6-28-2017

Comparing Building Modeling Software to the Energy Record of a Preexisting Structure

Nathan Lasley
Western Kentucky University, nathan.lasley421@topper.wku.edu

Follow this and additional works at: http://digitalcommons.wku.edu/stu_hon_theses

Part of the Computer-Aided Engineering and Design Commons, Energy Systems Commons, and the Sustainability Commons

COMPARING BUILDING MODELING SOFTWARE TO THE ENERGY RECORD

OF A PREEXISTING STRUCTURE

A Capstone Project Presented in Partial Fulfillment

of the Requirements for the Degree Bachelor of Science

with Honors College Graduate Distinction at

Western Kentucky University

By

Nathan S. Lasley

May 2017

*****

CE/T Committee:

Professor Robert Choate, Chair

Professor Chris Byrne

I dedicate this thesis to my parents, Mary and Kevin Lasley, who are the greatest role models and educators I know. Thank you for all the love and support through all my endeavors. As you begin retirement I hope you are able to enjoy it to the fullest, you have certainly earned it.

ACKNOWLEDGEMENTS

ABSTRACT

Buildings are complex systems - even "simple" residential structures. Many factors go into building energy consumption and the design to reduce it. Computer energy modeling allows the simultaneous consideration and balance of many of those variables. Computer models are only as good as the information provided however. Tools like blower door and duct blaster can be used to aid in verifying the model or to provide more information to build a better model.

In order to verify of building computer energy simulation methods, the Western Kentucky University (WKU) Office of Sustainability located at 503 Regents Ave. in Bowling Green KY was selected for blower door analysis. The building is a residential structure constructed in 1931, which was acquired by WKU and repurposed as office space. In 2014, a proposal was made outlining improvements to make the building LEED certified with a goal of making the building net zero in its energy consumption. A blower door test was run pre and post mitigation.

Using blower door measurements to assess infiltration and exfiltration of air flow through the building envelope, a post analysis was conducted with the aid of building modeling software. Using collected geometrical and blower door measurements a model was constructed and compared to the previous year's utility record. For this analysis, EnergyPlus™ was used using BEopt as an interface.

Keywords: Blower Door, BIM, Computer Modeling, EnergyPlus, BEopt, WKU Office of Sustainability

VITA

EDUCATION

Western Kentucky University, Bowling Green, KY   May 2017
       B.S. in Mechanical Engineering – Honors College Graduate
       Honors Capstone: *Comparing Building Modeling Software*
          to the Energy Record of a Preexisting Structure

Gatton Academy, Bowling Green, KY   May 2012

PROFESSIONAL EXPERIENCE

New Mather Metals Inc; Franklin, KY   May 2016-
       Engineering Intern   Present

Bridgestone Tire Operation; Warren, TN   May 2014-
       Engineering Coop   Aug 2015

AWARDS & HONORS

Magna Cum Laude, WKU, May 2017
Gatton Academy Student Scholarship, WKU, 2012-2017
Evan McCasland Award in Mechanical Engineering, WKU, April 2017
WKU Student Research Conference Poster Presentation Session Winner, March 2017
Eagle Scout, Nov. 2011

PROFESSIONAL MEMBERSHIPS

Tau Beta Pi (TBP)
The American Society of Mechanical Engineers (ASME)

INTERNATIONAL EXPERIENCE

Harlaxton, Grantham, England   June 2011
       ENG 200 Summer Semester

PRESENTATIONS

Choate, R., &Lasley, S. (2017, February). *Comparing the Building Modeling Software to*
      the Energy Record of a Preexisting Structure. 1 Hour Presentation at the 2017
      Midwest Residential Energy Conference. Lexington, KY.

Lasley, S. (2017, March). *Comparing the Building Modeling Software to the Energy*
      Record of a Preexisting Structure. Poster presented at the WKU Student Research
      Conference. Bowling Green, KY.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

BACKGROUND

This project is the continuation of efforts started by a mentoring professor and maintained through several generations of students. This team, known informally as the Energy Audit WKU Student Team, includes Hussain Altammar, Justin Hayes, Caitlyn Clark , Ben Arnold, Wes Russelburg and Nathan Lasley. It all began with the following challenge issued in a statement by Dr. Gary Ransdell president of Western Kentucky University. "Recognizing that universities are the places where innovative solutions are born, the WKU campus is being used as a living laboratory for the energy efficiency and conservation efforts. Through this policy and other efforts, we are encouraging students, faculty, and staff to apply ideas and research to advance sustainability." (Dr. Gary Ransdell, university statement, March 2009).

The goal of these projects was to apply engineering science to the understanding of modeling or quantifying the performance of a structure in regards to energy. Four of these projects were funded by FUSE. They included Air Flow Leaking Investigation through Common Geometric Shapes, Air Flow Visualization using IR Thermographic Imaging, Environmental Effects on Blower Door Measurements, and this project; Comparing Building Modeling Software to the Energy Record of a Preexisting Structure. This involved maintaining an understanding and ability to apply fluid mechanics and heat transfer. This also included trying to understand an industry standard tool mentioned above: Blower Door.

Bloor Door is a measurement tool to aid in quantifying the properties of a structure related to fluid mechanics. It quantifies the air tightness of the construction (The Energy Conservatory, 2012). This air tightness is a volume flow rate characteristic of the

air infiltrating and ex-filtrating through all the cracks and crevices that permeate the building envelope. To measure this quantity a fan is used to maintain a pressure differential between the inside and outside of the structure. The volume flow rate across the fan is then measured and used as the leakage rate for the structure. This based on the conservation of mass and the assumption that the volume of air flowing through the fan equals the volume permeating through the envelope. The standard practice units measured are in CFM50. This equates to x cubic feet per minute of flow through the building envelope when the pressure differential between the interior and exterior of the structure being tested is 50 Pascals. For thoroughness this is done under a positive pressure and again at negative pressure. Figure 1 demonstrates this concept graphically and Figure 9 in the appendix contains a Bloor Door unit that is being run in the field.
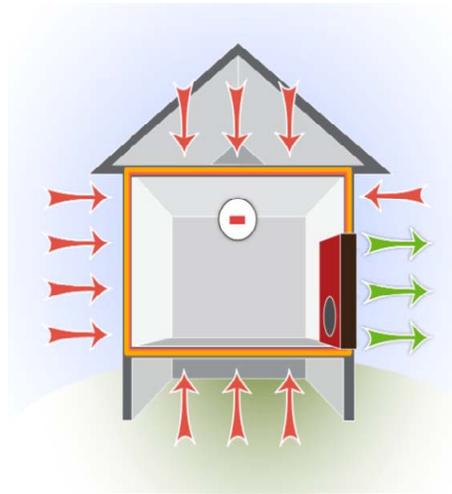

