

Merging the Power of Simulation with the Simplicity of a Spreadsheet: Heat Pump Savings Calculator

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ABSTRACT

One of the ultimate goals of simulation tool development is to achieve a results feedback loop that is quick enough to be useful throughout the entire design process, without sacrificing accuracy or flexibility. This has led to the pursuit of quicker, user-friendly, and more meaningful simulation tools, whose ease of use could deliver simulation from the margins of design practice to mainstream usage. At one end of the spectrum is the humble spreadsheet, and at the other is the timestep dependent, text-based environment of powerful software engines. If the two could be combined in a fashion that capitalizes upon both of their strengths, the resulting tool would effectively leverage the high tech for a more widely accessible energy efficiency design support tool. The proposed paper explores this concept through the development of a user-friendly, macro-free spreadsheet that employs performance curves derived from EnergyPlus simulations of multiple baseline and heat pump HVAC systems and scenarios. The simulations provide a ratio between load and predicted energy consumption, in relationship to the size of the equipment. These regressions produce performance curves that the spreadsheet can call to apply advanced HVAC energy calculations, including part load efficiencies, to hourly load data derived from temperature-normalized load calculations using Typical Meteorological Year (TMY) weather data. The product is an easy to use spreadsheet that can conduct sophisticated load reduction and HVAC analysis for a custom-input building, thereby making a performance-based design process a far more achievable reality.

Introduction

Within architectural simulation tools, the relationship of speed, ease of use, and affordability with accuracy, flexibility, and power is often adversarial. Multiple building heating, ventilating and air-conditioning (HVAC) load calculation methodologies exist, all with varying levels of detail that range from annual to sub-hourly capabilities. HVAC calculation, or energy estimation methodologies, are equally if not more diverse. This spectrum covers simply dividing the calculated load by the rated equipment efficiency, to taking into account variable equipment efficiencies according to load and outside temperature. One can quickly see why whole building simulation programs have become so critical in energy analysis within the past 50 years (Crawley, Kummert, and Griffith 2006). Currently, the Department of Energy's (DOE) Building Energy Software Tools Directory (DOE 2014), lists 142 tools under the category of "Energy Simulation," and 115 tools under the "Load Calculation Engine."

Despite the wide range of tools available today, it is still difficult to find a program that can be used deftly throughout the entire design process, whose requirements vary from the requisite speed to conduct rapid conceptual design iterations, to detailed HVAC component-by-component analysis. A market assessment conducted in 2013 by the University of Idaho Integrated Design Lab (UI-IDL) for architects and engineers still listed the learning curve,

program price, and time for analysis as the top three reasons why firms don't use simulation (Dunn and Shaver 2014). A similar study conducted in 2011 by Carl Sterner (2011), corroborates these perceptions. The study found that while architecture firms value "ease of use" and "ease to understand results" and features of analysis programs, both categories had relatively low satisfaction rates. The study also found that among four of the more popular analysis programs, the time required to obtain useful results ranged from 10-25 hours on average, with standard deviations that also range from 10-25 hours.

This paper documents the development of a spreadsheet analysis tool that leverages "pre-cooked" simulation runs to increase the accuracy of rapid energy calculations. The project aimed to provide a tool that was easy and quick to use, but still provided the rigor of simulation-based results. The spreadsheet provides an easy to use interface that allows custom input, while pre-calculated simulation results provide performance curves for ASHRAE Appendix G baseline systems for a variety of heat pump configurations. This type of structure can facilitate tool use throughout the entire design process. Additionally, it makes accurate and flexible analysis more approachable to practitioners and potentially non-expert users. The ability to access the power of simulation by non-trained professionals, especially for the residential industry, is becoming more and more appealing as energy awareness increases publicly.

Project Background

The UI-IDL has developed a series of simplified energy analysis tools over the last five years. The first generation tools included the development of spreadsheets that analyzed peak cooling loads as compared to the capacity of various passive natural ventilation and thermal mass cooling strategies. The second generation tools calculated loads and energy savings from several other technologies such as passive solar and earth tube applications. The tools largely translated existing textbook passive design calculations from Mechanical and Electrical Equipment for Buildings (Reynolds et al. 2006) and Sun, Wind, & Light (Brown and Dekay 2001) into spreadsheet form. This paper documents a third generation of tools, specifically the "Heat Pump Energy Savings Calculator (HePESC)", which provides comprehensive energy use and cost savings estimations for a variety of heat pump technologies.

