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# Analysis of EnergyPlus for Use in Residential Building Energy Optimization

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ANALYSIS OF ENERGYPLUS FOR USE IN  
RESIDENTIAL BUILDING ENERGY OPTIMIZATION

by

JUSTIN S. SPENCER

BS Mechanical Engineering, Princeton University, 2003

A thesis submitted to the

Faculty of the Graduate School of the

University of Colorado in partial fulfillment

of the requirement for the degree of

Master of Science

Department of Civil, Environmental, and Architectural Engineering

2010

*This thesis entitled:  
Analysis of EnergyPlus for use in Residential Building Energy Optimization  
written by Justin S. Spencer  
has been approved for the  
Department of Civil, Environmental, and Architectural Engineering*

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*Date* \_\_\_\_\_

*The final copy of this thesis has been examined by the signatories, and we  
Find that both the content and the form meet acceptable presentation standards  
Of scholarly work in the above mentioned discipline.*

## **Abstract**

Justin S. Spencer (M.S. Civil, Environmental, and Architectural Engineering)  
Analysis of EnergyPlus for Use in Residential Building Energy Optimization  
Thesis directed by Professor Michael J. Brandemuehl.

This work explored the utility of EnergyPlus as a simulation engine for doing residential building energy optimization, with the objective of finding the modeling areas that require further development in EnergyPlus for residential optimization applications. This work was conducted primarily during 2006-2007, with publication occurring later in 2010. The assessments and recommendations apply to the simulation tool versions available in 2007.

During this work, an EnergyPlus v2.0 (2007) input file generator was developed for use in BEopt 0.8.0.4 (2007). BEopt 0.8.0.4 is a residential Building Energy optimization program developed at the National Renewable Energy Laboratory in Golden, Colorado.

Residential modeling capabilities of EnergyPlus v2.0 were scrutinized and tested. Modeling deficiencies were identified in a number of areas. These deficiencies were compared to deficiencies in the DOE2.2 V44E4(2007)/TRNSYS simulation engines. The highest priority gaps in EnergyPlus v2.0's residential modeling capability are in infiltration, duct leakage, and foundation modeling.

Optimization results from DOE2.2 V44E4 and EnergyPlus v2.0 were analyzed to search for modeling differences that have a significant impact on optimization results. Optimal buildings at different energy savings levels were compared to look for biases. It was discovered that the EnergyPlus v2.0 optimizations consistently chose higher wall insulation levels than the DOE2.2 V44E4 optimizations. The points composing the optimal paths chosen by DOE2.2 V44E4 and EnergyPlus v2.0 were compared to look for points chosen by one optimization that were significantly different from the other optimal path. These outliers were compared to consensus optimal points to determine the simulation differences that cause disparities in the optimization results. The differences were primarily caused by modeling of window radiation exchange and HVAC autosizing.

## **Dedication**

This thesis is dedicated to my wife, Abigail, and my daughter, Wilma. Thank you both for your support and understanding.

## **Acknowledgments**

This work would not have been possible without the assistance of members of team BEopt and the EnergyPlus development team housed at the National Renewable Energy Laboratory. Thanks in particular to Scott Horowitz, Adam Courtney, and Brent Griffith. In addition, I would like to acknowledge the patience, support, and guidance of my thesis committee, Craig Christensen, Moncef Krarti, and Michael Brandemuehl.

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# 1 Background

## *1.1 Objective*

The objective of this work was to analyze EnergyPlus as a tool for residential building energy modeling and optimization, with the ultimate goal of improving the capability and accuracy of BEopt as a decision-making tool. This work characterizes the modeling gaps in EnergyPlus v2.0 and details what is required to meet and exceed the needs of a residential optimization tool, BEopt 0.8.0.4. These gaps and some additional capabilities were compared with the capabilities of DOE2.2 V44E4/TRNSYS as implemented in BEopt 0.8.0.4. Optimization results using EnergyPlus v2.0 are compared with optimization results using DOE2.2 V44E4/TRNSYS for 5 climates, in an attempt to quantify the impact of differences between the two models on residential optimization results. These biases were compared to biases uncovered by BESTEST procedures. Differences in the optimization results were used to highlight differences in the energy simulation engines. The differences in optimization runtime were also quantified. It should be noted that building energy simulation is a fast changing field, so this study represents a snapshot of capabilities and results obtained in early 2007 with the specific program versions cited. By 2010, EnergyPlus, DOE2.2, and BEopt had all received significant improvements and different results would be obtained.

## *1.2 History of Building Energy Simulation Leading to EnergyPlus and DOE2.2*

Building energy simulation programs were first developed in the mid 1960s (Van der Veken, 2004). By the late 1970s, a variety of energy simulation tools had emerged, including early versions of TRNSYS, DOE2, BLAST, and ESP-r. These programs used different heat transfer calculation methods, with the heat-balance method and the weighting factor method being the two main methods (Clarke, 2001; Crawley, 1997; Van der Veken, 2004). During this time,

building simulation programs were run using mainframe computers, with runtimes of hours or even days. In the United States, the Department of Energy launched DOE-1 and then DOE-2 during the late 1970s, which was based on a variety of earlier programs (Mills, 1995). At the same time, the Department of Defense developed BLAST, which was based on an earlier program from the National Bureau of Standards (Crawley, 1997). BLAST utilizes a heat balance approach, while DOE2 utilizes a room weighting factor approach for calculating heat transfer. During the mid-1990s, the US Government began efforts to merge BLAST and DOE2. This effort would eventually give birth to EnergyPlus, which started by combining code from BLAST version 3.0 and DOE2.1e. It uses a heat-balance method like BLAST. In contrast to both parent engines, EnergyPlus runs building loads and HVAC systems and central plants at each time step in an integrated fashion, instead of running loads, then systems, then plants (Crawley, 2000). At the same time EnergyPlus development was starting, an updated version of DOE2 was produced by J. J. Hirsch and Associates and named DOE2.2. DOE2.2 is the simulation engine behind the popular eQuest building simulation program. EnergyPlus is the Department of Energy's energy simulation engine of choice going forward and no further resources are being put into refining DOE2.1e by DOE.

### ***1.3 Current Applications of Building Energy Simulation***

What do people really use energy simulation for?

People generally use energy simulation to predict the difference in energy use between two or more different building design alternatives, or between a base building and the new and improved version of the building. These differences are used to guide decision making processes by answering questions like: Does it make economic sense to replace existing windows with low-E, low SHGC windows? Will this building meet the criteria for Leadership in Energy and

Environmental Design certification? What is the best suite of energy saving measures to reduce peak loads in Manhattan?

The differences between the analyzed building designs can be one dimensional or multidimensional, and the impacts of design changes can also be one dimensional or multidimensional. In the simplest case, the impacts of a one dimensional design difference may be calculated by hand. If the dimension of change is in the efficiency of outdoor lighting, there is a first order impact (electricity used for the lighting fixtures) that is much larger than any other impacts (small change in radiation incident on exterior surfaces, change in current flowing through wiring, reducing line losses, etc.). This is the simplest case, a one dimensional change in design, with a one dimensional change in the output. The results are easy to calculate by hand. As we add complexity with multiple design dimensions and multiple output dimensions (space thermal loads affected by change in gains from equipment, altering envelope performance, etc.), then the calculations become more difficult, but it is still possible to obtain a satisfactory result using straightforward calculations. If conditions can reasonably be approximated over longer time periods, then monthly methods can be developed and utilized to arrive at reasonable approximations of annual energy use.

However, if time matters, that is, if the design change will have interactive impacts that are felt on shorter time scales, then hourly or shorter simulation is necessary. It may not be necessary to use hourly simulation to see the impacts of adding insulation to a low mass building, depending on the desired accuracy of the result. But to see the impact of a solar hot water collection system with tank losses and specific irregular hot water draws, an hourly simulation or other adjustment is necessary. It is still possible to develop monthly methods correlations for a single time-dependent design dimension that has a single output dimension.

But, as soon as there are additional interactions, as well as time-dependent output dimensions, hourly simulation is necessary. To be effective, hourly simulation needs to accurately model temporal variability and interaction of different variable dimensions. Almost all residential buildings need to be modeled using hourly methods because of the temporal mismatch between solar variation and temperature variation, the two major driving forces on space conditioning loads. In addition, interactions between mass and thermal gains, plus variable performance of heating, cooling, and hot water equipment require hourly simulation. The following example shows how this temporal mismatch drives optimal orientation-specific glazing choices in Boulder, Colorado. While this example shows how intuition might be used to make a qualitative judgment about glazing choice, it also shows why hourly simulation is required to quantify the impact of glazing choice.

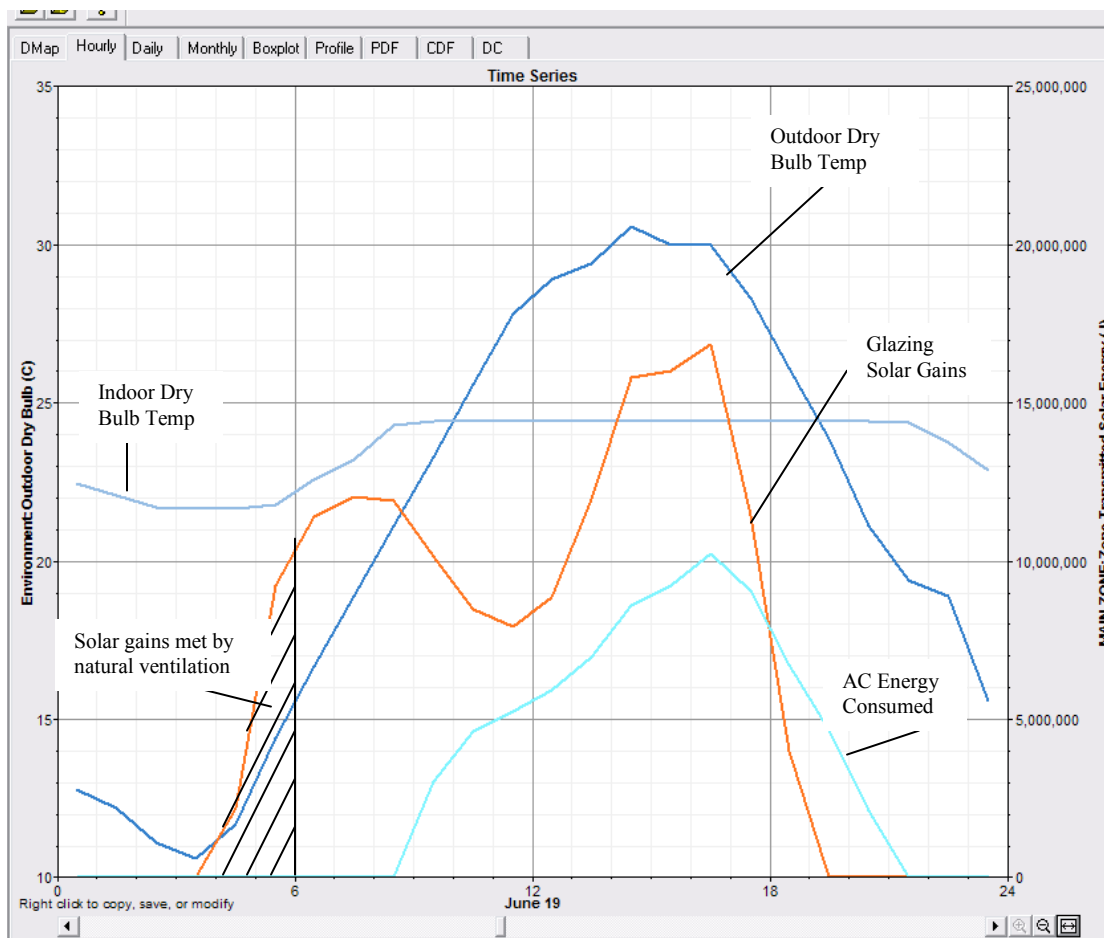
First, is it better to put low SHGC windows on the east side or the west side of a commercial building? The initial intuitive response to this problem might be that reduced solar gains on the east and west aspects have equal impact on gains to the space, cooling loads, and electricity consumed by the cooling system.. However, the scheduling of cooling availability in commercial buildings typically does not allow for cooling after 6 PM. As a result, glazing solar gains during the last hours of the day do not result directly in cooling loads. As long as temperatures get cool enough over night for the building to reject the heat, solar gains late in the day (after 6 PM) will not result in cooling loads.

Next, consider the same question, except analyzing a basic residential building with a fair amount of south glazing and equal amounts of east and west glazing in a temperate climate. The home has air conditioning in the summer, heating in the winter, and natural ventilation available all year round. The initial response to the question of where low SHGC windows should be used

might be that it doesn't matter between east and west like it did in the commercial building, because heating and cooling are available all day. The argument continues that solar gains to the space will reduce heating loads whether they occur in the morning or in the afternoon, and will increase cooling loads whether they occur in the morning or in the afternoon. However, a more careful analysis that accounts for temporal mismatch of temperature and solar resources shows that the answer is not this simple.

In the summer, during the morning hours, a gain to the space is generated by the east facing glazing. In Boulder, this gain to the space can initially be offset using natural ventilation. Once the temperature outdoors gets too warm, then this source of cooling is no longer available. During the middle part of the day, all loads must be met by the air conditioning system, until the outdoor temperature drops enough to meet loads with natural ventilation. The energy balance on the space is such that the total gains to the space must be equal to the total cooling provided to the space. The total glazing and other gains to the space are equal to the total heat removed by the air conditioner and the total heat removed by natural ventilation. On the gains side of the equation, if solar patterns are even, then east and west facing glazing will both add the same amount of heat to the space. Therefore, distribution of types of glazing between east and west will have no impact on the total solar gains to the space, given a symmetric solar resource.

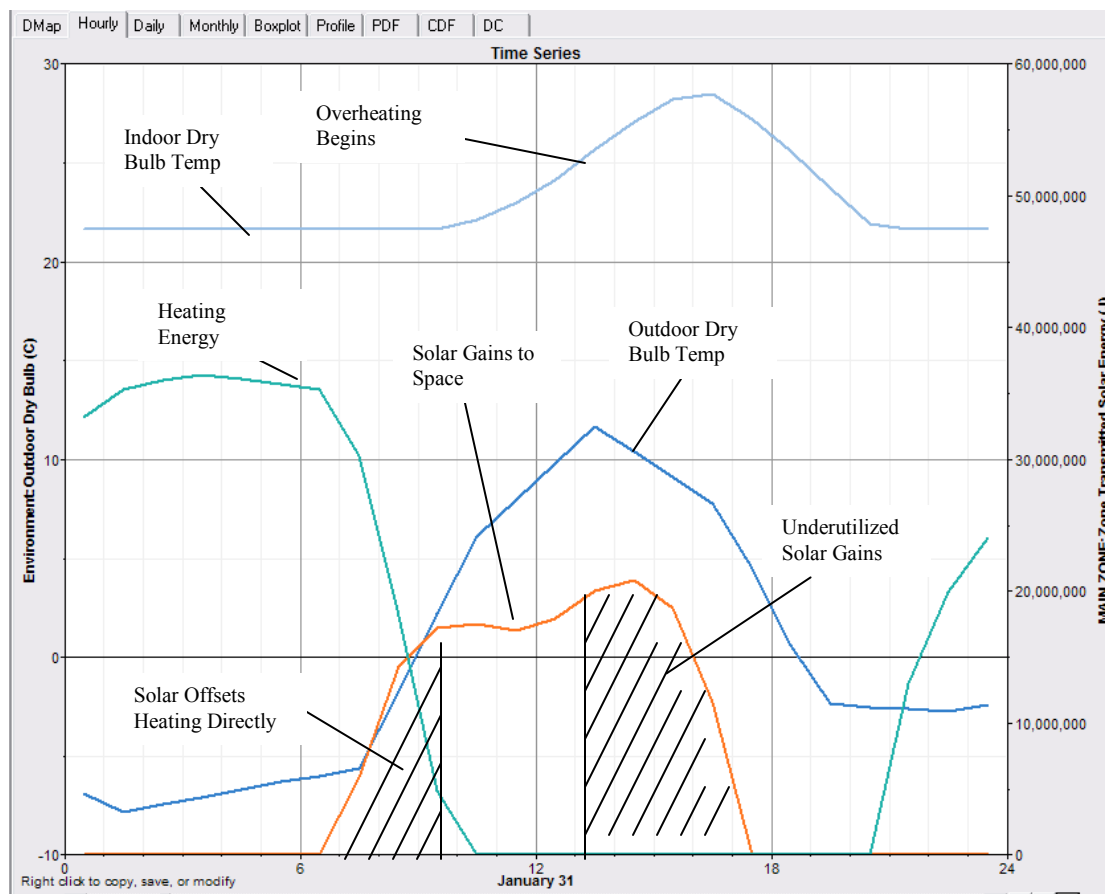
However, on the cooling supply side of the equation, gains during the early morning hours can be met for free using natural ventilation. As a result, higher solar gains from east windows get met using natural ventilation. On the west side, outdoor environment temperatures are too high to use natural ventilation during the afternoon/ evening hours, so loads generated must be met using the air conditioner. A typical summer cooling day in Boulder is shown in Figure 1.



**Figure 1: Typical Summer Cooling Day, Boulder, CO**

During winter, the same phenomenon occurs. During the morning hours, temperatures are cold, so any solar gains contribute to meeting the heating load. If overheating of the space occurs, then heat will be dumped to the outdoors. When solar gains to the space occur at the same that there is a heating load, then the total heat added to the space is the same as if everything was being added by the furnace. A typical winter heating day is shown in Figure 2.





**Figure 2: Typical Winter Day, Boulder, CO**

So, east-facing glass contributes directly to meeting the load. Solar gains from west-facing glazing may not contribute directly to meeting the load. As a result, if the thermal capacity of the house is exceeded, then some of the daytime solar heat gains will be dumped.

In the end, this means that it is desirable to have more solar gains during the morning hours, unless there is sufficient mass that it is always possible to sink all gains into the mass, which either meets night time heating loads or is cancelled with night ventilation. In climates where morning natural ventilation is not available, then the balance of east and west glazing solar gains will not have as much of an impact on cooling energy – all solar gains during cooling season will turn into loads on the cooling system. Only differences in heating between different glazing types on east and west will be seen in those conditions. Almost all residential

construction will have less mass than is necessary to damp out the temporal variations in the solar gains. The interaction of the envelope solar gains, conduction losses, and mass effects must be modeled using hourly simulation to have any real chance at accurately predicting the differences in energy consumption between window design alternatives in residential construction.

Simulation has generally been more applicable to commercial buildings. Typically, the energy savings that can be realized by modeling commercial buildings add up to 10s or 100s of thousands of dollars annually, enough to justify modeling on a single building basis. In contrast, single family residences spend on the order of 1000s of dollars annually on energy, so simulation of residential buildings is generally done more for large scale analyses, evaluating different energy saving measures for a given climate zone, or on a smaller scale, a utility service area or a given metro area or even a set of houses for a given development, like Building America teams do (US DOE, 2004). These analyses are often performed to evaluate the efficacy of measures for saving energy or reducing demand, for utilities, governments, and non-profit energy assistance agencies. Performing these analyses can require simulating a broad range of building settings and geometries. This makes the time for each analysis more significant, especially if many different building variable dimensions are to be included. In the extreme case, it is desirable to use optimization techniques to automate the search process used to evaluate energy saving strategies.

#### ***1.4 Issues Particular to Residential Simulation***

In residential modeling, operation of the building has a high degree of temporal variability. Single family residences have large surface area to mass ratios, with significant infiltration. Use schedules have a high degree of variability. All of these characteristics are in

direct contrast to commercial buildings, which have low surface areas, low infiltration, very regular use schedules, and high mass. Residential buildings also have more unconditioned spaces that may be coupled to the conditioned space, including attics, basements, crawlspaces, and garages.

**Table 1: Loads Energy Modeling Areas**

Modeling Area	Overall Energy Impact (1-5)	Modeling Difficulty (1-5)	Necessary Models for Improved Accuracy / Notes
Wall Conduction	5	2	Easy for basic wood frame constructions, harder for walls with short circuits
Windows	4	3	Shading, incidence angle, reveals, daylighting – occupancy and lighting usage
Infiltration	4	5	Wind, stack for complicated geometry, unbalanced interactions, directional wind effects
Ground Coupling/ Foundations	3	4	Ground characteristics, 3-D effects, modeling of unconditioned spaces, crawlspace ventilation rate
Lighting	4	2	Capturing occupant behavior is difficult.
Appliances	2	2	Capturing occupant behavior is difficult.
Showers	3	3	Occupant behavior can be difficult, short duration draws, high latent gains to space
Baths	1	3	Same as showers, with lower latent gains to space.
Sinks	2	3	Very short durations

Areas of energy modeling importance are shown in Table 1 and Table 2. Areas with the highest energy impact receive a 5. The most difficult modeling areas receive a 5. Areas with a 5 in energy impact and a 5 in modeling difficulty are where the most effort would need to be expended to improve simulation engine performance. These results are purely subjective in

nature and reflect the opinions of the author and the BEopt development team. The areas that appear to require the most energy simulation resources are infiltration, cooling equipment, and duct losses.

**Table 2: Systems and Distribution Energy Modeling Areas**

Modeling Area	Overall Energy Impact (1-5)	Modeling Difficulty (1-5)	Necessary Models for Improved Accuracy / Notes
Pipe Losses	1	4	Transient draws will drive pipe loads. Good draw data required.
Gas Hot Water Heaters	3	2	In theory, tank losses should change with stack exfiltration rate.
Electric Hot Water Heaters	3	2	May require stratified tanks
Solar Water Heating	3	3	Stratified tank model necessary for most systems, overall hot water schedule important, load-side heat exchangers require finer draw data.
Tankless Water Heater	3	2	Finer draw data required to capture transient cycling behavior.
Drainwater Heat Recovery	1	4	Fine draw data and stratified tank required for some systems. Simple systems (shower drain to shower cold tap) are easy to model.
Cooling	4	4	Better control and tracking of latent loads is difficult. Variable speed systems, various desiccant-DX combination systems are non-trivial. Ground source systems need good ground characteristics.
Heating	3	2	Forced air gas systems are easy. Condensing boilers, ground source heat pumps are more difficult.
Duct Losses	4	4	Unbalanced duct leakage interacts with infiltration flows and other cross-envelope airflows. This creates an additional load that can be tough to calculate and creates autosizing problems.

### ***1.5 BEopt***

BEopt is Building Energy optimization software developed by the National Renewable Energy Laboratory for use in residential construction (Christensen, 2004). BEopt 0.8.0.4 can be used for single point comparisons, parametric analyses, or optimization of building characteristics. BEopt 0.8.0.4 consists basically of a graphical user interface for specifying building characteristics and analysis, an options editor for entering new building options for use in analyses, an optimization engine, and files for creating input to simulation engines and output for viewing applications. BEopt 0.8.0.4 takes the results of each simulation (the building options selected, their costs, and the resulting energy consumption), and calculates the total source energy and total monthly energy-related costs. Total monthly energy-related costs consist of two parts, the cost of energy consumed by the building and the increase in monthly mortgage payment associated with the incremental costs of the building options compared to a base building. The objective of the optimization engine is to find the lowest total energy cost at different levels of energy consumption, until the optimal zero net energy home is reached. The core of BEopt 0.8.0.4 consists of the user interface, the options framework, a post-processor of results, an economic analysis module, and the optimization engine. BEopt 0.8.0.4 can interface with other tools to do the actual building energy simulations or view output. This flexibility allows advanced users to connect BEopt 0.8.0.4 to different simulation engines or output viewers that suit their needs. Up until now, BEopt 0.8.0.4 has used DOE2.2 V44E4 to model the building envelope, appliances, and HVAC systems, while using TRNSYS to model all solar and hot water systems. Earlier versions of BEopt used DOE2.1e; the current version of BEopt 0.8.0.4 uses DOE2.2 V44E4. The current version of BEopt 0.8.0.4 includes enough options in different option categories to model most production houses.

The user can add new options or new option categories as long as the options can be modeled using the current simulation engines. If an option can be modeled using the currently available simulation variables, then adding new options is very simple. The user can create a new option and specify the pertinent simulation information, including cost, lifetime, and energy simulation characteristics. The new option will then be available for use in BEopt 0.8.0.4. If the user wants to add a new option category or a new option type that cannot be modeled using the available option characteristics, adding new options is slightly more difficult. Advanced users who are reasonably proficient in energy simulation can make changes to the BEopt 0.8.0.4 macro interpreter (.bmi) files to model new option types or option categories. The BEopt 0.8.0.4 macro interpreter files contain the logic and templates for creating the energy simulation input files that are sent to the simulation engines. Making changes to these files will create changes in the simulation engine input files. If the user wants to add a new option type or option category to BEopt 0.8.0.4 and the new component can be modeled using the available simulation engines, then they can enter simulation code into the correct .bmi file and use the simple BEopt 0.8.0.4 macro interpreter language to add logic that will activate the new simulation code when desired. Therefore, it is possible for advanced users of the current version of BEopt 0.8.0.4 to model any envelope or HVAC component that can be modeled using DOE2.2 V44E4 and any hot water or solar component that can be modeled using TRNSYS. A new .bmi file was developed during this work to allow BEopt 0.8.0.4 to generate EnergyPlus input files, which will allow future users to model buildings using EnergyPlus.

BEopt 0.8.0.4 can use eQuest or Sketchup to render a building. BEopt 0.8.0.4 uses DView for displaying hourly, daily, or monthly output. These output programs are especially useful for debugging new energy simulation code. During this work, dissection of hourly output

allowed multiple bugs to be found in the existing versions of DOE2.2 V44E4, TRNSYS, and BEopt 0.8.0.4, many of which have since been fixed.

## ***1.6 Applications of BEopt***

BEopt 0.8.0.4 can currently be applied to any energy consumption cost optimization problem in residential construction. These applications include analysis of production home building designs, advanced building energy technology assessment, and energy code development.

### **1.6.1 Production Home Building Energy Analysis**

BEopt was developed for use by Building America teams for modeling and improving production home building practices, with the goal of getting production home builders to build more efficient, more cost effective homes and make progress towards the ultimate goal of achieving zero net energy houses (ZNEH). As a result, BEopt 0.8.0.4 option development thus far has focused on building components that are currently in use by production builders across the country. In many cases, these options go beyond builder standard practice, but only widely available advanced technologies are included in the basic set of options, since these are what actually get used in significant numbers of homes. For optimization of production homes, BEopt 0.8.0.4 looks at the sum of the annual cost to consumers for energy consumed in the home and the additional mortgage payment resulting from investment in energy-efficient technologies. While this method does not translate as well into traditional economic analyses, it translates directly to consumers of energy efficient homes.

### **1.6.2 Advanced Technology Assessment**

The adoption of new building technologies is being held back by the lack of good information about the performance impact of new technologies (NCEMBT, 2007). Some manufacturers may overstate the effectiveness of their technologies. Implementation of multiple advanced building

technologies often produce negative interactions, while manufacturers' claims are made on the basis of energy savings in some benchmark house. Unfortunately, early adopters of new building technologies do not typically see the claimed benefits of every technology, because they typically choose a whole suite of envelope and equipment improvements and the savings over the benchmark for each individual technology do not add when applied together.

In theory, building simulation allows scientists and engineers to explore these interactive effects before buildings are constructed. In particular, optimization of building simulations allows the building scientist to effectively determine the cost-optimal selection of building components at a given energy savings level or the cost-minimum for a particular set of energy prices. Optimization using current costs will tell scientists how a particular new technology shifts the current optimization curve in each part of the country. Using projected future costs for options will give some idea of how the new technology will shift the future optimization curve. The shifts in these optimization curves can be used by policy makers to determine which technologies offer the best opportunities for meeting near term and long term energy saving goals, and to determine cost and performance targets for new technologies to make a significant difference in the market and the optimization curves.

