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BSTD-19-02 CVRH Project, Red Bead Experiment, Speculation and Paradigms

BSTD-19-02 CVRH Project, Red Bead Experiment, Speculation and Paradigms

HVAC accounts for the largest use of electricity in homes and commercial buildings in the United States. Modern air conditioners and heat pumps include variable speed compressors and fan motors with variable frequency drives (VFDs), which require power to go through a DC phase before converting to the desired AC frequency. The most efficient air conditioners use VFDs and DC permanent magnet motors. Variable-speed operation of compressors and fans allows the output of HVAC equipment to be closely matched to the needs of the building occupants, thus improving energy efficiency.

The above is from Energy Commission published document "Direct Current as an Integrating and Enabling Platform for Zero-Net Energy Buildings"

https://ww2.energy.ca.gov/2019publications/CEC-500-2019-038/CEC-500-2019-038.pdf

CVRH Project is perfectly designed to get the results in the reports. Of course that can be said of anything humans design and build.

If CVRH Project were run for all possible combinations, I believe it would soon be identified that there is process variability that would show the method does not have value in accurately predicting energy efficiency of buildings and their HVAC systems.

CVRH Project brings to mind Deming's Red Bead Experiment, https://youtu.be/geiC4UgpDyw that addresses process variability.

Other writings such as "Improved Modeling of Residential Air Conditioners and Heat Pumps for Energy Calculations" https://www.nrel.gov/docs/fy13osti/56354.pdf appear to address the same problems the CVRH Project is trying to solve. Each appear to try to provide a solution by adding a special factor or two to prior known tests such as SEER, EER, HSPF and COP.

CVRH Project shows control system bias in not reporting real-time humidity with temperature even though there is a attempt to simulate humidity and temperature of a occupied building. Is there a test setup procedure for the simulated humidity and temperature method? Perhaps the simulation did not perform as required?

CVRH Project methods have not been tested and reviewed enough to provide a results beyond speculation. Speculation has no place in regulations.

Perhaps SEER, EER, HSPF and COP should be compared with coil sizes and air flow for each

HVAC system?

Motor rpm and run capacitor value tolerances and power requirements should be compared to published motor specifications to ensure that worst case is taken into account.

Motor inrush current duration should be given values to encourage reduction of the effect of synchronous events caused by time of day electricity pricing.

Perhaps in changing metrics for HVAC systems, improving energy efficiency as spoke of in CEC-500-2019-038 can be realized with less variation, thus providing high quality of service?

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Additional submitted attachment is included below.

Improved Modeling of Residential Air Conditioners and Heat Pumps for Energy Calculations

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NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Technical Report
NREL/TP-5500-56354
January 2013

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NATIONAL RENEWABLE ENERGY LABORATORY

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Prepared under Task No. BE12.0103

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Executive Summary

This report presents improved air conditioner (AC) and heat pump (HP) modeling methods in the context of whole-building simulation tools. Its goal is to enable more accurate evaluation of cost-effective equipment upgrade opportunities and efficiency improvements in residential buildings.

EnergyPlus and DOE-2 AC and HP model algorithms and required inputs were investigated (see Section 2). This was accompanied by a survey of the available AC and HP performance data. Manufacturer-expanded performance tables were initially deemed the best option for generating model inputs, and an effort was undertaken to compile these tables into a usable format. This effort resulted in a database that contained performance data on 460 AC and HP systems. Section 3 describes the data evaluation process and highlights several issues. The database was used to generate the necessary model inputs for each system.

Annual simulation results using unit-specific inputs were not as consistent as expected (see Section 4). These differences included wide ranges of predicted efficiency for a given seasonal energy efficiency rating (SEER) value (both within a single manufacturer's product lines and across manufacturers), and significant SEER overlap (lower SEER families outperformed higher SEER families). Current shortcomings in consistency and completeness of manufacturer data are presented.

These inconsistencies prompted an analysis of the performance data used to generate model inputs. Section 5 presents an analysis of the sensitivity to the modeling inputs that revealed little sensitivity to the selected performance curves used to predict off-rated performance. Using unit-specific performance curves did not have a significant impact on predicted efficiency. Therefore, annual simulations in Houston, Phoenix, Atlanta, and Chicago were run at three airflow rates to select and test a standardized set of performance curves. The results supported initial observations that the impact of unit-specific curves was limited. Using a standardized set of performance curves greatly reduces the complexity of generating model inputs.

Following the performance curve sensitivity study, the impacts of the rated performance values on the annual simulation results were evaluated. The study showed that the rated values were driving the variation and inconsistency observed in initial simulations. It was therefore necessary to evaluate the quality of the rated value modeling inputs generated from manufacturer data (see Section 6). This was accomplished by comparing manufacturer data to the Air Conditioning, Heating, and Refrigeration Institute (AHRI) Directory of Certified Product Performance (AHRI 2012). Its data are based on well-regulated testing procedures; AHRI is the most consistent data source available. These comparisons showed significant differences between AHRI and manufacturer data.

When simulating ACs and HPs in the context of a whole-building simulation tool, the standard set of performance curves presented in this report should be used with unit-specific rated performance values obtained from AHRI. Section 7 presents a library of AC and HP modeling inputs with a set of standardized performance curves to facilitate energy and cost comparisons. This modeling approach simultaneously reduces the complexity of the model inputs and increases the agreement with the SEER and heating seasonal performance factor rating procedures.