All three generations of calculation tools were developed in Microsoft Excel, with the ultimate goal of executing analytics earlier in the design process by closing the feedback loop between input, analysis, feedback, and iteration. This third generation tool was designed with more comprehensive analysis capability than its predecessors. The tool has the capability to conduct hourly loads according to TMY data, and utilizes performance curves derived from simulation to estimate energy consumption. The spreadsheet user interface allows custom inputs for geometry, envelope assemblies, internal loads, and schedules to calculate loads for a wide variety of building types. For instance, users can specify wall areas and orientation, U-values for walls, lighting and equipment power densities, infiltration rates, and use default or custom input fractional schedules. On the energy estimation side, system-specific simulated performance curves provide a means to simulate various types of HVAC configurations (heat pumps in this case). This type of tool requires little specialized training and quickens the feedback loop between input and output visualization, thereby making performance-based design process more achievable on more projects. While this tool can be used to help design more efficient buildings, its applications range beyond design and into incentive program development, manufacturer equipment testing, homeowner energy analysis, and academic tools. Additionally, the way the simulated performance curves are used in the tool provides a means to expand its database and

incorporate more functionality and flexibility in the future. The third generation tool is currently at the end of the development phase and is undergoing alpha testing (ICST 2008). It was designed with the following functionality in mind:

Hourly Load Calculations for the Boise, Idaho Climate - other reference cities and climates can be simulated with simple manipulation of the weather file embedded within the spreadsheets. The spreadsheet contains instructions on how to load alternate weather files.

Single Zone Analysis - calculations are performed for a single zone, which requires judgment on how more complex buildings are modeled with the tool. For instance, the spreadsheet could be completed multiple times for distinct thermal zones, or an entire building can be modeled as a single zone depending on what level of simplification is acceptable.

Baseline and Proposed HVAC System Analysis - the tool can model the entire array of the ASHRAE 90.1 2007 baseline systems at different system sizes (ASHRAE 2007). For proposed systems, the development team was most interested in the ability to analyze heat pump technologies including air-source heat pumps, water-source heat pumps, and multi-zone variable refrigerant flow (VRF) systems.

Energy and Utility Cost Analysis - the HePESC provides estimates for annual energy end use, utility costs, and fuel split ratios.

First Cost Analysis - the tool relies on some simple RSMeans (2012) cost estimating exercises, but calculates baseline, proposed, and incremental first costs based on heating and cooling equipment only.

Life Cycle Cost Analysis - a simplified life cycle cost analysis looks beyond simple payback at more advanced metrics that take into account both fuel and currency escalation rates. A cash flow table shows total life cycle cost savings and present worth calculations over equipment service life analysis periods.

Literature Review

The tool development process began with a literature review of the ASHRAE Handbook of Fundamentals (HOF) (ASHRAE 2013) energy estimation techniques, followed by the exploration of currently free, publically available tools developed by other firms or research institutions.

Literature Review – ASHRAE Energy Estimation Calculations

The ASHRAE HOF informed the hybrid load and calculation method used by the HePESC, based on a variety of its energy estimation techniques. First, the “degree-day method” serves as a simple, steady state model that provides an estimate of annual loads and energy consumption (ASHRAE 2013). This method is the simplest process for energy analysis and can be the most appropriate when the building loads and HVAC system efficiency remain constant. It is the most accurate when estimating the annual heating energy for single-zone buildings dominated by skin and outdoor air losses.

All of the simple ASHRAE HOF techniques, including the degree-day method, rely on estimating a balance point and using it in conjunction with a weather file to quantify the effect of

climate on a specific building. Equation (1) shows annual heating consumption based on annual degree-days and how the balance point per degree-days value ($DD_j(t_{bal})$) can be multiplied by the quotient of the total heat loss coefficient (K_{tot}) divided by the system efficiency (n_h) to calculate yearly heating energy. A similar process can be followed for determining annual cooling energy and additional equations can be added account for economizer interactions and latent heat gain. **Error! Reference source not found.** also shows the limitation of this method in that the heat loss coefficient and system efficiency is assumed to remain constant over the year, which is rarely the case. Additionally, this method assumes a constant balance point temperature, which varies over the course of the day, while missing thermal inertia effects and the ability to model HVAC system control.

$$Q_{h,yr} = 24 \left(\frac{K_{tot}}{n_h} \right) DD_j(t_{bal}) \quad (1)$$

Where:

$Q_{h,yr}$ = yearly heating energy

n_h = efficiency of the heating system

$DD_j(t_{bal})$ = number of degree days at a certain balance point K_{tot} = heat loss coefficient