### **1.6.3 Energy Code Development**

BEopt 0.8.0.4 can be applied to determine which energy-saving measures are most cost effective and therefore should be included in building energy codes. Existing prescriptive codes can be added as reference buildings in BEopt 0.8.0.4. Optimizations can be compared against the code to determine where the code can be improved. Optimization with sequential search also finds near-optimal points, many of which may be an improvement over the current code. In sequential search, the optimization proceeds "one step at a time," with the engine trying changes in only



one option at a time, finding the best of those points, then repeating with one option at a time from the new optimal building. In comparison to other optimization methods, this produces a large number of near-optimal points, because every point that is tried is a single option different from the optimum up until that point. Code development professionals could use BEopt 0.8.0.4 to write new prescriptive codes, including alternative code-compliance mechanisms. BEopt 0.8.0.4 might also be used by builders in order to support energy-code variances (i.e. using a more massive construction with shading devices rather than low solar heat gain glass) when consulting local code officials.

## **2 Analysis of Residential Energy Modeling Gaps in EnergyPlus v2.0**

Development of EnergyPlus v2.0 has focused on commercial building analysis thus far. As a result, even though the software has been significantly developed, there are remaining gaps in modeling capabilities with respect to residential buildings. A gaps analysis was conducted to characterize residential modeling shortcomings so that they can be filled in completely for future use in residential modeling and in BEopt 0.8.0.4 in particular.

### ***2.1 Methodology***

The gaps analysis was intended to fully explore the capabilities of EnergyPlus v2.0 with respect to using BEopt 0.8.0.4 for residential energy optimization. In many cases, gaps could be identified simply by reading the documentation and clarifying capabilities with members of the EnergyPlus development team. There are likely to be additional gaps in modeling capabilities beyond the scope of this work. There are probably pieces of prototypical residential space conditioning equipment that are in R & D laboratories right now and could not be modeled using EnergyPlus v2.0 in its current form. These future modeling capabilities are beyond the scope of this work. The gaps identified all involve technologies available today.

The process for uncovering potential gaps involved internal discussions of the BEopt development team. First, all of the options currently available in the DOE2.2 V44E4/TRNSYS version of BEopt 0.8.0.4 were added to the EnergyPlus version, with some problems uncovered. Additional measures were then brainstormed by the BEopt team and further research was conducted into the feasibility of modeling those options that appeared to reflect currently-available technology. Members of the EnergyPlus development team were consulted to make sure EnergyPlus v2.0 capabilities were not being overlooked. (Griffith, 2007, Ellis, 2007). The

list of gaps is not necessarily comprehensive, but it is comprehensive from the perspective of people modeling new residential production homes in the United States.

In cases where the EnergyPlus v2.0 documentation indicated that a residential modeling capability exists, limited testing of the capability was conducted to determine that it works as advertised. This involved implementing the capability in an EnergyPlus v2.0 version of BEopt 0.8.0.4 and running parametrics and comparing results with the DOE2.2 V44E4/TRNSYS version of BEopt 0.8.0.4. The initial gaps analysis was conducted using EnergyPlus version 1.4.0. The results of this analysis were checked against the latest release, version 2.0.0, and any changes in the characterization of the gaps were noted.

## ***2.2 Characterization of Gaps***

### **Problem List:**

1. Duct Leakage/Infiltration
2. Residential HVAC Autosizing
3. Floating Basement/Crawlspace Model
4. Simplified Ground Temperature Model
5. Ventilation/Mixing Controls
6. Two Speed Fans for Residential AC
7. Stratified Tanks
8. BIPV/PV-T
9. Condensing Boilers
10. Humidity Control with Variable Speed Fan
11. Fully Modulating DX Compressor
12. PV Shading

### 2.2.1 Duct Leakage/Infiltration

Problem Area: Duct Leakage/Infiltration with 2 Speed Systems

EnergyPlus v2.0 Category: Ventilation/Infiltration AirflowNetwork

Technology Level: Current

Desired Capability: Ideally, EnergyPlus v2.0 should be able to model all of the unbalanced airflows within the building, integrating infiltration, HVAC ducts, and ventilation, with changes in the HVAC system operation or exhaust fans causing a change in the pressurization pattern of the house and changing the airflow pattern. The system should do this based on pressure balances, adding all of the flows correctly to get the new airflow between different zones and between a zone and the outdoors and the thermal impact of these flows. This system should also work during autosizing of the HVAC system.

Current Capability: The Airflow Network in EnergyPlus v2.0 is designed to do exactly what the BEopt development team wants to do. Unfortunately, it is currently limited to constant flow systems. The Airflow Network has not been tested well enough to determine what other gaps there might be.

Work Around: Currently, the only way to model duct leakage with the BEopt 0.8.0.4 system is to set up a slave zone direct air object while specifying the airflows. This requires either iteration on the impact of duct leakage or an offline analytical solution for the design day to size the system. This is not really possible for optimizations. The workaround that has been implemented in BEopt 0.8.0.4 is described in the appendix.

Detailed Discussion: Balancing the airflows correctly in a residential building is a critical modeling task, since unbalanced flows and infiltration can be the most significant source of heating and cooling load in some buildings. The current airflow network model does not

allow the use of two speed air conditioners. High efficiency, two speed air conditioners are becoming relatively common in the marketplace (Proctor, 2006) and should be included in building energy optimizations. The simplified infiltration and duct leakage models in EnergyPlus v2.0 are inadequate for truly modeling the impact of unbalanced duct leakage. The simplified duct leakage model available in EnergyPlus v2.0 is specifically for supply duct leakage inside a return plenum (EnergyPlus v2.0 Input-Output Reference, 2007). Alternatively, it is possible to specify outdoor air, exhaust air, and supply and return air flows from a duct location, but this requires significant side work and iterative sizing. There is no simplified residential duct leakage model in EnergyPlus v2.0. The simplified infiltration model has the following equation:

$$Infiltration = (I_{design})(F_{schedule}) [A + B |(T_{zone} - T_{odb})| + C(Windspeed) + D(Windspeed^2)]$$

This simplified infiltration model can be used to make a reasonable approximation of infiltration from wind and stack effects, but it does not interact with other flows across the envelope, such as duct leakage, exhaust, and active ventilation flows. The new airflow network in EnergyPlus v2.0 could do all of these things in theory, but it is very complex. Making the airflow network work in more residential applications and creating a simplified airflow network specification scheme seems like a more fruitful approach than putting effort into improving the simplified duct leakage model for use in residential buildings. Improving the simplified duct leakage model would make it possible to use a similar approach to what is currently used for DOE2.2 V44E4.2 in BEopt 0.8.0.4. In contrast, the airflow network with interactive duct leakage would calculate pressure balances and resulting flows at each time step. The system should work with openings, scheduled exhaust or mixing fans, balanced or unbalanced flows, forced air HVAC, wind, stack effects, and duct leakage. Development of this sort of system is a non-trivial task, but the airflow network appears to be getting close to a relatively fully-functioned airflow modeling system. This is probably the highest priority item for improving residential modeling, because duct

leakage reduction is one of the best energy conservation measures available in residential construction, but the impacts must be combined with infiltration and mechanical ventilation to determine the savings, which cannot be done cleanly in EnergyPlus v2.0 or DOE2.2 V44E4.2.

Related Problems:                      Ventilation Control

### 2.2.2 Residential HVAC Autosizing

Problem Area: Residential HVAC Autosizing

EnergyPlus v2.0 Category: HVAC

Technology Level: Current

Desired Capability: EnergyPlus v2.0 should accurately determine the building loads, then the total load on the system with input assumptions for supply air temperatures, including the impacts of duct leakage interaction with infiltration. The system should then be sized according to a user-defined oversizing factor, or an approximation of ACCA Manual S, using the system capacity at design conditions. The design heating and cooling airflows can be calculated using this approach. The system airflow for a single speed system should be set to the maximum of the two design airflows. The equipment should then be sized to provide the desired supply temperature at the system airflow. That is the required conventional approach from the Air Conditioning Contractors of America (ACCA). Unfortunately, this may not be adequate for high performance homes. What would ideally be included in EnergyPlus v2.0 would be some sort of runtime algorithm language for doing autosizing, so that various experimental algorithms could be used within EnergyPlus v2.0 with novel equipment that needs more advanced sizing procedures to optimize performance than are provided by ACCA Manual J and Manual S. Manual J and Manual S optimize the system size to minimize system size and cost while meeting minimum comfort criteria, and are used by HVAC contractors for sizing equipment. They use only sensible loads. More advanced equipment may have two different cooling modes, such as combining an evaporative cooling system or desiccant wheel with a DX system. The optimization of system size then has a slightly different cost objective, which includes the energy consumption of the equipment with various component sizes. Having a runtime sizing language

would allow researchers and standards developers to experiment with different sizing algorithms for complicated equipment. In addition, future equipment designs or sizing requirements may include humidity control as a constraint, in order to maintain better indoor air quality

(IAQ). Current Capability: EnergyPlus v2.0 has most of the desired capability.

EnergyPlus v2.0 does not include an adequate duct leakage model yet, so it also lacks autosizing for duct leakage. The current system accurately chooses design air flows for input supply temperatures and building characteristics. It then sets the system airflow for constant volume systems to the maximum of the two design airflows. EnergyPlus v2.0 does not resize the equipment after this step, but uses the design equipment size with the new system airflow.

Work Around: There are two possibilities here. The first possibility is to do a sizing-only run, then interpret the results offline and implement a sizing algorithm independent of EnergyPlus v2.0. The second possibility is to attempt to post-process the results from EnergyPlus v2.0 to make up for a lower supply temperature during some heating conditions, adjusting the fan energy accordingly and/or making an adjustment for part load performance.

Detailed Discussion: Autosizing of systems is very convenient for use in optimization, since sending and receiving data from BEopt 0.8.0.4 takes a certain amount of time and adds some complexity to the system. In theory, running a sizing simulation for sizing, then running an annual simulation as a separate job for EnergyPlus v2.0 should not take any more simulation time than doing the two simulations as a single job. Asking the optimization engine to interpret sizing run results and send two jobs for each building is not too unreasonable. However, the sizing run will need to be run in some clever manner to capture the system sizing impacts on the loads (generally resulting from interaction of duct leakage, infiltration, and exhaust flows).



Unfortunately, proper sizing of systems for high performance homes is not a settled, well-understood issue. Many energy efficiency measures contribute to reducing sensible loads without impacting latent loads, which result from cooking, people, pets, showers, sinks, and baths. The conventional ACCA sizing procedures focus on meeting the peak sensible load, with little attention paid to meeting latent loads or operating efficiently at part load. There is no addendum to the ACCA manuals to deal with homes in which the SHR ratio is typically rather low.

Another problem with current sizing methods is how they deal with humidity control at part loads, which has been shown to have negative effect on IAQ (Shirey, 2004). If better IAQ at part load is desired in the future, sizing algorithms will need to be developed with latent performance included. Latent capacity degradation is relatively well understood. Systems that are running at part load cycle on and off. When they first cycle on, the coil is dry. Water condenses on the cold coil until there is enough water on the coil to overcome surface tension and begin dripping, at which point the water collects in the drip pan and flows out the condensate line. Latent cooling is not fully realized until the water flows out the condensate line. Up until that point, the water is available for evaporation. When the coil cycles off, the fan may continue to run for a short time, then turn off. During this time, the water on the coil evaporates, providing sensible cooling at the expense of latent capacity. If the cycle on time is short enough and the time between cycles or the time between the coil cycling off and the fan cycling off is long enough, then there may not be any latent capacity realized, since the coil does not collect enough water to start dripping before cycling off and there is enough opportunity for all of the water on the coil to evaporate again before the coil cycles on again. In other cases, the coil may cycle back on again before it is completely dry, so it may reach saturation and start dripping,

experiencing partial latent degradation. There may be numerous control strategies for achieving improved latent performance, but they vary from unit to unit, with different manufacturers using different combinations of coil and fan operating schemes. The important piece from a modeling perspective is accurately capturing the latent degradation for different strategies and enabling the use of different control and sizing methods to accomplish accurate autosizing for both design day and part load operation with a dual objective of sensible comfort and adequate humidity control.

Related Problems: Duct leakage, ventilation controls, mixing controls, infiltration, two speed AC systems.

### 2.2.3 Floating Basement/Crawlspace Model

Problem Area: Floating Basement/Crawlspace Model

EnergyPlus v2.0 Category: Auxiliary Foundation Models

Technology Level: Current Technology

Desired Capability: The basement model should allow the user to deal with a floating zone temperature and a ventilated basement/crawlspace. Allow the user to specify a ventilation/infiltration rate, a monthly temperature for the adjacent conditioned space, and properties of the surface separating the basement from the conditioned space.

Current Capability: The basement model uses ground characteristics, limited insulation characteristics, and a specified basement temperature to run the 3D heat transfer iterative solution and find the surface temperatures.

Work Around: Currently, there are two ways to deal with this problem. First, and most common, is to assume some nominal basement temperatures, run the model, and then use the surface temperatures. If the user wants to be more accurate, they can iterate by running the subsequent surface temperatures through an annual energy simulation and finding new monthly basement temperatures, then rerunning the basement model, until convergence occurs. This takes quite a bit of time.

Detailed Discussion: In typical commercial applications, basement spaces are conditioned, so choosing the temperature for the basement to run the basement model is easy. This temperature will affect the energy transfer from the ground in the following manner:

$$Q = UA*(T_{surf} - T_{basement})$$

$T_{\text{surf}}$  is what is calculated by the 3d ground heat transfer program. Unfortunately,  $T_{\text{surf}} - T_{\text{basement}}$  is typically on the order of 0 to 5 degrees C, while the UA is large. So an error of a few degrees C in the initial assumed basement temperature from the actual basement temperature could cause a 50% change in the ground heat transfer. Therefore, it is clear that seeding the ground heat transfer mechanism with accurate basement temperatures is crucial to the results having any meaning whatsoever.

It may be preferable to have the basement model be broken from the building model at the conditioned/unconditioned interface, instead of at the at the ground/space interface. An alternative approach is to run an integrated version of the basement model and the other building models on an hourly basis just once, then split off the basement at the outer soil interface.

Update: Still a problem

Related Problems: Simplified Ground model

## 2.2.4 Simplified Ground Model

<u>Problem Area:</u>	Simplified Ground Model
<u>EnergyPlus v2.0 Category:</u>	Auxiliary Foundation Models
<u>Technology Level:</u>	Current Technology
<u>Desired Capability:</u>	It would be useful to have a simplified ground heat transfer model that allowed modeling in more or less real time, in order to allow quick changes in foundation construction or indoor set point during optimization.
<u>Current Capability:</u>	The current ground heat transfer model does a 3d simulation of ground heat transfer in an auxiliary program. This model is quite accurate (as accurate as the input information will allow). But it takes a lot of run time, so it has been split off into its own separate program. The model is split off at the ground/space interface. The basement model uses ground characteristics, limited insulation characteristics, and a specified basement temperature to run the 3D heat transfer iterative solution and find the surface temperatures.
<u>Work Around:</u>	Run the model for a range of set point temperatures, annual temperature shapes, and effective basement R-values. Use the resulting map to derive empirical fits for the impact of the variables. Run the ground model once to get baseline temperatures, then apply adjustments to the map. Or, track the ground temperature modeling separately and remember when a certain set of inputs have been run, saving those results for all future use in optimization.
<u>Detailed Discussion:</u>	Ground temperature modeling is one of the most difficult building energy modeling tasks from a strictly technical standpoint. The EnergyPlus v2.0 ground model stands out for its technical capability, but it does not do moisture transfer between

the ground and the basement (which is all too common in many residential situations). The model does do surface evapotranspiration as an option. Unfortunately, all of this accuracy comes at significant computing time cost, since the ground heat transfer model typically takes about an order of magnitude longer than the rest of the residential simulation. This is fine when modeling individual buildings or when running parametric or optimization analyses with variable dimensions that have no impact on the ground heat transfer. However, if the ground heat transfer is changing, without a change to the ground temperatures being made, then the model results may be inaccurate. To run the ground heat transfer model in real time increases the run time dramatically. The end result is that using the EnergyPlus v2.0 basement model for optimization of variable dimensions that affect ground heat transfer causes an order of magnitude increase in run-time.

Related Problems:

Floating Basement/Crawlspace Model

## 2.2.5 Two-speed residential HVAC

Problem Area: Two speed residential HVAC

EnergyPlus v2.0 Category: HVAC models

Technology Level: Current High Performance Technology

Desired Capability: There are two speed residential air conditioners and heat pumps in the market today that essentially act like two different units. The fan typically cycles between two speeds as the compressor cycles between two speeds or stages, depending on the design. The system should allow the ratio of the two speeds of the fan to be specified, along with the two speed unitary coil that is already available in EnergyPlus v2.0.

Current Capability: EnergyPlus v2.0 has a viable simple two speed coil model, which is good enough to capture the performance of the coil and compressor. It can use the same equation sets as DOE2.2 V44E4.2, for modifying capacity and efficiency as a biquadratic function of coil entering wet bulb and outdoor dry bulb, adjusting capacity based on part load degradation, etc. EnergyPlus v2.0 also has VAV fan models. What EnergyPlus v2.0 does not have is a two speed fan model and controller to modulate between the two speeds depending on the loads.

Work Around: A workaround is hard to work out for this modeling difficulty. The preferred path would appear to be to set up two pieces of equipment, with their sizes proportional to the capacity split between low and high speeds. The two pieces of equipment could be controlled using the availability manager, so that the second piece would only be used above a certain threshold, which would need to be fixed, unfortunately. This

precludes the use of autosizing, because the threshold cannot be autosized. As a result, this work around is not really applicable for use in optimization.

Detailed Discussion: Two speed air conditioners are relatively common in the marketplace today and can easily be modeled using the latest version of DOE2.2 V44E4.2. These systems function by modulating both the compressor and the fan in tandem, so that there is a high output and low output operating mode, with the fan operating at higher speed and the compressor either adding a stage or operating at a higher speed. These systems are generally sized so that the high speed mode matches the desired cooling capacity. The ratio of the high and low speeds depends on the manufacturer's equipment. Depending on the ratio of the cooling and heating loads and the desired heating and cooling supply air temperatures, the furnace might be sized to run with the fan in high speed or low speed. In many climates with relatively higher cooling than heating loads, having a two speed air handler allows the furnace to be sized smaller. Autosizing in EnergyPlus v2.0 would set the high fan flow (typically for cooling) and determine which airflow the furnace (if it has a furnace) will operate at, depending on the required heating and cooling supply air temperatures. The user would input the ratio of the high and low speeds, so the lower airflow would be set by this ratio times the design airflow.

Update: Still a problem

Related Problems: Humidity Control with Variable Speed Fan, Fully Modulating DX Compressor, Residential Autosizing



## 2.2.6 Ventilation Controls

Problem Area: Ventilation Controls

EnergyPlus v2.0 Category: HVAC controls / Ventilation

Technology Level: Current Technology

Desired Capability: Allow complete control of natural ventilation turning on and off, so that flow rate and temperature range can be scheduled to allow for seasonal variations in operation. Multiple ventilation objects would also be nice.

Current Capability: EnergyPlus v2.0 currently allows ventilation of spaces with the VENTILATION object for venting outside. The object is controlled with a minimum and maximum indoor and outdoor temperature, an inside-outside temperature difference, and a schedule that enables or disables operation. Only one ventilation object is allowed per zone.

Work Around: Create a series of adiabatic dummy zones with cross mixing objects that interact with the desired zone. Dummy zones can float in space with infinitesimal wall areas and adiabatic conditions, but with a large volume. If the dummy zone is linked to the objective zone with a cross-mixing object with a high enough flow, then any ventilation of the dummy zone will impact the objective zone. Build up the desired operation schedule for ventilation by having a different ventilation object with a different schedule in each of the dummy zones. Essentially, you have one ventilation object for each different set of operating conditions, with the each ventilation object turned on for the time period corresponding to the scheduled desired operation.

Detailed Discussion: When modeling residences, passive cooling with open windows has a big impact on energy use. The operation of these windows varies from season to season. During winter, it may be desirable to allow natural ventilation to prevent overheating,

without turning on the air conditioning system. The setpoint for that ventilation might be 76 or 78 or 80 degrees F. Meanwhile, during the summer, different sorts of natural ventilation might be employed. During night cooling, the setpoint might be 65 or 68 degrees F, while during the day, the setpoint might be the same as the active cooling setpoint. EnergyPlus v2.0 makes it very difficult to model this sort of thing. A temperature schedule would alleviate these problems. The other thing that might change is the amount of window area opened during different seasons. During summer, all windows might be open. During winter, somebody might be opening just a few windows. These operating procedures become even more important in high performance passive homes, where ventilation setpoints are critical for preventing overheating and effectively precooling the space.

Related Problems:

Mixing Controls

### 2.2.7 Stratified Tanks

Problem Area: Stratified Tanks

EnergyPlus v2.0 Category: Water/HVAC

Technology Level: Current Advanced Technology

Desired Capability: Accurately model stratification with a multinode model in thermal storage tanks, most notably for use in solar hot water heating applications (especially low flow systems).

Current Capability: The current tank model is a well-mixed, single node tank, which can experience inflows and outflows and track heat exchange with the ambient environment.

Work Around: Create a group of tanks strung together with a small amount of continuous water flow between them to approximate slow mixing between layers of a stratified tank.

Detailed Discussion: Stratified tanks play a big role in the overall efficiency of solar water heating systems. They also affect other water heating/thermal storage systems that have efficiency affected by water temperature. One example is a heat pump water heater that draws cold water from the bottom of the tank and returns it someplace else (either the middle or top). Within a well-designed, insulated stratified tank, convective mixing within the tank is minimized, so heat transfer between layers happens primarily via conduction through the tank liquid. In the extreme case of very low flow solar water heating systems (single pass per day), the water at the bottom of the tank may be at mains temperature (50 F or 10 C), while the temperature of the water at the top of the tank is at a hot solar collection temperature (160 F or 70 C). In these cases, the mean temperature of the tank might be 75 F, while the temperature

going out during a hot water draw event is 160 F, so the simple tank model would be off by 85 degrees, missing most of the energy production from the Solar DHW system. In simple electric water heater tanks, there is typically a difference in the setpoint of the upper and lower heating elements, resulting in some degree of stratification, with the average tank temperature being somewhere between the two setpoints. A stratified tank models this temperature stratification explicitly. Multinode tank models are a basic feature of TRNSYS. EnergyPlus v2.0 needs to have the same level of capabilities in this area as TRNSYS to be useful as a research tool for solar water heating and other advanced thermal systems.

Update: A new multi-node tank model has been added to EnergyPlus in version 2.2. This tank was added to EnergyPlus model in BEopt 0.8.0.4, with limited exploration of the performance. The performance does not appear to match the TRNSYS model performance and the runtime increased by a factor of 3. This will require further exploration and validation to achieve good modeling accuracy without the tremendous increase in simulation time. In the meantime, the single node tank is being used for analysis, which results in some deviation in water heater losses from the simple electric water heaters.

Related Problems:

## 2.2.8 Building-Integrated PV / PV – Thermal

Problem Area: Building-Integrated PV/PV-Thermal

EnergyPlus v2.0 Category: Equipment

Technology Level: Advanced Current Technology

Desired Capability: The PV equivalent one-diode model should enable the same types of building integration as the other Sandia and Simple models. Cell temperature should be calculated by EnergyPlus v2.0, then used to drive the efficiency calculation for the PV panels.

Current Capability: The current EnergyPlus v2.0 PV models are somewhat limited. There are three PV model options: simple, one-diode, and sandia. The simple model has constant efficiency, but can be integrated into the construction, including as an exterior vented cavity or as a transpired collector. The one-diode model has variable efficiency, depending on either a normal operating cell temperature (NOCT) correlation or a dynamic model by Ulieberg. The one-diode cannot be integrated with the building. The Sandia model has variable efficiency depending on the Sandia model values for a particular PV-module in the Sandia database. The Sandia model allows full integration with the EnergyPlus v2.0 envelope, with exterior vented cavity and transpired collectors as additional options.

Work Around: The best work around available is to use the simple PV model, then output the surface temperatures to post process the module efficiency based on a NOCT correlation.

Detailed Discussion: The current capability in EnergyPlus v2.0 would work well if Sandia model data was available for new PV products. Unfortunately, this is not happening in a timely manner, and in any case requires significant testing, so there is some minimum time lag

between a panel's market readiness date and completion of the Sandia testing. The equivalent one-diode model should be adequate for use with new PV products, but it needs to have building-integrated functionality built in, with the same functionality that is available in the other two models. The current building integration options should be adequate to allow the modeler to take care of a number of possible configurations. The only additional problem I can think of is the possibility of PV-glass double skin facades, or PV-glass glazing solar thermal collectors. The added complexity comes from the PV substrate transmitting solar radiation to the lower layers.

Update: Still a problem

Related Problems: PV Shading

## 2.2.9 Condensing Boiler

Problem Area: Condensing Boiler

EnergyPlus v2.0 Category: HVAC

Technology Level: Current Advanced Technology

Desired Capability: EnergyPlus v2.0 should be able to model condensing boilers accurately, which means that it must be possible to input a performance curve that includes efficiency/fuel use as a function of flow rate and firing rate, or leaving/entering water temperature, flow rate, and firing rate, such that there can be a plateau in the heat output/efficiency curve, where efficiency is high in the low output part of the curve, then drops off as the output increases relative to the flow rate/entering/leaving water temperature.

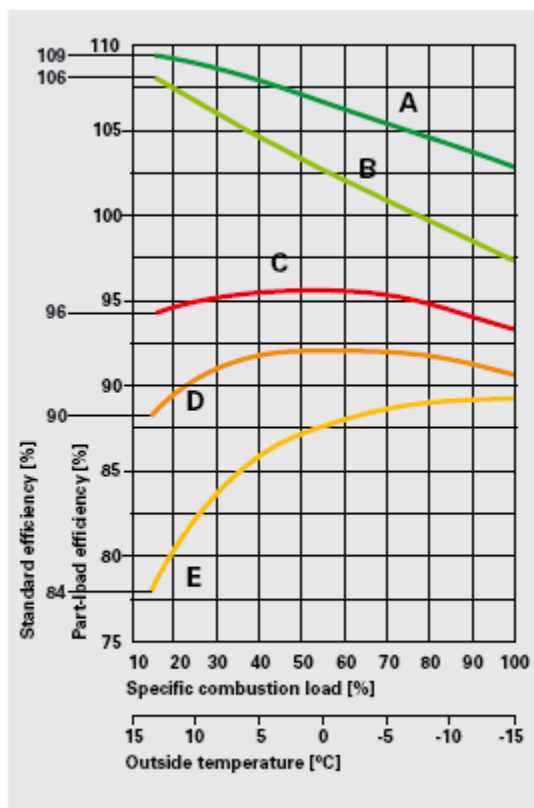
Current Capability: The current curve has fuel use as a function of part load ratio:

$$FuelUsed = \frac{TheoreticalFuelUsed}{C1 + C2 * OperatingPartLoadRatio + C3 * OperatingPartLoadRatio^2}$$

This simple quadratic function does not get the job done if the boiler water temperature is changing over time.

Work Around: It is possible to get a simple curve into the condensing boiler that will work as function of PLR alone. This approximates the curve, with low PLR having higher efficiency, with the same quadratic shape.

### Detailed Discussion:



**Fig. 9:** Standard efficiency levels for various boiler designs

- A Gas fired condensing boilers 40/30°C
- B Gas fired condensing boilers 75/60 °C
- C Low temperature boiler (without lower temperature limit)
- D Boiler made in 1987 (lower temperature limit: 40 °C)
- E Boiler made in 1975 (constant boiler water temperature: 75 °C)

**Figure 3:** Boiler Efficiency Curves (Viessmann, 2006)

Figure 3 shows part of the problem. Unfortunately, the efficiency of the condensing boiler is fundamentally a function of the exhaust temperature, which depends on the boiler temperature, shown in the difference between curves A and B. One possible solution is to make the performance a function of entering water temperature and PLR. The last difficulty is how to put the clean hump in the curve, since efficiency will be flat for some larger area at lower temperatures. This is comparable to the SHR problem for air conditioning curves, where when the wet bulb/dewpoint is below a certain point, sensible output will be constant at a given entering drybulb temperature.

