on a summer morning and leave them open, inadvertently allowing the sun to heat up the building and causing slightly higher air conditioner energy consumption. Rea and Foster both find in their surveys of a commercial building's shade usage, that although the percentage of the window covered by the shading device varied depending on the level of cloudiness in the sky and varied with respect to seasons, in general shades remained at a more or less constant level unless the sun was at a level where glare became a disturbance, and not as much with regard to incurring solar heat gains [35]. In the baseline simulation, therefore, it was assumed that all blinds were constantly half-closed.

4.3.2.3. Shade Schedules

The other treatment of the shading problem, used later with the zero-energy home simulation, was incorporated by creating a logic pattern, automating the level of blind usage. It was constructed very similarly to the occupancy and setback schedules, leaving the shades open when natural lighting or heat is needed, such as during occupancy times or during the winter, and closed when heat is unwanted, such as unoccupied summer hours.

4.4. HVAC

TRNBUILD offers two basic methods to allow HVAC systems to be modeled. The first is internal to the TRNBUILD program, where a set point and heating/cooling capacity are attached to each thermal zone. The second method involves connecting the output temperature and airflow of a heater to the building as a "ventilation" stream. The second method was chosen due to its superior flexibility compared with the internal mode. In order to simulate the HVAC systems in this manner, it was assumed that the same mass flow rate of conditioned air per unit floor space was introduced into each room, ignoring the effects of pressure loss due to height differences between floors and differences in duct length leading to each individual zone.

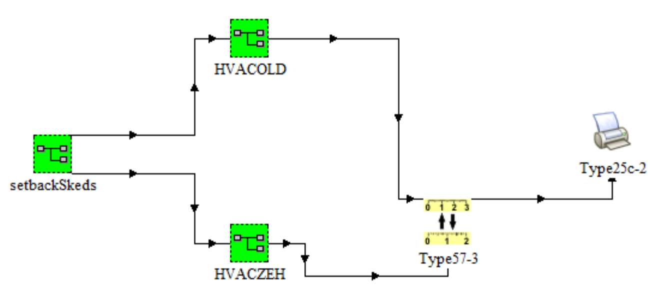


Figure 4: HVAC Macro

The HVAC macro, shown in Figure 4, consists of four main objects. These are: two submacros representing the HVAC systems of the new and old house, a set of schedules for thermostat setback and season identification, and an external monitor set to record data associated with calculating the Seasonal Energy Efficiency Ratio of the buildings' cooling units.

4.4.1. Baseline HVAC system

The baseline HVAC system, shown in Figure 5, imitates the heating and cooling system of a normal American residence. Thus it employs a gas-fired furnace for heating, a vapor-compression air-conditioner, a vapor-compression dehumidifier, and a humidifier. A recurring theme in this thesis will be that although it is possible to determine the abilities of current technology, by way of consulting product specification sheets, it is less easy to determine the performance capabilities of technology which was installed decades ago. As a guideline, baseline house technology will assume the house was built in 1985, and that it was outfitted with HVAC technology of satisfactory performance for the technology level of the time, which puts it at a disadvantage compared to new-construction houses which are subject to more stringent efficiency requirements.

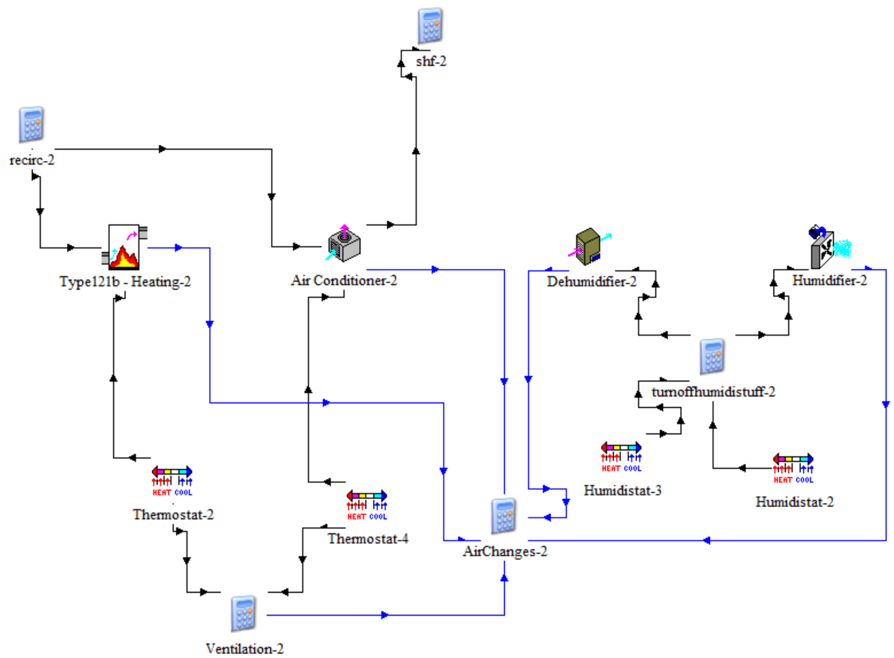


Figure 5: Baseline HVAC System

4.4.1.1 Furnace and Humidifier

The furnace in the baseline model was modeled as a commercially available 7 kW gas-fired furnace with an efficiency of 0.85. A humidifier is attached to the output of the furnace. It is modeled as a wick humidifier, over which furnace output air blows and evaporates the water into the indoor environment. This humidification setup is self-regulating and requires no appreciable increase in energy consumption except for an extra load of capacitance which the heating system must overcome to raise the thermal zone’s temperature.

4.4.1.2. Air Conditioner

The baseline air conditioner is a conventional, vapor-compression cycle air conditioner. Its performance data was derived from a default TRNSYS model for a 2-ton air conditioner. The method for choosing this size of air conditioner is described below in the “Sizing the Air-Conditioner” section. The air-conditioner’s performance is dictated by a data file containing data about power consumption and heat removal rates at various humidity and temperature levels of indoor and outdoor air.

Seasonal Energy Efficiency Ratio (SEER) was monitored by compiling the power consumption of and heat removed by each air conditioner at each timestep during the cooling season. The baseline’s air conditioner was modeled to have a SEER of 11. Current law dictates that SEERs of new central air conditioning systems must meet a minimum of 13, but until 2006, the minimum was only 10, and the DOE finds that many older central air-conditioning systems have SEERs as low as 6 [33].

4.4.1.3 Duct Leakage

The IECC has found that in nearly 80% of buildings have ducts that leak an unsatisfactory amount of conditioned air into unconditioned spaces. They find that the majority leak about 20% of the flow into the outside air [36]. IECC 2009, and therefore Maryland, requirements dictate that ducts should release no more than 8% of their flow into the outdoors. By placing ductwork out of the building's thermal envelope they become vulnerable to the extremes of local temperature patterns, causing unwanted heat transfer and infiltration into the recently-conditioned air. This problem can be avoided in a building where ducts remain inside the thermal envelope, as is recommended by ASHRAE, and as is already popular in many areas of the nation [37]. When these leaks happen indoors, a relatively small amount of conditioned air is lost, since it simply seeps conditioned air into a conditioned room. A study by Washington State University estimates that these indoor ducting systems achieve up to 96% efficiency, meaning that only 4% of the energy consumed by the air handling unit is wasted by sending the air through the duct system [38,39]. Lubliner estimates that approximately 41% of buildings are constructed with ducting entirely within the building's thermal envelope [40]. It was assumed in this simulation in keeping with the building code that all ducts were kept within the thermal boundary of the building. Despite that fact that such a layout is not present in a majority of houses, this decision likely prevents inaccuracies in the building model. Among those building simulations listed by previous experimenters, the methods currently available for duct modeling, meaning specifically heat losses and the airflow-modeling of leakage, much like infiltration modeling, were found to need significant improvement [38]. A model for simplified duct heat transfer is included in the model, but for the aforementioned accuracy concerns, that duct heat transfer mechanism was not used in the model during this study.

4.5. Setback Schedules

The Scheduling Submacro, shown in Figure 5, employs eight separate forcing functions as 24-hour schedules for the setpoint of the building's thermostat and humidistat. These schedules are separated into weekday and weekend schedules, and based on expected times of occupancy, refer to Department of Energy guidelines for thermostat setpoints [41]. The setback function was included in the systems of both houses, since although the average American house does not employ a digital thermostat, and accordingly such a rigid schedule of setpoints, most households have similar occupancy times to one another [42].

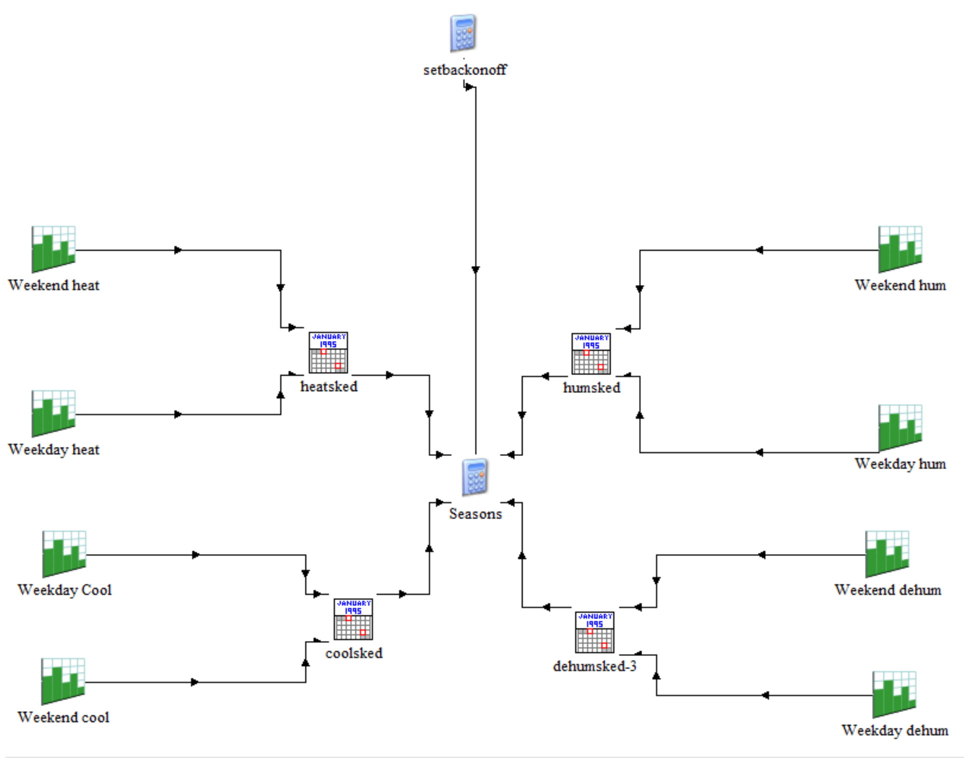


Figure 6: Scheduling Submacro

The setback schedules may be turned on and off by entering either a true or false Boolean operator into the calculation component “setbackonoff,” in order to more accurately evaluate the HVAC system’s ability to meet necessary heating and cooling loads. These profiles are then routed through a calendar component which recognizes the day of the week for each timestep and sends the appropriate schedule to the thermostat. Finally, the heating and cooling setpoint schedules are sent through a set of equations that essentially turns the heating and humidifying system off during the summer months, and turns the cooling and dehumidifying systems off during the winter months. The heating season has been defined as occurring between the hours of 0 and 3500, and 6000 and 8760, or approximately mid-September to mid-May, based on when the outdoor temperature data in the College Park TMY2 file reach temperatures below the human comfort level. The cooling season has been defined as hours 2500 to 7000, or early April to late October, also based on TMY2 temperature data. Thus it is possible for either system to activate during the overlapping shoulder seasons between hours 2500 to 3500 and 6000 to 7000.