For many applications, ASHRAE recommends that the degree-day method should be avoided, since the balance point temperature, the heat loss coefficient, and the efficiency of the systems typically vary over time. This is especially true with heat pumps, whose efficiencies vary greatly with part load and outdoor temperature. To address these issues, a “bin method” evolved out of the degree-day method. This more advanced method evaluates separately the energy consumption over different temperature intervals, time periods, and operational schedules. The name refers to the method of calculation, where consumption is calculated for several temperature intervals and multiplied by the number of hours within this “bin.” Equation (2) shows that the amount of consumption for said bin (Q_{bin}) is based on multiplying the difference between the load (K_{tot}) and the system efficiency (n_h) by the difference between a constant balance point and specific outdoor temperature ($[t_{bal} - t_o]$), multiplied the number of hours with the outdoor temperature (N_{bin}). Breaking apart the analysis into bins based on outdoor temperature allows for variable conditions to be met, but increases the time and effort required when executing this more detailed analysis. Furthermore, finding part load performance data for equipment can be challenging. Performance curves must often be developed for each system type or model number and applied to the appropriate individual temperature bin.

$$Q_{bin} = N_{bin} \left(\frac{K_{tot}}{n_h} \right) [t_{bal} - t_o]^+ \quad (2)$$

Where:

Q_{bin} = energy consumption for said bin

N_{bin} = number of hours in the temperature interval bin centered on said temperature

K_{tot} = total heat loss coefficient of the building in Btu/hr-deg F

n_h = efficiency of heating system at said bin

t_{bal} = balance point temperature in deg F

t_o = outside air temperature in deg F

The HePESC tool uses the same energy balance equation as the bin method, but calculates loads on an hourly basis. This allows the tool to calculate the balance point, heat loss coefficient, and internal loads for every hour of the year according to custom user inputs and schedules. The result is the most detailed bin method, or granularity, possible while automating calculations within the spreadsheet for speed and ease. Additionally, the equipment efficiency is calculated and applied hourly for these variable conditions and loads using performance curves derived from simulation. Section 4 describes these methodologies in more detail.

Literature Review – Existing Tool Summary

The second phase of the literature review involved searching for existing tools that utilized these types of energy estimation methodologies. The search was limited to tools that specifically analyzed heat pump energy calculations and sizing procedures. The team studied nine different tools, all publically available on the internet for no cost.

Table 1 shows these nine tools, in addition to the HePESC, and whether they meet 17 different criteria. Each criterion is described below:

- Year – the year the tool was “published” and made available.
- Excel Based – whether or not the tool is based in Excel. Some tools were HTML websites, others were pieces of software that required downloading and installation.
- Residential Only – shows if the tool only models residential projects.
- Not Equipment Specific – designates if the tool models specific HVAC types, or if the user only inputs a generic efficiency value.
- ASHP – shows if the tool can model air source heat pumps
- WSHP – shows if the tool can model water to air heat pumps
- Simplified Load Calculations – a simplified load calculation assumes a heating and cooling load, typically by building type, instead of calculating the peak loads based on user inputs about the building in question.
- Detailed (hourly and specific) load Calculation – describes if the tool calculates project-specific hourly loads, i.e. supports user input of building envelope, geometry, operating characteristics, loads, etc.
- Simplified Energy Calculation – calculates energy by dividing the load by a constant equipment efficiency.
- Detailed (hourly and specific) Energy Calculation – provides energy calculations that take into account equipment part load efficiencies in some form.
- Provides Performance Levels – the tool provides a way to simulate different performance specifications for energy calculations such as low efficiency, code baseline, high performance etc.
- First Cost Analysis – the tool has the ability to calculate first costs of different building or HVAC configurations.
- Energy Cost Savings – calculates energy costs based on utility cost assumptions or inputs.

- Life Cycle Cost Analysis – combines energy savings calculations with first cost and utility savings to conduct simplified life cycle cost analysis.
- Comparative – structures calculations to compare different cases against one another.
- Graphic Outputs – displays results in a graphic form.
- Existing Buildings – allows for the specification of existing building information and systems; some tools only allowed for the analysis of new construction.