### Related Problems:



### 2.2.10 Humidity Control with Variable Speed Fan

Problem Area: Humidity Control with Variable Speed Fan

EnergyPlus v2.0 Category: HVAC controls

Technology Level: Current Advanced Technology

Desired Capability: Control humidity levels by varying the fan speed and/or compressor output. EnergyPlus v2.0 should be able to incorporate multiple control algorithms for different combinations of fans and compressors. Some of these might include humidity priority with temperature band, temperature priority with humidity band or ideal performance on a runtime basis. In some simple cases, there may be only discrete fan speeds. In other cases, the fan may be continuously variable.

Current Capability: EnergyPlus v2.0 has coil models that will work with variable air flow. EnergyPlus v2.0 also has a relatively advanced latent/sensible shifting algorithm to deal with coil cycling. EnergyPlus v2.0 can control coils to control humidity, but it cannot control airflow to control humidity. EnergyPlus v2.0 has variable speed fans available for VAV systems, but it does not have a two speed fan, nor does it have adequate controls to alter fan speed and coil operation in the way a residential variable speed humidity control system might work.

Work Around: There does not appear to be a good work around for this problem. The only approximation that seems plausible is to make a guess at the sensible heat ratio of different operating conditions, then control the equipment to use a lower airflow, higher latent output system when sensible loads are below a certain level. This is not an adequate modeling approximation.

Detailed Discussion: The value of residential humidity control is a contentious issue, but the general trend of late appears to be towards controlling for lower levels of humidity. Most humidity control today is done with crude reheat dehumidifiers. Much more efficient humidity control is possible using various DX HVAC schemes that involve running lower airflow rates when more latent capacity is desirable. In high performance homes, sensible loads are typically significantly reduced. During times of lower sensible loads, these houses will have very low sensible heat ratios, but they might still be attainable using a DX coil. There are some products on the market today that take advantage of variable airflow to do dehumidification. While the basic strategy of putting more cooling into less air remains the same across multiple products, the detailed controls and strategies vary from product to product. It seems that the proposed advanced runtime HVAC control language capability in EnergyPlus v2.0 should enable modeling of any manufacturer's control strategy.<sup>1</sup> The typical control strategy would control the cycling of the compressor to control temperature, while changing the airflow according to the humidity tracking. Some variation on typical PID control would probably be necessary to capture the recent history and incorporate that into the airflow control, so that the system would run at low airflows when the required SHR is low, and higher airflows (or lower compressor input) when the required SHR is high. There are significant opportunities for saving energy with air conditioners of this type, compared to using more typical reheat systems for humidity control. When lower latent capacity is required, the compressor output will be reduced and airflow will be increased, resulting in higher evaporator temperatures and lower condenser temperatures,

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<sup>1</sup> The EnergyPlus development team has indicated that they are working on a new runtime HVAC control language capability for a future release. These generic control objects will allow control algorithms to be programmed, linked to any node in the air-side or water-side equipment, rather than the simple temperature-based control points currently allowed. The language will allow the use of if-then-else and other logical instruction statements. The primary application of the runtime controls language will be modeling commercial system controls, but it will also have applications in advanced residential equipment.

which equates with higher efficiency. When high latent capacity is required, then the airflow would be reduced and the compressor output increased, in order to lower the evaporator temperature to the point that gives a leaving air temperature sufficient to supply the required latent cooling. In a fully integrated system, there would then be a variable reheat coil, allowing the system to achieve lower sensible heat ratios than can be achieved with the DX coil alone. There is also the possibility to map performance of a piece of equipment on the basis of outdoor dry bulb, sensible part load, and latent part load, which would be a simplified approach to modeling any combined DX sensible/latent cooling device. Equations to fit manufacturers performance data could then be derived, similar to the current equations in the current coil models.

Related Problems: Fully modulating DX compressor, Two-speed residential HVAC, Residential Autosizing

### 2.2.11 Full Modulating DX Compressor

Problem Area: Fully Modulating DX compressor

EnergyPlus v2.0 Category: HVAC Equipment

Technology Level: Current Advanced Technology

Desired Capability: There are advanced residential AC systems available on the market that modulate compressors in multiple ways. One option is the multiple speed compressor, where the speed of the compressor is changed between two levels. Another option is the multiple displacement compressor, where a second stage is turned on an off sometimes. A third option is a compressor with continuously variable speed. It is desirable to enable modeling of a DX coil linked to a compressor with continuously variable speed, which means there will be an efficiency modifier to make efficiency higher as a function of part load ratio.

Current Capability: EnergyPlus v2.0 has a two speed air conditioner available right now, where the fan and compressor speed change between two speeds. It essentially works like there are two stages, modulating between the two or between the low stage and zero. EnergyPlus also has a part load ratio modifier of energy usage.

Work Around: It should be possible to construct a part load curve that approximates the energy use of this sort of compressor, but it will have a funny shape, so that efficiency will increase as the load drops.

Detailed Discussion: Operation of a fully modulating compressor is fundamentally different than operation of an on-off compressor or two speed compressor. The fully modulating paradigm probably has a compressor and fan both on variable speed drives. Instead of utilizing on/off control or mode-switching control (on/low/high), the fully variable system is continuously modulating the compressor and fan to control temperature and humidity, probably with some

kind of PID or related control algorithm, with a much tighter comfort tolerance than a typical on/off thermostatic control. In theory, this type of system provides impeccable comfort without any of the problems associated with cycling. If the HVAC system is controlling everything based on a single thermostat (fan speed, latent, and sensible capacity), then in theory the model can become simpler, with energy use solely a function of the latent and sensible loads, humidity and temperature in the space, ignoring the actual speed variations of the fan and compressor.

Related Problems: Humidity Control with Variable Speed Fan, Two speed residential HVAC, Residential Autosizing

## 2.2.12 PV Shading

Problem Area: PV Shading

EnergyPlus v2.0 Category: Equipment

Technology Level: Current Technology

Desired Capability: Provide some basic methods for estimating the effects of shading on an individual module and string of modules. One possibility would be to assume that each cell is on a bypass diode, the next that each module is on a bypass diode, and the last that there are no bypass diodes and the whole string goes down when one cell goes down. A shading impact curve could be constructed, with the user specifying the coefficients for each string, which would tell EnergyPlus v2.0 how to approximate the impact of shading on array output.

Current Capability: EnergyPlus v2.0 models the effects of shading on PV by looking only at the overall level of radiation incident on the array surface. It assumes that performance is ideal and there are no additional losses within a module or string.

Work Around: Define array surfaces such that they are properly shaded. Track the degree of shading with output from EnergyPlus v2.0. Postprocess the PV array output based on this shading.

Detailed Discussion: In some cases, slight amounts of shading can cause nearly complete disruption of PV array electricity production. Shading is the leading cause of having lower array output than expected. In the vast majority of residential situations, shading of the array is important, due to self shading from the building and shading from neighboring buildings, power lines, and trees. EnergyPlus v2.0 has excellent shading and reflection algorithms built in. In designing a house with building-integrated PV arrays, with the modern proliferation of dormers, it is highly likely that the array will shaded by the building for portions of the day.

Capturing the impact of that shading is crucial to the economics of placing PV in one location or in another location. The impacts of this decision are huge. As people begin to look more at building-integrated PV options in new residential single-family construction, the shading issues will only become more important. EnergyPlus v2.0 should quantify the impacts of that shading. The method we suggest is to allow the user to specify some coefficients that relate the output to the shading for each PV surface, roughly segmenting the PV into each piece broken out with bypass diodes and strings.

Related Problems:    Building Integrated PV, PV-Thermal Integration

### 2.3 Comparison of EnergyPlus v2.0 to Other Simulation Engines

The capabilities of EnergyPlus v2.0 were compared with the capabilities of DOE2.2 V44E4.2 and TRNSYS for their current uses in BEopt 0.8.0.4. The component modeling capabilities of each engine were qualified as being either inadequate for use in BEopt 0.8.0.4 (-), adequate for use in BEopt 0.8.0.4 (+), or having more advanced capabilities than are generally necessary for use in BEopt 0.8.0.4 (++), but which might be of use for some future applications. The table below represents the opinions of the author and the BEopt development team, with some consultation with the EnergyPlus development team for the purposes of conjecturing about future capabilities in EnergyPlus.

**Table 3: EnergyPlus Capabilities Compared with DOE2.2 V44E4**

Modeling Area	Priority (1 – 3)	DOE2.2 V44E4 / TRNSYS	EnergyPlus 1.4	EnergyPlus 2.0	EnergyPlus Future
Infiltration	1	+	-	-	++
Duct Leakage	1	+	-	-	++
ACCA Autosizing	1	+	-	-	++
Conditioned Foundations	1	+	+	+	++
Unconditioned / Ventilated Foundations	1	+	-	-	++
Ventilation / Mixing Controls	2	+	+	+	++
Latent Tracking / Control	2	+	++	++	++
Two Speed AC	2	+	-	-	++
HVAC Controls	2	-	+	+	++
Stratified DHW Tank	2	++	-	+	++
Boiler	2	+	++	++	++
BIPV	2	-	+	+	++
Thermal Comfort Calculations	3	-	++	++	++
Phase Change	3	-	-	+	++



Modeling Area	Priority (1 – 3)	DOE2.2 V44E4 / TRNSYS	EnergyPlus 1.4	EnergyPlus 2.0	EnergyPlus Future
Materials					
Condensing Boiler	3	-	-	-	++
Micro CHP	3	-	-	+*	++
Heat Pump Water Heater	3	-	+	+	++
Humidity Control with Variable Speed Fan	3	-	-	-	++
Fully Modulating Compressor	3	-	-	-	++
PV-Thermal	3	+	+	+	++
PV Shading	3	-	+	+	++

\* These options have not been fully explored, but the documentation claims the capability

The results in Table 3 show that EnergyPlus v2.0 has two major deficiencies with respect to what is necessary to model buildings accurately in BEopt 0.8.0.4: EnergyPlus v2.0 cannot use its airflow network model with multispeed air conditioning and therefore cannot accurately model duct leakage, infiltration, and exhaust interaction, or model duct leakage in any reasonable manner. EnergyPlus v2.0 cannot easily be used to simulate two speed air conditioners. The other major deficiency comes in modeling unconditioned basements, which also cannot be done adequately.

The simpler duct leakage, exhaust, and infiltration models in EnergyPlus v2.0 do not readily provide accurate results, which was discussed in detail in Section 2.2. DOE2.2 V44E4 also suffers from problems in this area, but it is easier to achieve adequate results. The infiltration interaction method currently used in BEopt 0.8.0.4 with DOE2.2 V44E4 was duplicated in EnergyPlus v2.0, except that modeling duct leakage is impossible without doing a sizing run before each simulation. Therefore, only houses with ducts inside and a fixed ground heat transfer condition can currently be efficiently optimized.

### **3 BEOpt 0.8.0.4 with EnergyPlus v2.0**

BEOpt 0.8.0.4 has a flexible architecture that allows the basic software package to interact with different simulation engines that take text input files. In order to do this, the software must be able to create input files from a template file, and then read back in results from a text output file. The optimization engine chooses the set of options to run and then sets the values for a set of variables, which in turn are interpreted by a series of files with a .bmi suffix containing programming instructions for creating the required text input files. The .bmi files can be modified by advanced users of BEOpt 0.8.0.4 to change the way the simulation input files were constructed. The largest task in hooking BEOpt 0.8.0.4 up to a new simulation engine is the creation of a new .bmi input template file.

#### ***3.1 Methodology for Creating EnergyPlus.bmi***

The first step in creating a template .bmi file for producing EnergyPlus input files was to create a nominal residential EnergyPlus .idf file for a house that is similar to the Building America Benchmark. This work was started using EnergyPlus version 1.2.2 and the 2005 Building America Benchmark<sup>2</sup>. The model started with a simple envelope and a single nominal wall construction, with a simple furnace and air conditioner generated using the EnergyPlus v2.0 compact HVAC object<sup>3</sup>. Then interior gains were scheduled and added, along with a simple infiltration model and simple hot water equipment. Annual and monthly energy use outputs were checked against results for a similar building generated with DOE2.2 V44E4/TRNSYS

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<sup>2</sup> The Building America Benchmark defines a research benchmark for the purposes of measuring progress in designing more energy-efficient new residential buildings. It is nominally based on mid-90s code requirements, but it is periodically revised for clarification purposes. The research benchmark defines the characteristics of the comparison building for any residential new construction prototype.

<sup>3</sup> The EnergyPlus compact HVAC object allows users to enter a minimal number of variables to define an HVAC system, with EnergyPlus then assuming defaults for the remaining variables and creating a full HVAC system with these defaults.

BEopt 0.8.0.4. This allowed gross debugging of the basic model to determine if there were major errors in inputs.

This basic model was then transitioned to a .bmi file by replacing input fields with variable names from the global.bmi<sup>4</sup> and options in BEopt 0.8.0.4. Some equations and logic were moved out of the DOE2.2 V44E4.bmi file and into the Global.bmi file, with the intention of putting all general logic and equations into the global file, enabling their use with any of the energy simulation engine template bmi files. BEopt 0.8.0.4 was altered by Scott Horowitz to enable switching between simulation engines.

Unfortunately, there was a units convention difference between the files generated for DOE2.2 V44E4 and the input standards for EnergyPlus v2.0. As a result, each variable used by EnergyPlus v2.0 needs to be converted into the proper units. A section of variable unit conversions was added to the top of the EnergyPlus.bmi file. To hook a BEopt 0.8.0.4 option up to EnergyPlus v2.0, the variables of interest were added to the unit conversions section, then added in the proper fields in the EnergyPlus v2.0 code, then tested by running the new file with BEopt 0.8.0.4. If BEopt 0.8.0.4 failed to run properly, the EnergyPlus v2.0 error file was examined, looking for the error. Errors in hooking BEopt 0.8.0.4 options up generally show up as a variable name left in the EnergyPlus v2.0 input file. This error can be traced back through the global file operation by looking at the LIST.out file for a given run, which summarizes the results of each line of code in the global file. This allowed the disconnect between EnergyPlus v2.0 and BEopt 0.8.0.4 to be pinpointed quickly.

Over the period of template file development, there were multiple new releases of EnergyPlus. Each time, the EnergyPlus.bmi file was updated and debugged with the new

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<sup>4</sup> The global.bmi file is used by BEopt to perform a series of intermediate calculations for creating input variables for the simulation engines. It can be user-edited.

version of EnergyPlus. The current version is now 2.0.0 (as of summer, 2007). Some option categories were flagged as being difficult to model appropriately in EnergyPlus v2.0, on the basis of reviewing the EnergyPlus v2.0 documentation of the objects used in modeling these categories. The modeling details of these “trouble” categories were explored further. Some of these options (duct leakage, foundations) have been left out or simplified, in anticipation of changes being made to EnergyPlus v2.0 that will enable better modeling in the future. For other options that lie within the current capability of EnergyPlus v2.0, further rigorous testing of options was conducted to determine differences between DOE2.2 V44E4 and EnergyPlus v2.0 results in the modeling of certain options.

### ***3.2 Basic Comparison of EnergyPlus v2.0 and DOE2.2 V44E4 results***

What makes the results of a simulation engine valid? This question has been asked by a number of researchers over the years. The basic options include comparing model results to empirical results, analytical verification of model components, and comparison of model results to results from other models (Judkoff, 2006). Among these, comparison of model results to empirical results is the most rigorous but also most expensive option, as it involves major field data collection tasks to determine the precise performance characteristics of a building. Multiply this effort by hundreds if not thousands of combinations of building types and climate regions, and you have an insurmountable task to empirically validate a building simulation model across the range of applicability. What is more commonly used is a combination of analytical validation of components (Rees, 2002) and comparison to other simulation models. A model comparison protocol is specified by ASHRAE 140-2007 (2007), which includes a series of reference building tests based on BESTEST (Judkoff, 1995). Both EnergyPlus (Henninger, 2006) and DOE2.2 (J.J. Hirsch and Associates, 2009) have had their results verified using ASHRAE 140. ASHRAE 140

results do not prove that the results of the simulation engine are true. Rather, they prove that the model results are comparable to the current state of the art in energy modeling programs at the time of their comparison (Judkoff, 2006). In the fast-changing world of energy simulation, new versions of programs will generally have somewhat comparable, but different results. ASHRAE 140 results from older versions do not prove that newer versions meet the standard, but they do indicate that the newer versions are likely to meet the standard.

In order to validate that the DOE2.2 V44E4 and EnergyPlus v2.0 versions of BEopt 0.8.0.4 do not have a larger difference in results than is common in the current state of the art in energy modeling programs, a four-part process was followed:

1. Create simple test buildings within BEopt 0.8.0.4.
2. Run the buildings with EnergyPlus v2.0 and DOE2.2 V44E4 versions of BEopt 0.8.0.4.
3. Compare the heating and cooling energy consumption of the two versions.
4. Compare the differences between DOE2.2 V44E4 and EnergyPlus v2.0 in the BEopt 0.8.0.4 test buildings to differences between simulation engine results for appropriate ASHRAE 140 test buildings.

Four test buildings were constructed, a base building, the base building without windows, the base building without natural ventilation, and the base building with high efficiency, R- walls. These are intended to represent the breadth of simple envelope and mass issues: conduction gains through the walls, solar gains through the windows, and natural ventilation. The base simple test building characteristics are listed in Table 4.

**Table 4: Base building characteristics**

Area	1800 square feet
Aspect Ratio	1
Number of Stories	2
Bedrooms	3
Bathrooms	2

Garage	Yes, on left, 10 foot projection
Orientation	North (side of garage)
Neighbors	None
Miscellaneous Electric Loads	2007 BABM
Window Area	20% of FFA
Roof	Gable, 6:12 Pitch
Eaves	None
Foundation	Ventilated Crawlspace, R19 ceiling
Duct Leakage	Ducts Inside
Plug-in Lighting	0% CFL
Cooking Range	Electric
Dryer	Electric
Thermal Mass	None extra (1/2 inch ceiling drywall, 40 lb/ft furniture)
Wall Height	8 feet
Window Area	20% of FFA
PV Tilt	Back Roof (6:12)
PV Azimuth	Back Roof (south)
Walls	R11 Batts 2 x 4
Ceiling	R40 Ceiling
Infiltration	Normal, FLA = 0.0005
Crawlspace	Ventilated, R100 Ceiling
Window Areas	20% FFA, Equal distribution
Window Type	Double Clear, U = 0.447, SHGC = 0.547
Refrigerator	Standard
Dishwasher	Standard
Clothes Washer	Standard, Vertical
Hardwired Lighting	0% CFL
Air Conditioner	SEER 10
Furnace	80% AFUE
ERV	No ERV
Water Heater	Electric, Standard, 86% Energy Factor
PV	0 kW
Natural Ventilation	On

The buildings were run in four test climates, Boulder (cold and dry), Chicago (cold and moist), Phoenix (hot and dry), and Houston (hot and moist). The primary heating and cooling consumption for EnergyPlus v2.0 and DOE2.2 V44E4 were compared for each of the building and climates. Figures 4 through 7 show the annual heating and cooling energy consumption of the reference buildings in the four climates.

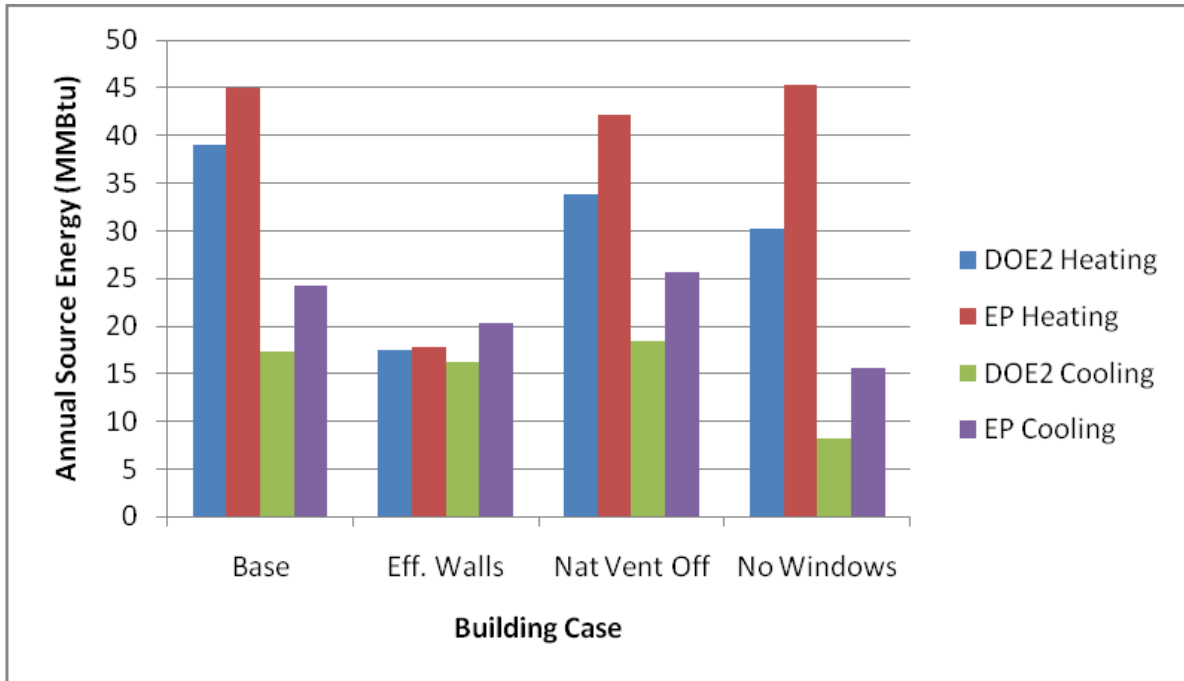


Figure 4: BEopt 0.8.0.4 Reference Building Comparison – Boulder

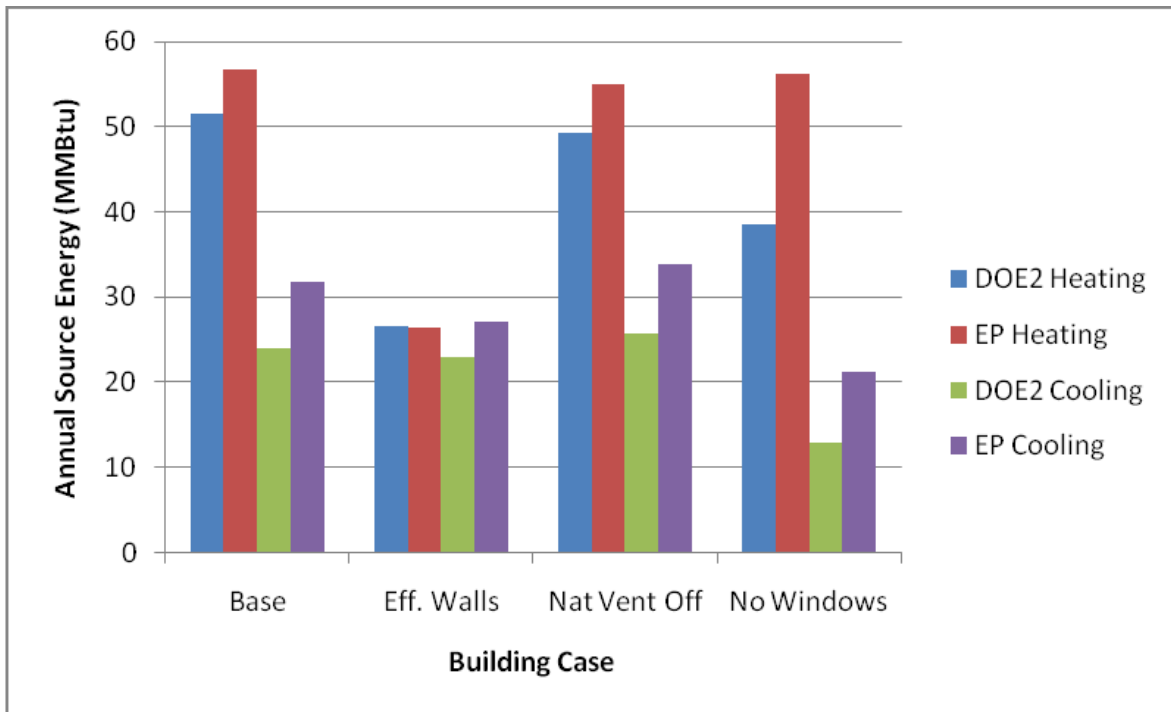


Figure 5: BEopt 0.8.0.4 Reference Building Comparison – Chicago

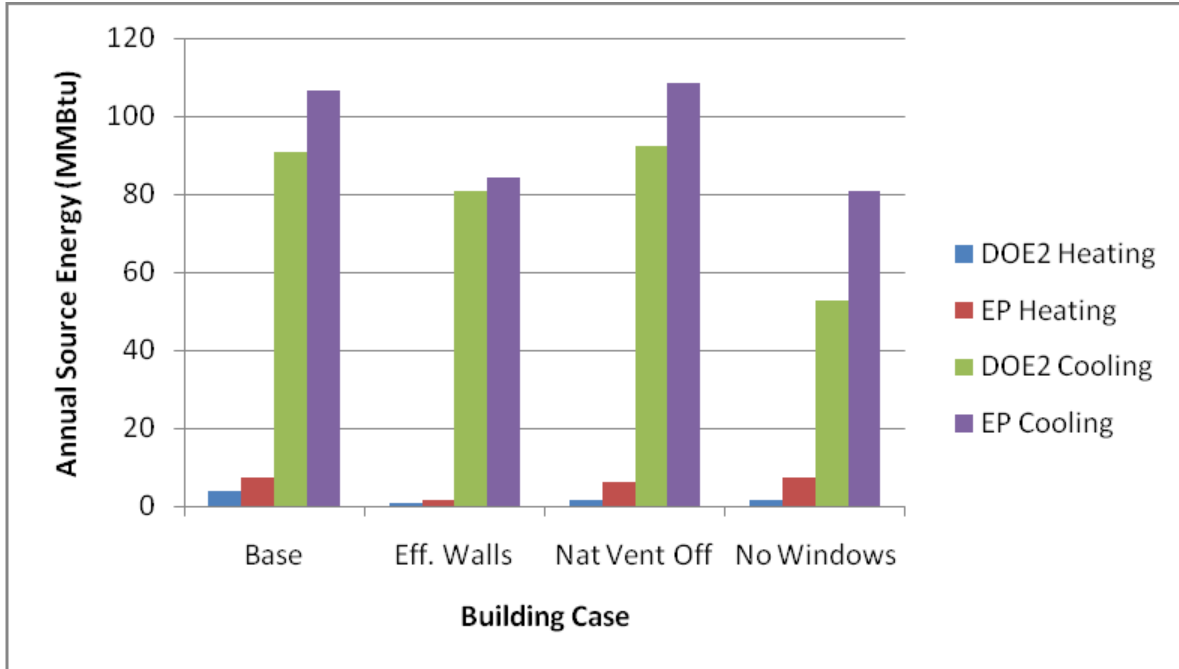


Figure 6: BEopt 0.8.0.4 Reference Building Comparison – Phoenix

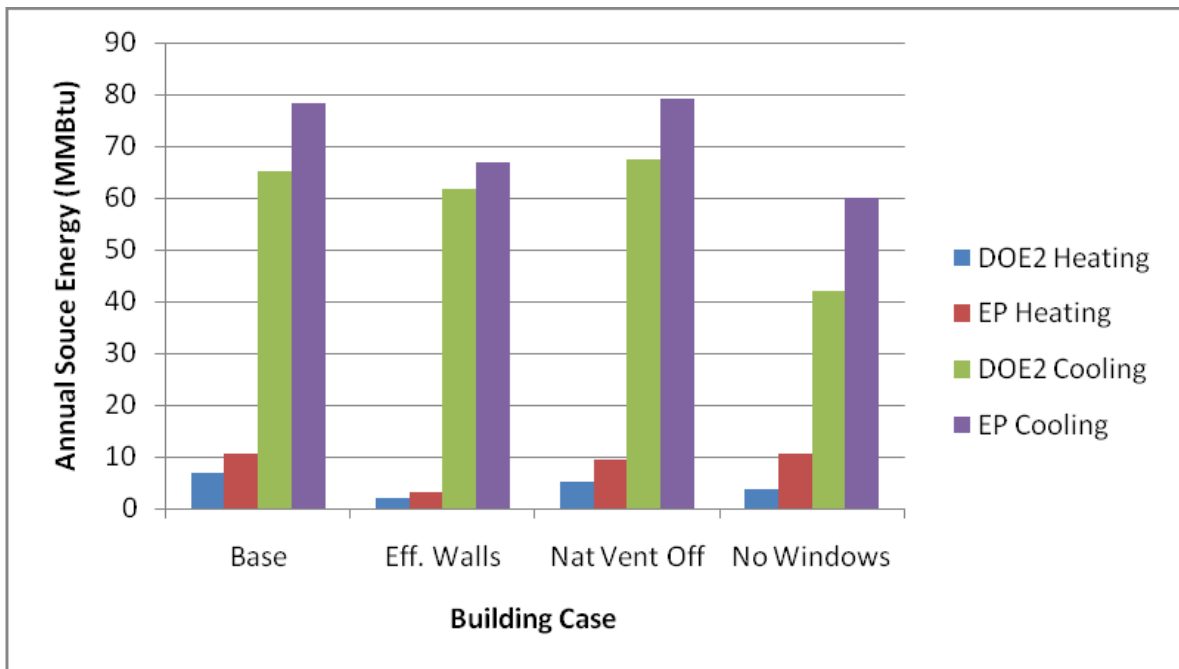


Figure 7: BEopt 0.8.0.4 Reference Building Comparison – Houston

The results show that the EnergyPlus v2.0 model consistently uses more heating and cooling energy than the DOE2.2 V44E4 model, generally 10-20% more for the primary HVAC use in a given climate, with errors up to 35% in the no windows case. While it would be better if there



was stronger agreement between the models, BESTEST results show that this is not any different than the current state of the art in building energy modeling programs. Figures 8 and 9 show BESTEST results for cases 600-650 in Denver.