This “switching off” of the respective systems is not actually achieved by disabling the system but by superimposing a constant value on the profile to remove the temperature setpoint from normal room conditions. For example, the logic for controlling the heating system located within the “Seasons” calculation component, is as follows:

$$Heatschedule = \left(-30 * not(winter) + T_{set,heat}\right) * eql(onoff,1) + 21.5 * eql(onoff,0) \quad (11)$$

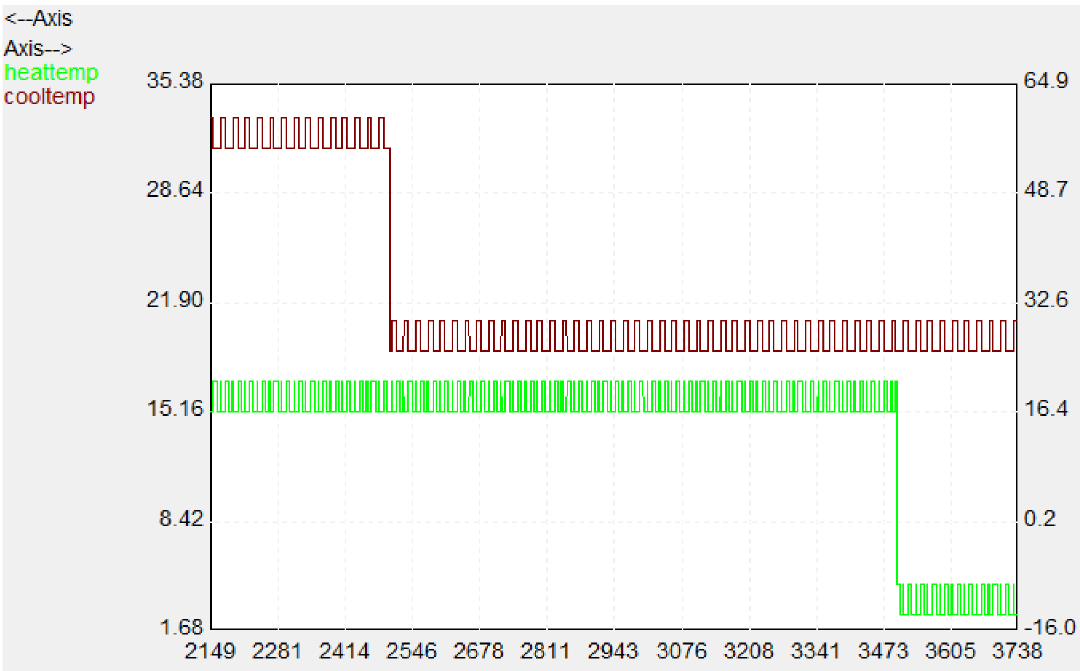


Figure 7: Setpoints with Setback and Season Change

Thus, when the setback system is turned off, the setpoint is assumed to remain at a constant 21.5 C. When it is activated, the EPA setback schedules determine the temperature to which the zones are heated depending on the time of day and day of the week. Figure 6 displays the limits set by the setback schedule in and around the spring shoulder season. All setpoints before 2500 hours are recognized as "winter" and thus the cooling system is effectively shut off by shifting up the cooling trip level. During the shoulder season, when one could feasibly require the services of either the heating or cooling system, both trip levels hover at the maximum and minimum temperature for human comfort.

4.5.1 Thermostat Habits

The scheduling system, as stated before, relies on the assumption of certain interactions by the homeowner. Unfortunately, often, a homeowner does not follow the recommended course of action in operating climate control systems. This idea has been explored in previous research. Data compiled by the EIA in the 2005 Residential Energy Consumption Survey shows that only 39% of American residences make use of programmable thermostats [43]. The same survey shows that during the cooling season, a majority of Americans alter their preferred thermostat setting (75° F) neither when asleep nor during the day when no one in home [44]. In the heating season, however, most Americans, while maintaining a 70° F environment during the day while occupants are present, lower the temperature setting to about 63° F upon leaving the house or going to sleep. Thus the baseline home was simulated as using no setback during the cooling season, maintaining a constant temperature of 75° F, and during the heating season setback was used altering between 70° F and 65° F based on the occupancy schedules. The settings used for the setback profile, shown in Table 3, are based on a slightly modified version of the EPA's recommended set of thermostat levels [45]. The setback system was used in both seasons in later comparative sets of simulations to test the potential energy savings of a correctly-programmed programmable thermostat, and the effects of deviating from EPA-recommended set points.

Setting	Time	Setpoint Temperature (Heat)	EPA Setpoint Temperature (Cool)	Base Setpoint Temperature (Cool)
Wake	6:00 a.m.	70° F	78° F	78° F
Day	8:00 a.m.	62° F	85° F	78° F
Evening	6:00 p.m.	70° F	78° F	78° F
Sleep	10:00 p.m.	62° F	78° F	78° F

Table 3: Thermostat Setback Settings

4.6. Sizing the Climate Control System

The size of an air-conditioner, meaning the cooling load which the unit is designed to handle, differs from simulation to simulation. In order to determine the appropriate tonnage for the baseline home, a second TRNSYS simulation was constructed, referred to here as the HVAC Load Monitor Module, to test the ability of the system to support the cooling load which is placed on the building. Figure 8 depicts the makeup of the simulation. The following paragraphs will detail the operation of the module:

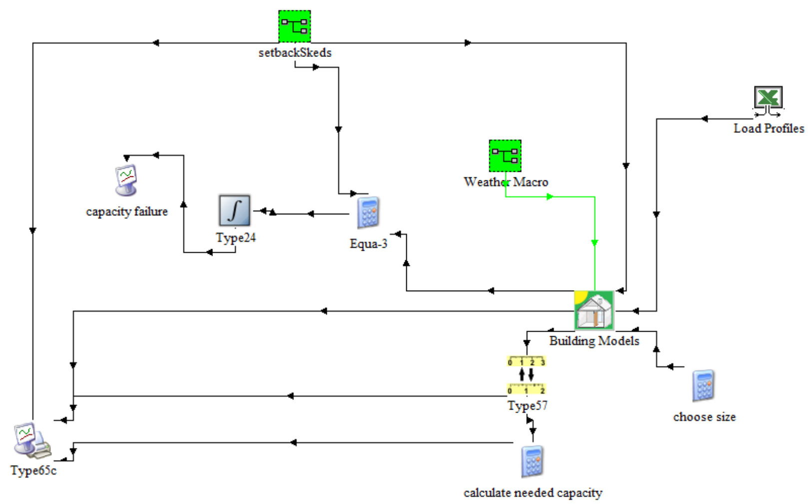


Figure 8: HVAC Load Monitor Construction

4.6.1. Test Building

Much of the model is identical to the original building model. The setback schedules, load profiles, and weather macro are all unchanged from the main TRNSYS Program. The main difference is that all heating and cooling system inputs external to the TRNBULD model have been removed and the heating and cooling functions within TRNBUILD have been engaged. By doing this it is possible for TRNBUILD to monitor the instantaneous heating and cooling loads being placed upon the building. TRNBUILD determines the amount of sensible and latent energy that must be added or subtracted from the indoor environment at each time step in order to reach the desired temperature and humidity set points. The results of this simulation are shown in Figure 9, where the red curve depicts the amount of sensible energy that must be added to the room to reach the set point of 22.5 C, and the blue curve represents the amount of sensible energy that must be removed by an air- conditioner. Also available as outputs are latent and total energy loads. This data was employed by monitoring, for example, the tons-cooling-equivalent of the total dehumidification and sensible cooling load of the air conditioner, which was just under 2 tons in this case, and selecting the most appropriate commercially-available size.

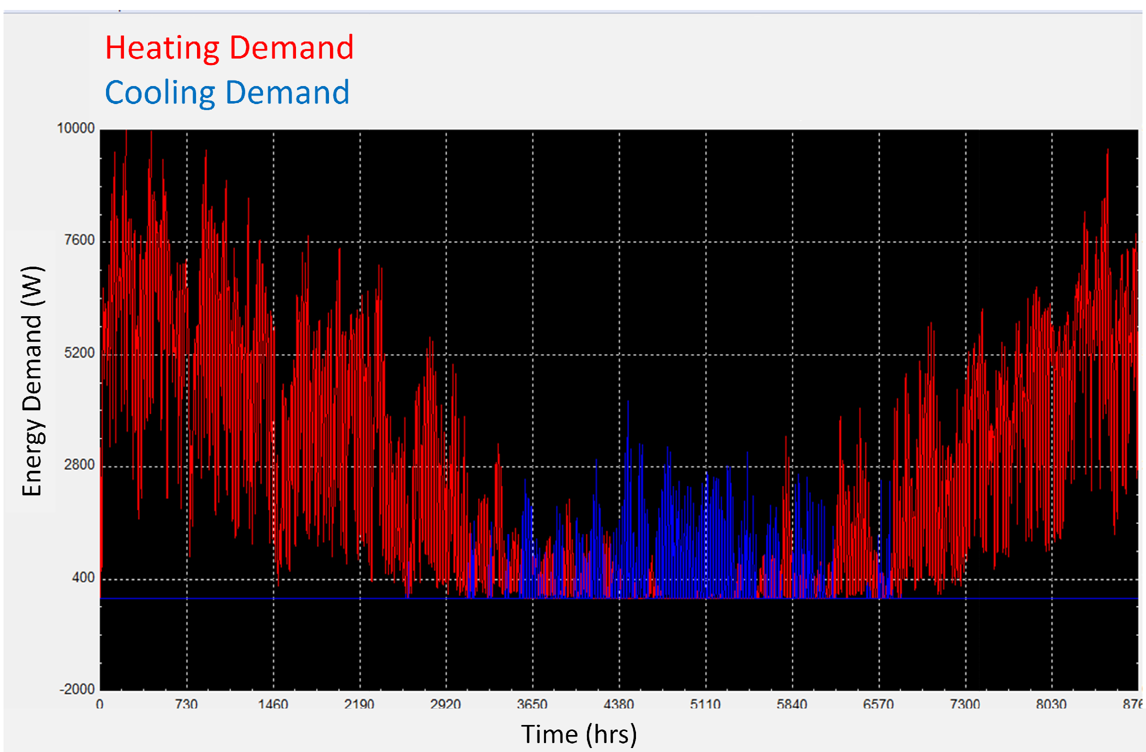


Figure 9: HVAC Load Monitor Output

4.6.2 Capacity Failure Monitor

A device was included in this program to detect the number of hours in a year when the climate control system does not meet the needs of the building's heating, cooling or humidity loads. This was done by placing a monitor on the temperature of the thermostat-controlled space. When the temperature or humidity strayed outside of the error allowed by the thermostat's deadband, a Boolean signal of 1 was generated, multiplied by the timestep, and integrated over the course of the year to find the amount of time during which the climate control system was unable to meet the demands of the building's heating or cooling load. The following equation shows the logic used:

$$True_{heat} = if(temp < t_{set} - deadband - .1)$$

$$True_{cool} = if(temp < t_{set} - deadband - .1)$$

This system also incorporates a unit to monitor the climate control system's ability to change setpoint levels in a satisfactory amount of time. This sort of monitoring is performed by comparing the thermostat setpoint of the current timestep with that of an earlier timestep, in this default case, the timestep one hour previous. It ensures that the air conditioner is capable of achieving the level of human comfort in an acceptable period of time. The following equation details how the signal is tripped:

$$True_{cool,change} = if\left(temp > t_{set,t-5}\right) * if(t_{set,t-5} > t_{set,t})$$

$$True_{heat,change} = if\left(temp < t_{set,t-5}\right) * if(t_{set,t-5} < t_{set,t})$$

where “True” indicates the trip of the capacity failure monitor either for cooling or heating, temp is the temperature monitored by the thermostat, $t_{set,t-5}$ is the setpoint 5 timesteps earlier, and $t_{set,t}$ is the setpoint at the current timestep.

4.6.3. Comfort Zone Monitor

The Comfort Zone monitor makes use of human comfort levels as described by the ASHRAE Handbook of Fundamentals and serves as a means of checking the performance of the HVAC system [30]. It receives absolute humidity and temperature data from the interior environment and records them for each timestep. Each of these points is then entered into an Excel workbook, which plots each point on a psychrometric chart. Figure 10 shows a sample output of this comfort zone monitor. The data shown was developed by running the simulation without any change in thermostat setpoints. The cooling setpoint remained at 25.5 degrees and the heating at 21.5 degrees. This is another measurement of the climate control system’s ability to meet the heating and cooling loads demanded by the indoor environment. To show the chart after a normal setback simulation would result in a number of meaningless and indistinguishable points outside the range of human comfort and would not help in judging the merits of the climate control system; therefore the comfort zone results of such a simulation were not shown.