Figure 1. Blower Door Concept

The value measured of x CFM50 is traditionally converted to an ACH50 which is air changes per hour. This is calculated by Equation 1 where volume is the interior

2

volume of the space under test. This normalizes the rate of infiltration and exfiltration so that structures of varying size can be compared equally. The target value is established by the IECC code year dictated by local legislature. For Kentucky this is 2012 IECC which dictates that for the corresponding region the maximum ACH50 allowed is 5 ACH50 for a new residential construction. Structures built prior to this are unaffected.

$$ACH50 = \frac{CFM50 * \left(\frac{60\ min}{1\ hour}\right)}{volume(ft^3)}$$

Equation 1. Conversion Between ACH50 and CFM50

Along with the measured quantity ACH50 is another quantity called ACH(n) or natural air changes per hour. According to Robbins (2017), "These natural air leakage rates, ACH(n), are 1/20 - 1/14 of ACH(50)" (p. 82). Using Equation 2 it is possible to convert between measured ACH50 and ACH(n). The value N in Equation 2 depends on the structure. Robbins (2017) states that in this region for a 1-story structure N is 20, for a 2-story N is 16.2, and for a 3-story structure N is 14.4 (p. 82). Table 1 lists common ACH(n) values and the structure they would typically be associated with.

$$ACH(n) = \frac{ACH(50)}{N}$$

Equation 2. Conversion Between ACH50 and ACH(n)

Being able to quantify leakage rate is important because of the impact air leakage has on the design and performance of a structure.

Table 1. Scale of Natural Air Changes Per Hour (Robbins 2017 p.82)

Natural Air Changers Per Hour - ACH(n)	
2.0 ACH or more	Worst, most loose assemblies with many leaks especially during windy times
1.0 - 2.0 ACH	Poor or old construction with plenty leaks
0.5 - 1.0 ACH	Average new & airtightened existing construction
0.75 ACH	Standard assumption in pre-1980 ASHRAE handbooks
0.25 ACH - 0.5 ACH	Tight new & very tight existing construction
0.25 ACH	Level below witch intentional ventilation is recommended
0.10 ACH - 0.25 ACH	Very tight new construction **(0.15 - 0.21 is the typical max rate in IECC 2012)**
0.10 ACH or less	Extremely tight new construction **(0.03 is the typical max rate in Passivhaus)**

The U.S. Department of Energy (2004) states that:

> Some reasons for establishing building tightness include avoiding moisture condensation problems, avoiding uncomfortable drafts caused by cold air leaking in from the outdoors, determining how much ventilation might be needed to provide acceptable indoor air quality, and reducing energy consumption due to air leakage.

That last bullet is critical because air leakage impacts the design and sizing of an HVAC that adequately meets a structure's need. A leaky structure will require a larger HVAC unit than a more air tight structure of the same size. This larger unit typically requires more energy to run. Second an HVAC unit expends energy to condition space for human comfort. If that conditioned air escapes then it is essentially wasted and more energy must be expended to replace it.

Tools like Blower Door are useful for assessing an "as built" construction and comparing that to the design or code verifying that the structure was built correctly. These tools however examine specific factors and can most often only be used post construction. Buildings are complex systems - even "simple" residential structures. Many factors play in to the performance of a structure and must be accounted for in the design. These factors include radiation effects, convection effects, factors due to geography such as weather, building geometry and materials, and how the structure is used. Aspects such as occupant's interior set point preferences factor in to the performance of a structure. Thankfully these items can all be addressed simultaneously with the aid of a design tool: Building Information Modeling (BIM).

BUILDING INFORMATION MODELING

Building Information Modeling, further referred to as BIM, is a design tool that can be used to examine all the factors that influence a buildings energy performance. Zhai (2001) indicates that BIM for HVAC and energy performance is in the forms of Energy Simulation (ES) and Computational Fluid Dynamics (CFD). ES and CFD each have their own function and methodology. They each also have their own advantages and disadvantages. Zhai (2001) concludes that, "With the information from both ES and CFD calculations, designers can design environmental control system for buildings that satisfy multiple criteria." (p. 59).

CFD examines specific values considering factors such as velocities, pressures, and temperatures. CFD considers these items in greater detail as well. It functions by applying numerical methods to attempt to solve the Navier-Stokes equations, which can be seen in Figure 10, for fluid flow. These equations apply the conservation of mass and momentum to a control volume. The volume being studied is segmented into a finite number of cells that these equations are applied to repeatedly over a given time interval. The solution is dependent however on the boundary conditions which are applied by the user (Zhai, 2001, p. 61).

ES examines the building envelope, HVAC, and whole building energy analysis. This is similar to a bulk parameter method as specific values are often replaced with averages in order to simplify calculations. ES solves using energy balance equations. Traditionally the structure is split into zones and the energy balance equations are applied to the zone air and surface heat transfer at each of the structures primary surfaces (windows, walls, roof, or ceiling). Heat conduction is calculated using finite difference

and convective heat transfer coefficient, h, is typically estimated or maintained constant. Due to the nature of HVAC and desire to condition a space the interior temperature is held constant. With this process the energy consumption of a structures HVAC system can be estimated (Zhai, 2001, p. 60).

One such ES software that is commonly used, and was used for this study, is EnergyPlus[TM]. The U.S. Department of Energy (DOE) (2016), who developed it, states that, "Energy Plus is a whole building energy simulation program that engineers, architects, and researchers use to model both energy consumption-for heating, cooling, ventilation, lighting, and plug and process loads - and water use in buildings." It is a free and open-source software that functions extremely similar to how Zhai outlined an ES software to perform. It is a simulation tool that is versatile. It can aid in design of a new structure or test energy performance of an existing structure.