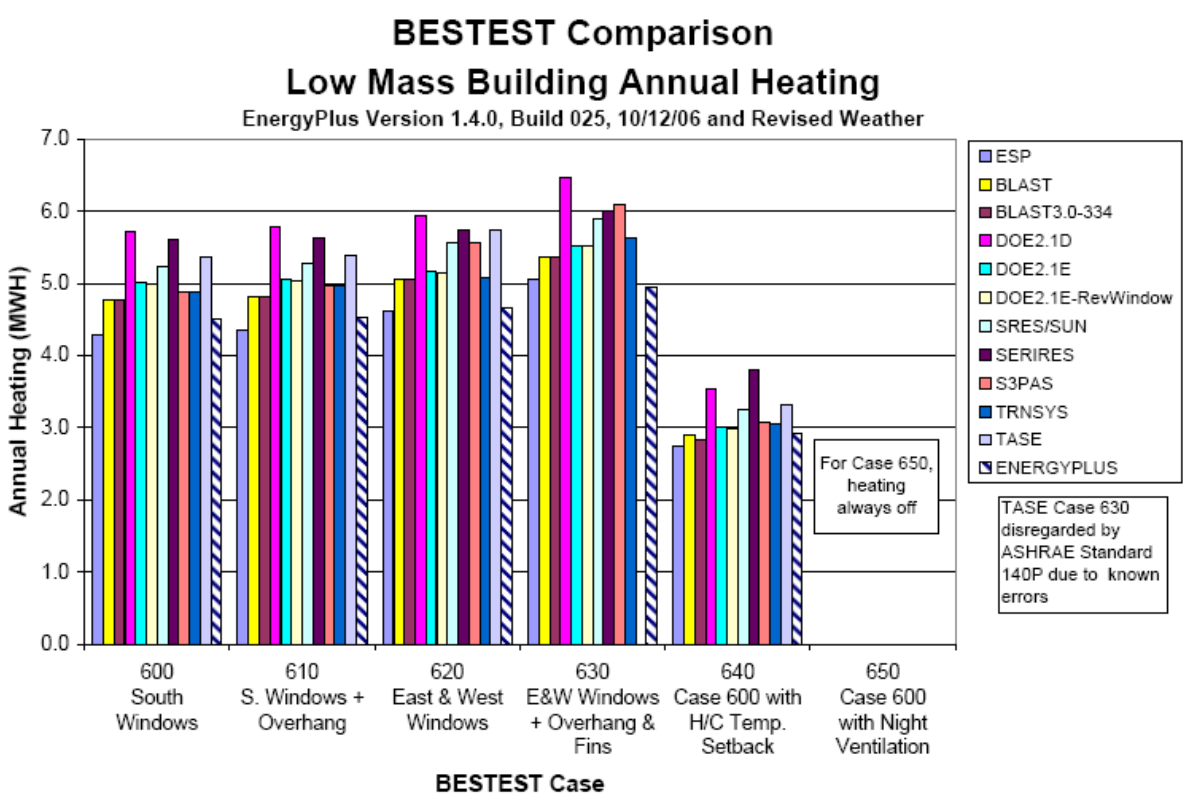
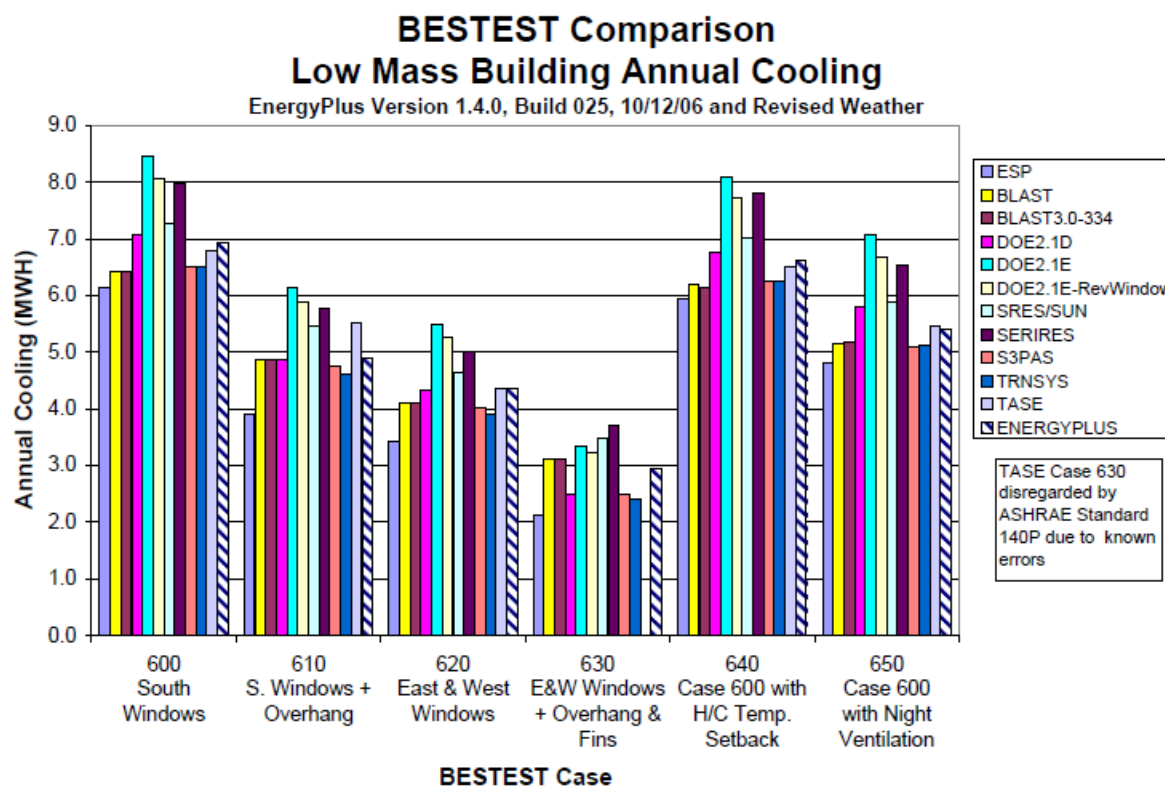


Figure 8: Low Mass Building BESTEST Annual Heating Results (Henninger, 2006)



**Figure 9: Low Mass Building BESTEST Heating Results (Henninger, 2006)**

The BESTEST results shown represent the test cases that are most appropriate for residential modeling, low mass buildings testing solar response, temperature setbacks and night ventilation. The total range of heating energy variability is 25% to 34% across the BESTEST cases, while the total range of cooling variability is 32% to 53%. In comparison, the BEopt 0.8.0.4 reference buildings showed heating differences of 2% to 33% and cooling differences of 21% to 48% in Boulder. The results are comparable. There are differences between the EnergyPlus v2.0 and DOE2.2 V44E4 results with BEopt 0.8.0.4, but they are not any larger than the range of variability observed in BESTEST. In the other climates, the differences between DOE2.2 V44E4 and EnergyPlus v2.0 are similar to Boulder for the primary HVAC usage. In Chicago, heating differences range from -1% to 32%. In Phoenix, cooling differences range from 4% to

35%. In Houston, cooling differences range from 8 to 30%. The differences are largest in the case with no windows.

### ***3.3 Methodology for pinpointing differences between EnergyPlus v2.0 and DOE2.2 V44E4***

The most general and rigorous test to compare the two simulation engines for use in optimization is to run the same optimization with each engine and compare the resulting choices (the parallel optimization test). If the simulation engines have identical results, then each point in the optimization should be the same building being modeled in EnergyPlus v2.0 and in DOE2.2 V44E4. However, it is quite possible for the overall accuracy of the simulations to be less than perfect, while the decision-making results are very good. DOE2.2 V44E4 and EnergyPlus v2.0 are both imperfect. The fundamental question that must be answered about the accuracy of simulation engines used for optimization is: Do the imperfections in the simulation results cause significant deviation from the true optimal path? This is essentially a small part of the larger question: Do the optimization results provided by the tool cause significant deviation from the true optimal path? Therefore, the comparison of optimizations conducted using DOE2.2 V44E4 and EnergyPlus v2.0 provides the best test of overall decision-making accuracy. This is the reasoning behind using the parallel optimization test in the context of evaluating simulation engines for use in optimization.

### ***3.4 Coarse level optimization path comparison***

The optimization tool is providing information about the optimal choice of building optimization parameters. In the case of BEopt 0.8.0.4, this is the set of building energy efficiency options that give the lowest energy-related cost at a given energy use level. Accuracy in the relative difference between two option choices is the most important component in getting accurate optimization results. This will affect the order in which energy efficient building

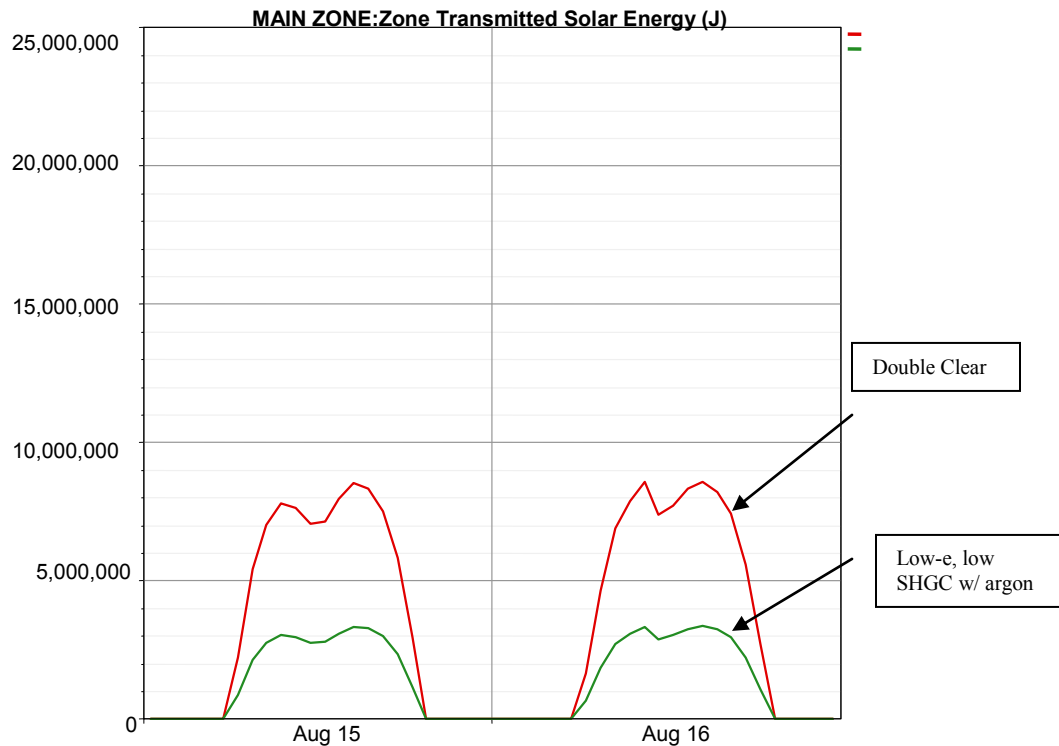
options appear in the optimal curve. The sample optimization results in Table 5 show the order in which options were added to the building using EnergyPlus v2.0 and using DOE2.2 V44E4.

**Table 5: Sample Optimization Order Comparison**

	EnergyPlus v2.0	DOE2.2 V44E4
	Window Area 2	Window Area 2
	Walls 4	Walls 4
10% Savings		
	Lighting 4	Lighting 4
	Cooking 2	Cooking 2
	Dryer 2	Dryer 2
	Lighting 8	Window Type 2
	Dishwasher 2	
20% Savings		
	Walls 10	Lighting 8
	Infil 2	Infil 2
		Window Type 3
30% Savings		
	Refrigerator 2	Dishwasher 2
	Infil 3	Walls 8
	Ceiling 2	Walls 10
	Window 5	Refrigerator 2
		Infil 3
		Ceiling 2
		Window 4
		Window 6
Final Savings	41%	38%
Sims	216	205
Time	4 hr 46 min	33 min

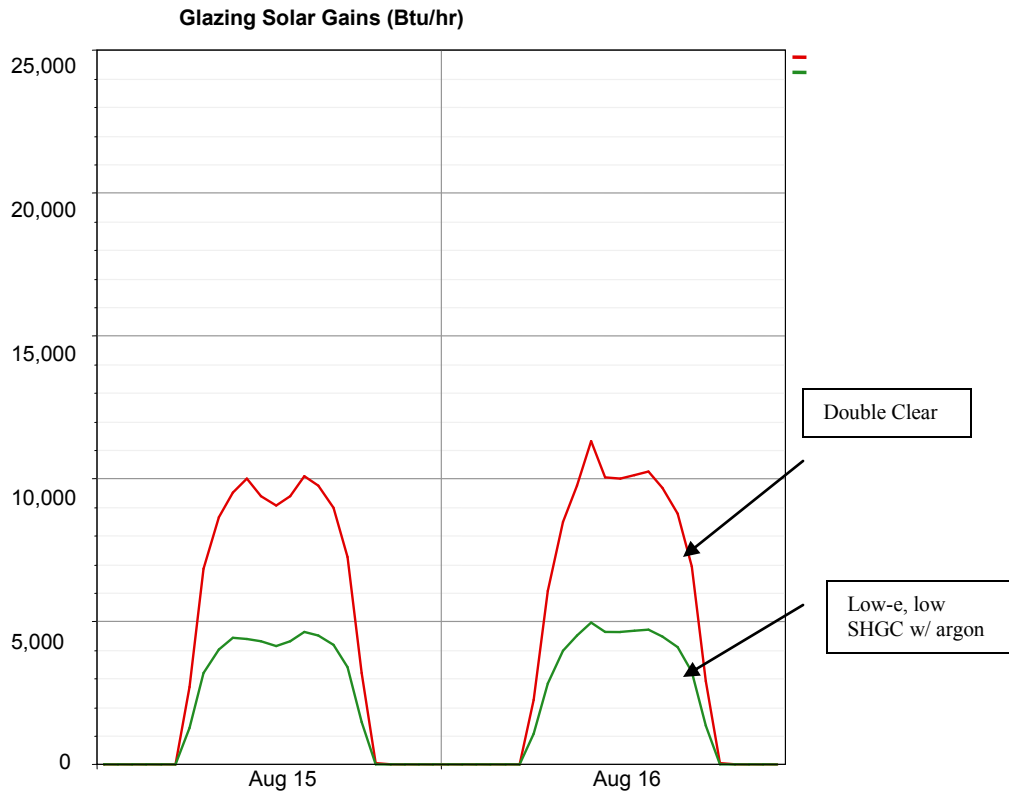
In this example, results are in generally good agreement, with the exception of the windows category. Whereas the DOE2.2 V44E4 optimization starts improving windows before 20% savings, the EnergyPlus v2.0 optimization does not choose a window option until the 40% mark. This simple comparison of the order of optimization choices allows for the detection of gross differences in the optimization results at a coarse level.

### 3.5 Using DView to Explore Coarse Differences



**Figure 10: Building Transmitted Solar Energy, Phoenix w/ EnergyPlus v2.0**

After a coarse disagreement is detected, the next step is to run a series of simple 2 case parametrics with what is nominally the same exact option change in DOE2.2 V44E4 and EnergyPlus v2.0, with the dimension of change being chosen to explore the different possible performance differences. These 4 different cases, EnergyPlus v2.0 A, EnergyPlus v2.0 B, DOE2.2 V44E4 A, and DOE2.2 V44E4 B can then be compared using DView to look at daily or hourly output. Figure 10 shows building glazing solar transmitted in J/hr for a building with double clear glazing and the same building with low SHGC, low-E glazing modeled in EnergyPlus v2.0. Figure 11 shows the building glazing solar gains for the same two buildings modeled with DOE2.2 V44E4.



**Figure 11: Glazing Solar Gains, Phoenix w/ DOE2.2 V44E4**

The ratio of gains can be checked against the ratio of nominal SHGC for the two glazings. A good example of this approach is to look at two different types of glazing only on the north facing side, then look at hourly output of heating fuel consumption for cold periods at night, in order to look at differences in the U-value modeling of the window assembly in EnergyPlus v2.0 and DOE2.2 V44E4. Then do the same for two types of glazing on the south side only, and look at hourly solar transmission and window heat gains to the space, to look at differences in window solar gains in EnergyPlus v2.0 and DOE2.2 V44E4. This set of 8 hourly runs (2 window types \* 2 orientations \* 2 simulation engines) should be enough to tell an energy analyst where to start looking for glazing modeling differences between the two simulations. This process was used for examining glazing option differences in EnergyPlus v2.0 and DOE2.2 V44E4.

There are three possible outcomes from looking at a given difference. The first and most common outcome is that there is a problem in either the DOE2.2 V44E4.2 or EnergyPlus v2.0 input files, that the two are not actually modeling the same thing. The second possible outcome is that there is a bug in either EnergyPlus v2.0 or DOE2.2 V44E4.2. A few simulation engine bugs were discovered during the course of this work. The third possible outcome is that there is a fundamental difference in the modeling approach taken by EnergyPlus v2.0 and the approach taken by DOE2.2 V44E4 that is causing the difference.

Almost all input file problems should be picked up by the optimization comparison test, but it is possible that a few may have slipped through. Analysis of hourly output differences can reveal bugs in the simulation engine. For example, the hourly window heat loss for one high performance window relative to another window was dramatically different from what one would predict. The remaining differences are likely caused by fundamental differences in modeling approach between EnergyPlus v2.0 and DOE2.2 V44E4. These were searched out using a detailed comparison of optimal paths. This search method is described in section 3.9.

Employing this systematic results analysis technique allowed multidimensional differences to be dissected, eliminating one difference at a time until any remaining difference in results could be explained by a fundamental difference in approach. In some cases, one of the two simulation approaches is clearly superior, reflecting a deficiency in one simulation engine or the other. In other cases, there may be a shortcut employed in one simulation engine that results in significant improvements in runtime at the expense of some modeling accuracy. The parallel optimization testing approach reveals if the loss in modeling accuracy will result in a significant difference in the results of BEopt 0.8.0.4-driven decision making.

### ***3.6 Interpreting Discrete Sequential Search Optimization Results***

BEopt 0.8.0.4 employs a sequential search optimization algorithm. In sequential search, the optimization proceeds “one step at a time,” with the engine trying changes in only one option at a time, finding the best of those points, then repeating with one option at a time from the new optimal building (Christensen, 2006). In comparison to other optimization methods, this produces a large number of near-optimal points, because every point that is tried is a single option different from the optimum up until that point. In addition, the sequential search produces a large number of near-optimal points all along the lower boundary of the optimization. Optimization of discrete parameters will result in spacing of the simulated points appearing in the output. When interactive effects are added on top of this spacing, the overall optimization results can be rather “lumpy.” A particular option may come into play because it results in reduction of peak loads just enough to reduce the equipment sizing below the next discrete sizing option. A few iterations later, this option may drop out in favor of a two-option combination that achieved the same load reduction and had lower energy cost. As a result, one cannot place too much import on the points that make up the actual lower boundary. There are typically dozens of near-optimal points that are close to the lower boundary, say within 1% of the energy cost for a given level of energy savings. If an optimization chooses one point in the band of near-optimal points over another point, the overall impact on the decision outcome from the optimization result is minor. The decision is essentially between a large number of equally good options. Whenever options appear that have very similar rates of return (slopes in the parlance of sequential search), they are essentially interchangeable. Therefore, comparison of the points in two optimal paths is not sufficient to determine if there is a significant difference in the results of two optimizations. If all points appearing in the optimal path calculated with one optimization



tool are near-optimal points in another optimization tool, the results are approximately equivalent.

### ***3.7 Optimization Building Modeling Assumptions***

The buildings modeled for the optimization use building operation schedules from the 2007 Building America Benchmark (BABM), except for two variations: The cooling and heating seasons are slightly longer than the BA Benchmark and natural ventilation is available above 77 degrees all hours of the year to prevent overheating in high performance buildings. This is necessary because high performance buildings have much smaller envelope conduction loads than typical buildings. This makes internal gains and solar gains relatively large, which can cause overheating during mild sunny weather. Real occupants are likely to open windows to prevent excessive overheating, regardless of season, rather than allowing their homes to be overheated and store large amounts of thermal energy in the mass of the home. Heating and cooling setpoints are 76 and 71 degrees F, respectively. All of the modeled buildings share certain assumptions, shown in Tables 1 and 2.

**Table 6: Economic Assumptions**

Electricity	\$0.08/kWh, \$8 fixed charge, 3.16 source to site ratio
Natural Gas	\$0.80/therm, \$8 fixed charge, 1.02 source to site ratio
Mortgage	30 year 7% nominal rate, 28% Income Tax Rate
Project Analysis Period	30 years
Inflation Rate	3%
Discount Rate	5%
PV Cost	\$7.50 / installed W
Efficiency Cost Multiplier	1

**Table 7: Optimization Building Characteristic Assumptions**

Area	1800 square feet
Aspect Ratio	1
Number of Stories	2
Bedrooms	3
Bathrooms	2
Garage	Yes, on left, 10 foot projection

Orientation	North (side of garage)
Neighbors	None
Miscellaneous Electric Loads	2007 BABM
Window Area	18% of FFA
Roof	Gable, 6:12 Pitch
Eaves	None
Foundation	Ventilated Crawlspace, R19 ceiling
Duct Leakage	Ducts Inside
Plug-in Lighting	0% CFL
Cooking Range	Electric
Dryer	Electric
Thermal Mass	None extra (1/2 inch ceiling drywall, 40 lb/ft furniture)
Wall Height	8 feet
Window Area	18% of FFA
PV Tilt	Back Roof (6:12)
PV Azimuth	Back Roof (south)

The optimization included the following list of options (Table 3) to choose from, starting with the lowest number option in each category as the reference building. The same available building options and reference building were used for each of the five climates, Boulder, Phoenix, Chicago, Atlanta, and San Francisco.

**Table 8: Optimization Available Options**

Category	Option Number	Option Description
Walls	1	R11 Batts 2 x 4
	4	R19 Batts 2 x 6
	5	R21 Batts 2 x 6
	8	R19 Batts, 2 x 6 + 1 in foam
	9	R21 Batts, 2 x 6 + 1 in foam
	10	R19 Batts, 2 x 6 + 2 in foam
	12	Double Stud, R39
Ceiling	13	Double Stud, R45
	14	Double Stud, R51
	1	R30 Ceiling
	2	R40 Ceiling
Infiltration	3	R50 Ceiling
	4	R60 Ceiling
	1	Normal, FLA = 0.0005
	2	Tight, FLA = 0.0003

Category	Option Number	Option Description
	3	Tighter, FLA = 0.00015
	4	Tightest, FLA = 0.00008
Crawlspace	4	Ventilated, R19 Ceiling
	5	Ventilated, R30 Ceiling
Window Areas	3	18% FFA, Equal distribution
	4	18% FFA, 40% Back (South), 20% Front, 20% Right, 20% Left
Window Type	1	Double Clear, U = 0.447, SHGC = 0.547
	2	Low-e, argon, U = 0.285, SHGC = 0.266
	3	Low-e, argon, U = 0.285, SHGC = 0.295
	4	Low-e, argon, U = 0.298, SHGC = 0.418
	5	Low-e, argon, U = 0.325, SHGC = 0.511
	6	3 pane, 1 HM, U = 0.257, SHGC = 0.346
	7	4 pane, 2 HM, U = 0.196, SHGC = 0.324
Refrigerator	1	Standard
	2	EnergyStar
Dishwasher	1	Standard
	2	EnergyStar
Clothes Washer	1	Standard, Vertical
	2	EnergyStar, Horizontal
Hardwired Lighting	1	0% CFL
	4	30% CFL
	7	60% CFL
	10	90% CFL
Air Conditioner	2	SEER 10
	3	SEER 13
	4	SEER 14
	5	SEER 15
Furnace	2	80% AFUE
	3	92.5% AFUE
ERV	1	No ERV
	2	70% Effective ERV
Water Heater	1	Electric, Standard, 86% Energy Factor
	2	Electric, Premium,
PV	1-18	0-8.5 kW, ZNE

### 3.8 Optimization Results Comparison

The points contained in the optimal paths selected using EnergyPlus v2.0 and DOE2.2

V44E4/TRNSYS were compared in five climates, Boulder, Phoenix, Chicago, Atlanta, and San

Francisco. The objective of this exercise is to determine if there are any notable biases between the two sets of results, favoring the selection of one option or one group of options over another at an earlier point in the optimization. The results in any one optimization may be adversely affected by differences in reference building energy consumption and the lumpiness of discrete optimization, but consistent biases across climates indicates a difference that should be further investigated. In the following tables the differences are flagged by highlighting the cells. See for example, Table 7. If the EnergyPlus v2.0 optimal design at a particular savings level includes a more efficient option than the DOE2.2 V44E4 optimal design at that level, the cell is flagged in yellow. If the DOE2.2 V44E4 optimal design has a more efficient option, the cell is flagged in blue. If the two optimal designs have different options that do not obviously result in different source energy savings, like window type, then the cell is flagged in green.

### **3.8.1 Boulder Optimal Buildings**

**Table 9: Boulder Optimal Building Designs (EnergyPlus v2.0/DOE2.2 V44E4)**

						PV Takeoff	Min Cost
	Base	10%	20%	30%	40%	44.2% / 42.2%	30.3% / 25.8%
Walls	1	4/4	5/5	9/5	14/10	14/14	9/5
Ceiling	1				1/2	3/3	
Infiltration	1			1/2	3/3	3/3	
Crawl Space	4					4/5	
Window Areas	3	4/4	4/4	4/4	4/4	4/4	4/4
Window Type	1	1/2	3/3	3/3	3/4	3/4	3/3
Refrigerator	1				2/2	2/2	
Dishwasher	1			2/2	2/2	2/2	2/1
Clothes Washer	1			2/2	2/2	2/2	2/2
Hardwired Lighting	1	4/1	10/7	10/10	10/10	10/10	10/10
Air Conditioner	2				2/5	5/5	
Furnace	2		3/3	3/3	3/3	3/3	3/3
ERV	1						
Water Heater	1			2/2	2/2	2/2	2/2
PV Size	1						

There appears to be an EnergyPlus v2.0 bias towards wall improvements in Boulder, compared with DOE2.2 V44E4 (Table 4). DOE2.2 V44E4 chooses different windows than EnergyPlus v2.0 and chooses infiltration, ceiling, and air conditioner options earlier, while EnergyPlus v2.0 chooses lighting and dishwasher improvements sooner. The PV takeoff buildings are the same, except for the window type choice and DOE2.2 V44E4 making a further improvement to the crawl space.