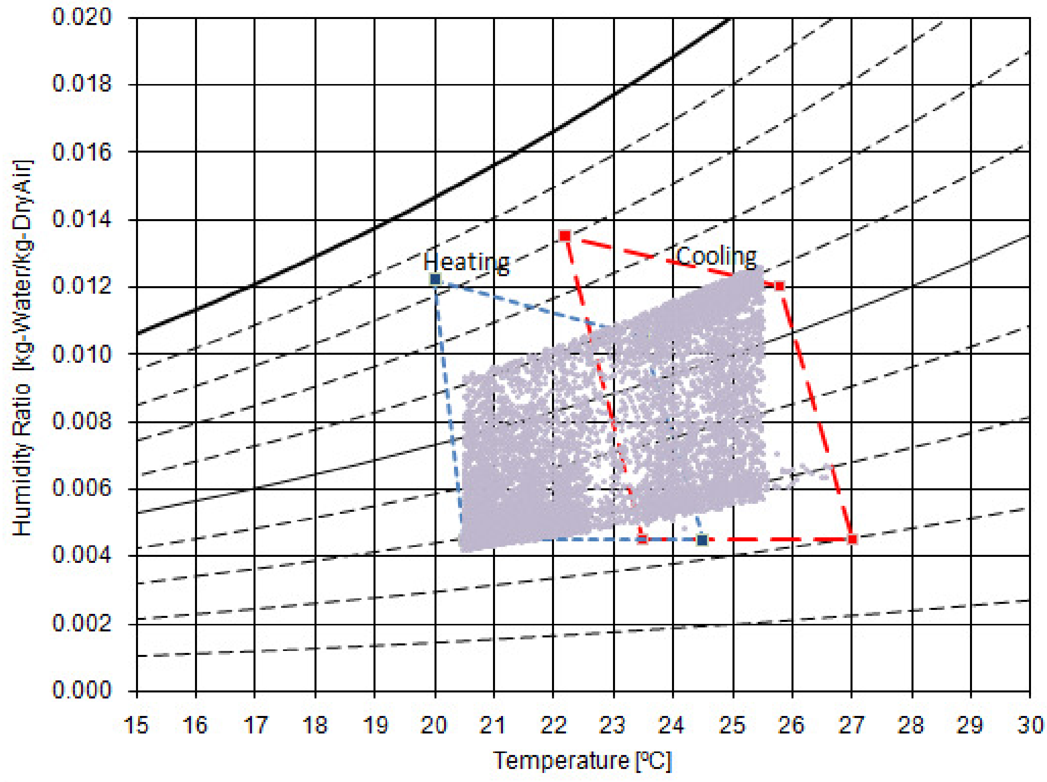


Figure 10: Sample Comfort Zone Monitor Output

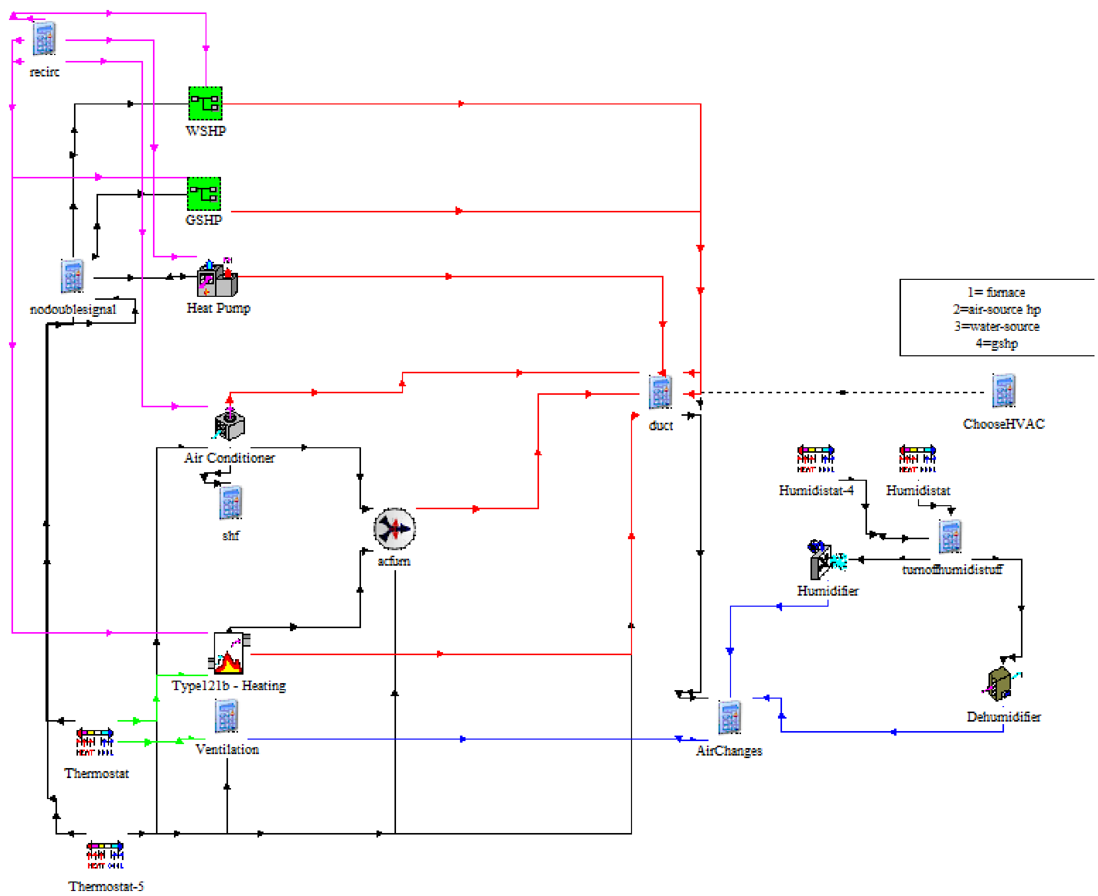


Figure 11: Modified HVAC System

4.6.4. Modified HVAC System

The modified HVAC system, shown in Figure 11, was modeled to allow four different options for condtioning the spaces within the low-energy building. These were a traditional air-conditioner/furnace system, an air-to-air heat pump, a water-source heat pump, and a ground-source heat pump. The air-conditioner and furnace are exactly similar to those in the baseline, although their capacities, flowrates and performance maps can be altered to simulate a higher-efficiency furnace/air-conditioner setup, as will be performed later, when the air-conditioner SEER is modified to 13 from 11. The heat pump was modeled after a commerically available heat pump, marketed as “standard efficiency,” of 13 SEER in cooling mode and an HSPF of 8.5 [46]. Various calculation components throughout the macro simply divert control signals to the chosen HVAC setup, divert the energy consumption of the appropriate unit to the Energy Macro, and divert the outlet air conditions of the appropriate apparatus to the building model. The simulation’s ground-source and water-source heat pumps have not yet been sufficiently checked and compared to published data concerning their performance, and therefore those options were not yet explored in this study.

4.7. Photovoltaics Macro

The Photovoltaics Macro, shown in Figure 12, contains a Photovoltaic panel and inverter combination which provides a source of energy to offset the energy consumption of the home throughout the year. As was stated before, half of the roof area is assumed to be available for PV arrays and solar thermal collectors. The solar thermal collector for the size of family assumed present in this building was recommended by the U.S. DOE to be 3.3 m^2, [47] and therefore approximately 60 m^2 was left to be covered by photovoltaic panels.The photovoltaic array is modeled as a set of normal crystalline silicon collectors. These panels are attached to the roof at the same angle the roof was constructed, 36 degrees from the horizontal. It is normal to achieve approximately 8% to 12% efficiency in silicon modules [48]. As can be seen in the PV macro's graphical output in Figure 13, this system normally achieves approximately 10.5% efficiency. Such an efficiency is typical of monocrystalline modules.

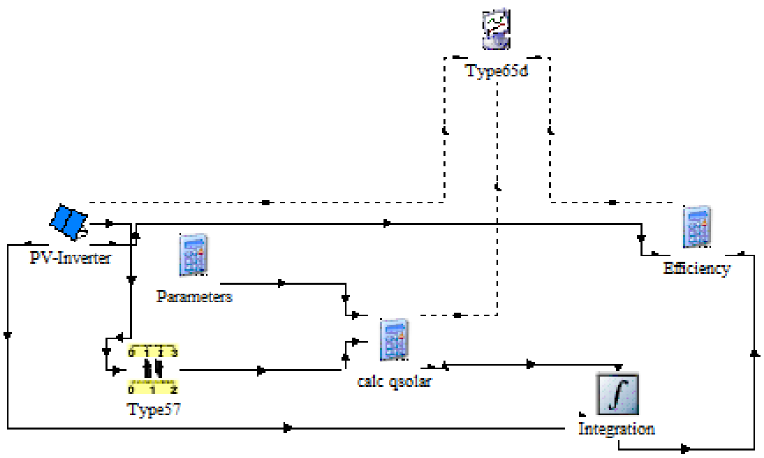


Figure 12: Photovoltaics System

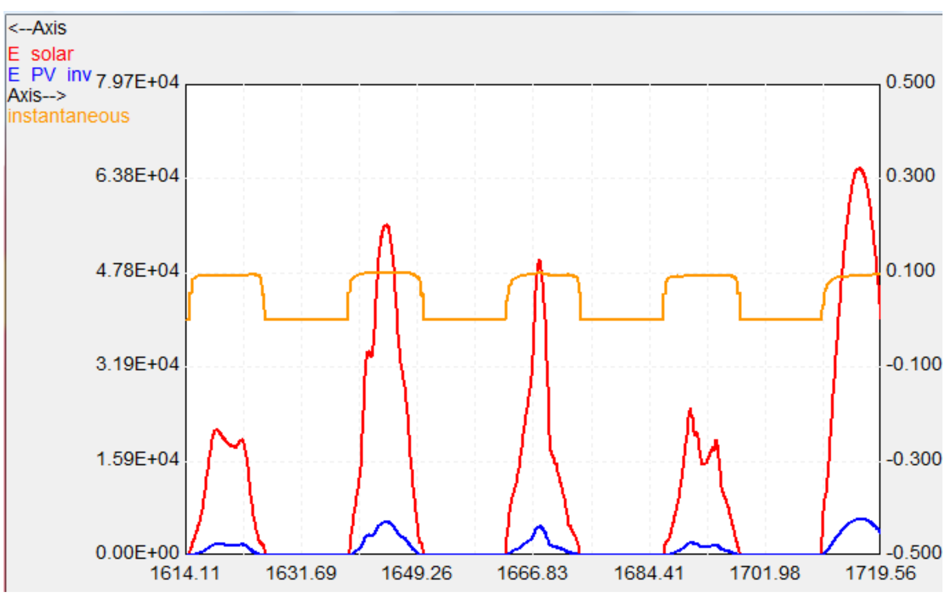


Figure 13: Photovoltaics Output.

4.8. Energy Macro

The Energy Macro, shown in Figure 14, serves as a central point where the information concerning energy consumption from each device is compiled. It provides the user with two graphical outputs: the power monitor and the energy monitor. The energy monitor integrates power consumption by each component over the span of a year to show the total amount consumed by each part of the building's energy system. All information is fed to a unit converter, which sends the power consumption of each specific part of the building energy system to the "Power Monitor" graphical output and to the integrator, which sums up the power to find the total kWh amount of energy consumed by each building component.