Strand (2000) outlines the history and methodology of EnergyPlus. The DOE established EnergyPlus primarily as a simulation engine in response to the growing popularity of ES established as early as the 1960s. The popular programs were BLAST and DOE-2 however each of these had issues that the DOE hoped to overcome. This was accomplished by taking the strengths of BLAST and DOE-2 and integrating them together. Strand (2000) suggests that "some of the more important [strengths] include realistic system controls, moisture absorption and desorption in building elements, radiant heating and cooling systems, and interzone air flow." (p. 4). Figure 2 outlines the framework for this integrated approach. The Surface Heat Balance Manager acts like conventional ES as mentioned previously and handles heat balance, boundary conditions, the three modes of heat transfer, and mass transfer effects. The Air Mass Balance Module

acts similar to a CFD while still looking at bulk averages by handling the effects of air infiltration and exfiltration due to design or natural leakage. Inside these tools there are some assumptions however. Strand (2001) outlines, "It is assumed that room surfaces have: uniform surface temperatures, uniform long and short wave radiation, diffuse radiating surfaces, and internal heat conduction." (p. 4).
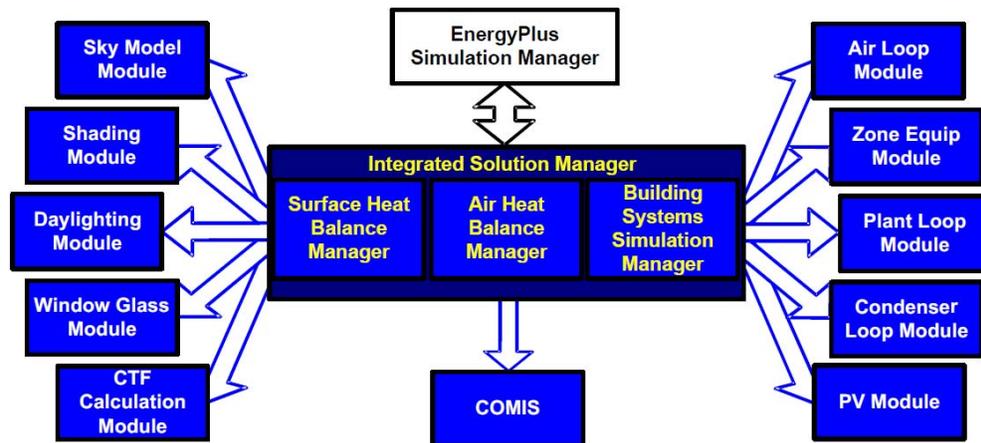

Figure 2. EnergyPlus Integrated Simulation Manager (Strand 2000 p. 9)

EnergyPlus does not use a graphical interface. Instead it is console based meaning that the input and output of the software is in the form of text files. This can add challenge to learning how to use and actually use EnergyPlus. Fortunately EnergyPlus allows for the use of third-party user interfaces to handle the input and output of making it easier to use. This process can be seen in Figure 3 on the right side. A custom interface that is typically a mixture of console and graphics base receives the information from the user, passes it into EnergyPlus for interpretation and reduction. That data is then passed back to the custom interface which in turn displays it for the user in a format that may be easier to review (Strand, 2000, p. 7).
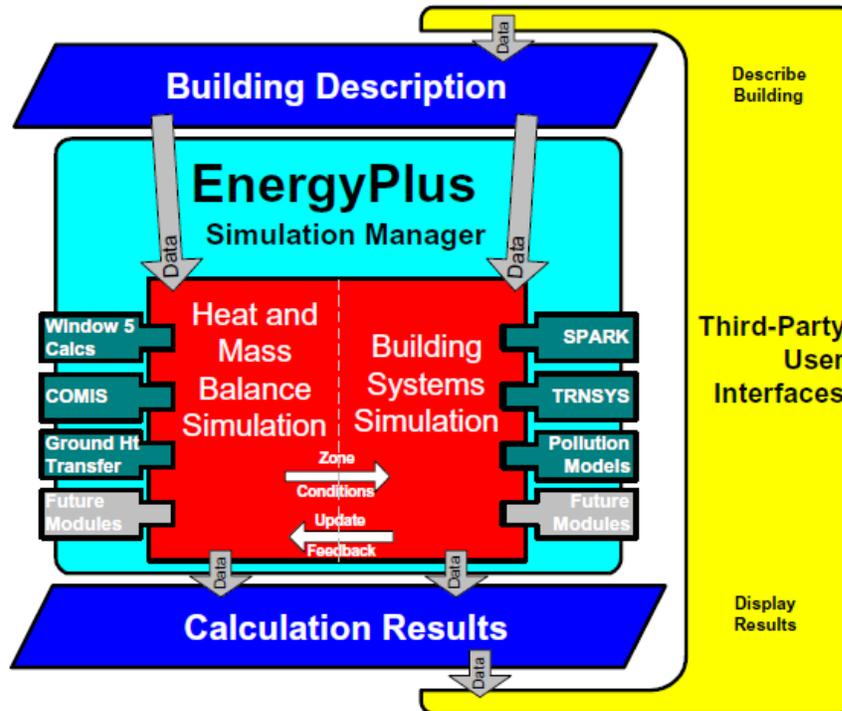
Figure 3. EnergyPlus Structure (Strand 2000 p.9)

One such third-party user interface is Building Energy Optimization (BEopt) which was developed by the National Renewable Energy Laboratories (NREL). BEopt is used to primarily evaluate residential building design and cost optimal efficiency packages. It can be used to analyze both new construction and existing home retrofits, as well as single-family detached and multi-family buildings. It provides detailed simulation-based analysis based on specific house characteristics, such as size, architecture, occupancy, vintage, location, and utility rates. It also accounts for the geography of the structure under test through the use of a text file available from the DOE that contains all the relevant weather data needed for the simulation.

BEopt offers many simulation methods and promotes being a tool toward the Path to Zero Net Energy (ZNE). It can be used effectively towards this mean because BEopt does not solely consider the science in its simulations, it can also estimate the economics. Figure 4 illustrates the steps BEopt outlines on the path to ZNE. This graph can be used to answer the following questions (NREL, 2016): "How much should be invested in efficiency before investing in Photo Voltaic? What is the optimal configuration of energy efficiency measures? What if only a partial reduction in energy use (from a reference case) is desired?".
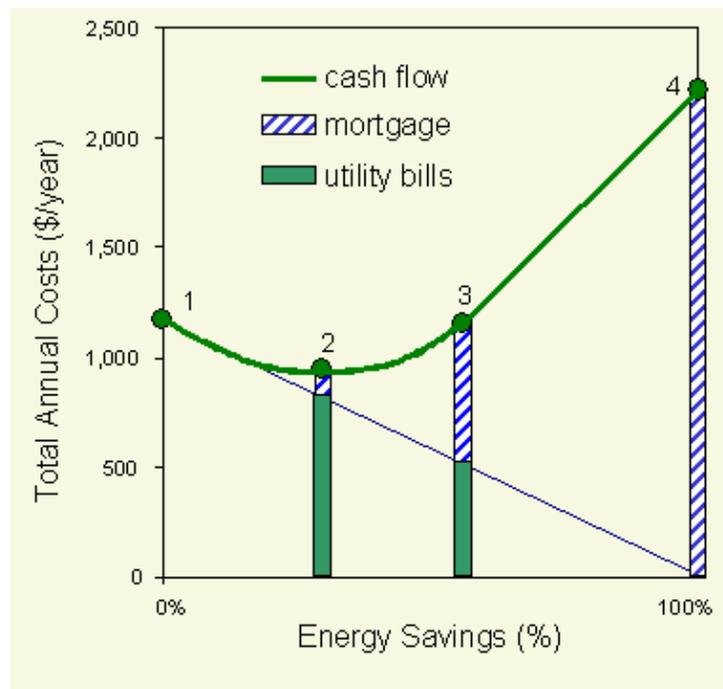