A wide variety of capabilities and functionality existed amongst the tools analyzed, although most tools were based in excel. Some were very simple spreadsheets and others contained sophisticated macros and calculation worksheets, or were housed completely on the web. Only three of the tools calculated specific loads for specific geometry, user-defined internal gains, and schedules, while most used very simplified assumptions to estimate energy savings. These three tools used some form of the bin method to calculate detailed loads, although the exact method used was hidden by the spreadsheet's formatting and password-protected cells. Additionally, only four tools provided detailed energy calculations taking into account part load conditions of heat pumps and other system types. One tool calculated both detailed loads and used detailed energy calculations, however, it only calculated the size of heat pumps and not energy consumption. Finally, any tool that calculated a life cycle cost analysis utilized very simple assumptions and generally did not account for inflation, fuel escalation, or maintenance costs.

Tools worth noting include the Energy Star Tool (Energy Star 2014), developed by ENERGY STAR®, which was both formatted well and performed life cycle cost analysis. However, it did not calculate loads specifically or HVAC energy in a detailed manner. It does allow input of a wide variety of cities, but contains automated assumptions for first costs and equipment efficiencies of both a conventional and ENERGY STAR®-qualified air source heat pump units only.

Next, as the Arizona School Facilities Board's (AZSVB) Heat Pump Energy Usage and Payback Calculator (AZSVB.gov 2014) was one of the three tools that calculated detailed energy calculations. It accomplished this level of functionality by allowing the designation of two bins, off-peak and on-peak hours, although no guidance was provided on how to define these values. The energy calculations designated equipment efficiencies based on these two values, but the equations were not made available to the user. Additionally, this tool does not contain user inputs for building characteristics or loads, and only focused on mechanical equipment specification.

The Puget Sound Energy (PSE) Heat Pump Sizing Calculator (PSE 2014), served as the only tool that allowed custom inputs for building characteristics and detailed energy calculations. The spreadsheet included dropdown options for envelope characteristics and other inputs. However, these calculations were intended to help size heat pumps for residential projects only. Additionally, the assumptions and data for the different generic heat pump capacities were housed within two unorganized and unformatted spreadsheet tabs.

Finally, the DOE FEMP Energy Cost Calculator for Commercial Heat Pumps tool (Energy.gov 2014) provided analysis on a wide range of heat pump types and calculated fairly detailed life cycle cost analysis, but failed to calculate loads for a user input building. It did, however, compare existing HVAC to new heat pumps and took into account detailed energy calculations through the specification of integrated part load value (IPLV). The tool also suggested default values for its multiple user inputs. Finally, it calculated a wide range of metrics

based on the user input case, a baseline model, the FEMP recommended equipment performance level, and the best available heat pump.

Table 1. Literature review comparison matrix

Tool	Year	Excel Based?	Residential Only	Not Equipment Specific	ASHP	WSHP	Simplified Load Calc	Detailed (hourly and specific) load Calc
EnergyStar Tool	2008	x			x		x	
Wis Energy Center - Back of Envelope Calc		x		x	x	x		x
AZSFB Energy Usage and Payback Calculator		x		x	x	x	x	
John Cantor's Tool	2008	x	x			x		
PSE Heat Pump Sizing Calculator		x	x					x
DOE FEMP Calculator					x	x	x	
Nebraska Public Power District			x				x	
Sun Wind & Light Beta Heat Calc	2013	x			x	x		x
HPESC Tool	2014+	x			x	x		x

Tool	Simplified Energy Calc	Detailed (part load/performance curve) Energy Calc	Provides Performance levels?	First Cost Analysis	Energy Cost Savings	Life Cycle Cost Analysis	Comparative	Graphic outputs?	Existing Buildings?
EnergyStar Tool	x		x	x	x	x	x		
Wis Energy Center - Back of Envelope Calc	x				x			x	
AZSFB Energy Usage and Payback Calculator		x		x	x	x			
John Cantor's Tool		x							
PSE Heat Pump Sizing Calculator		x						x	
DOE FEMP Calculator	x			x	x	x	x		x
Nebraska Public Power District	x				x		x	x	
Sun Wind & Light Beta Heat Calc	x		x		x	x	x	x	
HPESC Tool		x	x	x	x	x	x	x	

After the literature search, the team decided on the final format and capacity of the tool, shown as tool 10 (HPESC TOOL) in

Table 1. The team chose an excel-based tool without macros to provide the widest accessibility possible. The main goal included execution of both detailed, specific load and energy calculations. Additionally, the tool aimed to allow the simulation of multiple HVAC system types at different performance levels, which could feed into energy savings, utility cost savings, first cost, and life cycle cost analysis. The tool can be used for either residential or commercial custom applications, although its default values only reference commercial building types. Much effort was put into automating as many of the default values as possible by building type to speed up the input process, without sacrificing customizability through user ability to override these values. The tool also has the ability to analyze an existing building, although baseline analysis is limited to ASHRAE 90.1 2007 baseline building types. Finally, the tool sought to provide rich graphic outputs as well as a fairly intuitive user interface. All background equations, calculation engines, and methodology were to be transparent to allow for both education of the user and the ability to customize or modify calculation methodology.