### 3.8.2 Phoenix Optimal Buildings

**Table 10: Phoenix Optimal Building Designs (EnergyPlus v2.0 / DOE2.2 V44E4)**

						PV Takeoff	Min Cost
	Base	10%	20%	30%	40%	44.7% / 40.8%	37.7% / 34.8%
Walls	1	4/4	5/4	5/5	14/9	14/10	9/5
Ceiling	1				2/2	2/2	
Infiltration	1				1/2	2/2	
Crawl Space	4						
Window Areas	3	4/4	4/4	4/4	4/4	4/4	4/4
Window Type	1		3/2	3/2	3/2	3/2	3/2
Refrigerator	1				2/2	2/2	
Dishwasher	1				1/2	2/2	
Clothes Washer	1				2/2	2/2	2/2
Hardwired Lighting	1	4/4	7/7	10/10	10/10	10/10	10/10
Air Conditioner	2			5/5	5/5	5/5	5/5
Furnace	2						
ERV	1						
Water Heater	1			2/1	2/2	2/2	2/2
PV Size	1						

In Phoenix, EnergyPlus v2.0 shows a bias towards better wall options (Table 5). EnergyPlus v2.0 makes a water heater improvement earlier, while DOE2.2 V44E4 makes improvements to the dishwasher and infiltration earlier. The two engines choose different high efficiency window options, with DOE2.2 V44E4 choosing a lower solar heat gain coefficient than EnergyPlus v2.0. The PV takeoff buildings are the same, except for the different window options and EnergyPlus v2.0 having a further improvement in the walls category.

### 3.8.3 Atlanta Optimal Buildings

**Table 11: Atlanta Optimal Building Designs (EnergyPlus v2.0 / DOE2.2 V44E4)**

						PV Takeoff	Min Cost
	Base	10%	20%	30%	40%	42.9% / 39.1%	32.1% / 25.7%
Walls	1	4/4	5/5	5/5	14/10	14/10	9/5
Ceiling	1				1/2	3/2	
Infiltration	1				2/3	3/3	
Crawl Space	4						
Window Areas	3	4/4	4/4	4/4	4/4	4/4	4/4
Window Type	1		1/2	3/2	3/2	3/2	3/2
Refrigerator	1			1/2	2/2	2/2	
Dishwasher	1			1/2	2/2	2/2	
Clothes Washer	1			2/2	2/2	2/2	2/2
Hardwired Lighting	1	4/7	10/10	10/10	10/10	10/10	10/10
Air Conditioner	2		3/2	5/5	5/5	5/5	5/2
Furnace	2		3/3	3/3	3/3	3/3	3/3
ERV	1						
Water Heater	1		2/1	2/2	2/2	2/2	2/2
PV Size	1				1/2		

In Atlanta, DOE2.2 V44E4 and EnergyPlus v2.0 choose different high performance windows (Table 6). EnergyPlus v2.0 shows a bias in favor of better wall options. DOE2.2 V44E4 makes improvements in the ceiling, infiltration, window type, refrigerator, and dishwasher before EnergyPlus v2.0, while EnergyPlus v2.0 improves the air conditioner and water heater earlier than DOE2.2 V44E4. The PV takeoff buildings differ in window choice and EnergyPlus v2.0 makes further improvements to the walls and ceiling relative to DOE2.2 V44E4.

### 3.8.4 Chicago Optimal Buildings

**Table 12: Chicago Optimal Building Designs (EnergyPlus v2.0 / DOE2.2 V44E4)**

	Base	10%	20%	30%	40%	45.5% / 44.1%	38.9% / 32.1%
Walls	1	4/4	5/5	14/5	14/10	14/14	14/5
Ceiling	1			1/2	1/2	3/4	1/2
Infiltration	1			2/2	3/3	3/3	2/2
Crawl Space	4					4/5	
Window Areas	3	4/4	4/4	4/4	4/4	4/4	4/4
Window Type	1		3/3	3/2	3/2	3/3	3/2
Refrigerator	1				2/2	2/2	
Dishwasher	1				2/2	2/2	
Clothes Washer	1			2/2	2/2	2/2	2/2
Hardwired Lighting	1	4/4	10/7	10/10	10/10	10/10	10/10
Air Conditioner	2					5/5	
Furnace	2		3/3	3/3	3/3	3/3	3/3
ERV	1						
Water Heater	1			2/2	2/2	2/2	2/2
PV Size	1						

In Chicago, there appear to be two major biases: EnergyPlus v2.0 has a bias towards wall improvements, while DOE2.2 V44E4 has a bias towards ceiling improvements (Table 12). In addition, DOE2.2 V44E4 chose a crawlspace improvement before PV takeoff, while EnergyPlus v2.0 did not. DOE2.2 V44E4 made some rather counterintuitive window choices, opting for the low-e low SHGC options for some of the buildings, even in Chicago, which is a heating-dominated climate. This is most likely related to HVAC sizing, since reduction of cooling loads drives down the overall system airflow, reducing both the cooling and heating capacity. EnergyPlus v2.0 made one improvement to the lighting category before DOE2.2 V44E4 did. This is likely the result of a small difference in the slope of the other option around 20%. EnergyPlus v2.0 had this option being a little bit worse than the 90% CFL option, while DOE2.2



V44E4 had this option being a little bit better, resulting in the 90% CFL option being added after reaching 20% savings.

### 3.8.5 San Francisco Optimal Buildings

Table 13: San Francisco Optimal Building Designs (EnergyPlus v2.0/DOE2.2 V44E4)

					PV Takeoff	Min Cost
	Base	10%	20%	30%	39.1% / 33.7%	31.6% / 22.8%
Walls	1	4/5	5/5	9/5	14/9	9/5
Ceiling	1				1/2	
Infiltration	1			1/2	2/2	
Crawl Space	4					
Window Areas	3	4/4	4/4	4/4	4/4	4/4
Window Type	1		3/1	3/4	3/4	3/1
Refrigerator	1			1/2	2/2	
Dishwasher	1			1/2	2/2	
Clothes Washer	1		1/2	2/2	2/2	2/2
Hardwired Lighting	1	4/7	10/10	10/10	10/10	10/10
Air Conditioner	2					
Furnace	2		2/3	3/3	3/3	3/3
ERV	1					
Water Heater	1		2/2	2/2	2/2	2/2
PV Size	1					

EnergyPlus v2.0 shows a bias towards wall options relative to DOE2.2 V44E4 in San Francisco.

EnergyPlus v2.0 and DOE2.2 V44E4 choose different window types in multiple cases. DOE2.2 V44E4 compensates by choosing energy efficient options sooner than EnergyPlus v2.0 in multiple categories, including ceilings, infiltration, refrigerator, dishwasher, clothes washer, lighting, and furnace.

### 3.8.6 Summary of Optimal Building Differences

Walls biases showed up in the optimization results for every climate. EnergyPlus v2.0 consistently chose more efficient wall options, especially at the higher energy savings levels. EnergyPlus v2.0 and DOE2.2 V44E4 repeatedly chose different window options. EnergyPlus v2.0 always chose either the base double clear or the standard SHGC low-e glazing. DOE2.2 V44E4 chose different window types in different climates. In some climates DOE2.2 V44E4

chose different flavors of similar windows at different energy saving levels. Some amount of this difference may be due to slightly different window constructions in the two models. EnergyPlus v2.0 never chose a better crawlspace option – DOE2.2 V44E4 chose an improved crawlspace in Boulder and Chicago. DOE2.2 V44E4 chose ceiling options earlier than EnergyPlus v2.0 in some climates, but this was not a clear bias. The two simulation engines chose very similar PV takeoff points in each climate. EnergyPlus v2.0 consistently chose more energy efficiency improvements than DOE2.2 V44E4 at the minimum cost point.

### ***3.9 Pinpointing Remaining Differences with Detailed Search***

#### **3.9.1 Screening for Outliers Using Optimal Paths**

To determine whether or not the optimal path selected by one optimization is significantly different than the path selected by another optimization, one must determine whether the optimal path selected by one optimization falls outside the band of near-optimal points in the other optimization. In the case of many simulation engine differences, pinpointing differences with direct numerical comparison of reference building results may not be fruitful, because of the myriad ways differences in simulation engines manifest themselves in the results. The goal of this work is to pinpoint the particular modeling areas that cause errors in optimization results. Differences that do not lead to errors in optimization results are not important to the overall utility of the optimization tool. Simple one dimensional parametric searching does not capture interactive effects between different types of options. Parametric searching of all of the possible interactions necessary to pinpoint the detailed differences between the two models would require exhaustive analysis of data from thousands of simulations to sort out the impacts of numerous small differences. Instead, it makes more sense to focus the

search for differences in the area where it matters most, near the optimal path. Each iteration in the sequential search includes each of the available options added to the last optimal point, so each iteration is essentially a one dimensional parametric. This properly contextualizes what are a series of one-dimensional parametric searches with each point along the optimal path. The results of the sequential search can be mined for clues about the differences in energy modeling. The goal is to screen for outliers among the optimal points, to find the points where EnergyPlus v2.0 and DOE2.2 V44E4 disagree about whether or not the building is an optimal or near-optimal point. For the purposes of this study, outliers are defined as optimal points in one simulation engine's lower total energy-related costs boundary that are more than 1% above the other simulation engine's lower total energy-related costs boundary. This is not a large difference, on the order of 10s of dollars per year, which is relatively strict, given the large uncertainties around occupant behavior.

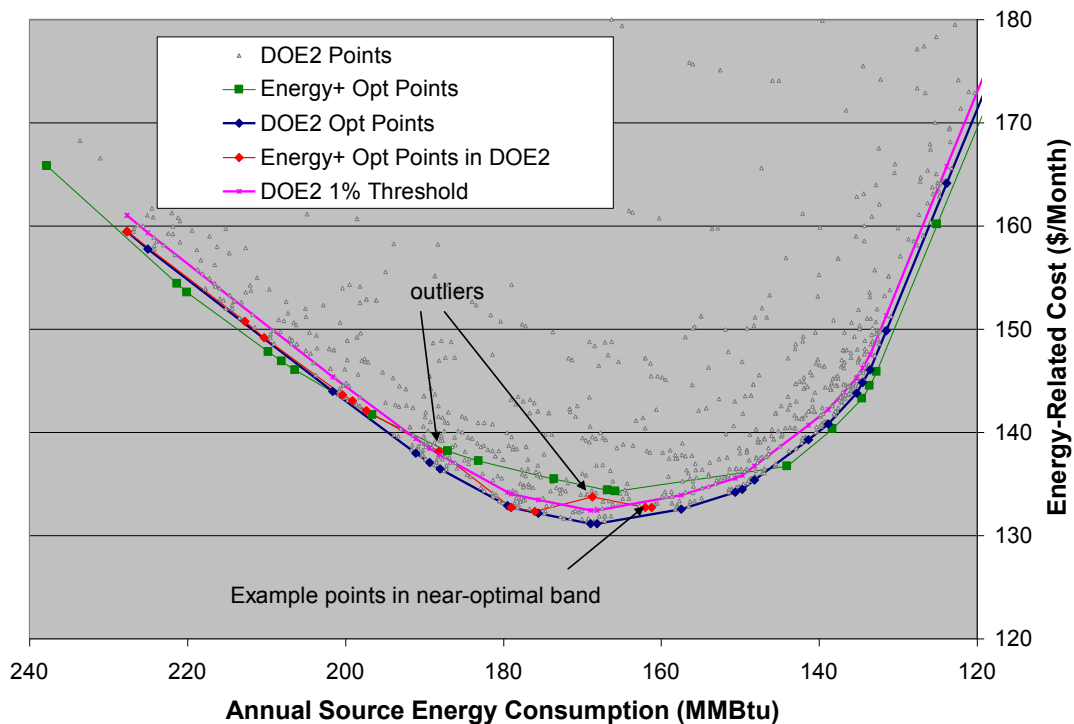
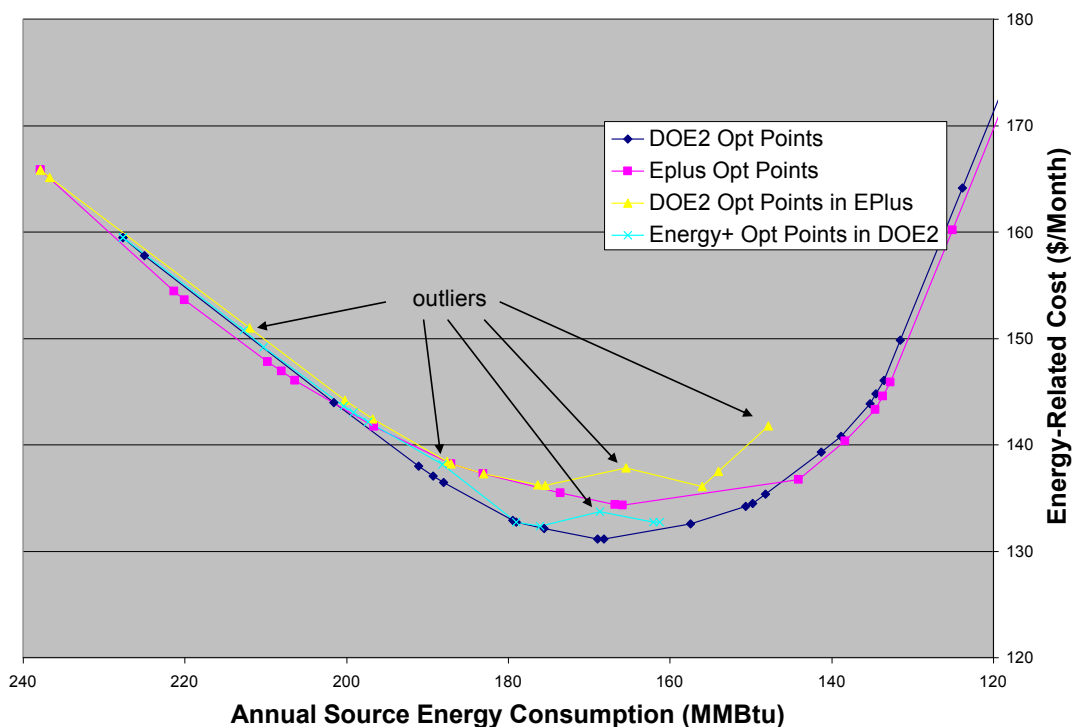


Figure 12: Sample Optimal Path Comparison

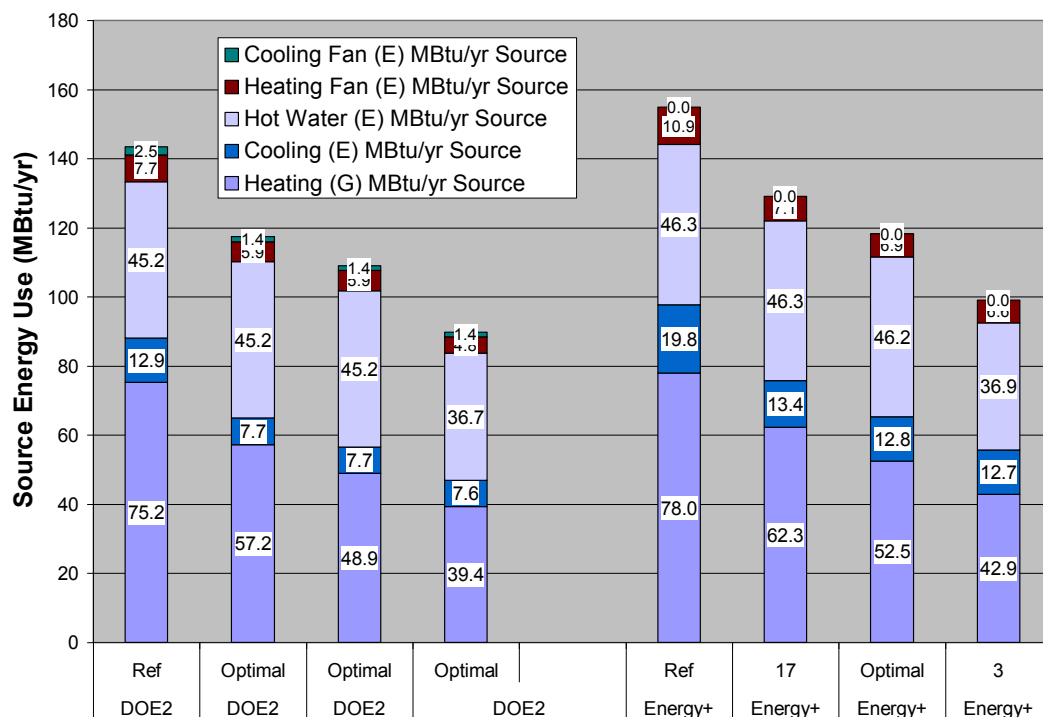
In Figure 12, the simulation points from the optimization in Boulder are shown as gray dots. The optimal points along the lower boundary selected by DOE2.2 V44E4 are highlighted in blue. When the optimal points from EnergyPlus v2.0 are overlaid on top (highlighted in green in the figure), it is difficult to say anything definitive about where the differences in the results occur – the curves are different everywhere, with the largest difference at the reference building. Sequential search fortuitously creates additional similar building points in sufficient numbers to find many of the points on the path from one optimization within the cloud of points in another optimization. In the figure above, buildings from the EnergyPlus v2.0 optimal path that were also simulated in the DOE2.2 V44E4 optimization are highlighted in red. The location of these points can then be compared to the optimal path to determine if they reside outside the 1% band of near neighbors, which indicates a difference of some significance. Red points in the figure above that lie above the 1% boundary drawn in pink are outliers by this definition and should be further analyzed to look for modeling differences. In the following results, only the optimal paths are shown.

### 3.9.2 Boulder Optimal Path Comparison



**Figure 13: Boulder Optimal Path Comparison**

Interpolation between optimal points was used to calculate the difference between the two optimal paths as modeled by DOE2.2 V44E4/TRNSYS and EnergyPlus v2.0, i.e. the difference was calculated as the distance above the lower boundary, not the distance above the nearest actual point on the lower boundary. In Boulder, there were three outliers identified by looking at the DOE2.2 V44E4/TRNSYS path as modeled by EnergyPlus v2.0 and two outliers identified by looking at the EnergyPlus v2.0 path as modeled by DOE2.2 V44E4/TRNSYS (Figure 13). The paths included one consensus optimal point in addition to the reference. Consensus optimal points are optimal points in both optimizations, meaning that EnergyPlus v2.0 and DOE2.2 V44E4 agree that the point is an optimal point. The end use breakdown of the outlying points as modeled by DOE2.2 V44E4/TRNSYS and EnergyPlus v2.0 was compared with the end use breakdown of nearby consensus optimal points to determine which end uses are most responsible for the deviation between DOE2.2 V44E4/TRNSYS and EnergyPlus v2.0.

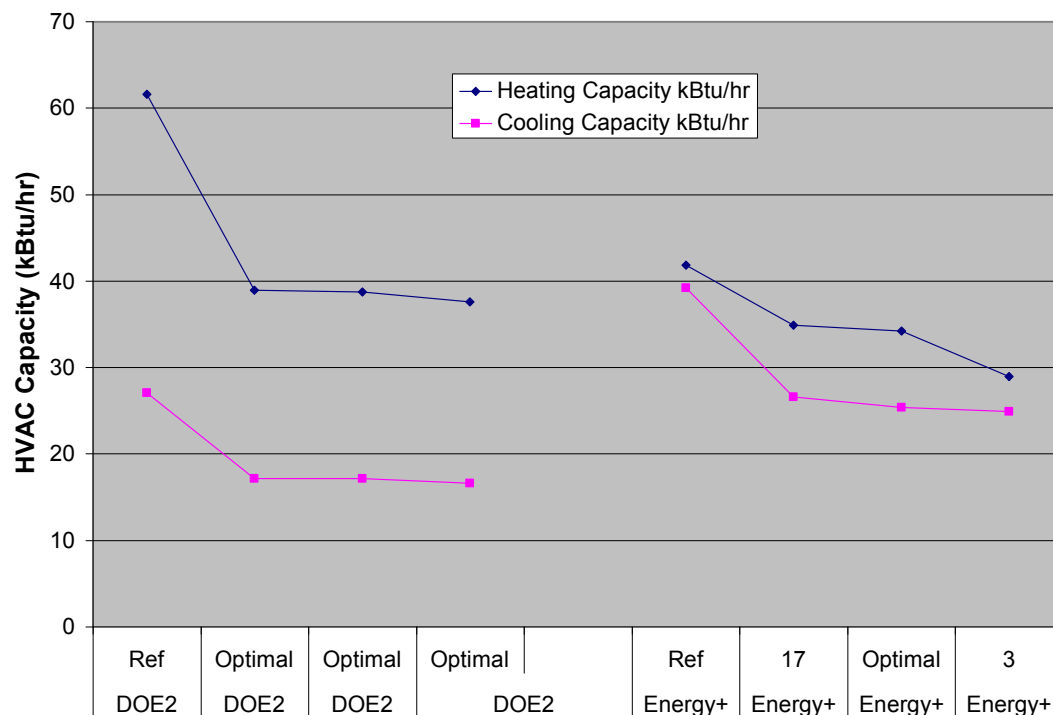


**Figure 14: DOE2.2 V44E4 Boulder Optimal Path Outliers End Use Breakdown**

Figure 14 shows the source energy end use breakdown for 4 buildings modeled in DOE2.2

V44E4 and EnergyPlus v2.0 that were on the optimal path selected by DOE2.2

V44E4/TRNSYS. End uses that are the same in EnergyPlus v2.0 and DOE2.2 V44E4 are omitted. The first and third buildings were also on the optimal path selected by EnergyPlus v2.0, with the first point being the reference building. The second and fourth buildings are outliers – when they were modeled in EnergyPlus v2.0, the points had monthly energy related costs that were more than 1% above the optimal path selected by EnergyPlus v2.0.



**Figure 15: HVAC Capacity for DOE2.2 V44E4 Optimal Path in Boulder**

Figure 15 shows that HVAC autosizing varies greatly between DOE2.2 V44E4 and EnergyPlus v2.0. The autosizing algorithms are fundamentally different in the two simulation engines.

EnergyPlus v2.0 decouples the ultimate heating and cooling equipment sizing, which can result in lower heating supply temperatures and longer runtime, leading to higher fan energy use. This is discussed further in section 4.1.5.

By comparing the changes in the input characteristics, the HVAC capacity, and the annual energy end uses as calculated by DOE2.2 V44E4 and EnergyPlus v2.0 for the buildings above, one can analyze why buildings 2 and 4 might be outliers.

**Table 14: Changes from Boulder Building 1 to Building 2, Modeled in DOE2.2 V44E4 and EnergyPlus v2.0**

	DOE2.2 V44E4 Optimal Path	DOE2.2 V44E4 Path in EnergyPlus v2.0
Building Characteristics	Walls R11 → R19, Glazing shift to South, Glazing Double Clear → low-e, low SHGC	
Cooling Capacity (tons)	2.3 → 1.4	3.3 → 2.2
Heating Capacity (kBtu/hr)	61 → 39	42 → 35
Heating Source Energy (MBtu/yr)	-18.0	-15.7
Cooling Source Energy (MBtu/yr)	-5.2	-6.4
Fan Source Energy (MBtu/yr)	-2.8	-3.8
Water Heater Source Energy (MBtu/yr)	No Change	No Change

Table 14 summarizes the differences between building 1 and building 2 as modeled in DOE2.2 V44E4 and EnergyPlus v2.0. DOE2.2 V44E4 shows a larger absolute reduction in heating energy (from smaller absolute heating energy in the reference building). DOE2.2 V44E4 also realizes a larger discrete reduction in the heating capacity. The larger discrete reduction in heating capacity is probably the main difference to highlight here. Further investigation of the problem revealed that the fundamental differences in the modeling of the windows and solar gains in DOE2.2 V44E4 and EnergyPlus v2.0 are likely responsible for the apparent difference in heating and cooling energy. This will be discussed further in sections 4.1.3 and 4.1.4.

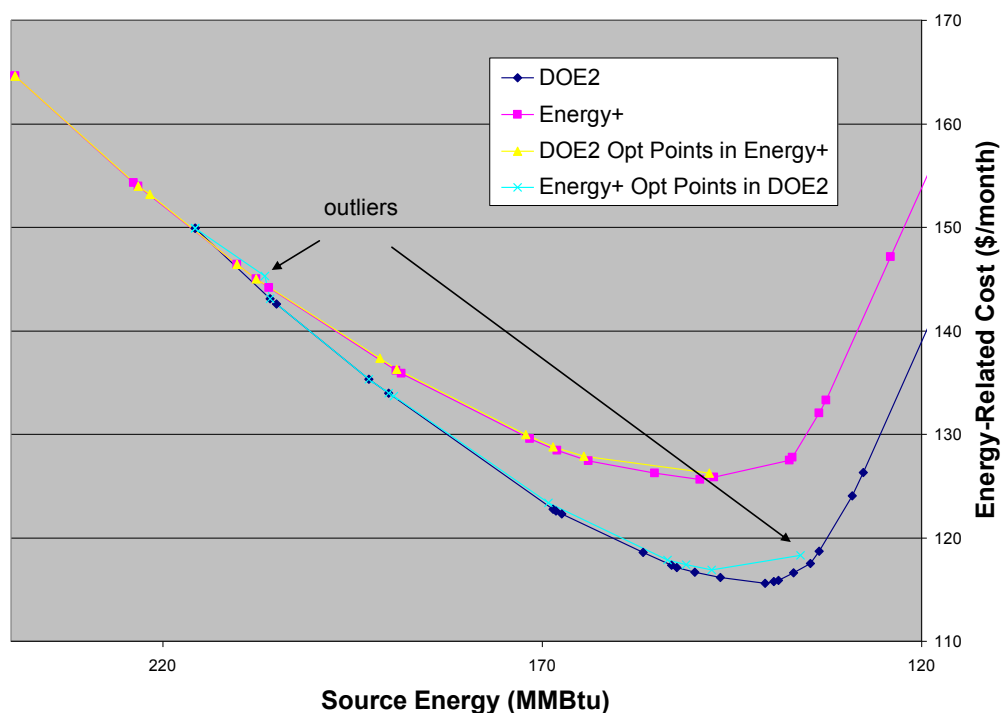
**Table 15: Changes from Boulder Building 3 to Building 4, Modeled in DOE2.2 V44E4 and EnergyPlus v2.0**

	DOE2.2 V44E4 Optimal Path	DOE2.2 V44E4 Path in EnergyPlus v2.0
Building Characteristics	Infiltration Standard → Tight, Dishwasher Standard → EnergyStar Clothes Washer Standard → EnergyStar Water Heater Standard → High Efficiency	
Cooling Capacity (tons)	No change	No Change
Heating Capacity (kBtu/hr)	No change	No Change
Heating Source Energy (MBtu/yr)	-9.5	-9.6
Cooling Source Energy (MBtu/yr)	-0.1	-0.1
Fan Source Energy (MBtu/yr)	-1.1	-0.3
Water Heater Source Energy (MBtu/yr)	-8.5	-9.3



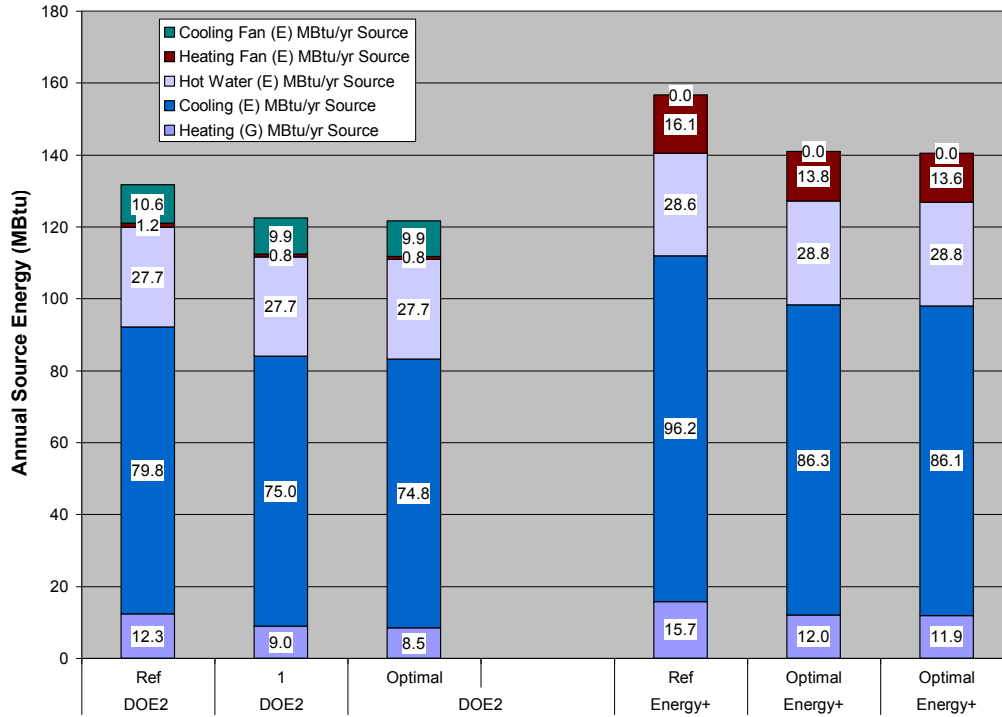
Building 4 shows a larger reduction in hot water energy in EnergyPlus v2.0 than in DOE2.2 V44E4 and a larger reduction in fan energy in DOE2.2 V44E4 than in EnergyPlus v2.0 (Table 15). One possible explanation for the hot water energy use difference is a numerical solver bug in EnergyPlus v2.0 which has trouble with plant loops when run on AMD processors. This bug has been confirmed with the EnergyPlus v2.0 development team and is discussed further in section 4.1.8. The fan energy differences are primarily caused by autosizing differences between DOE2.2 V44E4 and EnergyPlus v2.0. See section 4.1.5.