Figure 4. Path to Zero Net Energy (NREL 2016)

The points in Figure 4 are outlined by NREL as follows: Point 1 is the Reference Case. The process begins here as utilities are paid in full and the energy savings are zero. Point 2 is the Minimum Annual Cost. At this point energy everything has been done to

10

increase energy efficiency without raising annual cost. Beyond this point energy can only be saved with an increase in annual costs. Point 3 is the Take-off Point. At this point it is more costly to reduce energy than it is to produce it. Prior to this point energy savings originated from increasing efficiency. Lastly point 4 is ZNE. At this point the building is essentially self sustaining and produces as much energy from PVs as it consumes.

The path to ZNE is determined via one of BEopt's three simulation methods. BEopt has the option to run a single point design simulation, an optimization, or a parametric. Each of these simulation paths offer their own utility. To understand the difference between them it makes sense to understand the process of running a simulation and what information is applied. This process consists of four steps. Screen grabs from this process can be viewed in the appendix, Figure 13 through Figure 18.

First geometry of the structure must be established, Figure 13. In the software each level is selected and the user highlights the floor plan. The software projects this to a selected type of area (slab, crawlspace ,attic ,garage, etc) at a height selected by the user. The user also selects the roof style and pitch. The software then returns the square footage and approximate bed and bath distribution based on common residential home sizes.

Second the features of the structure need to be established, Figure 14 and Figure 15. This is where the details of the structure are input. The critical items include structure orientation, frame type, construction materials, appliances, appliance and load schedules, and temperature set points. The software provides detailed explanations of all the components if needed. Common construction materials are preloaded into the software

however the user is given the option to input new items if needed. These items along with the geometry define the structure and how it is predicted to be used.

Thirdly the location of the structure and relevant economic data such as utility rates can be entered, Figure 16. Location data can be obtained from the EnergyPlus website (DOE 2016). This information is gained in the form of a text file that has data provided by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) that will be fed directly from BEopt to EnergyPlus. Figure 17 contains a screen grab of the weather file for Bowling Green, Ky. This weather data is primarily used to determine how much energy the HVAC system will need to use to maintain the interior set points established in step 2.

Step 4 is to run the simulation and wait for the results. Figure 18 contains an example of results run using a design simulation. The plots on the left can be adjusted to show different type of information. By default the top displays the Energy Rating Index (ERI) which is a national standardized scale for comparing residential energy efficiency. The bottom scale displays the ERI as well or it can be changed to show the amount or also the cost of energy consumed. The data from the B10 Benchmark also on display is another standard or benchmark that can be used to compare to the structure under study. Lastly the information on the right displays the design options that were selected to generate the given result. For a design simulation this is less critical as there is typically only one option selected. This is more useful for parametric or optimization simulations where multiple design options may be selected (NREL 2016).

To determine ZNE an optimization simulation is run. An optimization simulation takes into account several design options selected during step 2 across multiple features

and determines the combinations that are the most efficient, most cost effective or some

mix between the two. It accomplishes this through a sequential search method which can

be explained using Figure 5. In the figure each point 1-4 represents one iteration of

calculation. Sequential Search works by calculating each possible combination and then

looking at the slope of each combination as it works towards the next iteration. The

combination of items that produces the largest negative slope is kept for iteration 2. This

cycle then repeats for all the combination of features until the most efficient and cost
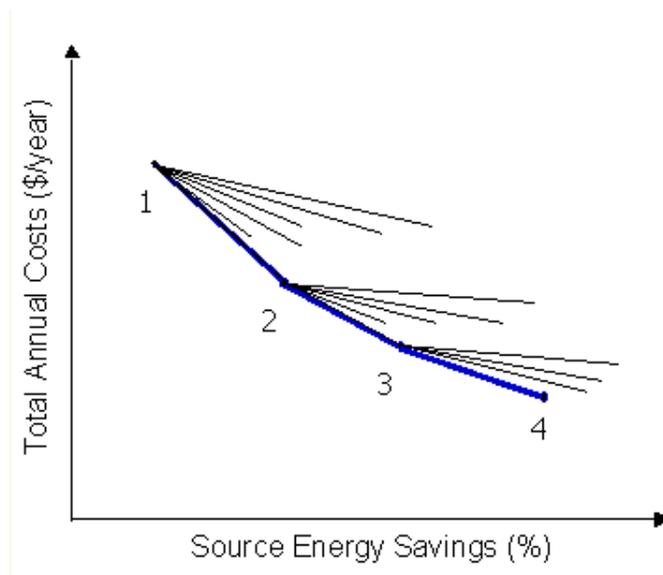
effective combinations remain. (NREL 2016).

Figure 5. BEopt Sequential Search Method (NREL 2016)

Optimization simulation is not the only or most important simulation type

however. As was mentioned above, a design simulation only considers one combination

of the structure features. This is ideal for when the design of the structure is known

because it has the lowest run time. The alternative is the parametric. If there are possible

materials or combinations being considered they can all be compared simultaneously using a parametric simulation which will return the results for every case.

Prior to a simulation being selected and run however the software must be tested to ensure that it provides useful information free of operator error. The purpose of this project was to take ES and compare the results to the utility records of a known structure. This would provide information on the usefulness or quality of the software. Unfortunately the building to be tested did not have enough information (plans, material information, etc) to promote learning the software as well. Therefore a building, a Passivhaus, was selected that had drawings available. Unfortunately the utility records of this structure were unavailable. It was possible however to gauge a sense of correctness with the model due to the nature of the Passivhaus being extremely efficient. With understanding of the software caused by practice with the Passivhaus the final stage of the project could occur.

MODELING THE OFFICE OF SUSTAINABILITY

The WKU Office of Sustainability located at 503 Regents Avenue in Bowling Green, KY is a residential structure constructed in 1931, see Figure 6. It was acquired by WKU in the summer of 2012 to become an office space. It is a single story construction with an unfinished basement home to the Big Red Bike Repair Shop. It has approximately 1362 ft^2 of finished and conditioned Space, 10896 ft^3 of interior volume, and 3924 ft^2 interior surface area. Utilities include an electric vapor compressor refrigeration system – AC; natural gas and electric forced air system – heat; an electric tank less water heater and incandescent lighting. On the exterior are double hung windows – most with storms; brick veneer exterior walls; composite shingle roof and masonry foundation. There is also a photo voltaic array (PV) on the roof to supply electricity.