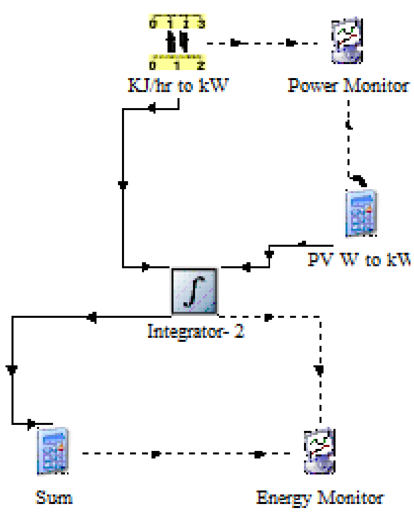


Figure 14: Energy Macro

4.9. Load Profiles

The “Load Profiles” component represents an Excel spreadsheet containing a schedule of electrical and domestic hot water (DHW) consumption for the building. The set of data was derived from the results of a study by the International Energy Agency’s (IEA) Annex 42 on non-HVAC household electricity and hot water usage schedules [49].

4.10. Non-HVAC Electrical Profile

Annex 42 acquired the data for the electrical load profiles by using a probabilistic profile generator. Each appliance was given a probability of turning on within a certain span of time according to a study conducted by the results of a survey of the average energy consumption of certain household appliances.This average level of consumption became an annual consumption goal, determined by the average energy consumption of each appliance type in Canadian households, was applied to this scheduling mechanism. A 5-minute-resolution energy breakdown for American households was not available, necessitating the use of these profiles based on Canadian households, which, it is assumed, use appliances in a similar manner to their American counterparts.

4.10.1 Changes to Non-HVAC Electric Profile

It was determined at the time of applying the load profile to this simulation that modifications needed to be made to the original Annex 42 load profile. These changes stemmed from the long list of miscellaneous appliances that had been included in the study and assumed to be present in the building. Annex 42 used data from a Natural Resources Canada report delineating typical power ratings and usage levels of several miscellaneous electrically-powered items, which resemble suggested guidelines more closely than established fact. A few appliances on that list were deemed to be impractical to expect in an average American home. For example, the lathe, which is listed in the Annex 42 Report as being in use for two hours of every month, was eliminated from the database. It was determined that although many houses may indeed contain lathes, but to presume their presence in an average house, as this simulation attempts to model, let alone to presume that the average American homeowner would engage that appliance for a full 24 hours in a year, would be somewhat bold. The same was done to the circular saw, the table saw, the deep fryer, the electric kettle, the sewing machine, and the electric blanket, which were all identified as appliances too irregularly employed to include in the load profile of an average residence. Other appliances were diminished in usage time. For example, the vacuum cleaner, estimated by Annex 42 to be operated for 10 hours per month was reduced by half, since 10 hours of vacuuming seems to assume a level of hygiene and responsibility foreign to many homeowners. Likewise the energy consumption of the laptop computer was halved, since in the profile it is a ssumed that the desktop and laptop computer are occupied for 240 hours each per month, which is an extremely large amount of computer time for the three-person household which is being attempted to be simulated. All preceding changes were applied to the load profiles of both houses.

All other appliances, such as refrigerators, televisions, small electronic devices, and others were kept the same as in the original load profile. The full breakdown of the components of the load profile can be seen in the Annex 42 report [42] or at the Annex 42 website.[1]

4.10.2 Simulation of Energy-Efficient Appliances

The non-HVAC electrical profiles of both houses were determined using the same base schedule, as explained above, but to simulate the replacement of old appliances with new, efficient models, the profile for the low-energy building was slightly modified. This section will explain the divergence between the two profiles.

The original Annex 42 load profiles provide no data for specific appliance models, since they instead opted to use an average consumption level determined by survey results.

[1] http://cogen-sim.net/index.php?pg=datafiles&download=Canadian_Electrical_Load_Profiles_Excel_Format_high.zip

The profile for each energy-efficient appliance was constructed by applying a multiplier to each appliance's original load profile, which preserves the usage pattern of each appliance but reduces the amount of energy consumed during each use. Energy efficient appliance usage targets were determined by consulting National Resource Canada's 2007 database of average annual energy ratings of new appliances [50]. The lighting percentage reduction was decided upon by assuming that the baseline home's lighting was performed by nearly all incandescent bulbs, whereas the modified home's was performed by nearly all compact fluorescent lamps (CFLs). The values for the reduction in energy due to use of CFLs is in accordance with the difference in power rating between similar light-output incandescent bulbs and CFLs as reported by manufacturers [51]. Normally this value is about 75%, but the savings were decreased a small amount to allow for a few incandescent bulbs.

Appliance	Baseline kWh	Modified kWh	% reduction
Dryer	1360.693	912	0.32975329
Washer	91.27875	23	0.74802459
Dishwasher	90.598	57	0.37084704
Lighting	2026.188	709.1658	0.65
Refrigerator	805.0822	483	0.40006126
Freezer	614.7211	384	0.37532647
Range	740.1333	524	0.29201946

Table 4: Load Profile Usage Targets

4.11. Domestic Hot Water

The DHW profiles, like the electrical profiles, were created by the IEA's Annex 42, based on a probabilistic hot water usage profile created by the IEA's Solar Heating and Cooling Program Task 26. The profile assumes a daily hot water usage of 300 L, and distributes flow demands throughout the day based on probability profiles generated from a number of water consumption surveys.

Today many improvements to appliances have reduced hot water consumption. For example, front-loading clotheswashers use approximately 56% less energy than a top-loading model from the 1980s [52], and new low-flow shower head models use approximately 50% of the water compared to old fixtures [53]. However, this reduction in water usage was not modeled in the zero-energy home simulation. Unlike the electricity profiles, the hot water profiles were not separated into usages by separate appliances, but were compiled as one gross usage profile. Thus to somehow reduce the flowrates at certain times of the day would require highly arbitrary, and probably highly inaccurate, guesswork. Annex 42 offers a low-usage profile for DHW consumption, however this involved assuming behavioral changes in the occupants. Since the experiment was meant to model changes to the building, it was determined that such a behavioral change would possibly render slanted and overly-optimistic results. However, this will be of note in later simulations, for example with solar water heating, which are not as well-equipped to handle high flowrates of hot water as a common gas-fired furnace.

Hot water consumption was assumed to not have any effect on the relative humidity or temperature of the building. It was assumed that exhaust fans sufficiently remove the water from bathrooms during showers, and that all but a negligible amount of energy drains from a sink or washing machine before it can be transferred to the indoor atmosphere.

4.11.1. Modification to DHW profiles

The profiles provide volumetric flow rates of hot water based on a 45 °C delivery temperature (T_p) and a 10 °C incoming cold water temperature. Since the storage tank modeled in this simulation supplies water at a set point of 50°C rather than 45 °C, the profile flow rate has to be adjusted based on the actual outlet temperature of the tank (T_h). Additionally, since the temperature of incoming cold water (T_c), which replaces the hot water drawn from the top of the tank, varies based on ambient and ground temperature, it should not be assumed to be constant, and is therefore simulates as a time-varying value in this modified version.

One may develop the following relationship by conducting an energy balance on the mixture of two constant- specific-heat, constant-density fluids at different temperatures:

$$\dot{m}_{mix} T_{mix} = \dot{m}_1 T_1 + \dot{m}_2 T_2$$

In the present case, the original load profile flow rate is represented by the “Mix” stream, and the hot (tank) and cold (tap) streams as the other two, giving:

$$\dot{m}_p T_p = \dot{m}_h T_h + \dot{m}_c T_c$$

Where $\dot{m}_p$ is the flow rate specified in the load profile, $\dot{m}_h$ is the mass flow rate of water from the hot storage tank, and $\dot{m}_c$ is the flow rate of tap water being mixed with the hot stream. Furthermore, the total flow rate given by the profile is equal to the sum of the two streams:

$$\dot{m}_p = \dot{m}_h + \dot{m}_c$$

Combining the above two equations yields a relationship between the flow rate out of the tank and the original profile flow rate.

$$\dot{m}_h = \dot{m}_p \frac{(T_p - T_c)}{(T_h - T_c)}$$

The profile temperature is a constant (45 ℃), and the profile mass flow rate is specified at every timestep, so this is a function of the tank outlet and tap inlet temperatures. In general, since the tank outlet temperature is higher than 45 ℃, the drawdown rate from the tank will be significantly lower than the flow rate specified by the original Annex 42 load profile.

4.12. Hot water system

The hot water macro, as shown below in Figure 15, simulates the operation of a water-heating system. The system intakes groundwater, assumed to be at the temperature of the ground at 1 m below the surface, which is then heated by one of a few different possible heating methods. The choice of heating method is controlled by changing the ID number in the “Choose” calculator component, which turns a series of switches on and off to send the energy consumption and temperature data from the desired heating apparatus to the appropriate places, for example energy consumption data to the energy macro and temperature data to the building model. The most common method of hot water supply among American households involves storing water in a thermostat-controlled, gas-heated hot water storage tank [54]. Therefore this was chosen for the baseline simulation. Given the size of the family, an 80 gallon (300 L) tank was used, based on the recommendation by Krigger [53]. Its thermostat was set at 50 degrees C (122 F), also based on data from Krigger.

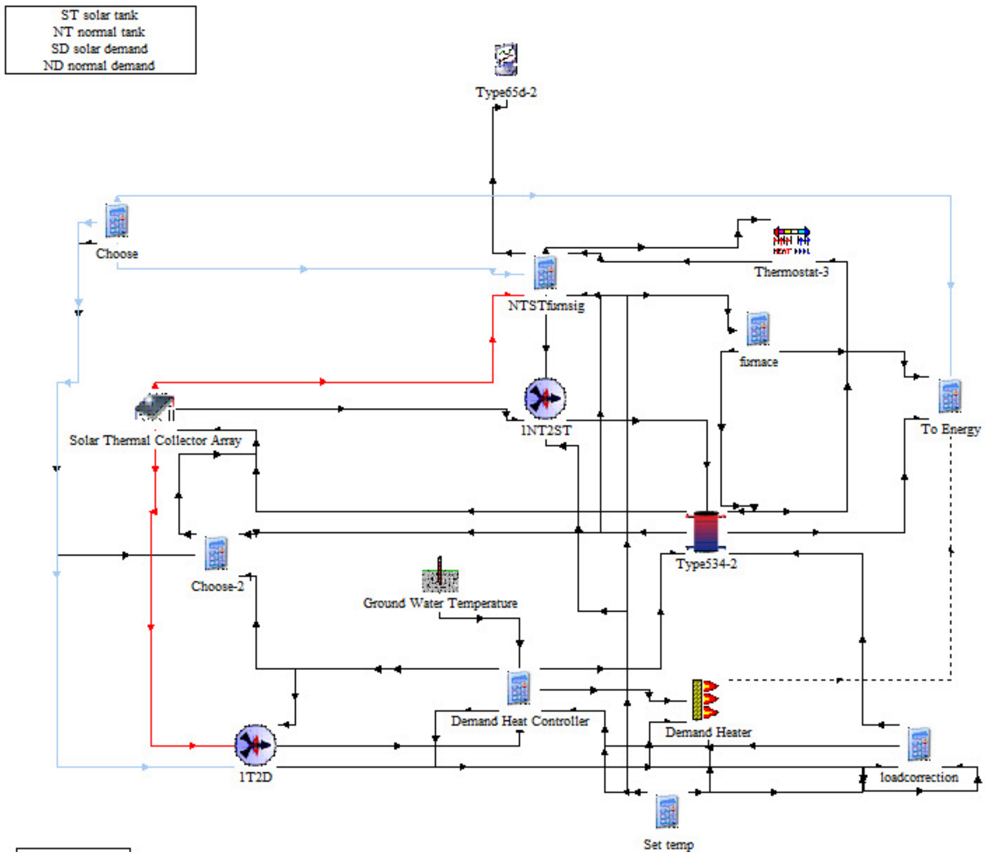


Figure 15: Domestic Hot Water System

4.12.1. Assumptions Made in Sharing Hot Water System

As mentioned previously, only one hot water system was simulated in each run. The creation of two systems and the calculations required by running two such systems side-by-side were great. During this portion of the series of simulations it required performing more runs, but during the simulation of the many other variables it slowed the simulation speed so much that performing the second set of calculations was not deemed necessary. Thus the hot water system, which can be varied between the four setup possibilities listed above, was located in the baseline house, and its energy consumption was applied to both buildings. It is possible that this could introduce error into final annual consumption, especially in the modified building, since the basement of the baseline house will have different temperatures from the modified house, which would cause higher or lower rates of heat loss through the hot water storage tank. Thus, the effects of this assumption will be investigated.