### 3.9.3 Phoenix Optimal Path Comparison



**Figure 16: Phoenix Optimal Path Comparison**

In Phoenix, there were no outliers identified by modeling the DOE2.2 V44E4 path in EnergyPlus v2.0; there was one significant outlier identified by modeling the EnergyPlus v2.0 path in DOE2.2 V44E4 (Figure 7).



**Figure 17: Phoenix EnergyPlus v2.0 Optimal Path End Use Breakdown**

Figure 17 shows the annual energy end use breakdown for a few points of interest on the EnergyPlus v2.0 optimal path. The second building is the one flagged as the outlier, but the first building (the reference point) has much higher cooling energy use in the reference case in EnergyPlus v2.0 than in DOE2.2 V44E4. The HVAC capacity plot in Figure 9 shows another piece of the picture explaining why building 2 may be an outlier. One can see the large discrepancy in heating capacity sizing between EnergyPlus v2.0 and DOE2.2 V44E4. This is covered in detail in section 4.1.5.

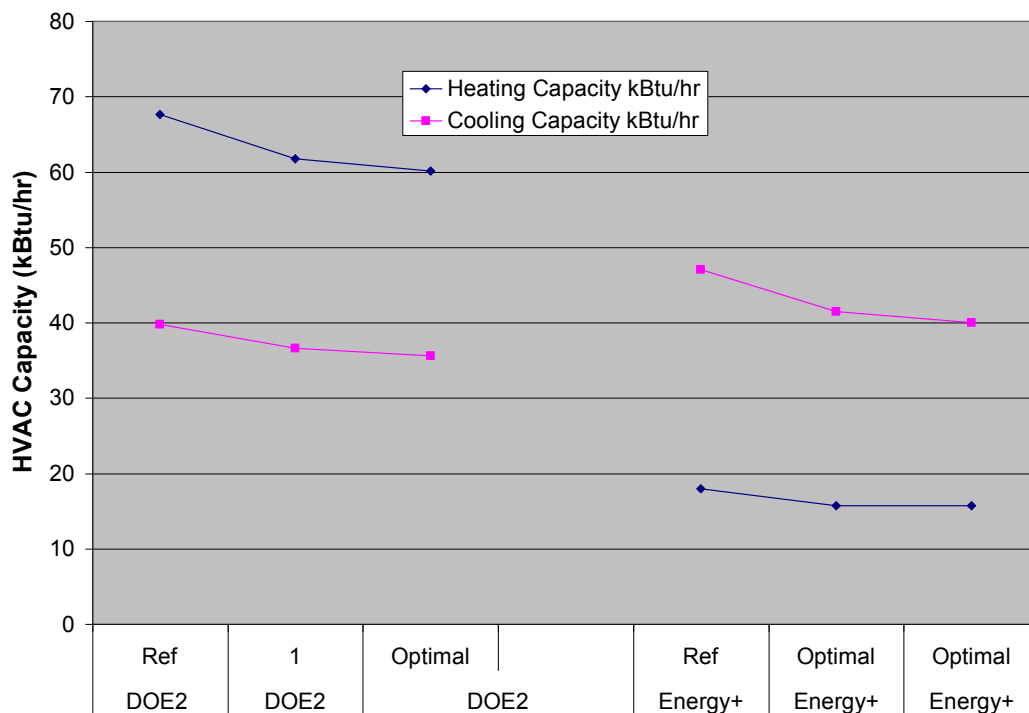


Figure 18: Phoenix HVAC Capacity Comparison

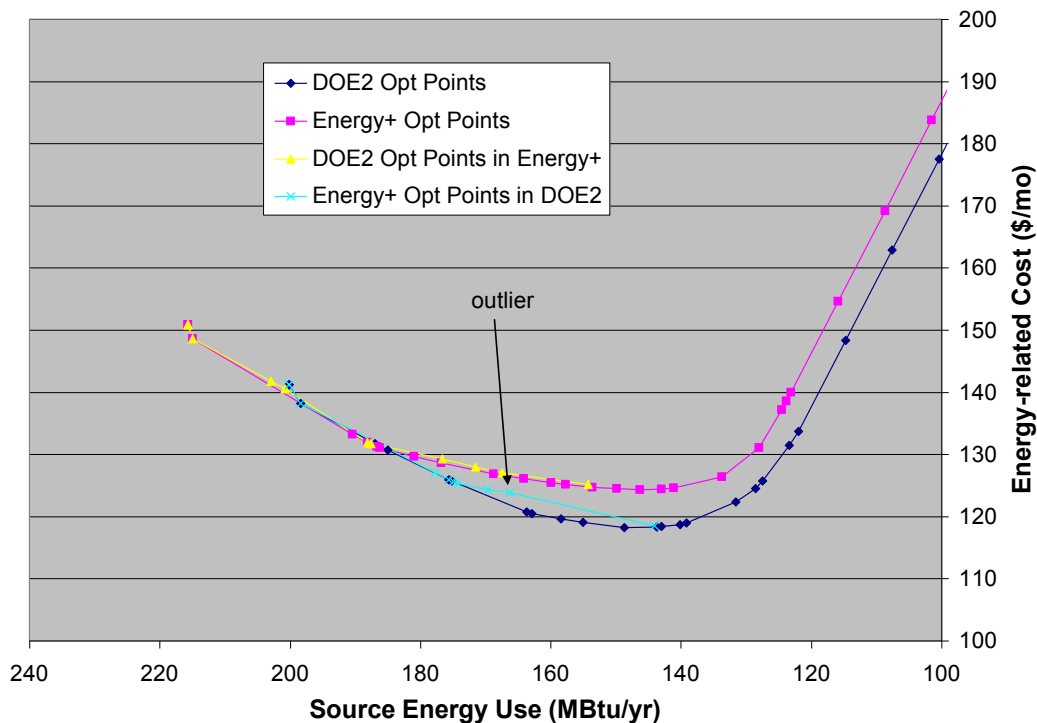
Table 16: Changes from Phoenix Building 2 to Building 3, Modeled in DOE2.2 V44E4 and EnergyPlus v2.0

	EnergyPlus v2.0 Path in DOE2.2 V44E4	EnergyPlus v2.0 Optimal Path
Building Characteristics	Glazing Shift to South	
Cooling Capacity (tons)	3.05 → 2.96	3.46 → 3.33
Heating Capacity (kBtu/hr)	36.6 → 35.6	41.5 → 39.97
Heating Source Energy (MBtu/yr)	-0.5	-0.1
Cooling Source Energy (MBtu/yr)	-0.2	-0.2
Fan Source Energy (MBtu/yr)	No Change	-0.2
Water Heater Source Energy (MBtu/yr)	No Change	No Change

The difference between the reference and the second and third buildings lies in the windows and the window arrangement. It appears that there is a modeling difference in the windows and solar gains. Between the second and third buildings, which are nearly on top of one another, there is only a shift of glazing to the south side. This results in a much larger reduction in heating energy in DOE2.2 V44E4 than in EnergyPlus v2.0, which is consistent with there being a model

difference in the way that solar gains are coupled to the space, with DOE2.2 V44E4 showing more benefit from the passive solar shift. These issues are discussed in detail in sections 4.1.3 and 4.1.4. The cooling size calculated by DOE2.2 V44E4 is just over 3 tons in building 2, then just under 3 tons for building 3. BEopt 0.8.0.4 uses discrete HVAC sizing costs, so moving from 3.05 tons to 2.96 tons results in a significant change in the HVAC cost, based on switching from 3.5 tons to 3.0 tons. This discontinuity in the HVAC cost adds to the discrepancy in window modeling, which is a relatively small effect. The cooling size is between 3 and 3.5 tons for both buildings 2 and 3 in EnergyPlus v2.0.

### 3.9.4 Atlanta Optimal Path Comparison



**Figure 19: Optimal Path Comparison in Atlanta**

In Atlanta, there is one outlier among the EnergyPlus v2.0 optimal points modeled in DOE2.2

V44E4 (Figure 10), with no outliers among the DOE2.2 V44E4 optimal points modeled in

EnergyPlus v2.0. The end use breakdowns of the EnergyPlus v2.0 optimal path outlier, the reference building, and the nearest consensus optimal point for both DOE2.2 V44E4 and EnergyPlus v2.0 are shown in Figure 20. The first two buildings are the reference and another optimal point. The third building is the outlier.

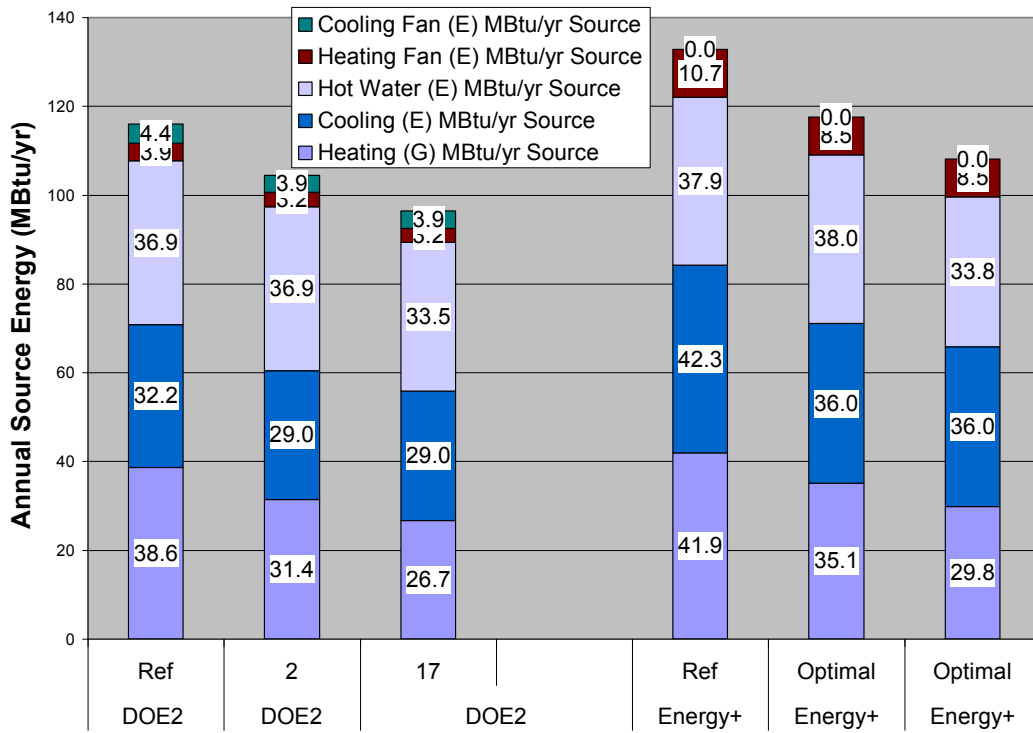
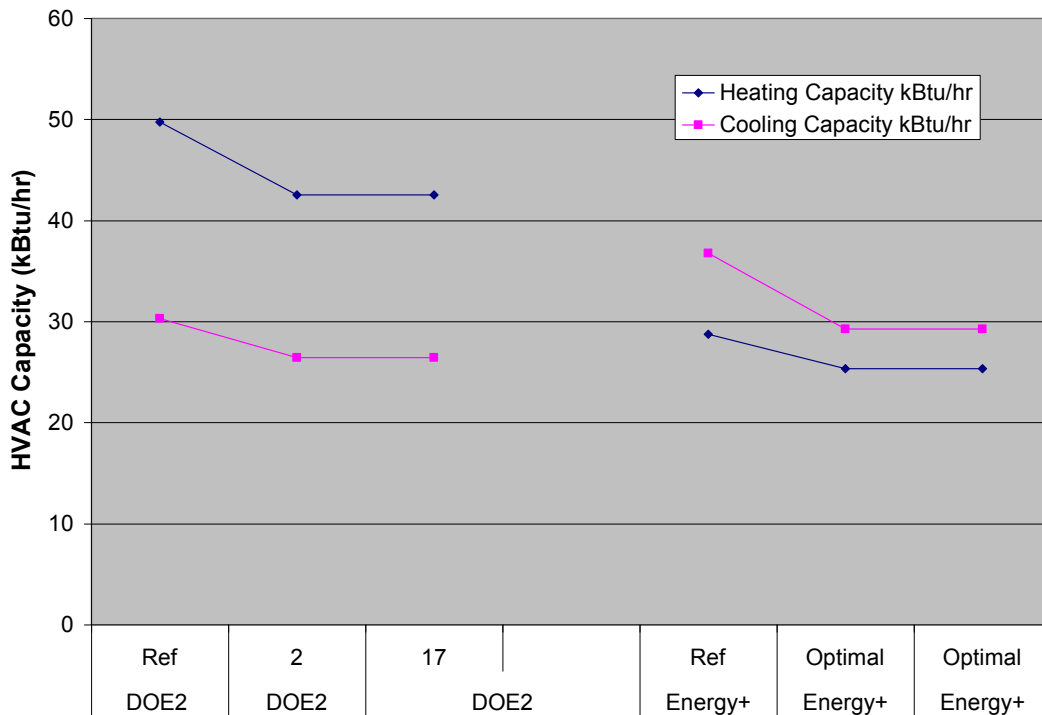


Figure 20: Atlanta EnergyPlus v2.0 Optimal Path End Use Breakdown

The only differences between building 2 and building 3 are an improved furnace and water heater in building 3. This means that the difference between the two buildings is not caused by modeling of the envelope. The heating energy use scales at the same geometric ratio from building 2 to building 3 in both DOE2.2 V44E4 and EnergyPlus v2.0, just as one would expect.



**Figure 21: Atlanta HVAC Capacity Comparison**

The HVAC capacity for the selected buildings is shown in Figure 21. EnergyPlus v2.0 opts for a higher cooling capacity in every building, with a lower heating capacity due to an EnergyPlus v2.0 residential HVAC autosizing problem (Section 4.1.5).

**Table 17: Changes from Atlanta Building 2 to Building 3, Modeled in DOE2.2 V44E4 and EnergyPlus v2.0**

	EnergyPlus v2.0 Path in DOE2.2 V44E4	EnergyPlus v2.0 Optimal Path
Building Characteristics	Water Heater Standard → High Efficiency Furnace Standard → High Efficiency	
Cooling Capacity (tons)	No Change	No Change
Heating Capacity (kBtu/hr)	No Change	No Change
Heating Source Energy (MBtu/yr)	-4.7	-5.2
Cooling Source Energy (MBtu/yr)	No Change	No Change
Fan Source Energy (MBtu/yr)	No Change	No Change
Water Heater Source Energy (MBtu/yr)	-3.4	-4.2

The water heater energy use does not scale at the same geometric ratio in EnergyPlus v2.0 and DOE2.2 V44E4. There are larger savings realized in EnergyPlus v2.0, which has a single node tank with a single heating element set to 120 F, than in TRNSYS, which has a multinode tank with two heating elements set to 105 F and 120 F. The resulting difference is not surprising. Unfortunately, there are instabilities in the plant loop numerical solver in EnergyPlus v2.0 (Griffith, 2007; Ellis, 2007). The multinode tank takes too long to run in optimizations at this time. This issue is discussed further in section 4.1.7.

### 3.9.5 Chicago Optimal Path Comparison

In Chicago, there are 4 outliers among the EnergyPlus v2.0 optimal points modeled in DOE2.2 V44E4 and there is one outlier among the DOE2.2 V44E4 optimal points modeled in EnergyPlus v2.0 (Figure 22). Also of interest is that the total energy use and energy-related cost of the PV takeoff points for DOE2.2 V44E4 and EnergyPlus v2.0 are very close, resulting in the PV section of the curves being coincident, which did not occur in any of the other climates.

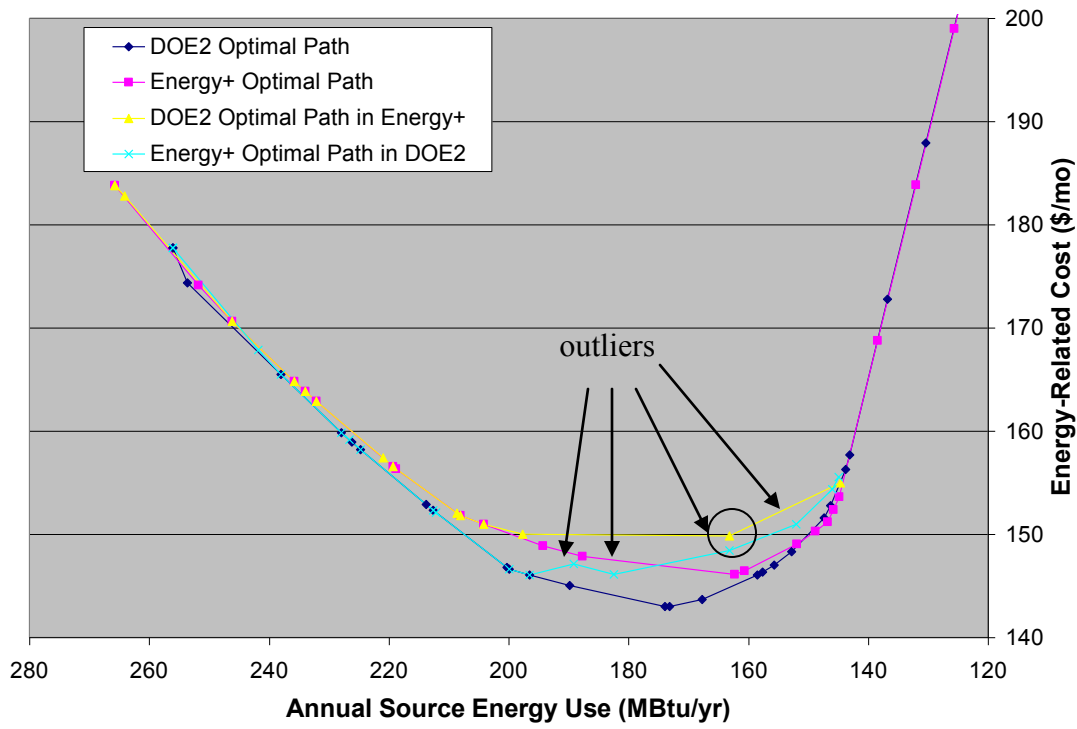


Figure 22: Chicago Optimal Path Comparison

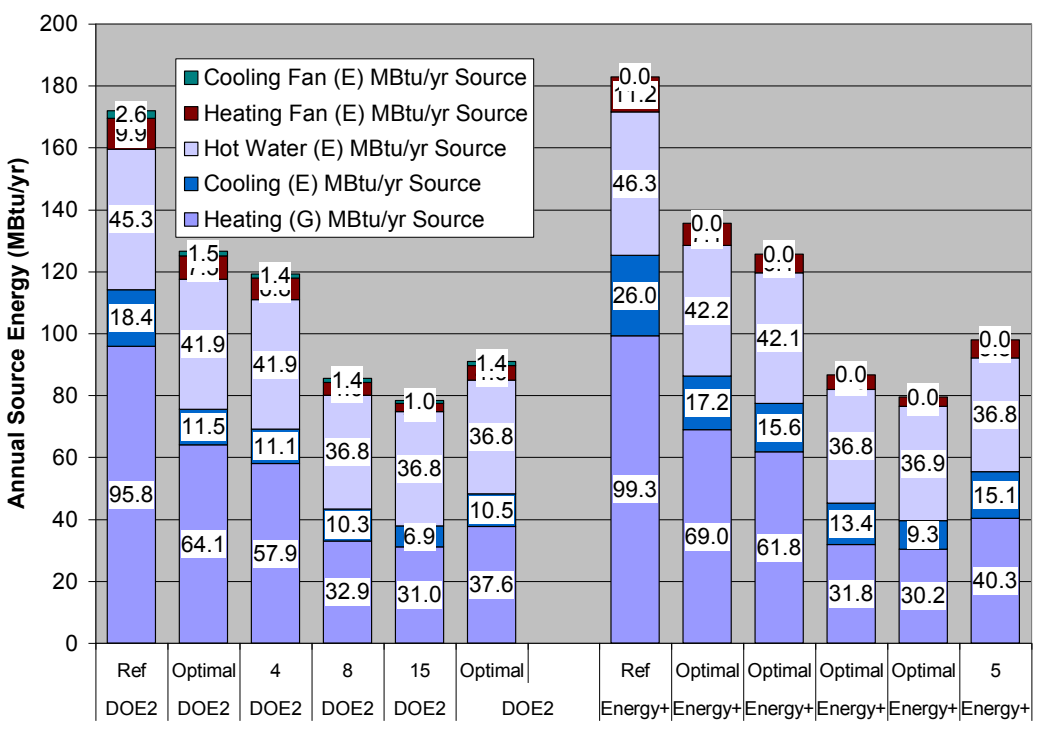
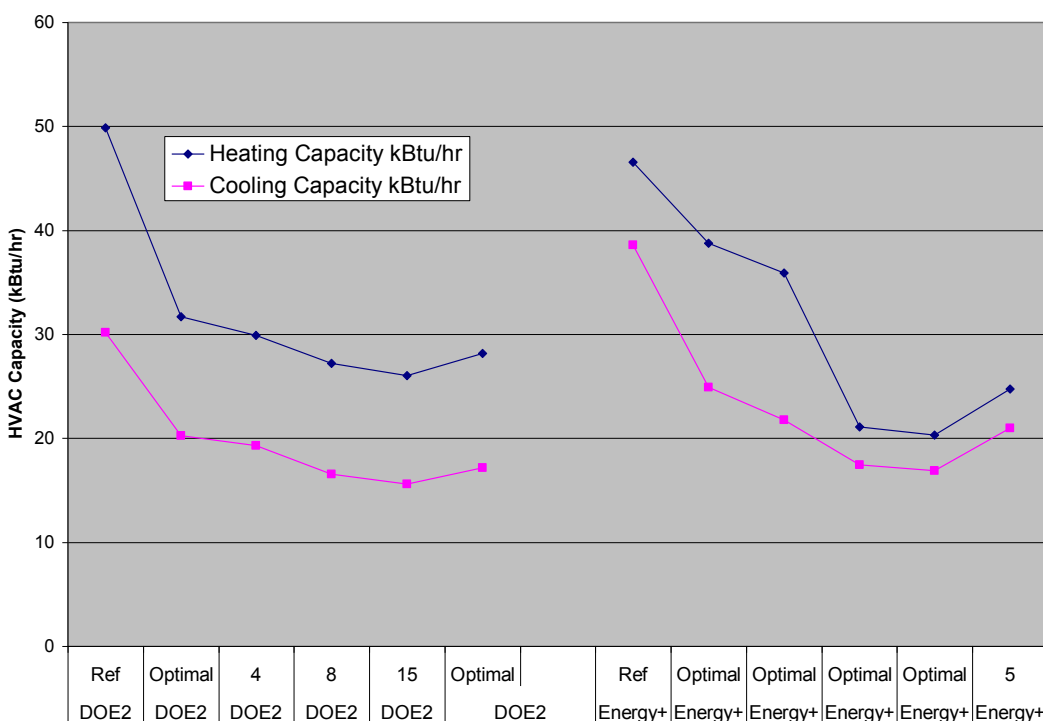


Figure 23: Chicago End Use Breakdown



The end use breakdown (Figure 23) shows differences between some buildings of interest from the EnergyPlus v2.0 optimal path modeled in DOE2.2 V44E4 and EnergyPlus v2.0. The first two buildings are the reference building and another consensus optimal point. The next two buildings are the first and last of the group of 4 DOE2.2 V44E4 outliers that lie on the EnergyPlus v2.0 optimal path. The fifth building is very nearly a consensus optimal point that coincides with the EnergyPlus v2.0 PV takeoff point. The last building is the DOE2.2 V44E4 optimal point that coincides with the EnergyPlus v2.0 outlier in the same region as the DOE2.2 V44E4 outliers, shown by the circle in Figure 22.



**Figure 24: Chicago HVAC Capacity**

EnergyPlus v2.0 has a higher cooling load in all of the buildings, but the buildings closer to the PV takeoff point are closer to being the same in EnergyPlus v2.0 and DOE2.2 V44E4. Also, EnergyPlus v2.0 shows a much larger decrease in cooling load from buildings 1 to 2 and 2 to 3

than DOE2.2 V44E4 shows. EnergyPlus v2.0 also calculates higher heating capacity for building 2 and 3 than DOE2.2 V44E4 does, which is slightly surprising. This shows that EnergyPlus v2.0 is calculating higher heating design day loads than DOE2.2 V44E4 in this case.

**Table 18: Changes from Chicago Building 2 to Building 3, Modeled in DOE2.2 V44E4 and EnergyPlus v2.0**

	EnergyPlus v2.0 Path in DOE2.2 V44E4	EnergyPlus v2.0 Optimal Path
Building Characteristics	Walls R21 → R21 + 1 in foam	
Cooling Capacity (tons)	1.69 → 1.61	2.07 → 1.81
Heating Capacity (kBtu/hr)	31.7 → 29.9	38.8 → 35.9
Heating Source Energy (MBtu/yr)	-6.1	-7.2
Cooling Source Energy (MBtu/yr)	-0.4	-1.7
Fan Source Energy (MBtu/yr)	-0.7	-1.0
Water Heater Source Energy (MBtu/yr)	No Change	No Change

The third building (outlier) varies from the second building (consensus optimal) in that it contains improved walls (R21 vs. R21 + 1 in foam). This causes a much larger reduction in cooling energy in EnergyPlus v2.0 than in DOE2.2 V44E4, as well as larger reductions in heating energy and fan energy in EnergyPlus v2.0 (Table 18).

**Table 19: Changes from Chicago Building 4 to Building 5, Modeled in DOE2.2 V44E4 and EnergyPlus v2.0**

	EnergyPlus v2.0 Path in DOE2.2 V44E4	EnergyPlus v2.0 Optimal Path
Building Characteristics	Ceiling R30 → R50 AC SEER 10 → SEER 15	
Cooling Capacity (tons)	1.38 → 1.30	1.45 → 1.41
Heating Capacity (kBtu/hr)	27.2 → 26.0	21.1 → 20.3
Heating Source Energy (MBtu/yr)	-1.9	-1.6
Cooling Source Energy (MBtu/yr)	-3.4	-4.1
Fan Source Energy (MBtu/yr)	-1.8	-1.5
Water Heater Source Energy (MBtu/yr)	No Change	+0.1

The fourth building (outlier) varies from the fifth building (consensus optimal) in that the fourth building is lacking a ceiling and air conditioner improvement (Table 19). Both buildings have the most energy efficient wall options available. The two buildings have similar changes in the

end use breakdown in EnergyPlus v2.0 and DOE2.2 V44E4, with EnergyPlus v2.0 showing a larger absolute cooling increase from building 5 to building 4, due to the larger overall cooling load calculated in EnergyPlus v2.0. The difference here likely occurs in the modeling of some points on the DOE2.2 V44E4 optimal curve near this outlier, which DOE2.2 V44E4 sees as being significantly better than building 5, but most of these buildings did not show up in the EnergyPlus v2.0 optimization. The sixth building is one of these points on the DOE2.2 V44E4 optimal curve.