Figure 6. WKU Office of Sustainability

Despite the age and repurposing of this structure there were reasons why it was chosen. The primary reason was because of how its utilities are recorded. Of all the buildings on campus this was the only one that had a utility record unique to it. Many of the other buildings get lumped together with their neighbors. Having this isolation in the record was critical for having a valid comparison. Second the Energy Audit WKU

15

Student Team had blower door data on the structure from around 2012. In 2014 the WKU Office of Sustainability did some mitigation work to make the 86 year old structure less leaky and more efficient. This project created the opportunity to do a post analysis and assess the difference before and after mitigation. This data was also used in the simulation in order to bridge the gap between the "as tested" and "as modeled" house.

Generating the geometry and establishing the properties (steps 1 and 2 of establishing the model) was likely the most challenging aspect of creating the simulation. It was for this same reason that the Passivhaus was used to learn BEopt. The house was built in *1931*; after 86 years, an unknown number of owners, and an unknown number of renovations there were no prints available to establish the geometry. That value had to be collected manually. Second, because there were no plans, there was no certainty on what insulation and building materials were involved. This information was assumed based on using common construction materials and practices from 1931 and taking into account the mitigation from 2014.

Lastly there was one final obstacle between the structure and BEopt. BEopt's usage and methods are based on residential structures. While 503 Regents was constructed residentially but it was no longer being used as such. This caused some challenge in trying to estimate a proper utility and plug load on the structure. This was accounted for in running a design simulation iteratively; an initial simulation was run and compared to the utility record, adjustments were made to the model as needed and the process repeated. The factors that were adjusted were plug load and appliance use since the office would produce different loads in those areas compared to a residential

structure. This process was repeated five time until the model shared below was discovered.

Table 2 and Table 3 below show what the utility usage for 503 Regents was over the course of 12 months. Table 2 contains the electricity usage and generation by the buildings PV. The difference was also taken, for months where PV generation was more the difference is in green. If PV generation was less than the usage then the difference is in red. Over the course of 12 months the electricity usage is 6389 kWh used and 6022 kWh generated by PV. Figure 7 contains the results of electricity consumption and generation of the final model. The model predicts 5862 kWh used and 5496 kWh generated by PV. That creates a percent difference between the model and the record of around 10%.

Table 3 contains the natural gas usage by the building. In the summer months this is essentially 0 which is expected because the gas furnace is the only gas appliance present. Over the course of 12 months the gas usage is 542 CCF. Figure 8 contains the results of natural gas consumption of the final model. The model predicts 507 Therms which is approximately 492 CCF. That creates a percent difference between the model and the record of around 6%.

10% difference in electricity usage and 6% difference in natural gas usage. Given the circumstances those favorable results. This difference can be attributed to three different sources of uncertainty in the model. First there was uncertainty in actual energy use. The structure is residential but used commercially, what is the actual appliance and plug load? How are the appliances used? There is a gas furnace and stove with no washer or dryer, there is only a fridge and tank less water heater. Also cooling is primarily

17

provided by opening the building envelope and therefore would not contribute greatly to

energy consumption.

Table 2. WKU Office of Sustainability Electric Utility Record

Electricity Usage and Generation			
Date (Bill Due Date)	Usage (kWh)	Panel (kWh)	Difference (kWh)
Oct-2015	277	509	232
Nov-2015	205	441	236
Dec-2015	358	381	23
Jan-2016	285	277	8
Feb-2016	336	319	17
Mar-2016	333	363	30
Apr-2016	256	605	349
May – 2016	261	671	410
Jun-2016	289	592	303
Jul-2016	1245	647	598
Aug – 2016	1103	624	479
Sep - 2016	1441	593	848
Year Total	**6389**	**6022**	**367**
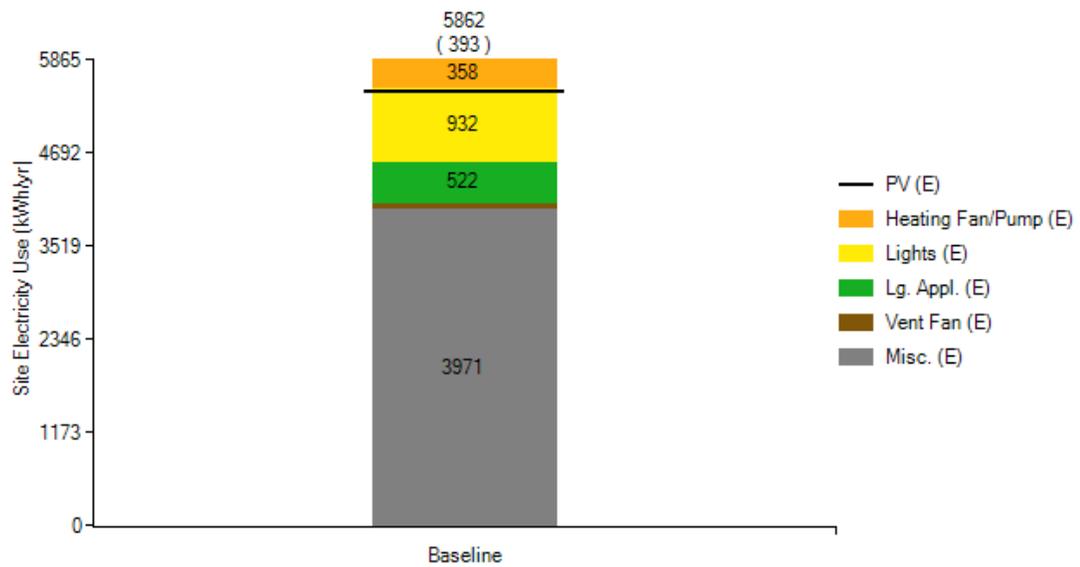
Figure 7. WKU Office of Sustainability Electricity Model Result