Methodology

Load Calculation Approach

The approach built upon existing ASHRAE calculation methodologies and integrated their format into spreadsheets that leverage whole-building simulation when necessary. At its core, the tool serves as the next step past the ASHRAE Annual Degree-Day and Bin Method of energy estimation techniques. Therefore, it can be considered a hybrid of Bin Method and whole building simulation, while it is substantially faster than most simulation programs in both its input and output processes. The tool also accounts for hourly load calculations, unique building geometry and operating characteristics, and varying HVAC efficiencies for a variety of heat pump technologies.

The tool achieves this level of analysis through the following improvements to the modified bin method and annual load calculation. First, the tool utilizes a complete TMY data file to achieve hourly “bin” analysis and load calculations. This provides the finest granularity of “temperature bins” according to the climate data and operational schedule, but does not impact the speed or difficulty of conducting analysis. The tool calculates annual heating and cooling loads by applying heat gain and loss coefficients, derived from envelope and outdoor air user inputs, on an hourly basis as shown in Equation (3). This equation also shows the incorporation of internal and solar gains into the hourly calculation. It is important to note that discussing how these heat transfer coefficients are calculated for the envelope, internal gains, etc., while important, are not within the scope of this paper. This particular research focuses more on innovative ways to apply heat transfer coefficients to annual weather data and new methods of HVAC energy estimation. More detail can be found on the specific component-by-component load calculation methods in a separate technical report created for this research (Dunn et al. 2013)

Equation (3) shows that once heat transfer coefficients are calculated, the tool applies these values to the weather data’s temperature difference between outdoor air (t_o) and user defined thermostat schedules (t_{sp}). The heating or cooling setpoint used for this calculation is based upon an hourly balance point calculation to determine which setpoint is used or if the building does not require conditioning. This method calculates the load in Btus through the

envelope and for ventilation/infiltration. Next, internal heat gains ($q_{\text{int gains}}$) and solar gains (q_{solar}) are also calculated on an hourly basis based on user inputs that are multiplied by default or user-defined fractional schedules. A positive sum of the equation's components results in a cooling load, while a negative value results in a heating load. The tool repeats this process for all hours of the year to create an annual load profile. The hourly load is used in the HVAC energy estimation methods covered in the following section of this paper.

$$q_{hr\ 1} = K_{\text{tot,env}}[t_o - t_{sp}]^+ + K_{\text{tot,OA}}[t_o - t_{sp}]^+ + q_{\text{int gains}} + q_{\text{solar}} \quad (3)$$

Where

$q_{hr\ 1}$ = load in Btus for the first hour of the TMY weather file

$K_{\text{tot,env}}$ = heat transfer coefficient for the opaque and glazed portions of the envelope

$K_{\text{tot,OA}}$ = heat transfer coefficient for the ventilation and infiltration air

t_o = outdoor air temperature from the TMY data

t_{sp} = thermostat set point – based on user input and balance point

$q_{\text{int gains}}$ = heat gain from lights, plug loads, and people in Btus

q_{solar} = heat gain from solar radiation

HVAC Equipment Consumption

As mentioned in the literature review, the bin method utilizes temperature data points to determine HVAC equipment efficiencies based on part loads, and applies them to a wider range of temperature bins for a more direct analysis of the project. However, this still required getting detailed performance data on target HVAC equipment and calculating the correct efficiency based on the temperature bin range in question. This can be a laborious task and the UI-IDL chose to use a different method using simulation to calculate HVAC energy based on the load calculation described earlier in this paper.

Once the user specifies building characteristics, geometry, and other operating parameters in the spreadsheet graphic user interface of the tool, they can also select both a baseline and a proposed HVAC system type. The HePESC can model all eight ASHRAE 90.1 baseline system types and also includes additional all-electric system options. For the proposed systems, the tool supports a variety of air source heat pumps, zonal water source heat pump systems, and single zone or multi-zone VRF heat pumps. The calculations include default heating and cooling equipment sizing factors, but can be easily overridden by the user. For system types whose efficiency requirements vary by size, users can also select from a range of Btu/hr capacity ranges. However, this requires judgment on the user's part in how to select the representative size of the equipment based on the thermal zoning of the building. Depending on the granularity of the zoning and the application of this tool, the system may be left at a smaller size to represent multiple smaller pieces of equipment. Alternatively, fewer larger units may also be specified depending on the project's zone configuration. This section of the tool also reports the reference occupant density, a critical value in determining which performance curve to use, and an efficiency table. This table provides the user with the cooling and heating Seasonal Energy Efficiency Ratio (SEER), Coefficient of Performance (COP), and thermal efficiency of the selected system.