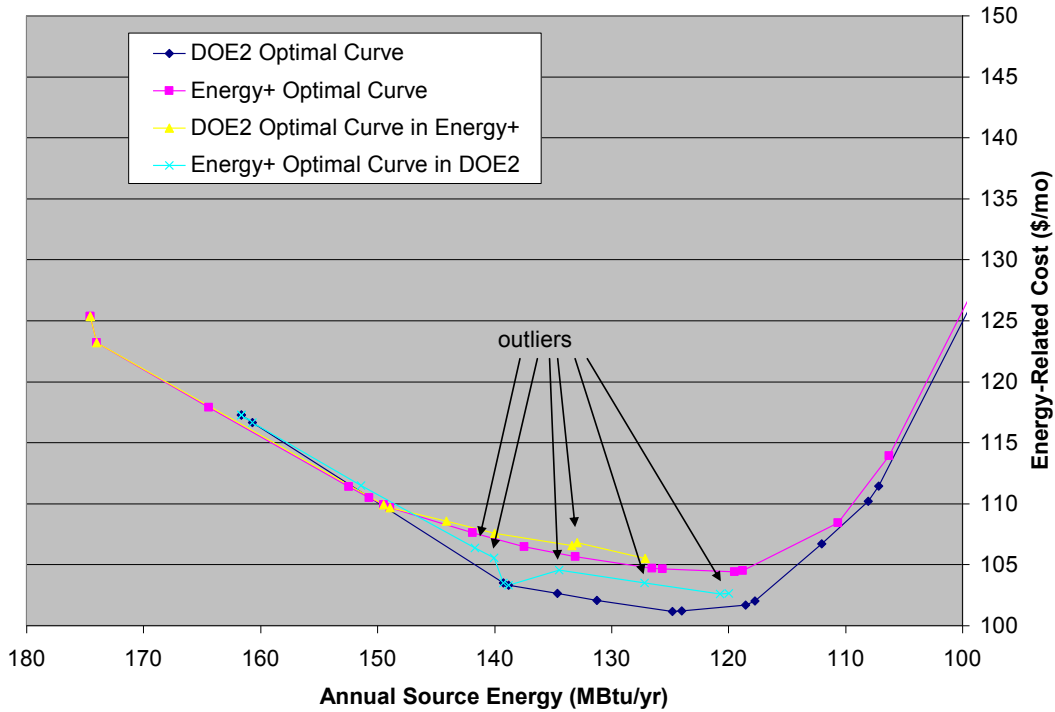
**Table 20: Changes from Chicago Building 4 to Building 6, Modeled in DOE2.2 V44E4 and EnergyPlus v2.0**

	EnergyPlus v2.0 Path in DOE2.2 V44E4	EnergyPlus v2.0 Optimal Path
Building Characteristics	Walls R51 → R21 + 1 in foam	
Cooling Capacity (tons)	1.38 → 1.43	1.45 → 1.75
Heating Capacity (kBtu/hr)	27.2 → 28.2	21.1 → 24.7
Heating Source Energy (MBtu/yr)	+4.7	+8.5
Cooling Source Energy (MBtu/yr)	+0.2	+1.7
Fan Source Energy (MBtu/yr)	+0.6	+1.1
Water Heater Source Energy (MBtu/yr)	No Change	No Change

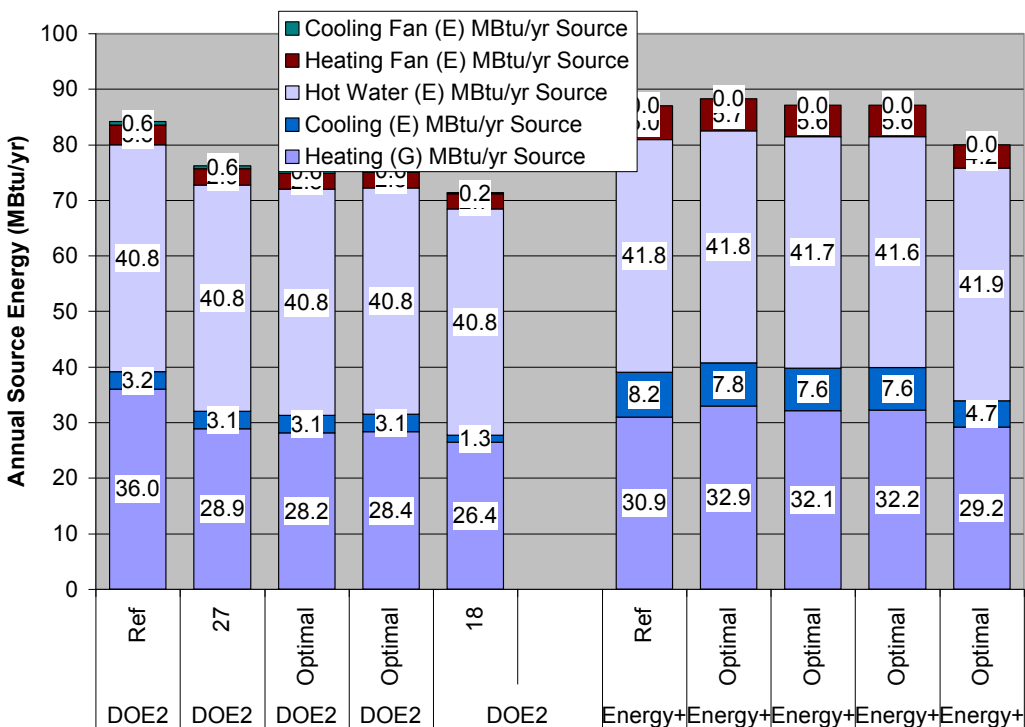
Comparing the fourth and sixth buildings, the only difference is in the walls category, where the fourth building has a better wall option (Table 20). EnergyPlus v2.0 shows a much larger difference in the heating and cooling energy between these two points than DOE2.2 V44E4 shows. This difference is added to the difference in HVAC sizing, where DOE2.2 V44E4 shows the cooling sizing being just under 1.5 tons in building six, enough to reduce its HVAC capital costs relative to EnergyPlus v2.0. It appears that the modeling of the wall options is responsible for each of these outliers in Chicago.

### 3.9.6 San Francisco Optimal Path Comparison

San Francisco has one outlier among the DOE2.2 V44E4 optimal path points modeled in EnergyPlus v2.0. There are numerous outliers among the EnergyPlus v2.0 optimal path points modeled in DOE2.2 V44E4, 6 in all, making up the majority of the points. However, there are two consensus optimal points in the middle of this string.



**Figure 25: San Francisco Optimal Path Comparison**



**Figure 26: San Francisco End Use Breakdown**

Figure 19 shows the end use breakdown for some of the points of interest along the EnergyPlus v2.0 optimal path. The first building is the reference. The second building is an outlier. The third and fourth buildings are consensus optimal points. The fifth building is another outlier. Energy+ shows much higher cooling energy and fan energy in all buildings. In the reference, Energy+ predicts less heating energy than DOE2.2 V44E4, while in the rest of the buildings Energy+ predicts more heating energy.

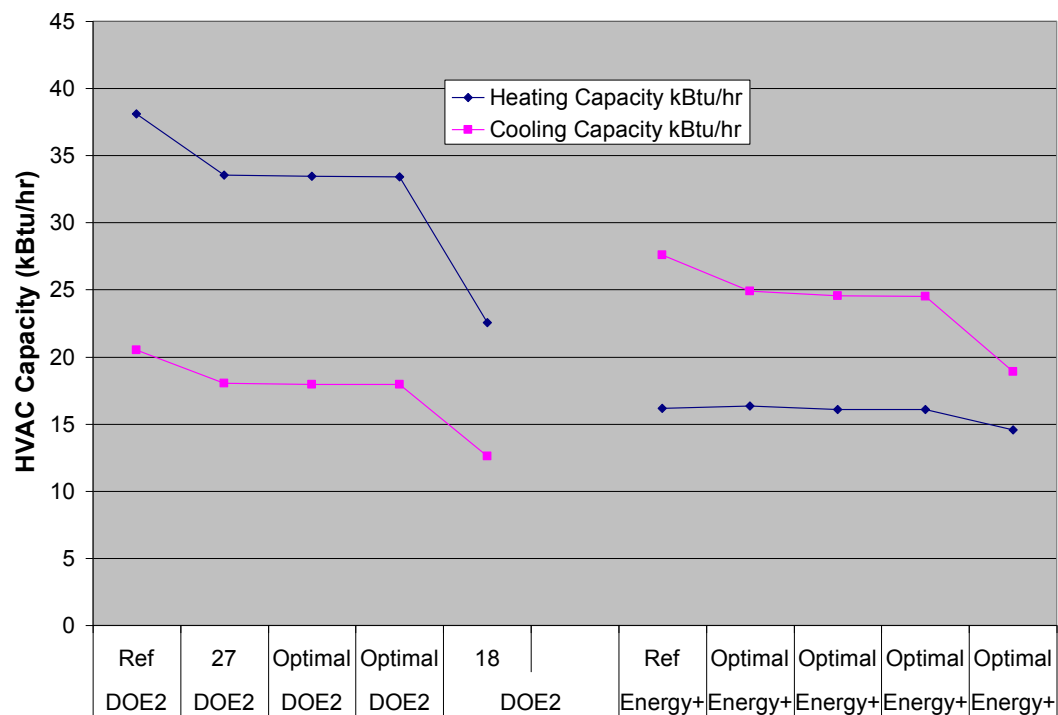


Figure 27: San Francisco HVAC Capacity

EnergyPlus v2.0 sizes the cooling equipment larger in all of the buildings (Figure 27). There are only very minor differences between Energy+ and DOE2.2 V44E4 modeling of the energy end uses in buildings 2 and 3 (Table 21).

Table 21: Changes from San Francisco Building 2 to Building 3, Modeled in DOE2.2 V44E4 and EnergyPlus v2.0

	EnergyPlus v2.0 Path in DOE2.2 V44E4	EnergyPlus v2.0 Optimal Path
Building Characteristics	Walls R19 → R21	
Cooling Capacity (tons)	1.502 → 1.496	2.07 → 2.05
Heating Capacity (kBtu/hr)	33.6 → 33.4	16.3 → 16.1
Heating Source Energy (MBtu/yr)	-0.7	-0.8
Cooling Source Energy (MBtu/yr)	-0.1	-0.1
Fan Source Energy (MBtu/yr)	-0.1	-0.1
Water Heater Source Energy (MBtu/yr)	No Change	-0.1

The difference in the position of building 2 can be ascribed to the cooling capacity calculation. In DOE2.2 V44E4, building 2 has a cooling capacity of just over 1.5 tons, while in building 3, it has a cooling capacity of just under 1.5 tons. In EnergyPlus v2.0, both buildings have a cooling capacity of just over 2 tons. As a result, in DOE2.2 V44E4, it looks like building 3 has a much lower cost than building 2. This is an outstanding example of a discontinuity in the output being caused by discrete HVAC sizing in BEopt 0.8.0.4. This issue is discussed further in section 4.2.

**Table 22: Changes from San Francisco Building 4 to Building 5, Modeled in DOE2.2 V44E4 and EnergyPlus v2.0**

	EnergyPlus v2.0 Path in DOE2.2 V44E4	EnergyPlus v2.0 Optimal Path
Building Characteristics	Glazing Double Clear → Low-e, std SHGC w/ argon	
Cooling Capacity (tons)	1.49 → 1.05	2.04 → 1.57
Heating Capacity (kBtu/hr)	33.4 → 22.6	16.1 → 14.5
Heating Source Energy (MBtu/yr)	-2.0	-3.0
Cooling Source Energy (MBtu/yr)	-1.8	-2.9
Fan Source Energy (MBtu/yr)	-0.5	-1.4
Water Heater Source Energy (MBtu/yr)	No Change	+0.3

The only difference in characteristics between building 4 and building 5 is the glazing type going from double clear in building 4 to low-e, standard SHGC with argon fill in building 5.

EnergyPlus v2.0 shows much larger savings from building 4 to building 5 in heating, cooling, and fan energy. There is difference in the modeling of window solar gains between EnergyPlus v2.0 and DOE2.2 V44E4. This is very apparent in a climate like San Francisco, where temperatures are very mild and solar gains are a much larger piece of the overall envelope heat transfer than other climates. This issue is discussed further in sections 4.1.3 and 4.1.4.

EnergyPlus v2.0 also shows a specious increase in water heating energy as a result of a change in a building characteristic that should have no impact whatsoever on the decoupled water heating

system. This is caused by the instability in the plant loop solver when running on AMD processors. This issue is discussed further in section 4.1.8.

### ***3.10 Speed Testing and Results***

Optimizations were run using DOE2.2 V44E4/TRNSYS and EnergyPlus v2.0 for 5 different climates. The number of simulations and time to completion varied among the climates and simulation engines. All of the optimizations were run on a Dell Inspiron Laptop with an AMD Turion 64 x2 dual core processor and 2 GB of RAM. Running optimizations takes a lot of memory and processor time. BEopt 0.8.0.4 has recently been modified to allow multiple instances of BEopt 0.8.0.4 to run concurrently, allowing BEopt 0.8.0.4 to take some advantage of dual core processing capabilities. The major advantage of this feature with EnergyPlus v2.0 optimization comes in running concurrent optimizations. The EnergyPlus v2.0 optimizations were run overnight in concurrent BEopt 0.8.0.4 processes. The DOE2.2 V44E4/TRNSYS optimizations were run in the same fashion during the day.

**Table 23: Optimization Runtime Comparison of EnergyPlus v2.0 and DOE2.2 V44E4/TRNSYS**

	EnergyPlus v2.0			DOE2.2 V44E4/TRNSYS		
	Sims	Time (min)	Time / sim (sec)	Sims	Time (min)	Time / sim (sec)
Boulder	679	952	84	579	116	12.0
Phoenix	613	1061	104	488	109	13.4
Chicago	646	877	81	649	138	12.7
Atlanta	716	966	81	473	122	15.5
San Francisco	497	627	76	428	111	15.6
Average	630	897	85	523	119	13.7

The speed testing results are shown in Table 23. On average, the EnergyPlus v2.0 optimizations took 1.2 times as many simulations as the DOE2.2 V44E4/TRNSYS optimizations. While there is some variation from place to place due to optimizations taking different paths, the overall trend is mainly due to the split water heating and space modeling employed by the DOE2.2



V44E4/TRNSYS optimizations. When only a space option changes between iterations, all of the water heating simulations from the previous iteration can be reused in the DOE2.2

V44E4/TRNSYS approach. Likewise, if only a water heating-related option changes between iterations, all of the space simulations from the previous iteration can be reused in the DOE2.2

V44E4/TRNSYS approach. Because the water heating and building are assumed to be essentially decoupled in the current version of BEopt 0.8.0.4, this approach has only minor impacts on accuracy. The water heater is assumed to be located in an unconditioned space at a constant temperature of 70 degrees F. The only interaction that is not being captured by the DOE2.2 V44E4/TRNSYS approach is the change in gains to the space associated with making an improvement to the washing machine or dish washer. These are ultimately rather small and have little impact on the results.

On average, EnergyPlus v2.0 optimizations take 7.5 times as long as DOE2.2 V44E4/TRNSYS optimizations. DOE2.2 V44E4 took an average of 2 hours to conduct each optimization, while EnergyPlus v2.0 took an average of 15 hours to conduct each optimization. On average, each EnergyPlus v2.0 simulation took 6.5 times as long as DOE2.2 V44E4 and TRNSYS.

## 4 Discussion/Conclusions

### 4.1 *Unresolved differences*

In the course of this work, there were some issues discovered that could not be fixed. Some of these are modeling capabilities that are missing from EnergyPlus v2.0. Some of them are model features that could be improved in future version of EnergyPlus v2.0 (and/or DOE2.2 V44E4). Others are fundamental differences between the two models that are unlikely to be reconciled.

#### 4.1.1 **Foundation models**

Fundamentally different foundation models are available in EnergyPlus v2.0 and DOE2.2 V44E4. DOE2.2 V44E4 relies on a perimeter conduction method with a fictitious resistance. The conductance is based on precalculated results developed by LBL that cover most basic foundation types, with the addition of a layer of dirt to capture thermal mass effects. In contrast, EnergyPlus v2.0 uses a separate foundation simulation tool to calculate the monthly underground surface temperatures using a 3D finite element solution. Unfortunately, the foundation simulation tool is not directly coupled to the space, in order to reduce simulation runtime. Simulation runtime is on the order of 10 minutes. As a result, the user must input the space temperature, which can vary on a monthly basis. The surface temperatures are highly dependent on the assumed space temperature. An iterative process would need to be used to get a good result, which would lead to more simulation runtime than can reasonably be allowed in an optimization. This issue is also discussed in the gaps analysis section. While the EnergyPlus v2.0 model is more accurate if there is enough time to iterate the foundation simulation, this is not practical for optimizations, so the DOE2.2 V44E4 model is currently more suited to residential optimization.

### **4.1.2 Duct leakage**

EnergyPlus v2.0 does not have a simple duct leakage model for residential systems, like DOE2.2 V44E4 does. There is an airflow network under development that will be able to calculate unbalanced flows between zones and the outdoors to calculate interactions between duct leakage, exhaust, wind and stack-driven infiltration. The only way to approximate duct leakage in the current version of EnergyPlus v2.0 is to do a manual sizing run and use a duct leakage fraction to calculate the flow to a slave zone where the duct leakage occurs. Unfortunately, this does not account for duct leakage interaction with the other flows. In the current version of BEopt 0.8.0.4, the impact of this duct leakage has been approximated by adjusting the constant leakage coefficient, resulting in questionable hourly results but reasonable annual energy results. Future version of EnergyPlus v2.0 will do a better job of modeling this duct leakage but for the purposes of this study, ducts are always assumed to be inside. This issue is also discussed in the EnergyPlus v2.0 gaps section.

### **4.1.3 Window long-wave radiation balance, interior shading devices**

EnergyPlus v2.0 treats radiation in a fundamentally different way than DOE2.2 V44E4. EnergyPlus v2.0 performs a long-wave radiation balance on all surfaces within a zone, including windows. DOE2.2 V44E4 only tracks heat transfer through each surface, from air to air. When walls, floor, and ceiling interior surfaces are nearly isothermal, the long wave radiation heat transfer is not very important, so the DOE2.2 V44E4 approach works fine. In other situations, there can be dramatic variation in surface temperatures within a space, causing DOE2.2 V44E4 to underestimate heat transfer rates through high conductivity constructions, including low-quality windows. This may be the root cause of an apparent difference in the modeling of houses

with double clear windows. The long wave radiant balance issue also can impact the modeling of shading devices.

In the DOE2.2 V44E4 model, shading multipliers are used in accordance with the BA Benchmark. In EnergyPlus v2.0, this shading multiplier method is not available. Instead, the same effect is modeled using a dirt factor on the outer glazing and an interior shade deployed seasonally. These characteristics will have different impacts on different window constructions – they create an effective shading multiplier with a larger impact when deployed on windows with a higher solar heat gain coefficient than they do when deployed on windows with a lower solar heat gain coefficient. The dirt will cause a higher glass temperature, resulting in some of the heat being radiated to the space. The interior shade also absorbs solar radiation and reradiates it to the house. EnergyPlus v2.0 is modeling the interior shade explicitly, with the gap between the shade and the window frame edges impacting convection, while the long wave radiant balance between the shade and the space is being modeled explicitly. EnergyPlus v2.0 has a decided advantage in modeling accuracy in this area.

#### **4.1.4 Solar interaction with furniture mass**

DOE2.2 V44E4 and EnergyPlus v2.0 use different solar-mass coupling approaches. EnergyPlus v2.0 is performing a long wave radiation balance on the surfaces in the space. When using the FullExterior solar distribution option, all of the short wave radiation entering the space through the windows is passed to the floor surface, which then reradiates to the rest of the space. Furniture mass is added using a thermal mass wall construction, which is a fictitious surface intended to represent partition walls, furniture, and other mass within the envelope. This thermal mass wall is radiatively coupled to the other surfaces in the space, with shape factors proportional to the area of the different surfaces. The thermal mass wall is convectively coupled

to the air in the zone. As a result, solar energy entering the space passes through the window, to the floor, then to the mass and all of the other surfaces.

In contrast, DOE2.2 V44E4 does not model the radiative coupling explicitly, but it does allow solar energy to directly interact with the mass of “stuff” within the envelope. There is a DOE2.2 V44E4 keyword that specifies the fraction of the incoming solar gains that are applied to the furniture mass, with the rest of the solar energy passing directly to the zone. In the DOE2.2 V44E4 version of BEopt 0.8.0.4, this multiplier is set to 0.4. This is a fundamentally different approach. It certainly makes sense to pass some solar gains to furniture mass directly, since these objects frequently interrupt solar gains before they strike the floor. Meanwhile, the EnergyPlus v2.0 approach of applying all of the solar gains to a surface makes sense – the remainder of the gains in DOE2.2 V44E4 get added directly to the space instead. A compromise between the two approaches would be more flexible and retain the radiation capabilities of EnergyPlus v2.0. EnergyPlus v2.0 should allow users to specify solar fraction going to internal mass surfaces as a modeling option when using the FullExterior solar distribution option.

#### **4.1.5 Residential autosizing**

The autosizing method used in EnergyPlus v2.0 is insufficient for use in BEopt 0.8.0.4. EnergyPlus v2.0 does calculate the design heating and cooling loads accurately. Then it calculates the required heating and cooling airflows and takes the maximum of these as the system airflow. The process thus far is the same as DOE2.2 V44E4. EnergyPlus v2.0 does not take the last step of resizing the equipment based on the system airflow and desired supply air temperatures. DOE2.2 V44E4 does take this step. The result is that the ratio of heating and cooling equipment size is always the same in DOE2.2 V44E4, regardless of the climate. This ratio is approximately equal to the temperature difference between the heating supply air and

heating setpoint divided by the temperature difference between the cooling supply air and the cooling setpoint. Since system airflows are typically driven by cooling airflow requirements, because of the smaller supply air to space temperature difference during cooling, the result is that EnergyPlus v2.0 typically chooses much smaller heating equipment than it should. This sizing difference has a few impacts on the optimization. First, it increases the heating fan runtime and energy use in EnergyPlus v2.0, since the resulting heating supply temperature is much lower than it should be. Second, it causes EnergyPlus v2.0 optimization results to be less sensitive to design cooling load reductions than they should be. In DOE2.2 V44E4, a reduction in design cooling load allows both the cooling and heating equipment to be downsized. In EnergyPlus v2.0, the equipment sizes are decoupled, so a reduction in cooling load only reduces the cooling equipment size. With respect to how systems are actually sized in real life, the DOE2.2 V44E4 approach is closer, because system installers will generally put in a large enough furnace to give comfortable heating supply temperatures. They are much more likely to install a dramatically oversized furnace than one that is close to meeting the design loads. Both simulation engines could benefit from an autosizing algorithm improvement with increased flexibility, which would allow current or new sizing practices to be accurately modeled, but the current DOE2.2 V44E4 approach does a better job of approximating how real residential system sizing is performed.

#### **4.1.6 Attic radiation**

The long wave radiant surface energy balance method employed by EnergyPlus v2.0 should result in improved modeling accuracy of attics compared to DOE2.2 V44E4. EnergyPlus v2.0 should be able to model radiant barriers as an energy saving measure and accurately predict their effects on heat transfer to the attic and the conditioned space. Radiation from the roof is a significant driver of heat transfer in some situations. This work did not include buildings that

were sensitive enough to these radiant effects for it to have an impact on modeling results. All ducts were placed inside conditioned space, so there were no unbalanced flows to and from the attic. Heat transfer to and from the attic is highly sensitive to unbalanced between the conditioned space and the attic. The reference (lowest) attic insulation in BEopt 0.8.0.4 is R-30. BEopt 0.8.0.4 rarely chose a ceiling improvement until near the PV takeoff point. The only optimization that included a ceiling improvement in the minimum cost point was the DOE2.2 V44E4 optimization of Chicago. The attic radiation does not appear to appreciably affect the building optimization with the new buildings modeled during this study, but it might have a larger impact in existing homes with lower attic insulation levels.

#### **4.1.7 Multinode tank runtime**

A multinode tank model was added to EnergyPlus v2.0 in Version 2.0.0. This should improve the modeling accuracy of electric water heaters, and any water tank with an external source (like Solar DHW or combined heat and power). The BEopt 0.8.0.4 TRNSYS model includes a multinode tank. Multinode tanks were not originally part of the scope of work of this project. However, there were differences in water heater energy usage modeling observed (enough to cause an overall monthly cost deviation of greater than 1%), so multinode tanks were explored in EnergyPlus v2.0. A multinode tank was implemented and tested. Unfortunately, the results were disappointing. The simulation runtime for EnergyPlus v2.0 tripled, to a little over 4 minutes. This problem may be related to the apparent numerical solution instability in the plant solver, which leads to some noise in the hourly results. See section 4.1.8. The annual energy results were not conclusively better or worse. When moving from a single node tank set to 120 F to a six node tank with the top element setpoint at 120 F and the bottom element setpoint at 105 F, the overall water heater source energy use increased from 38.0 MMBtu to 38.1 MMBtu. This

change was expected to cause a decrease in water heater energy. TRNSYS calculates source energy use of 36.9 MMBtu for its multinode tank. Unfortunately, adding multiple nodes to the hot water tank simulation adds significant complexity. Both the average surface temperature of the tank and the average temperature of the water leaving the tank will be different in a multinode tank. This issue should be further investigated to determine the root cause of the increase in simulation time and determine if there may be a simple way to reduce the runtime. A detailed validation of the EnergyPlus v2.0 stratified tank should be conducted and this validation should include comparison to the TRNSYS stratified tank. For the purposes of this work, the single node tank with acceptable runtime was used instead.

#### **4.1.8 Plant loop solver residuals on AMD processors**

The difference in water heater hourly energy use between AMD and Intel processors running the same version of EnergyPlus v2.0 on the same version of Windows is perhaps the most surprising and frustrating result to come from this work. While debugging the differences between water heating energy usage in EnergyPlus v2.0 and TRNSYS, it was determined that the annual energy use was slightly different when running an Intel Pentium P4 than when running an AMD Turion 64 x2. The hourly output, while noisy in both, was noisier using the AMD processor. Software operation should not depend on the processor used. This issue was brought to the attention of the EnergyPlus v2.0 development team.

## ***4.2 High Priority Opportunities for Residential Energy Modeling Improvement***

Through the completion of this work, it became apparent where some residential energy modeling improvements can occur, in BEopt 0.8.0.4, EnergyPlus v2.0, and DOE2.2 V44E4.



### 4.2.1 Residential Equipment Sizing

Energy cost optimization relies in part upon capturing the savings associated with installing smaller equipment to meet smaller loads in homes with envelope improvements. As a result, system sizing can have a big impact on optimization results, and it is important to have a system sizing algorithm that reasonably approximates real life. In practice, system installers use a wide range of sizing practices, including the “back of the truck” method, rules of thumb relating home size and system size, and some variation on Manual J. Systems generally wind up being oversized compared to Manual J and compared to real loads. Residential autosizing is a non-trivial problem. Difficulties or inaccuracies in equipment sizing were discovered in DOE2.2 V44E4, EnergyPlus v2.0, EnergyGauge, and BEopt 0.8.0.4. One major source of trouble is the feedback mechanism of duct leakage. Duct leakage increases the load on the system, which increases the airflow, which increases the duct leakage, and so on. In addition, duct leakage can interact with infiltration. As a result, load calculation and system sizing cannot be performed completely independently of one another. Some sort of mathematical guess or iterative algorithm is required to account for the duct leakage impact on equipment sizing. While the simulation programs are having trouble with current residential sizing procedures, the matter of proper sizing of equipment for high performance residential buildings is still a matter of debate. Many people conclude that the ACCA methods in Manual J and Manual S will not be adequate in future.