Table 3. WKU Office of Sustainability Gas Utility Record

Gas Usage	
Date (Bill Due Date)	**Usage (CCF)**
Oct-2015	21
Nov-2015	71
Dec-2015	96
Jan-2016	147
Feb-2016	139
Mar-2016	48
Apr-2016	19
May – 2016	0
Jun-2016	0
Jul-2016	0
Aug-2016	0
Sep-2016	1
Year Total	**542**
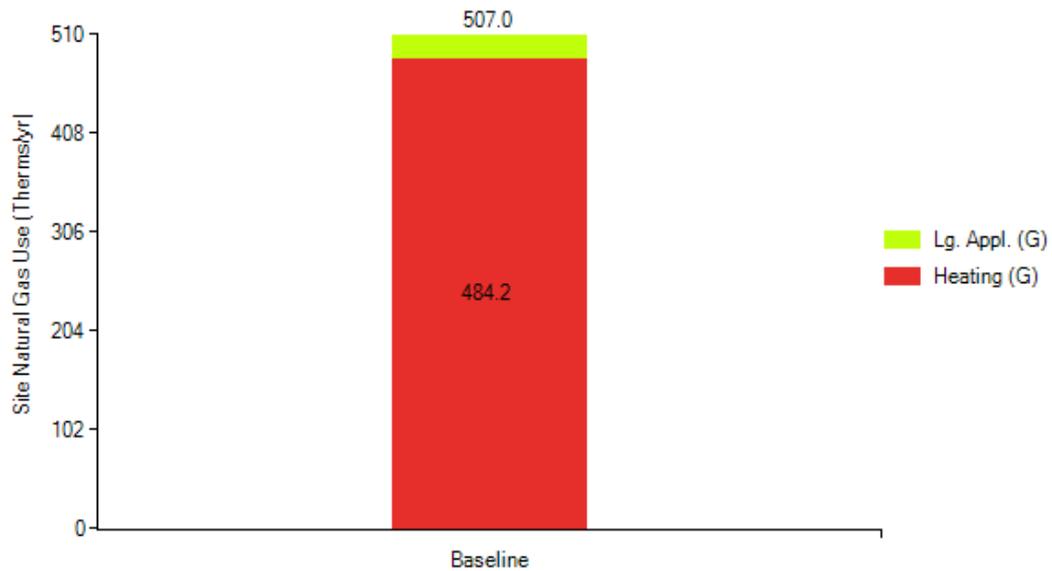
Figure 8. WKU Office of Sustainability Gas Model Result

Second there was uncertainty in actual building construction methods and materials. Not all the necessary modeling data was known so some assumptions were made on insulation materials. These assumptions were based on common construction practice from 1931. How much renovation was done to the structure? How is the frame really spaced? What materials are really being used and what are the insulation values? For a model that better represents the structure under study these questions would all need to be answered.

Lastly how did the weather from the year the utilities were collected compare with the average? How did the high and low temperatures compare with the record? The last few years have been slightly different than average. If the temperature varies too much from average then that causes discrepancy between the model and reality. At that point it is not longer an equal comparison between the two as the testing conditions are different.

CONCLUSION

Buildings are complex systems - even "simple" residential structures. Many factors go into building energy consumption and the design to reduce it. Computer energy modeling allows the simultaneous consideration and balance of many of those variables. Computer models are only as good as the information provided however. Tools like blower door can be used to aid in verifying the model or to provide more information to build a better model.

"Recognizing that universities are the places where innovative solutions are born, the WKU campus is being used as a living laboratory for the energy efficiency and conservation efforts. Through this policy and other efforts, we are encouraging students, faculty, and staff to apply ideas and research to advance sustainability." (Dr. Gary Ransdell, university statement, March 2009). As part of the continuing efforts of the Energy Audit WKU Student Team ES has been used to look at all factors collectively in a building structure. Despite uncertainties, energy consumption records of a preexisting structure were shown to compare favorably (within 10%) with ES Energy Plus and BEopt models.

REFERENCES

International Code Council. (2011) *2012 International Energy Conservation Code.* Country Club Hills, IL: ICC Publications.

National Aeronautics and Space Administration. (2015). [Figure illustrating Navier-Stokes equations]. *Navier-Stokes Equations 3-dimensional - unsteady.* Retrieved from https://www.grc.nasa.gov/www/k-12/airplane/nseqs.html

National Renewable Energy Laboratories. (2016). BEopt (Version 2.7.0.0) [Software]. Available from http://beopt.nrel.gov/

Robbins, J. F., (2017) Proceedings from HalfMoon Education Inc. Seminar: *Meeting and Exceeding Residential Energy Conservation Code*. Lexington, Ky.

Strand, R. K., Crawley, D. B., Pedersen, C. O., Liesen, R. J., Lawrie, L. K., Winklemann, F. C., ... Fisher, D. E. (2000). EnergyPlus: A New-Generation Energy Analysis and Load Calculation Engine for Building Design

Strand, R. K., Pedersen, C. O., Crawley, D. B. (2001). Proceedings from Sevents International IBPSA Conference: *Modularization and Simulation Techniques for Heat Balance Based Energy and Load Calculation Programs: The Experience of the ASHRAE Loads Toolkit and EnergyPlus*. Rio de Janeiro, Brazil.

The Energy Conservatory. (2012) *Operating Instructions for the DG-700 Pressure and Flow Gauge.* Minneapolis, MN

U.S. Department of Energy. (1999). *Insulation Materials*. https://energy.gov/energysaver/insulation-materials

U.S. Department of Energy. (2004). *Blower Door Tests*. https://energy.gov/energysaver/blower-door-tests

U.S. Department of Energy. (2016). Energy Plus (Version 8.6.0) [Software]. Available from https://www.energyplus.net/

Winkelmann, F. C. (2001). Proceedings from Sevents International IBPSA Conference: *Modeling Windows in EnergyPlus*. Rio de Janeiro, Brazil.

Zhai, Z., Chen, Q., Klems, J. H., & Haves, P. (2001). Proceedings from Sevents International IBPSA Conference: *Strategies for Coupling Energy Simulations and Computational Fluid Dynamics Programs*. Rio de Janeiro, Brazil.