Instead of using the annual degree-day or bin method equations as described in the literature review, this tool uses a hybrid simulation method to account for part load and seasonal

equipment efficiency calculations. This method relies on using multiple EnergyPlus simulations to calculate the ratio of energy consumption to load percentage. This relationship is then applied to the loads calculated by the spreadsheet to estimate equipment energy consumption. This method allows the spreadsheet to leverage simulation and easily provide equipment part load calculations at varying temperatures, a critical piece of information for heat pump analysis.

To achieve the hybrid simulation approach, the team created simplified energy models in EnergyPlus using a Boise, Idaho weather file and the DOE Commercial Reference Building (Deru et al. 2011) characteristics for the medium office prototype. Next, a model was created for each baseline HVAC system using each system size according to the ASHRAE 90.1 2007 efficiency requirements. Each HVAC system simulation also included two different occupancy densities (5 people/1,000 square feet and 30 people/1,000 square feet) to account for the variable outdoor airflow requirements depending on space type selection. These different performance curve permutations allow users to simulate a multitude of HVAC systems and configurations both accurately and quickly. The spreadsheet contains a total 91 curves, which account for over 10 different system types of varying system sizes, efficiencies, and outdoor air requirements.

Once the team simulated each case, the HePESC tool used the following outputs to create the regressions that informed the performance curves used in the spreadsheet. Figure 1 shows a scatter plot for two heating and two cooling regressions for a sample system, which reports the load-to-peak HVAC equipment size ratio on the horizontal axis, and the HVAC equipment consumption-to-peak HVAC equipment size ratio on the vertical axis for every hour of the year. Equations (4) and (5) show how these two ratios are calculated from the simulation.

$$Ratio_{load} = \frac{q_{hr}}{(q_{pkeq})} \quad (4)$$

$$Ratio_{consumption} = \frac{q_{cons}}{(q_{pkeq})} \quad (5)$$

Where

$Ratio_{load}$ = ratio of the load to the HVAC peak equipment size as calculated by the simulation, or the horizontal axis of Figure 1

$Ratio_{consumption}$ = ratio of the HVAC equipment consumption from the simulation to the simulated peak HVAC equipment size, or the vertical axis of Figure 1