It was discovered that the discrete costing of residential equipment can cause disparities in the optimization results. These differences are real, but should only be applied in the case of a specific, well-defined building, not in the case of a generic building. As a result, BEopt 0.8.0.4 should enable a new more continuous HVAC costing algorithm to eliminate this effect for

analyses of generic buildings. Given the difficulty of residential autosizing, it would also be useful for BEopt 0.8.0.4 to provide a summary of the loads not met for each simulation point. This feature would have some utility now, but would become especially useful whenever a new equipment model with a new sizing algorithm is being used.

The residential autosizing algorithm in DOE2.2 V44E4 is adequate for the systems currently used in BEopt 0.8.0.4, if the inputs are specified correctly. With the assistance of Paul Reeves, the DOE2.2 V44E4 autosizing inputs have been specified correctly for the systems currently in use in BEopt 0.8.0.4. DOE2.2 V44E4 does allow the specification of an oversizing multiplier, which can be adjusted to compensate for installers oversizing typical equipment.

EnergyPlus v2.0 needs to have its autosizing model upgraded to allow standard residential equipment sizing practice to be modeled. In addition, the model will need to integrate system autosizing with the airflow network development that is currently under way. See sections 2.2.1, 2.2.2, and 4.1.5.

One other possible solution is for BEopt 0.8.0.4 to perform the sizing calculations. BEopt 0.8.0.4 could call a DOE2.2 V44E4 or EnergyPlus v2.0 sizing simulation, then calculate the equipment size and run the full year simulation. This would be much slower than doing the sizing within the simulation engine.

#### **4.2.2 Duct Leakage and Infiltration**

Infiltration and duct leakage modeling is probably the highest priority for residential energy modeling improvements. Neither DOE2.2 V44E4 nor EnergyPlus v2.0 has sufficient capability to accurately model interactions between infiltration, duct leakage, and exhaust fans. A workaround was implemented in BEopt 0.8.0.4 to crudely capture some of the interactive effects by using a simple linear regression technique to derive coefficients for the simple mathematical

infiltration equation available in DOE2.2 V44E4 and EnergyPlus v2.0. The details of this workaround are contained in the appendix. Work continues on the airflow network for EnergyPlus v2.0, which holds great promise as a powerful tool for calculating airflows between zones and the outdoors based on the fundamental driving forces involved. As the airflow network capabilities are fleshed out to include variable speed systems, infiltration, and duct leakage interactions, EnergyPlus v2.0 will have superior infiltration modeling capability. The syntax for the airflow network should also be simplified if possible to enable its use.

In DOE2.2 V44E4, interactions between duct leakage and infiltration should be added if at all possible. The systems program already does some transformation to get from the loads created by loads to the system loads. The duct leakage load is currently added directly to the system load. The duct leakage load could be adjusted based on the hourly infiltration. For DOE2.2 V44E4 to do more complicated interactions between airflows is not possible without running loads and systems concurrently instead of sequentially.

### **4.2.3 Foundation Modeling**

There is almost always an opportunity for improving foundation modeling. Unfortunately, improving ground heat transfer modeling is very difficult to do without large computational expense. The DOE2.2 V44E4 approach suggested by Winkleman does not require a lot of computing time, but relies on canned simulation results that cannot be adjusted for soil properties or unusual climate behavior. The EnergyPlus v2.0 approach allows a very detailed model of the ground coupling to be constructed, but the simulation runtime is approximately 10 minutes and the model cannot be coupled to the space in any way, so it is nearly worthless for modeling ground coupling to unconditioned spaces that have highly variable temperatures (like crawlspaces with leaking ducts and poor insulation). The only way to get reasonable results with

the EnergyPlus v2.0 model in those situations is to iterate. The EnergyPlus v2.0 ground coupling model would be improved immensely if it could be coupled to the space simulation while it runs. Unfortunately, when dealing with an optimization where the space conditions are changing from building to building, a single run of the ground coupling model for each basement type may not be adequate. A faster ground simulation model that could be effectively coupled to the space would be better for use in optimization.

### ***4.3 Potential Areas for Speed Improvements in EnergyPlus v2.0***

The single biggest problem with using EnergyPlus v2.0 for residential optimization is its speed. EnergyPlus v2.0 optimizations took about 7 times as long as DOE2.2 V44E4/TRNSYS optimizations. The practical difference between an optimization taking a few hours and taking 24 hours is quite large. Perhaps computers will continue to improve dramatically in speed and this issue will be rendered obsolete in a decade's time. In the mean time, some improvements in speed would help EnergyPlus v2.0 become a better optimization tool.

The most robust method for improving speed without sacrificing accuracy in the results is to put in "switches" that enable the user to switch between different modeling algorithms when the speed improvement is worth more than the accuracy improvement. EnergyPlus v2.0 makes numerous such switches available to the user today. Adjustments can be made to the wall conduction method, the solar radiation distribution, the simulation time step, the system time step, the convergence criteria, various room air models, the system type, the tank model, the water heating system, etc. There is one glaring omission: long wave radiation balance. The user cannot turn off or adjust the long wave radiation balance in EnergyPlus v2.0. The solution of this set of equations is very complex, which means that as the number of building surfaces increases, the simulation time increases geometrically at best. While this is a wonderful

capability that tremendously improves the accuracy of modeling some buildings, it costs dearly in increased simulation time. In some buildings that lack large temperature disparities between surfaces, the increase in modeling accuracy may be nearly zero. This is true of high performance residential buildings that feature well-insulated walls, floors, ceilings, and high efficiency glazing. A switch that would enable to turn off the long wave radiation balance or choose a less expensive long wave radiation algorithm would be immensely useful for reducing simulation runtime and speeding up optimizations with EnergyPlus v2.0.

#### ***4.4 Opportunities Afforded by EnergyPlus v2.0***

EnergyPlus v2.0 has some modeling capabilities that greatly exceed the capabilities of DOE2.2 V44E4. Fundamentally, EnergyPlus v2.0 calculates surface temperatures and can perform radiation heat balances. This provides a better estimate of heat transfer, especially in situations with greater disparities in surface temperatures, such as when using radiant heating systems or when a surface has high conductivity (like single pane glass). EnergyPlus v2.0 runs the systems, plant loops, and envelope simulations concurrently, so it can model complex interactions between equipment and the envelope. DOE2.2 V44E4 runs the envelope and systems sequentially, which means that some of the interactions must be approximated. As a result, EnergyPlus v2.0 does a much better job of modeling spaces where temperature and humidity are fluctuating. DOE2.2 V44E4 does not model the humidity in the space explicitly, but depends on the system performance to approximate the humidity. If the system is not running very often, then DOE2.2 V44E4 does not really track the humidity at all.

In addition to the major issues described above, EnergyPlus v2.0 offers a whole laundry list of capabilities that are not present in DOE2.2 V44E4. These include thermal comfort calculations, phase change material walls, moisture absorbing walls, more advanced HVAC

controls, building-integrated PV, explicit modeling of the impact of PV on attic temperatures, heat pump water heaters, and micro combined heat and power systems. EnergyPlus v2.0 is adding new capabilities with each release. With significantly more resources available to the EnergyPlus v2.0 development team than the DOE2.2 V44E4 development team, the gap in capabilities is likely to widen over time.

#### ***4.5 Suggested Path for Tailoring EnergyPlus v2.0 to Residential Optimization***

The current version of EnergyPlus (2.0.0) has nearly all of the necessary capabilities to model most single family residential buildings. There are a few remaining modeling problems to be solved before EnergyPlus v2.0 will really be ready for widespread use in residential optimization, which were discussed earlier in this report. It seems likely that they will be completed over the next few releases. At that point, EnergyPlus v2.0 will be ready to be used as a residential building research tool. Over time, more advanced residential building models can be added, as they have been added over the EnergyPlus' life. EnergyPlus will be a very robust research tool for residential building energy analysis at that point. Unfortunately, the simulation time will still be much longer than DOE2.2 V44E4 and probably too long for broader applicability in residential optimization. For the tool to be more broadly applicable, the speed/accuracy tradeoffs will need to be analyzed to optimize the efficiency of the simulation engine. Enabling expert users to turn on speed shortcuts could provide the speedup necessary for broader use. One can hypothesize that in a high performance home, where the wall surfaces have temperatures that are close to each other, that the advantages of the full longwave radiation balance are nonexistent. There may be other possibilities for speeding up the longwave radiation balance. If EnergyPlus v2.0 was about 3-4 times faster than it is now and it included the necessary improvements in modeling capability, it would be the superior simulation engine for

residential energy optimization, in the opinion of the author. An EnergyPlus version that is any less speedy and powerful than that will have more limited applications.

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## **Appendix I: Infiltration, Natural Ventilation, Duct Leakage and Mechanical Ventilation in BEopt 0.8.0.4**

Modeling infiltration interactions accurately is not easy using any of the simulation tools currently available. The method of superposition should be used to add different flows in quadrature, according to ASHRAE HOF (2005), along the lines of the Sherman-Grimsrud (LBL) model (Sherman and Grimsrud, 1980). Infiltration is fundamentally driven by a pressure differential across the building envelope causing airflow through openings in the envelope. The pressure differential is caused by wind, buoyancy of indoor air, unbalanced exhaust, and unbalanced duct leakage. The airflows driven by each of these sources should be added in quadrature, since pressure is proportional to velocity squared and therefore is proportional to flowrate squared. Ideally, the Sherman-Grimsrud model would be used to calculate infiltration, with the 4 pieces added in quadrature on an hourly basis.

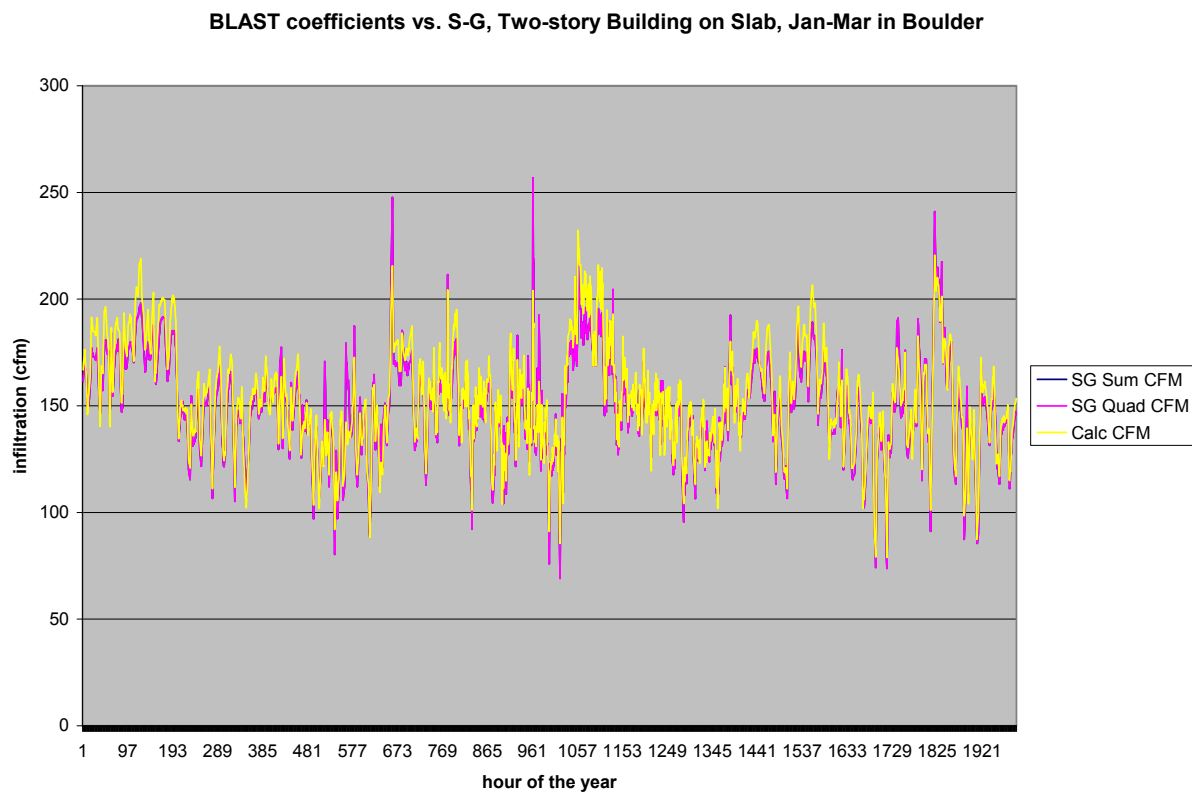
DOE-2 has the Sherman-Grimsrud model available, but does not add the unbalanced mechanical ventilation and duct leakage imbalance in quadrature. DOE2.2 V44E4 adds these unbalanced flows whole instead. The result is that the energy impacts of duct leakage and unbalanced exhaust flows are grossly overestimated when using the DOE2.2 V44E4 S-G model. These interactions are very important in BEopt 0.8.0.4 to determine the efficacy of different options. As a result, we have decided to use the DOE2.2 V44E4 residential infiltration model with adjustments applied for duct leakage, mechanical ventilation, and building characteristics.

In the DOE2.2 V44E4 residential model,

$$\text{ACH-infil} = C_1 + C_2 * V_{\text{wind}} + C_3 *(T_{\text{inside}} - T_{\text{outside}})$$

In BLAST, the default values for these coefficients  $C_1$ ,  $C_2$ , and  $C_3$  were 0.606, 0.0605, and 0.0202, respectively, for  $V_{\text{wind}}$  in knots and  $(T_{\text{inside}} - T_{\text{outside}})$  in degrees F (EnergyPlus, 2007). It turns out that these coefficients do a reasonable job of approximating the shape of the daily

variation seen with Sherman-Grimsrud. While the match is not perfect, one can see that the hourly results from the BLAST coefficients reasonably approximate the Sherman-Grimsrud results. The largest error occurs during hours when there would be no infiltration normally, since the residential model has a large constant term. These hours are not as important, since they have low infiltration and low temperature differential, so they also have low energy use impact.



**Figure 28: Comparison of BLAST and S-G Infiltration Calculation**

There is clearly the possibility to use the residential DOE2.2 V44E4 infiltration model as a workaround to approximate the energy impacts of infiltration interactions. The basic approach is to modify the residential coefficients in the following way:

$$\text{INFIL} = f(C_1, C_2, C_3) = C_1 + C_2 * V_{\text{wind}} + C_3 * (T_{\text{inside}} - T_{\text{outside}}) \text{ (from above)}$$

$$\text{INFIL}(\text{BLAST}) = f(B_1, B_2, B_3)$$

$$\text{INFIL}(\text{WORKAROUND}) = M * f(C_1, B_2, B_3)$$

The whole infiltration is adjusted to the building characteristics using the multiplier, M. The wind and temperature coefficients are used as is, while the constant term coefficient needs to be adjusted to include the effects unbalanced flow (U), which should be added in quadrature to the BLAST constant coefficient.

The resulting equations:

$$\text{INFIL} = f(M * (B_1^2 + U^2)^{0.5}, M * B_2, M * B_3)$$

$$M = f(\text{Bldg}, U_{\text{mech}}, U_{\text{duct}})$$

We now have a form of equations that we can use. The only thing left to do is come up with an empirical formula for M, so that the resulting annual energy use resulting from total infiltration calculated using the DOE2.2 V44E4-residential workaround is as close as possible to the total infiltration calculated using the Sherman-Grimsrud infiltration model with the principle of superposition for adding mechanical ventilation and duct leakage.

#### Applying the workaround in DOE2.2 V44E4

DOE2.2 V44E4 will calculate infiltration based on the infiltration model, then add in the duct leakage and mechanical ventilation at 100%, not using superposition. In the DOE2.2 V44E4 workaround, mechanical ventilation is rolled into the constant term of the residential infiltration model, while duct leakage is calculated by DOE2.2 V44E4 and added whole. The adjustment to

the overall infiltration includes the duct leakage impact, effectively reducing the infiltration model output to allow for DOE2.2 V44E4's treatment of the duct leakage.

Here is the infiltration statement from the doe2.bmi file:

```
RES-INF-COEF = (@ConstantInfilCoef*@ACHDesign, 0.0605*@ACHDesign,
0.0202*@ACHDesign)
```

This is equivalent to the infiltration workaround equation from before:

$$\text{INFIL(WORKAROUND)} = M * f(C_1, B_2, B_3)$$

M is equivalent to @ACHDesign; C<sub>1</sub> is @ConstantInfilCoef; B<sub>2</sub> is 0.0605; and B<sub>3</sub> is 0.0202.

@ACHDesign and @ConstantInfilCoef need to be calculated.

@ConstantInfilCoef can be calculated by adding the unbalanced mechanical ventilation to the constant infiltration term in quadrature,

$$C_1 = (B_1^2 + U^2)^{0.5}$$

Unfortunately, the balanced flow of the ERV needs to also be included in the infiltration calculation. The result is that

$$C_1 = (B_1^2 + U^2)^{0.5} + B_{\text{erv}}/M.$$

The ERV term needs to be divided by the multiplier to ensure that the ERV operation is independent of the infiltration.

Here is the resulting equation from the global.bmi file:

Set @ConstantInfilCoef = (((@LivingRoomAndGarageFLA \* 95/0.0005\*0.606)^2 +  
 @UnbalancedMechVentRate^2)^0.5 + @MechVentRate/@InfilAdjCoeff \* (1-@ERVeff) \*  
 (@ERV)) / (@LivingRoomAndGarageFLA \* 95/0.0005)

All of the equations in the doe2.bmi file are based on a reference case with fractional leakage area (FLA) = 0.0005, design infiltration = 95 cfm, floor area above grade = 1800 ft<sup>2</sup>, and design ACH = 0.423. In the equation above, @ERV is the ERV flag, equal to 1 when there is an ERV present, 0 when there is no ERV; @ERVeff is the efficiency of the ERV; @LivingRoomAndGarageFLA is the fractional leakage area of the living space; @UnbalancedMechVentRate is the unbalanced mechanical ventilation rate; and @InfilAdjCoeff is the infiltration multiplier, which is calculated using an empirical equation. The term (@LivingRoomAndGarageFLA \* 95/0.0005) is a conversion factor to convert the constant coefficient into reference case cfm.

Here is the equation for @UnbalancedMechVentRate from the global.bmi file:

Set @UnbalancedMechVentRate = (1-@ERV) \* @MechVentRate

When there is an ERV, there is no unbalanced mechanical ventilation, so the variable @UnbalancedMechVentRate goes to 0. In the case of the BABM, balanced mechanical ventilation is specified. In order to model this, the variable @ERV is set to 1 to simulate balanced mechanical ventilation, while the variable @ERVeff is set to 0, since there is no heat transfer between the entering and exhaust streams.

@ACHDesign needs to be calculated as a function of the fractional leakage area and the infiltration multiplier, @InfilAdjCoeff.

Set @ACHDesign = @LivingRoomAndGarageFLA \* 0.423/0.0005 \* @InfilAdjCoeff

The first part of the equation adjusts the design infiltration ACH according to the fractional leakage area. The last variable, @InfilAdjCoeff is a multiplier that adjusts the infiltration in order to match the annual energy results from a Sherman-Grimsrud with superposition calculation. The results will vary with the building characteristics and the size of the unbalanced mechanical ventilation flow rate and unbalanced duct leakage relative to the stack and wind-driven infiltration.

The basic form of the equation used to develop @InfilAdjCoeff is:

$$M = A + B * U_{duct,n} + C * U_{mech,n} + D * U_{duct,n} * U_{mech,n}$$

M is the infiltration multiplier;  $U_{duct,n}$  is the unbalanced duct leakage normalized to the design environmental (wind and stack) infiltration;  $U_{mech,n}$  is the unbalanced mechanical ventilation normalized to the design environmental infiltration; A, B, C, and D are empirical coefficients.

The coefficients A, B, C, and D will be different in different building types, based on how many stories the building is and what type of basement it has. This affects the leakage distribution and the size of the stack and wind effects on the building. Number of stories has the largest impact.

Here is the same equation, as depicted in the global.bmi file:



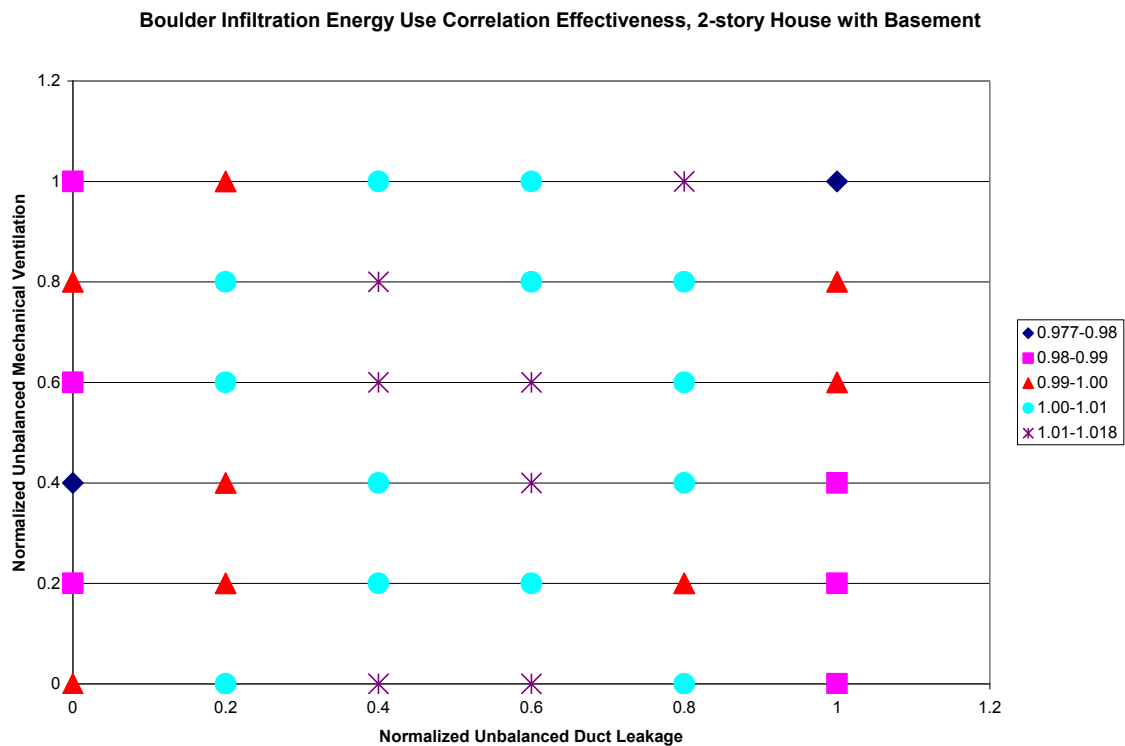
$$\begin{aligned} @InfilAdjCoeff = & A - (B * @DuctImbal + C * @AdjMechVentRate) / \\ & ((@LivingRoomAndGarageFLA * @TotalFloorAreaAboveGrade/1800 * 95/0.0005) + (D * \\ & @DuctImbal * @UnbalancedMechVentRate)/ (@LivingRoomAndGarageFLA * \\ & @TotalFloorAreaAboveGrade/1800 * 95/0.0005)) \end{aligned}$$

#### Developing Coefficients for the Infiltration Multiplier Equation:

In order to model the interactions and building variability accurately in DOE-2, a spreadsheet version of the Sherman-Grimsrud model was developed (s-g fitting new.xls). The spreadsheet calculates the different infiltration components separately, then adds them in quadrature to calculate the total infiltration that one would expect using the principle of superposition, in exactly the way ASHRAE suggests. The model estimates hourly duct leakage as a function of design duct leakage and temperature difference to the outdoors (strictly a UA-based model).

The hourly Sherman-Grimsrud spreadsheet model was used to find the best value of the infiltration multiplier, @InfilAdjCoeff for a range of duct leakage imbalance and mechanical ventilation values in four different building types: two-story with unventilated foundation, two-story with ventilated foundation, one-story with unventilated foundation, and one-story with ventilated foundation. The best value of @InfilAdjCoeff is the one that results in the lowest difference in the annual infiltration energy impact between the DOE2.2 V44E4 workaround infiltration and the proper Sherman-Grimsrud value. This places greater emphasis on accuracy when there is a large difference in air temperature between outside and inside. The hourly spreadsheet was run using Boulder TMY2 data and heating and cooling setpoints of 71 and 76 degrees F, respectively, with a parametric of 6 normalized duct leakage and mechanical ventilation values, 0, 0.2, 0.4, 0.6, 0.8, 1.

For each of the 4 building types, a set of values for the coefficients A, B, C, and D were derived for use in the equation for @InfilAdjCoeff, using a least squares fit of the 36 different normalized duct leakage and mechanical ventilation combinations. The resulting model of infiltration should give annual energy impacts that are quite close to Sherman-Grimsrud (very close in Boulder). Testing has not been performed to determine the error in using this method in other climates. In Boulder, the DOE2.2 V44E4 workaround correlation predicts annual energy impacts of infiltration within 2% of Sherman-Grimsrud with superposition for 2-story houses, and within 4% of Sherman-Grimsrud with superposition for 1-story houses. It was also determined that the foundation type only caused a 3% possible range of error between the slab and ventilated crawlspace. As a result, the set of coefficients derived for the slab are being used for all foundation types.



**Figure 29: Infiltration Correlation Compared to S-G Model for Range of Duct Leakage and Unbalanced Mechanical Ventilation**

The resulting values for the coefficients are summarized in the table below:

**Table 24: Residential Infiltration Adjustment Coefficients**

Building	A	B	C	D
Two-story	0.9334	-0.326	-0.109	0.0739
One-story	0.7374	-0.302	-0.031	0.0598

### Duct Leakage:

Duct leakage location varies according to the Benchmark. Leakage is split out into 4 different areas: return ducts, supply ducts, and return and supply side of the air handler.

If there is a basement or crawlspace then the air handler is in the basement. If there is a slab, then the air handler is in the attic. If there is one story, then all duct leakage is in the same location as the air handler. If there are two stories, then 65% of the supply duct leakage occurs in the same location as the air handler. In the case of the Benchmark, it is assumed that 60% of the air handler leakage is on the supply side and 40% is on the return side. The duct imbalance is given by subtracting the total return leakage (AH return leakage + return duct leakage) from the total supply leakage in unconditioned space (supply duct leakage in unconditioned space + AH supply leakage). In the case where the basement or crawlspace is unventilated/conditioned, then half of the duct imbalance is made up of outside air.

#### Mechanical Ventilation:

Mechanical Ventilation is set according to ASHRAE 62.2:

$$\text{CFM} = 0.01 * (\text{finished floor area}) + (1 + \text{Bedrooms}) * 7.5$$

The default (no ERV) option considers this mechanical ventilation to be provided by an exhaust fan (unbalanced flow), which interacts with the infiltration. In the case of the BABM, mechanical ventilation is balanced and does not interact with the infiltration. This is modeled as an ERV with 0 efficiency.

When an ERV is modeled, then an effective airflow is added whole to the constant portion of infiltration. The ERV assumes that the energy impact of the ERV is the same as having a balanced flow equal to  $(1 - \text{ERV}_{\text{eff}}) * \text{Mechanical ventilation flow rate}$ . There is an implicit assumption that the ERV has the same sensible and latent effectiveness. This is OK if the ERV is being used to model actual ERVs or HRVs in very dry climates. This approach should NOT be used to model HRVs in climates with moist outdoor air.

Natural Ventilation:

Natural ventilation swamps all other flows. In the benchmark, mechanical ventilation is turned off when natural ventilation is occurring. We do not model this effect, leaving ventilation on during times of natural ventilation, since the energy impact is small. Natural ventilation occurs according to the Benchmark, enabled 3 days per week, with flow rate set by the window area. It does NOT vary with wind speed or other environmental effects. When the natural ventilation is enabled, if opening the windows can meet the cooling load, then it is assumed that the windows are opened and there is just enough cooling to meet the load (the windows are essentially modulated).