Figure 9. Blower Door Field Measurement Setup

Figure 10. Navier-Stokes Equations (NASA 2015)
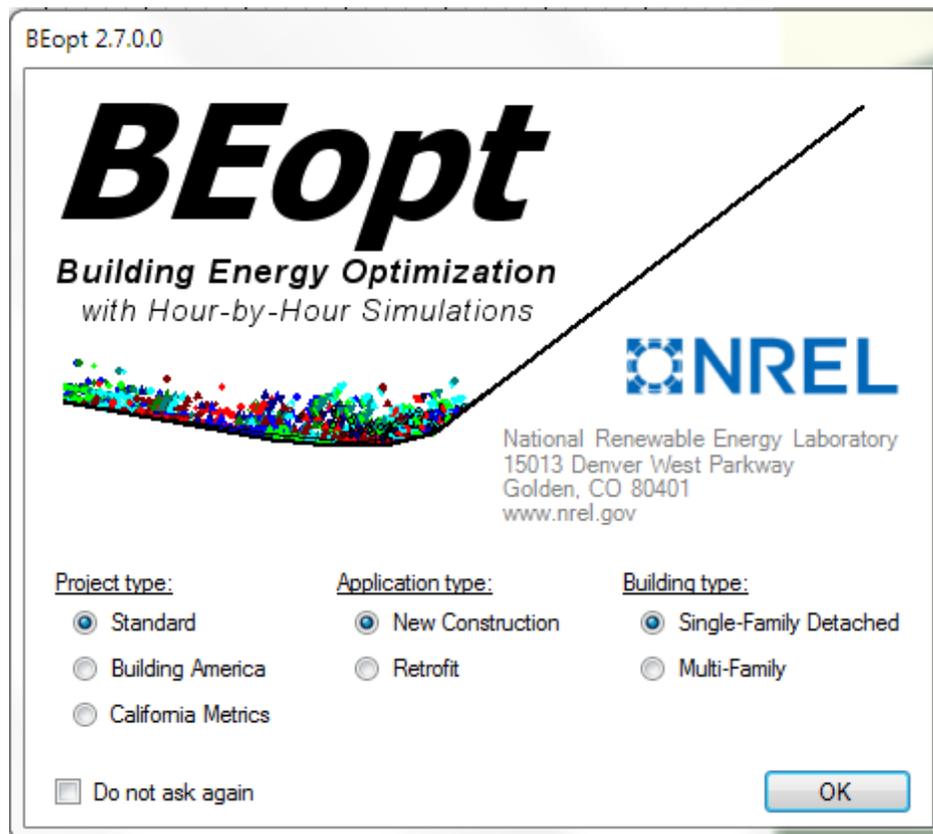
Figure 11. DOE EnergyPlus
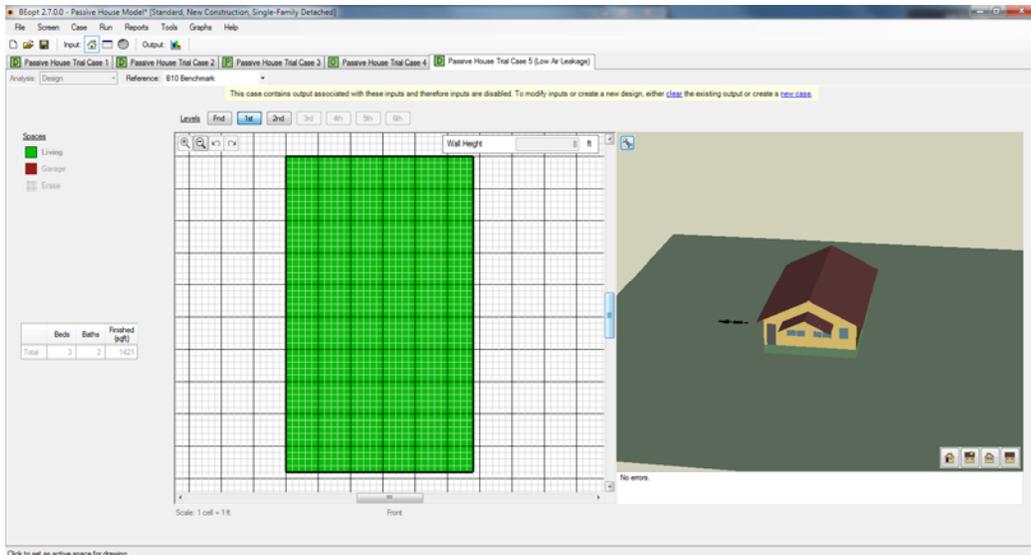

Figure 12. BEopt Splash Screen

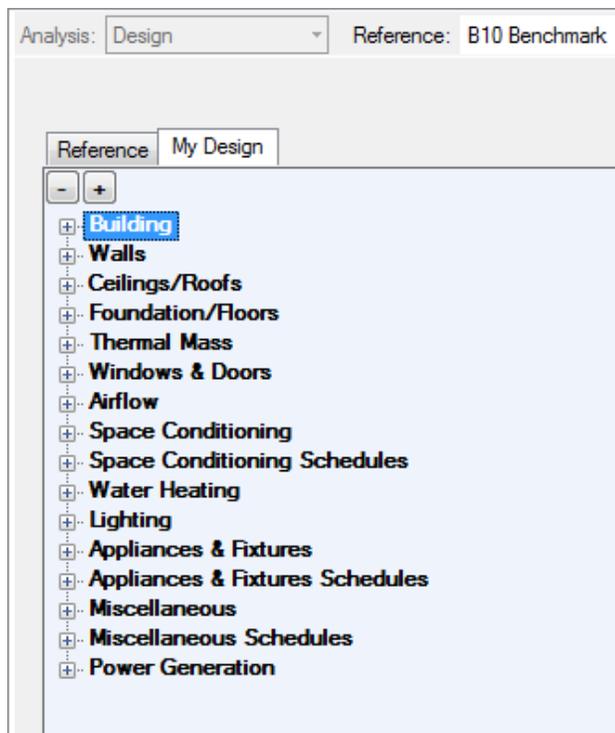**Figure 13.** BEopt Establishing Geometry

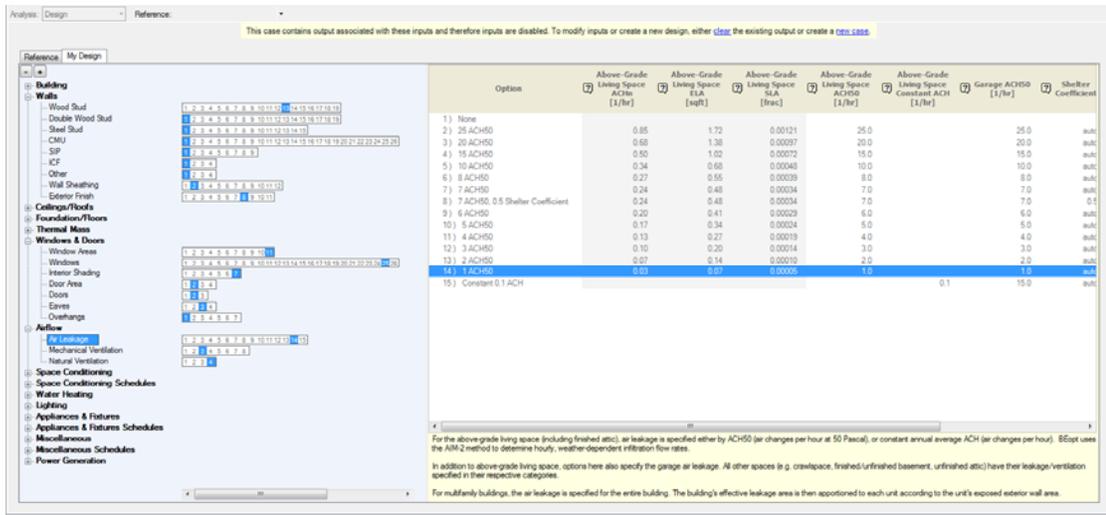**Figure 14.** BEopt Establish Design Features