4.12.2. Effects of Assumption

To ensure that the assumption of the existence of two water systems would not significantly affect the final consumption numbers of the simulation, a pair of simulations were run in order to compare hot water consumption when the water heater is located in the baseline house's basement and then the low-energy house's basement. The hot water tank is normally simulated in only the modified house. Figure 16 shows representative basement temperatures from both buildings in both the heating and cooling seasons. It shows that the temperature in the baseline house's basement stays a relatively constant one degree below the temperature of the modified house's basement during the winter. During the summer, the temperatures of both basements are within .5 degrees Celsius.

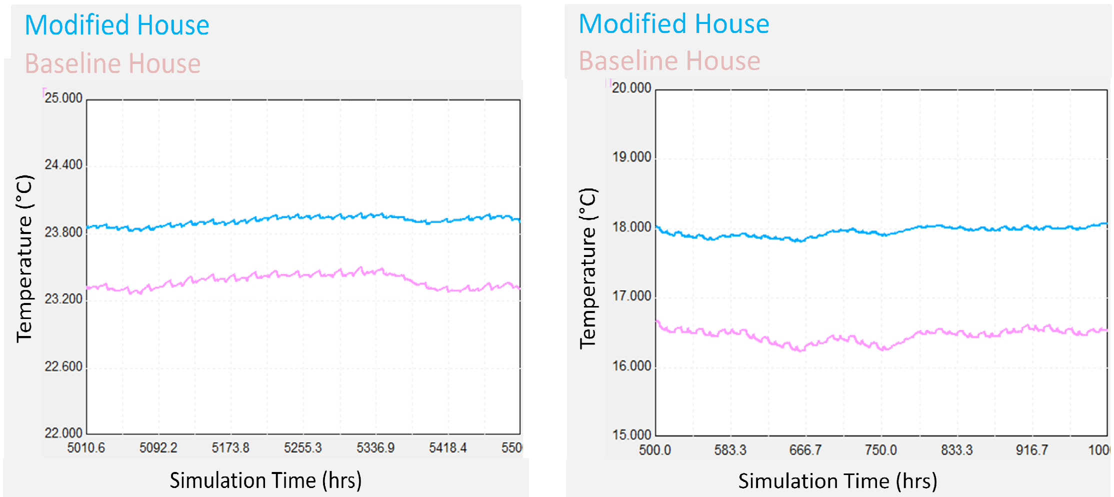
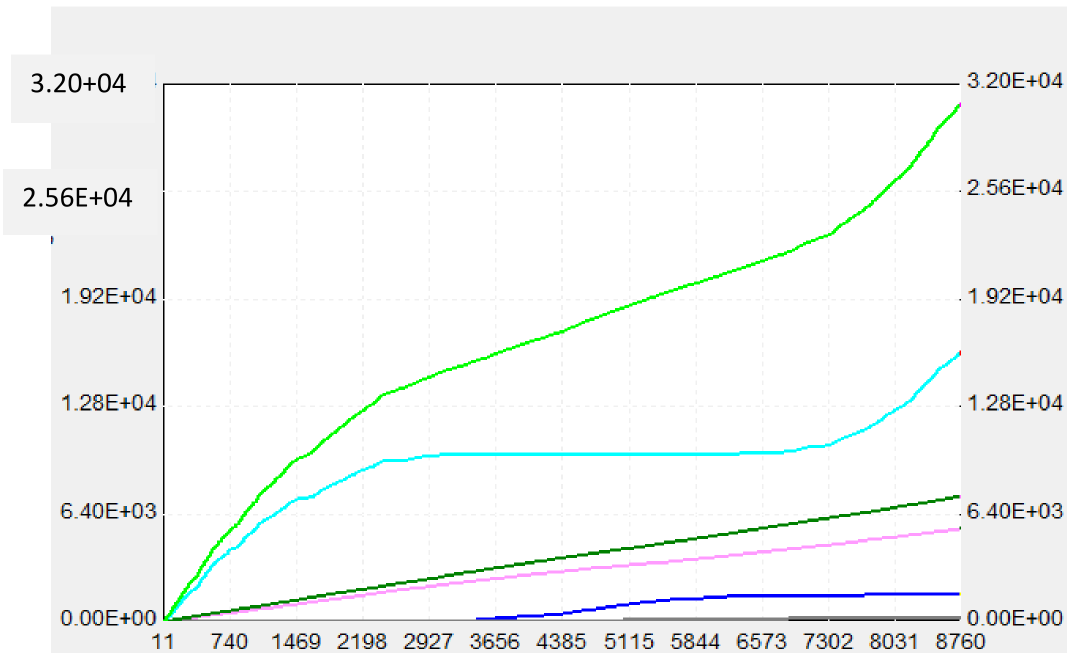


Figure 16: Basement Temperature Differences (C) – Summer (L) and Winter (R). Please note difference of scale.

The tank was simulated in the modified house, at its most energy-efficient state (as described later in Section 6.3), and then it was simulated in the baseline home (i.e. using the baseline's basement temperature conditions as the parameters for heat loss calculations), to determine whether foregoing simulating two separate systems causes any major discrepancy in energy consumption values. In the baseline home, where the basement stays slightly cooler, the baseline hot water system consumed 5470 kWh. Within the skeleton of the final zero-energy home configuration, which will be explained in greater detail later, but which represents the best-insulated configuration evaluated in this study, the system consumed 5428 kWh, only 42 kWh or 0.8% less energy. Thus it can be said with satisfactory accuracy that the placement of the water tank in only one house is not a source of significant error.

5. Validation of Baseline Model

In order to ensure the accuracy of the baseline model, one simulation was run so that the outputted data could be compared to recorded average values. Figure 17 displays the resulting energy consumption from the baseline simulation.



Legend		Value (kWh)
Hot water		5536
Heating		16109
Cooling		1610
Dehumidification		137
Appliances		7474
Total		30866

	Baseline (kWh)	RECS Avg, NE homes (kWh)	% Deviation
Hot Water	**5536**	**5302**	**4.23**
Heating	**16109**	**19688**	**-22.22**
Cooling	**1610**	**2163**	**-34.35**
Total electricity	**9221**	**8514**	**8.23**
Total Gas & Electricity	**30866**	**33504**	**-7.87**

Figure 17: Baseline Simulation Results

5.1. Cooling and Total Electricity Consumption

The electrical consumption for the baseline cooling system was 1610 kWh. The EIA's 2005 Residential Energy Consumption Survey found that the average N northeastern household with central air conditioning consumed 2163 kWh [55]. This constitutes an approximately 34.5% difference from that average. Considering the ducting assumption, that is, that all ducts are within the thermal envelope of the home, and that, at a SEER of 11, this air conditioning system would have exceeded the legal minima prior to 2005, this is a reasonable difference.

The average household electricity consumption in the Northeast was 8514 kWh, according to the RECS. The baseline's usage, at 9223 kWh, seems to be an appropriate value, at an 8.2% difference. One must take into account that in 20%

of these houses electricity is also used in space heating, and in 18% for water heating. Both of these values inflate the statewide average. Here the gap can be attributed to the level of energy consumption chosen in the load profiles.

5.2. Furnace and Natural Gas Consumption

RECS information shows that approximately 19688 kWh is consumed in the average northeastern house for space heating, a 22% increase compared to the baseline building. Hot water consumption in northeastern homes averages to 5302 kWh per year, only a 4.0% decrease from the baseline value. These natural gas consumption totals bring the total consumption amount to 33504 in an average home, compared to 30866 in the baseline house, a 7.9% decrease. In general these comparisons show that the baseline house is better insulated compared to the average house, and that despite the reductions made to the load profiles, this home uses significantly more energy for appliances than average.

5.3 Accuracy of Building Energy Simulation

NREL has noted that much uncertainty still exists in the field of building energy analysis. Given its somewhat large scale and its level of complexity and variability, given the great number and unpredictability of many variables, the need for exact replication of building geometry, and the great number of calculations per time step that would be required to fully replicate all the ongoing physical processes within a house, building simulation tools have not yet reached the same levels of accuracy that are common in other types of smaller-scale simulations. According to their report on validation methodologies, NREL finds that differences between actual building consumption and simulated building consumption tend to be at least 10%, and as much as 50% [56]. Thus the levels of consumption arrived upon by the baseline home simulation are within an expected range of error.

6. Simulation Results

Simulations were conducted in order to determine the effect of various changes to the building on total annual energy consumption. Since the final objective is to simulate a net-zero-site-energy home, the simulation results consider a system containing only the building, and not, for example, electrical generation efficiency, grid efficiency, or energy consumed in order to deliver natural gas to the home.

6.1. Envelope Simulations

A sensitivity study was performed upon each major characteristic of the buildings structure, in order to determine the most effective method of reducing total energy consumption by modifying envelope characteristics. In terms of cost and feasibility, these are perhaps the most demanding of the available retrofit solutions. However in most cases they are feasible, and the following will show where the greatest energy-saving potential lies when adding insulation to a home. In all cases, R-values are expressed in the units of ft^2-°F-hr/btu, which is the standard unit for designating insulation levels in U.S. building codes, and, in parentheses, the SI units of hr-m^2-°K/kJ.

6.1.1. Basement Insulation

R-Value [ft^2-°F-hr/BTU (m^2-°C-hr/kJ)]	10 (.54)	8 (.44)	12 (.65)
Heating (kWh)	16109	17781	15394
%	N/A	10.38	-4.44
Cooling (kWh)	1610	1213	1744
%	N/A	-24.66	8.32
Total (kWh)	30866	32291	29639
%	N/A	4.62	-3.98

Table 5: Basement Insulation Simulation Results

It can be seen by the simulation results in Table 5 that the basement acts as a cooling source in the building. A lower amount of insulation in the basement keeps that space at a temperature nearer to the ground temperature, which averages about 55 degrees over the course of the year. Although one greatly saves on cooling costs during the summer by reducing basement insulation and making use of the ground's cool temperatures, these savings are negated almost twice over by the energy consumption of the heating system during the winter.

This was found to have a particularly significant effect on the building's energy consumption. NREL notes that ground coupling is a relatively unexplored and relatively overlooked area when evaluating building simulations [57].

6.1.2. Infiltration

Avg ACH	**0.454**	**0.363**	**0.545**
Heating (kWh)	**16109**	**15154**	**18187**
%	**N/A**	**-5.93**	**12.90**
Cooling (kWh)	**1610**	**1623**	**1583**
%	**N/A**	**0.81**	**-1.68**
Total (kWh)	**30866**	**29531**	**32795**
%	**N/A**	**-4.32**	**6.25**

Table 6: Infiltration Simulation Results

During this simulation, the results of which can be found in Table 6, it was found that cooling costs actually increased as a result of lower infiltration. By examining the temperature profile of the indoor environment, this is because the heat transfer is dominated by radiation during the day, and while in the less air-tight home the cool night air filters into the home and the heat gains experienced during the day are relieved of the building, the more tightly-built house retains the warm air until morning, when the sun again filters into and heats up the building. This counterintuitive effect would be mitigated or eliminated by incorporating the shading schedule, by decreasing the solar heat gain coefficient of the building's windows, or by opening windows or using mechanical ventilation at night. Despite this gain in cooling power consumption, however, the lower infiltration values yield lower overall energy consumption, since heating during the winter requires much more energy, and infiltration provides a heating system no such hidden benefit.

Also, it can be seen that further weatherproofing of the house has a much smaller positive effect (-6.25% total consumption) than the negative effect of making the envelope more leaky (+9.26% total consumption). This is because of the fact that ventilation must be introduced to the building in order to maintain a safe indoor atmosphere. Although being able to control the passage of air from outside to inside allows for better efficiency than having a leaky home, there is a sudden drop-off in terms of how much this building characteristic can improve the energy consumption levels once the ASHRAE minimum is reached.