q_{hr} = the hourly load from the simulation

q_{pkeq} = the peak HVAC equipment size from the simulation

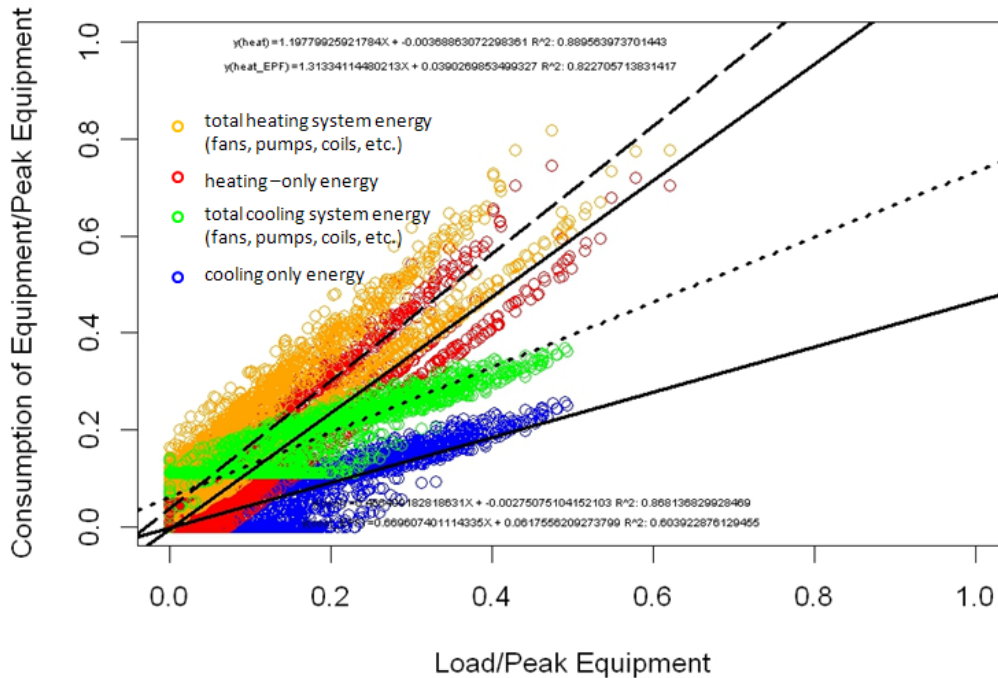


Figure 1. Example of heating and cooling regression curves created from EnergyPlus simulations on the Department of Energy Medium Office Commercial Reference Building. Note the two heating and two cooling curves, which show regressions for heating or cooling equipment only, and also for the total heating or system cooling energy.

The regression plots utilized linear or second-order polynomial regressions to produce the best-fit equation, which defines the relationship between part load performance and equipment consumption for that particular case. Multiple regression types were utilized, and the method with the highest R-squared was used for the performance curve. Equation (6) shows the best-fit equation for a small (less than 65,000 btu/hr) rooftop heat pump example, whose solution will calculate the equipment consumption ratio. Equation (7) shows how the spreadsheet calculates the coefficient that plugs into Equation (6). The spreadsheet inputs its hourly load value (q_{hr}), as described in the previous “Load Calculation Approach” section, divided by the peak equipment load (q_{peq}) into the best-fit equation, which outputs the percentage of equipment consumption relative peak size. In Equation (7), peak equipment size is determined by multiplying the peak loads calculated in the spreadsheet (not the simulation) by default or user input sizing factors for heating and cooling. While the simulation’s load and consumption ratios were used to create the performance curves, the spreadsheet’s hourly loads and peak loads calculations are used in the best fit equation to estimate energy consumption. This allows the tool to produce energy estimations based on a simulation curve for a system type and the loads from a custom, user-defined building.

$$Q_{ratio} = (X * .488) + .115 \quad (6)$$

$$X = \left(\frac{q_{hr}}{q_{peq}} \right) \quad (7)$$

Where

Q_{ratio} = performance curve, solving this equation will produce the consumption ratio of equipment-to-peak HVAC equipment

X = coefficient of the regression's best fit equation

q_{hr} = the load calculated from the spreadsheet for a given hour, shown in Equation (3)

q_{pkeq} = the peak equipment load calculated from the spreadsheet by multiplying the peak load by a default or user-defined sizing factor

Equation (8) shows that once Q_{ratio} is found by using the spreadsheet's hourly load as the coefficient for the performance curve's best fit equation, this percentage factor is then multiplied by the spreadsheet's calculated peak equipment size for heating and cooling separately. This determines the hourly HVAC energy consumption split by heating and cooling.

$$Q_{hr} = Q_{ratio} * q_{pkeq} \quad (8)$$

Where

Q_{hr} = HVAC equipment consumption for a given hour

Q_{ratio} = the ratio of HVAC equipment consumption-to-peak HVAC equipment size

q_{pkeq} = the peak load calculated from the spreadsheet by multiplying the peak load by a default or user-defined sizing factor

It is also important to note that Figure 1 shows four colors and four regression lines. Each color represents heating versus cooling energy, and whether or not the ancillary equipment consumption was calculated in the total, i.e. fans, pumps, etc. By running the calculations for both curve types, the tool calculates the difference between the two which separates the coil energy from the other equipment.

In most cases, these regressions produced reasonably strong R-squared values with an average of .63 for the heating curves and .68 for the cooling curves (fan and pumping equipment included). The curves for just the heating and cooling equipment showed better R-squared values at .78 and .80 for heating and cooling, respectively. Finally the runs with the "low" occupant density, meaning code density for an office, showed even better R-squared values for the heating and cooling curves of .84 and .78, even with equipment included. The R-squared values seemed to be lower when calculated from the simulations with higher densities of occupants (30 ppl/1000 sf).