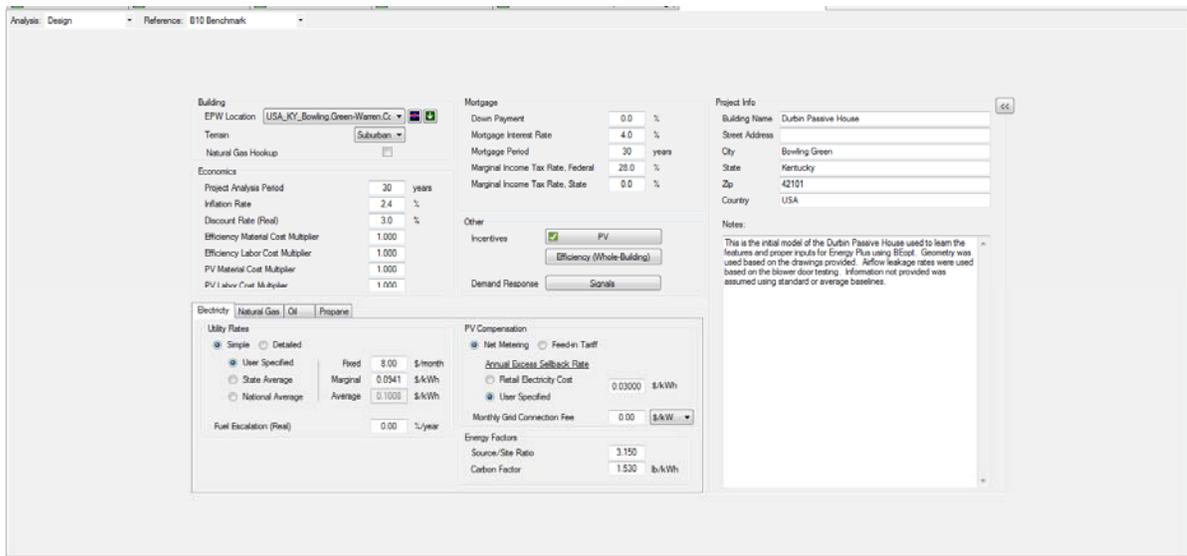**Figure 15.** BEopt Establish Features Detail

Figure 16. BEopt Establish Location and Economics

```
! The following Location and Design Day data are produced as possible from the indicated data source.
! Wind Speeds follow the indicated design conditions rather than traditional values (6.7 m/s heating, 3.35 m/s cooling)
! No special attempts at re-creating or determining missing data parts (e.g. Wind speed or direction)
! are done.  Therefore, you should look at the data and fill in any incorrect values as you desire.

Site:Location,
 Bowling Green Warren Co Ap_KY_USA Design_Conditions,     !- Location Name
     36.98,     !- Latitude {N+ S-}
    -86.43,     !- Longitude {W- E+}
     -6.00,     !- Time Zone Relative to GMT {GMT+/-}
    161.00;     !- Elevation {m}

!  WMO=746716 Time Zone=NAC: (GMT-06:00) Central Time (US & Canada)
!  Data Source=ASHRAE 2009 Annual Design Conditions
RunPeriodControl:DaylightSavingTime,
  2nd Sunday in March,     !- StartDate
  2nd Sunday in November;    !- EndDate

! Using Design Conditions from "Climate Design Data 2009 ASHRAE Handbook"
! Bowling Green Warren Co Ap_KY_USA Extreme Annual Wind Speeds, 1%=9m/s, 2.5%=8.2m/s, 5%=7.4m/s
! Bowling Green Warren Co Ap_KY_USA Extreme Annual Temperatures, Max Drybulb=-17°C Min Drybulb=36.1°C

! Bowling Green Warren Co Ap_KY_USA Annual Heating Design Conditions Wind Speed=2.9m/s Wind Dir=340
! Coldest Month=JAN
! Bowling Green Warren Co Ap_KY_USA Annual Heating 99.6%, MaxDB=-13.1°C
```
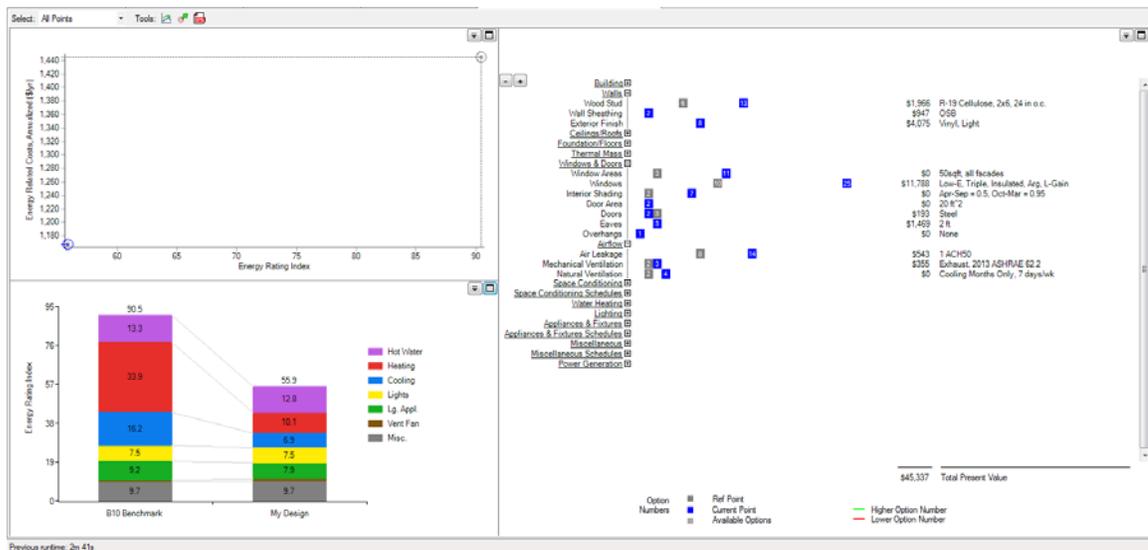
Figure 17. EnergyPlus Weather Data - B.G. KY

Figure 18. BEopt Design Simulation Results