6.1.3. Wall Insulation

R-Value [ft^2-°F-hr/BTU (m^2-°C-hr/kJ)]	12.3 (.67)	16 (.871)	23 (1.25)
Heating (kWh)	16109	15246	14783
%	N/A	-5.36	-8.23
Cooling (kWh)	1610	1588	1571
%	N/A	-1.37	-2.42
Total (kWh)	30866	29745	28180
%	N/A	-3.63	-8.70

Table 7: Wall Insulation Simulation Results

The wall insulation simulations, the results of which are shown in Table 7, were all run assuming a 2 by 4, 16 in. on center frame construction, and thus all provide feasible options for retrofit of existing buildings since they require no modification of the load-bearing structure. The baseline, as previously mentioned, uses fiberglass insulation in its cavities, allowing thermal bridging across its thermal boundary and leaving it with an R-value of R-12.3. The second variant of the wall construction used polyurethane foam in the cavities and achieved an R-23 insulation level. Other methods of increasing wall r-values normally require major remodeling work. For example, continuous insulation has been used instead of cavity insulation to eliminate thermal bridging across the wall. While this does not require destruction of the frame it requires replacement of much of the exterior wall. This option, therefore, is not the most feasible for retrofitting, but given the great potential for energy savings, is worth exploring. Using continuous insulation, i.e. by placing a continuous layer of fiberglass around the outside of the frame, R-16 was achieved. More often this continuous insulation is provided by rigid foam sheathing, but fiberglass batt insulation was chosen for the sake of comparison to the baseline home's cavity insulation method. Other methods of reducing thermal bridging deal with specific frame construction techniques, which are not at all viable options in retrofitting, and due to a great dependency on geometry are impractical to model in the current version of TRNBUILD.

6.1.4 Attic Insulation

R-Value [ft^2-°F-hr/BTU (m^2-°C-hr/kJ)]	**33 (1.8)**	**46 (2.5)**	**38 (2.07)**
Heating (kWh)	**16109**	**15312**	**15866**
%	**N/A**	**-4.95**	**-1.51**
Cooling (kWh)	**1610**	**1572**	**1595**
%	**N/A**	**-2.36**	**-0.93**
Total (kWh)	**30866**	**29992**	**30323**
%	**N/A**	**-2.83**	**-1.76**

Table 8: Attic Insulation Simulation Results

The attic insulation simulation, the results of which are displayed in Table 8, shows expected values in that more insulation yields lower consumption values; however, the levels of savings are of lesser magnitude than would be expected in a normal home. This discrepancy highlights one of the limitations of using the current version of TRNBUILD as a building simulation program. Since it is completely non-geometric, it does not recognize the fact that the attic is at a greater height than any other floor. The ceiling of the second floor is not recognized as a ceiling but instead as another wall. Because each zone is simplified as one node, there are no calculations performed to predict the effect of heat rising to the ceiling. Thus, whereas in reality the attic is among the most necessary places in the home to be well-sealed and well-insulated, the current version of this program finds little difference between the ceiling of the upper floor and any other wall.

6.1.5. Bottom floor insulation

R-Value [ft^2-°F-hr/BTU (m^2-°C-hr/kJ)]	10 (.54)	8 (.44)	12 (.65)
Heating (kWh)	16109	17004	15327
%	N/A	5.56	-4.85
Cooling (kWh)	1610	1537	1656
%	N/A	-4.53	2.86
Total (kWh)	30866	31194	30489
%	N/A	1.06	-1.22

Table 9: Bottom Floor Insulation Simulation Results

The bottom floor of the house, like the ceiling of the 2nd floor, is paid particular attention because it separates conditioned spaces from unconditioned spaces. As shown in Table 9, in this simulation it was found that the R-value of the bottom floor was indeed an energy-saver, but among the less effective procedures available for insulating one's home. In both cases, total energy consumption was affected by only approximately 1%. This seems to be because the baseline model's basement is already sufficiently insulated from outdoor temperatures, and the temperature differences, and therefore heat flux, across this floor are significantly smaller than those between a vertical exterior wall and the outdoors. One can still see the effect of the basement siphoning heat from the conditioned space, however. During simulation it was found that the insulation levels between the first floor and the basement were far less important to creating a thermal boundary compared to the coupling air flows between those two zones.

6.1.6 Window U-value

U-Value [BTU/ft^2-°F-hr (kJ/m^2-°C-hr)]	Double-Pane 3.5 (64.3)	Single-Pane 5.8 (106.5)	Krypton-filled 1.1 (20.2)
Heating (kWh)	16109	18814	13018
%	N/A	16.79	-19.19
Cooling (kWh)	1610	1789	1456
%	N/A	11.12	-9.57
Total (kWh)	30866	33193	27433
%	N/A	7.54	-11.12

Table 10: Window U-Value Simulation Results

6.1.7 Window SHGC

SHGC	0.6	0.7	0.5	0.2
Heating (kWh)	16109	15913	16188	16302
%	N/A	-1.22	0.49	1.20
Cooling (kWh)	1610	1716	1467	1017
%	N/A	6.58	-8.88	-36.83
Total (kWh)	30866	30997	30710	30115
%	N/A	0.42	-0.51	-2.43

Table 11: Window SHGC Simulation Results

The preceding set of simulations highlights the idea that windows are the weak point in a building's thermal boundary. The change of the 15% of the building's external wall area to a more insulating material, as shown in Table 10, combined with the effect of reducing the SHGC of the window glazing, as shown in Table 11, resulted in more drastic savings than any of the other individual envelope improvements, saving a combined total of 14.8% between the baseline and the efficient options which will later be used in the low- energy home simulation.

6.1.8 Cool Roof vs. Conventional Shingles

In 2009, a job-creating project was started in urban Baltimore, the purpose of which was to “green” one of the streets by painting the roofs of that street’s buildings white [57]. This type of project is routinely done to lower absorption of heat radiation during the cooling season and to reduce the severity of the “urban heat island” effect [58]. Such a solution has been shown to significantly reduce annual energy consumption in warm climates like, for example, Florida [59], but in cooler climates the benefits of the roof covering is more debatable. A white roof would reduce heat gains through the roof of the home during heating season, thus increasing the reliance on internal heating sources such as a furnace. However, significantly less radiation directly reaches the roof during the winter, since the sun stays lower in the sky and shines at an increased level on the exterior walls rather than solely the roof (i.e. the color of the roof becomes less significant during the winter months) [60]. This TRNSYS program can simulate the effect of altering the reflectivity of the building’s roof and simulate its effect on energy consumption over the entire year.

It should be noted that one aspect of reality that is not replicated by the simulation is the presence of snow on the roof, as is an occasional occurrence in the Baltimore area, and would serve to create a reflective roof on the building no matter the color of the roof itself; however, by examination of TMY3 data for the Washington, DC metro area, snow cover is limited enough to not drastically affect average albedo levels during the winter months, thus for this simulation, in this particular climate, such a consideration might be considered negligible [61].

Also, in high concentrations of artificial surfaces, such as urban areas, widespread use of cool roofs have been shown to appreciably decrease ambient temperatures, especially during the summertime [62], which as a secondary effect reduces the cooling load on the constituent individual houses. This simulation does not consider the effect of such a widespread change, but only examines the effects of changing an individual house's roof color.

Table 12 shows the results of the albedo change simulation. Two situations were simulated, one comparing a white-painted roof with a traditional asphalt-shingled roof, and the other comparing an aluminum roof, as is popular in such sun-drenched regions as Australia, with the traditional roof. TRNBUILD does not recognize albedo values per se, but rather solar absorptance values. This solar absorptance value (A_s) was altered in the equation for solar heat gains:

$$Q_{absorbed} = Q_{solar} * A_s \tag{9}$$

The absorptance values of these materials were decided upon by consulting the values recommended by the Solar Energy Laboratory in the TRNBUILD manual, which are generally consistent with those values given by other sources [63].

Roof Surface	Black Shingles	White Paint	Aluminum
Absorptance	0.75	0.2	0.35
Heating (kWh)	16109	16246	16192
%	N/A	0.85	0.52
Cooling (kWh)	1610	1482	1511
%	N/A	-7.95	-6.15
Total (kWh)	30866	30835	30829
%	N/A	-0.10	-0.12

Table 12: Albedo Change Simulation Results

6.1.8.1 Results and Comparison with Past Experiments

Table 12 shows that the color of the roof of the house had only a small effect on its annual energy consumption. Aluminum was the most efficient, but it had only a small impact, with about a .1% reduction in energy. It should be noted that part of the attractiveness of aluminum as a roofing material results from its low emissivity. In exterior wall calculations, TRNBUILD assumes that emissivity is equal to absorptivity, and thus in this sort of calculation that physical fact is not replicated. The reason for aluminum's primacy in the ranks of the roof coatings is due to the fact that heating energy consumption so far outweighs cooling consumption that the small percent change in heating consumption between aluminum and the white roof is enough to give aluminum a slight, almost negligible advantage.

Past simulations conducted by the Department of Energy have found that the savings gained by the use of "cool roofs" depend very much on location. By use of the Oak Ridge National Laboratory's DOE Cool Roof Calculator, one study found that while white roofs earned the most savings in the South, at approximately 1.2 kWh per sq ft in cities such as Miami, in the more northern areas of the East Coast, such as New York, where heating is of primary concern, white roofs cost more money due to lost absorption of the sun's heat [64]. Aluminum was found to be the most cost-effective coating, in these places, saving the homeowner approximately .5 kWh per sq ft of cooling costs yearly.

Another study in Florida compared a white-roofed building with a black-roofed building, first with a physical experiment and then with a simulation using DOE-2. The experiment found that a white roof coating there can save approximately 19% on cooling bills [65]. The Florida team noted in the course of describing the experiment that many building simulation programs fail to produce close-to-real-life data due to inability of many programs to accurately model exfiltration from ducts and other airflow phenomena.

The small change is explainable because of two reasons. First of all, even the baseline configuration of the building has a great deal of insulation in the attic, having met the standards of IECC 2009. Thus, despite the great amount of heat absorbed by the attic when black shingles are used, and the resulting high attic temperatures, which can be seen in Figure 18. Also, as mentioned before, because of ASHRAE and IECC recommendations, all ventilation systems were modeled as existing inside the building's thermal envelope. The Florida team notes that a large part of the benefit of the cool roof is because of this type of duct arrangement. With black shingles, the attic becomes overheated and warms the air-conditioner output air passing through the ducts. So by removing the ducts from the harsh environment of the attic and placing them within the insulation boundary of the house, and also adding insulation to the level required by building codes, this simulation would suggest that the question of roof color essentially becomes insignificant for Maryland's climate. However, the temperature differences shown in Figure 18 do show that it does have the potential of causing strain upon a cooling system if these specifications are not met. In all, rather than disproving the use of cool roofs in the Maryland area, this simulation shows the need for further exploration into this area of the building model.