Curve Variation

As mentioned previously, the performance curves are based on the geometry, internal loads, and schedules of a single-story version of the DOE Medium Office Commercial Reference Building. Although the geometry and operating characteristics of the simulations are generalized, the performance curves serve as reasonably accurate representations of the part load efficiencies of the simulated equipment. Since users will be creating load profiles of a variety of building

types and shapes, all of which use the performance curve derived from a set geometry and building type, an important question becomes whether or not the performance curve varies greatly in these types of situations. While not a true sensitivity analysis, this study provides initial insight into whether or not this method is applicable across a larger body of project sizes and geometries. For instance, if the curve variation is high, then the accuracy decreases on building sizes and shapes that do not match the simulation model the curves were derived from. If the curve does not vary substantially, the curve can be applied to a variety of conditions with reasonable confidence. To begin to explore these variations, the UI-IDL ran the same packed rooftop heat pump HVAC system on the small, medium, and large DOE Commercial Reference Buildings. Figure 2 shows the three performance curves for the three different building for both cooling (left) and heating (right). The cooling curves overlap very closely and are shown not to vary much according to the size or geometry differences between the three models. The heating curves show slightly more variation, but show reasonably similar positions. The variance may be due to the simplification of the zoning strategy of the simulations, which take into account the each floor as a single thermal zone. Higher thermal zone granularity may produce a closer relationship, although the tool is more geared toward single-zone analysis. A similar test was conducted for different climate zones, which showed substantially more variation than the curves below. Consequently, the tool can be considered reasonably representative across size and geometry permutations, but new curve sets need to be developed to represent different climate zones.

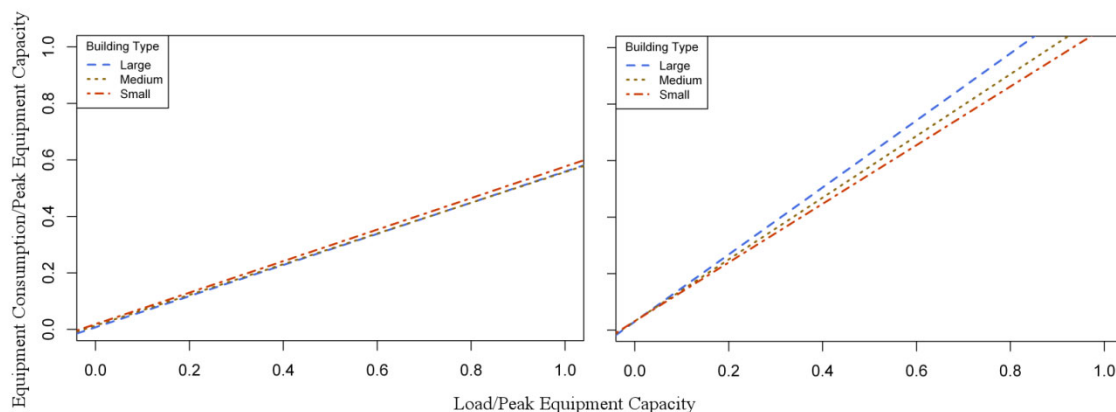


Figure 2. Cooling (left) and Heating (right) Curve Regression sensitivity test on geometry and office DOE Commercial Reference Building types.

Conclusions

The HePESC is a unique contribution to the existing pool of simplified energy calculation tools available. None of the previously available tools leverage simulation to provide detailed energy calculations for a range of different system types and characteristics. No other tool from the literature review can handle custom input of building loads, schedules, and envelope characteristics while outputting both peak load breakdowns and hourly load profiles for the entire year. The customizability, depth, and graphic output of this tool surpasses the capabilities of any public, freely available heat pump energy calculator currently available. While this paper focused primarily on the annual load calculation and energy estimation

methodology using simulation, more information on the tool's graphic user interface, inputs, and outputs can be found in other technical reports produced by the UI-IDL during development (Dunn 2013).

The potential of this type of tool is far reaching. The ability to calculate robust, hourly load calculations with a simple spreadsheet that calls upon a database of pre-simulated performance curves is only limited by the number of curves populating the database. The scope of this tool's development was limited to comparisons between ASHRAE Appendix G baseline equipment and heat pumps, but additional HVAC types and configurations could be simulated and added to the database. This would increase the amount of systems available for analysis. Further, additional options could be developed to support analysis of different control schemes, components such as heat recovery, and a wider range of performance specifications. Additionally, the curves for this tool were regressed from simulations developed using the single-storey version of the DOE's Medium Office Commercial Reference building. While some initial sensitivity tests showed that the performance ratio is not very sensitive to geometry and building size, increasing the curve database for these types of permutations would only increase accuracy and flexibility. Further research is planned for sensitivity studies that prove which parameters affect the curves more profoundly in order to inform future curve development and permutation direction.

With the development of parametric simulation tools with cloud computing integration, such as JEplus, BEopt, and OpenStudio's Parametric Analysis Tool (DOE 2014, running large amounts of pre-cooked simulations is faster and more accessible. This, combined with automating the curve regression process into a database for the spreadsheet to call upon could greatly increase the applicability and accuracy of this and similar tools.

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