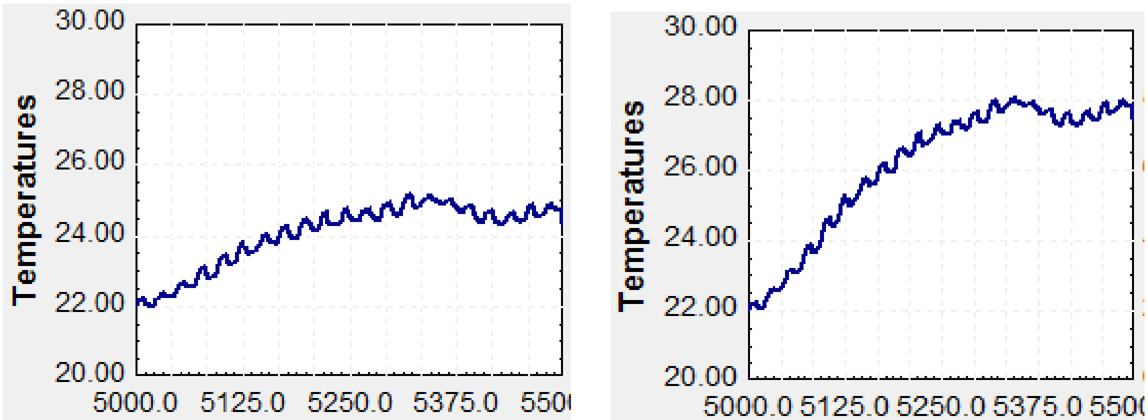


Figure 18: 3-Week Attic Temperature: White Roof (L) and Black Roof (R)

6.1.9 Total envelope

After each individual variable was altered, the most efficient option from each tested characteristic was combined to evaluate the potential savings possible by simply retrofitting a building's thermal envelope. The overall savings amounted to 10724 kWh, or 34.7%, from the baseline's, as seen in Table 13. To clarify, the building characteristics used were as follows:

- R-12 basement insulation
- 20% reduced infiltration
- R-23 wall insulation
- R-46 attic insulation
- R-12 first floor insulation
- U-1.1, 0.2 SHGC windows

- Aluminum roof

	Base	Modified
Heating (kWh)	16109	8178
%	N/A	-49.23
Cooling (kWh)	1610	776
%	N/A	-51.80
Total (kWh)	30866	20142
%	N/A	-34.74

Table 13: Total Envelope Simulation Results

6.1.10. Comparison of Building Characteristic Importance

To compare the relative importance of each building characteristic, the various sets of simulation results were compiled into a single tornado diagram. Figure 19 shows the results of the sensitivity comparison. In order to allow a meaningful comparison between the multiple studies, the energy consumption of each non-baseline simulation was normalized by dividing that energy consumption by the percent by which R-value was changed in that simulation.. The red bars signify the results of those simulations where the variable in question was decreased, and blue where that value was increased. When a bar goes to the right, in the positive direction, more energy was consumed per percent change in the variable. For example, infiltration, when increased (i.e the house made leakier), for every 1% change in air-changes per hour of infiltration from the baseline value, the total annual energy consumption of the building rose approximately .49%, or 154 kWh. When infiltration was decreased, approximately .13% (43 kWh) was saved per 1% decrease in air-changes per hour (This significant difference was due to the lower limit of safe infiltration levels, and the ventilation system kicking on to ensure a safe rate of fresh air circulation). It can be seen that infiltration and the basement insulation had the greatest effect upon the overall energy consumption of the building per percentage change, while such things as roof coatings and window glazing improvements had far less effect, at approximately .01%.

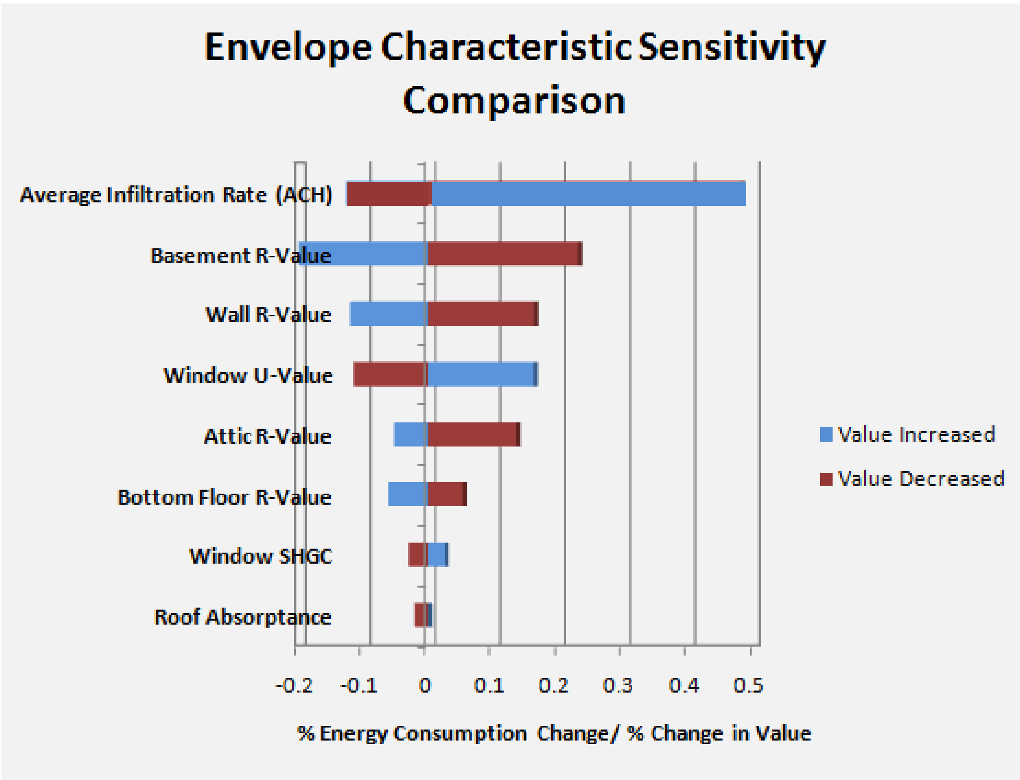


Figure 19: Envelope Characteristic Sensitivity Comparison

6.2 Indoor Equipment Simulations

The following simulations do not examine the construction of the building but rather the type of equipment used inside the building, and the methods by which they are used. Specifically, this section will survey the effects of changing HVAC equipment, water heating methods, thermostat settings, the use of shade to conserve energy, and the effect of increasing overall appliance efficiency. In each case the baseline model was made to vary one characteristic at a time.

6.2.1 HVAC Simulations

Simulations were performed to determine the value of replacing HVAC equipment, comparing the baseline's 11 SEER air conditioner/ furnace combination, to the alternative situations of replacing the air conditioner with a 13 SEER model, and by replacing the entire system with a 13 SEER, 8.25 HSPF. Table 14 shows the results of this simulation. The results show the amount to which heating energy consumption far outweighs the consumption by the cooling system in this home, since while improving the cooling energy consumption by approximately 15% reduces total energy consumption by about 1%, the reduction of heat energy consumption by 69% in using the heat pump reduces the overall energy consumption by almost 40%. In this simulation in particular it is important to consider that while a heat pump might consume half the energy of a furnace when considering a system containing only the house, in reality, since it's powered electrically, it could be using more energy than the furnace when the scope of the system is extended to the power plant. For the purpose of a net-zero-site-energy house, however, the heat pump results in considerable energy savings

	Furnace/ AC, SEER 11	Furnace/ AC SEER 13	HP
Heating (kWh)	16109	16110	4949
%	N/A	0	-69.28
Cooling (kWh)	1610	1371	1370
%	N/A	-14.84	-14.91
Total (kWh)	30866	30523	18716
%	N/A	-1.11	-39.36

Table 14: Furnace- Heat Pump Comparison Results

6.2.2. Thermostat Setpoint simulations

The following simulations were conducted in order to find how changes to the temperature setpoints recommended by the EPA affect annual energy consumption. They were conducted using the baseline model and modifying the schedule for the thermostat setback. As previously mentioned in Section 4.6, the baseline case assumes no setback during the cooling season, but uses popular thermostat setback temperatures during the heating season.

Cooling Setpoint

Setpoint (deg F) (home/away)	75/75	74/74	76/76	75/78
Cooling (kWh)	1610	1853	1472	1211
%	N/A	15.09	-8.57	-24.78

Heating Setpoint

Setpoint (deg F) (home/away/asleep)	68/62/62	68/62/68	68/off/62	68/68/68
Heating (kWh)	16109	18101	15867	20472
%	N/A	12.37	-1.50	27.08

Table 15: Setpoint Simulation Results

Table 14 shows the results of the thermostat setpoint simulation. Deviating from recommended thermostat levels was shown to have a significant effect upon the energy consumption of the building. By failing to set back the thermostat during the heating season, the home consumed a full 27% more fuel in heating than the baseline home, where some form of setback was used. During the cooling season as similar result was found, since by easing the load on the air conditioner by setting the cooling set point back to 78 °F during unoccupied hours saved approximately 24% in cooling electricity consumption.

6.2.3 Hot water Simulations

Four different methods of heating water were modeled. These were as follows:

- Gas-fired, tank-storage
- Solar-heated, tank storage, gas burner backup
- Gas-fired demand heating
- Solar preheated, gas backup demand heating

The most conventional water heating method, and thus the option that was employed for the simulation of the baseline residence, was the gas-fired, tank storage method. The water tank was modeled as an 80 gallon tank, and heat was provided with an efficiency of 80% from a gas burner at the bottom of the water storage unit. This currently at the lowest end of the spectrum of thermal efficiency in today’s natural gas burners, but compares well to slightly older systems, because an 80% Annual Fuel Usage Efficiency (AFUE), or annual average thermal efficiency, became the minimum legal AFUE in 1992, before which boilers had AFUEs as low as 62% [66].

As mentioned previously, the DOE recommends a solar thermal collector of $3.3m^2$ size for a house with this number of residents. Therefore this size of thermal collector was installed on the home.

Additional options exist for water heating, such as employing the desuperheater of a ground-source heat pump to heat or preheat the water, or using a heat pump water heater in place of the gas burner (heat pumps do not provide enough heat output to be practical in an instantaneous (demand) heating system). The heat pump water-heating option has been included in the simulation but its use was not explored in this study.

Hot water system Results			
Storage	**Solar?**	**Energy Usage (kWh equiv)**	**% Change**
Tank(Gas)	**N**	**5702**	**N/A**
Tank (Gas)	**Y**	**4324**	**-24**
Demand	**N**	**3222**	**-43**
Demand	**Y**	**550.6**	**-90**

Table 16: Hot Water System Simulation Results

The results shown in Table 16 suggest that standby losses are the major factor in this house's water-heating energy consumption, since the solar thermal collector is not of great enough capacity to maintain the necessary temperature demanded by the load profiles, and the demand heater uses less energy than the solar-tank combination by avoiding standby losses altogether. This problem could be solved by further insulating the hot water tank, a variable which was not looked into by this study. Predictably, the solar-preheated demand heater combination provided the most energy efficient alternative, almost eliminating hot water natural gas consumption with a 90% reduction. The solar tank setup and the conventional tankless system also show to be effective measures at reducing energy consumption, decreasing hot water gas consumption by 24 and 43 percent, respectively.

6.2.4. Shading Simulations

In this pair of simulations, the effect of using a rigid schedule of altering the position of window blinds was investigated. By activating the shade schedule, the cooling system's energy consumption was reduced to 1393 kWh (-13.48% change), the heating bill to 16031 (-0.48% change), and the overall energy consumption was reduced to 30530 (-1.09% change). While it has only a slightly beneficial effect on heating costs, attention to the condition of window blinds has a significant effect on cooling costs.

6.2.5. Appliance Simulations

Since appliances represent a major source of internal heat generation inside buildings, the effect of the reduction of appliance power consumption upon the space conditioning energy consumption was explored. By employing the energy-efficient appliances as shown above in Table 4, a reduction of 35.5% was made in the energy consumption of appliances, from 7407 kWh to 4770 kWh. By reducing this appliance energy consumption, the heating costs for the building rose slightly, from 16109 kWh to 17191 kWh, a 6.7% change, and the cooling costs decreased from 1610 kWh to 1113 kWh, a -12.2% change. In this study it was assumed that the electrical power consumed by appliances was entirely distributed to the home, while in some cases that isn't necessarily true, most especially in the case of the range, which is routinely operated in concert with a local ventilation system. It is apparent, however, that appliances, being a major contributor to total power consumption, have an effect on the indoor comfort level of buildings, due to the heat gains generated by their use.

6.3 Maryland ZEH Simulation

Finally, the many energy-saving alternatives presented in this thesis were combined to explore the feasibility of achieving zero-net-energy status in a College Park home. In order to do this, the following features were used:

- Heat pump heating & cooling
- Aluminum roof
- Solar-preheated demand water heater

- R-12 floors, R-20 Basement, R-23 Walls, R-40 attic
- Krypton-filled, double-paned, low-SHGC windows
- Reduced load profiles, with the reductions described above in Table 4
- EPA recommended thermostat settings, as described in Table 3
- Shading schedules activated
- 30% reduced infiltration
- 60 m^2 of photovoltaic panels

Comfort levels were maintained at the same levels as those of the baseline home. Since setback was employed, the comfort zone monitor does not display the useful information, but Figure 20 depicts the temperature readings in the low-energy home over the course of the year. Despite the main graph, which gives the impression that very cool temperatures are maintained during the winter, by zooming in it can be seen that that is merely the effect of the thermostat setback, and that comfortable levels are maintained during occupancy hours.

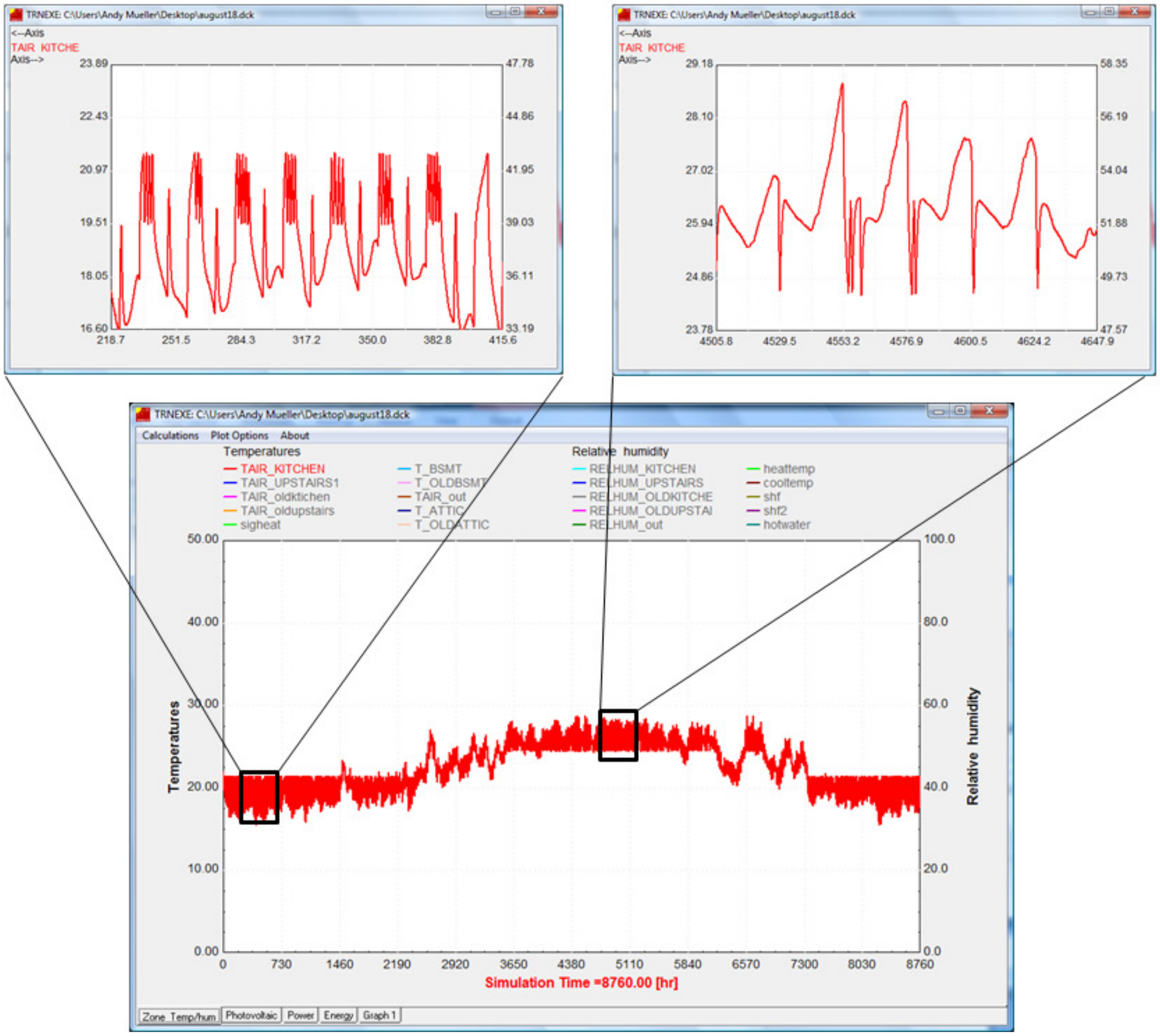


Figure 20: Low- Energy House Temperature Readings

Building	Baseline	ZEH
Heating (kWh)	16109	2457
%	N/A	-82.8
Cooling (kWh)	1610	788
%	N/A	-52.56
Gross Consumption (kWh)	30866	9781
%	N/A	-69.3
PV Production (kWh)	0	10565
Net Consumption (kWh)	30866	-784

Table 17: ZEH Simulation Results

Table 17 shows the numerical results of the ZEH Simulation. The results show a great potential for gross energy consumption reduction in the building, since this was reduced by 61%. Normally, using an industry rule of thumb, a building is expected to reduce its energy consumption by about 75% in order to be able to achieve full zero-energy status when photovoltaic modules are attached, but in this case, in this particular climate and with the building's favorable south-facing orientation, the array of photovoltaic panels was sufficient to overcome that shortcoming.

7. Conclusions

The previous data show that there are various, and in some cases equally valid measures of reducing the energy consumption of currently-standing residential buildings. Although the total number of combinations of technology were not completely inspected by this study, since given the large number of variables it would necessitate the simulation of thousands of combinations. The most effective energy saving methods are ranked as follows:

1. Using a heat pump rather than a furnace/ air conditioner combination saved approximately 39.1%.
2. Building Envelope insulation and integrity improvements, shown in greater detail in Figure 3, reduced consumption by approximately 34.7%.
3. The substitution of a solar-heated, on-demand backup water heater saved approximately 14.7%.
4. The use of thermostat setback, compared to using constant settings, achieved approximately 12.7% savings.
5. The reduction of appliance energy consumption by 2737 kWh reduced total annual energy consumption by 2235 kWh or 6.1%. This total value is

less than 2737 due to increased use of the furnace to make up for appliance heat gains.

6. The use of blinds in the most efficient manner possible, compared to leaving them halfway down constantly, was shown to decrease energy consumption by 1.1%.

It was verified that well-insulated glazing is among the most important features of a building, in line with consensus of the building industry, and found that given building-code-passing attic insulation and ducts contained within the building's thermal envelope, color changes to the building's roof had little effect on an individual house, no considering interaction with other buildings. Some simulations, including that of the attic insulation variance, show the need to increase the accuracy of modeling procedures beyond that of what were used in this program.

Another significant finding is the great importance of user behavior patterns on the final annual energy consumption of the building. One aspect of building technology that gains great credence from the simulation results shown in this paper is building automation. Especially in the case of thermostat levels, setback, and shading usage, it was found that great potential for energy savings exists when the responsibility of important energy-consuming aspects is taken out of the hands of a person and put under the purview of a computer's scheduling system. As was seen in Masoso and in Foster, reliance on human nature to flawlessly, consistently make energy-efficient choices is not always a safe assumption, and accordingly, in this set of simulations the various methods of building control saved at least 4500 kWh of energy consumption. In a similar vein, it was found that more research needs to occur regarding occupant behavioral activity in residential homes (e.g. occupancy and appliance usage) to improve the accuracy of building model when compared to reality.

The results of the ZEH simulation suggest that it could be feasible to refit a Maryland home to achieve net-zero site energy. This data, however, applies to only this particular home layout, and does not necessarily indicate that it is possible for all Maryland homes. Also, given the level of accuracy inherent to building simulation tools, and the fact that zero-energy status was achieved by only a factor of 784 kWh, the zero-energy status could possibly not be replicated in reality. However, this can be viewed as an encouraging sign that a real, 2-story, 2464-sq ft building could be feasibly converted into a zero-energy building.

8. Recommendations for Improvement

8.1 Economic Analysis

This thesis neglected the cost of each building modification and assumed that sufficient funds were available to make necessary changes; in the real world this is not the case and the economic trade-off is the prime concern. A rigorous method of evaluating the economic tradeoffs necessary when purchasing or installing each building modification would provide the data that is most important to many consumers. TRNSYS contains an economic analysis module, Type 582, which allows for a simple, if somewhat rigid, method of making calculations for economic predictions. Full functionality of this program as the basis for savings estimation software would definitely require a rigorous and flexible set of economic analysis calculations to be included within the simulation itself. However, adding cost modeling to the program would require taking into account peak usage charges for electricity, and would require such things as estimates of oil prices, etc, which given predicted future fuel shortages would likely introduce far more uncertainty than modeling solely the fuel usage levels as has been done here.

8.2 Building Detail

Some aspects of the building system were left uninspected, or simplified. In future work it could prove helpful to use more close detail in certain systems. Great care should be taken to streamline the calculations of the simulation program, however, since as building detail increases, so does the calculation time for each time step. Also, the inclusion of too much detail in building models has been shown to have great potential for reducing certainty if not carefully done [67]. Some suggestions for greater detail include:

-**Appliances**: The electric power consumed by appliances is released into the indoor environment of the building as heat. This was modeled by introducing heat gains over the entire conditioned area of the home, rather than, for example, placing the heat addition of the refrigerator and stove in the kitchen, or the lighting gains scheduled to coincide with occupancy schedules in different areas of the home. This limitation was derived from the method of drawing the load profile information from Excel and inserting it into TRNSYS. The current method of linking Excel and TRNSYS uses Excel's 1997 version, which allows for only 32000 data points. By altering the code of the Excel linking component in TRNSYS to allow it to link with Excel 03 it would be theoretically possible to expand the load profiles into the constituent individual appliances, therefore allowing the placement of each system in an appropriate room of the building, and allowing for easier modification of each device's energy consumption level.

-Scheduling: For greater flexibility in controlling thermostat levels and shading ratios, an Excel spreadsheet would work well in place of the TRNSYS forcing functions.

-**Controls**: A major source of discussion lies in the field of "smart buildings," that is, buildings with automated systems that reduce energy consumption. This model, despite consisting of several "zones" represents a home with one thermostat controlling the temperature of one large thermal zone. By adding thermostats in each room the effects of occupancy detection and shutting off thermal control of unoccupied rooms could be investigated.

-Air flows in TRNFLOW: The Solar Energy Laboratory makes an airflow program referred to as TRNFLOW. This software uses COMIS, Lawrence Berkeley Laboratories' Multi-Zone Airflow Model, and allows that model to communicate with Type 56. COMIS is specifically built to model such things as natural ventilation, interzonal air coupling, and infiltration, which were three of the prime concerns of Judkoff's critique of building simulations. Many of the inaccuracies discussed in the above result analyses were attributed to an inability to model heat flow within and between rooms, and thus the use of such a program would help to alleviate some uncertainty in those affected areas of the simulation.

On a similar note, local ventilation modeling would be useful. Two locations in homes routinely contain exhaust fans which remove air from the indoor environment and move it to the outside. These are above the range of a stove and in bathrooms. ASHRAE standards dictate they should be present. Bathrooms were not modeled in this program, and the stove heating rate was unable to be separated from the other non-HVAC electrical loads due to Excel conflicts, but given the frequency of showering and cooking in a home, being able to model such could play a role in the heat and humidity of the building.

-**TRNSYS 17:** The current building simulation program was constructed using TRNSYS 16. According to the developers of TRNSYS, Thermal Energy System Specialists (TESS) a new version of TRNSYS will be produced and released in 2010. Many improvements are expected, including a link with Google's drawing program, SketchUp. Such a link will allow far easier communication of building geometry to TRNSYS, and will allow a far more readily-modifiable building structure. The simulation tool should be better matched to an actual building geometry, since this new drawing tool will allegedly be available. Any increase of detail with the controls of the building would be of much less value if those controls control the simple box geometry found here. This possibility of including a new visual interface with the building design provides further promise for this building simulation program's potential use as a consumer building modification recommendation tool.

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