Figure ES–1 highlights the benefit of using a standard AC modeling library over unit-specific inputs (when comparing AC energy use across SEER families). The figure displays a simulated annual average efficiency for the unit-specific model inputs (shown as dots) and the standardized set of model inputs (shown as solid lines). The unexpected and inconsistent trends associated with using unit-specific inputs limit their usefulness when making energy and cost comparisons across varying efficiency levels.

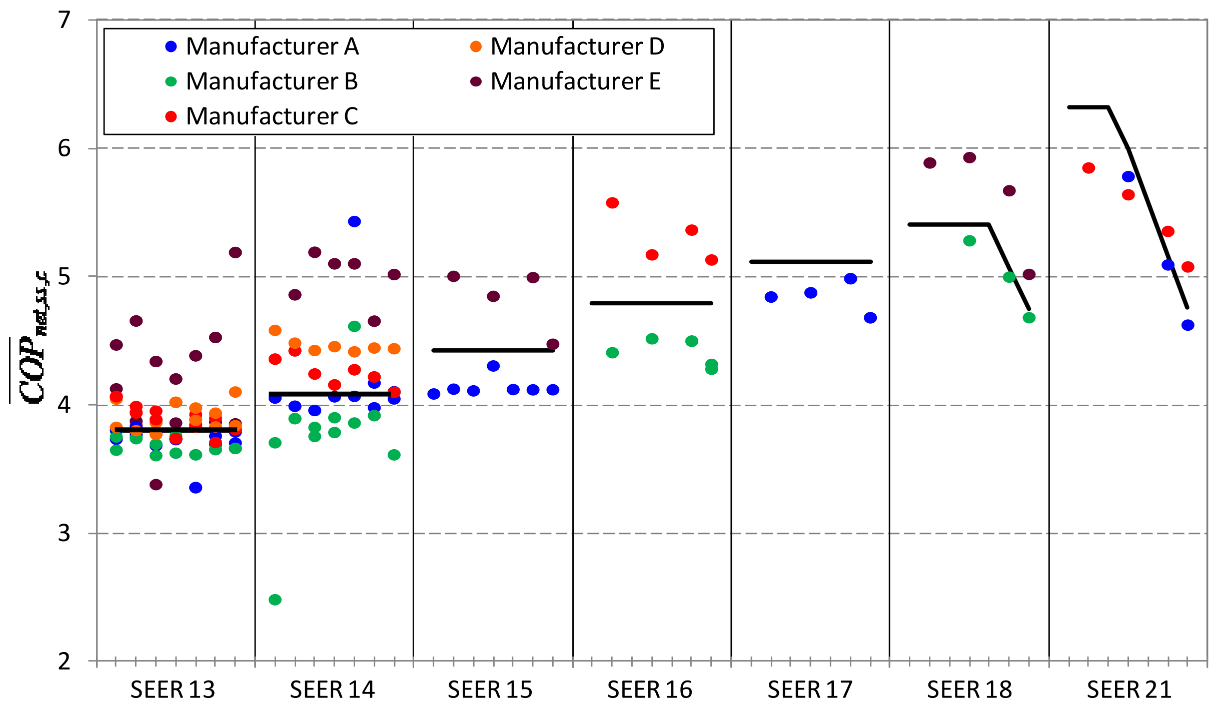

Figure ES–1. Simulation results comparing annual average efficiency of a standard AC component library (shown in black lines) to specific AC units for five leading manufacturers

(1.5-, 2-, 2.5-, 3-, 3.5-, 4-, and 5-ton sizes shown for each SEER family, when available)

This report describes how the standard AC library was developed by:

1. Collecting and evaluating AC and HP performance data (Sections 3 and 4)
2. Determining model sensitivity to the required input parameters (Sections 5 and 6)
3. Developing a library of appropriate model inputs (Section 7).

This work can inform future efforts to improve data reporting by manufacturers and AHRI and improve current modeling efforts.

Definitions

AC	air conditioner
ADP	apparatus dew point
AHRI	Air-Conditioning, Heating, and Refrigeration Institute
BEopt	Building Energy Optimization
BF	bypass factor
cfm	cubic feet per minute
COP	coefficient of performance
DX	direct expansion
EER	energy efficiency ratio (Btu/Wh)
EIR	energy input ratio (1/COP)
EPT	expanded performance table
EWB	entering wet-bulb temperature
FF	flow fraction
HP	heat pump
HSPF	heating seasonal performance factor (Btu/Wh)
ODB	Outdoor dry-bulb temperature
$\dot{P}$	power (W, Btu/h)
$\dot{Q}$	cooling or heating capacity (W, Btu/h)
PLF	part load fraction
PLR	part load ratio
RTF	runtime fraction
SEER	seasonal energy efficiency ratio (Btu/Wh)
SHR	sensible heat ratio
T	temperature
v'	fan air flow rate per unit of capacity (m^3/s/W, cfm/ton)
$\dot{V}$	air volumetric flow rate (m^3/s, cfm)
η_{fan}	fan efficacy (W/m^3/s, W/cfm)

Contents

List of Figures

List of Tables

1 Introduction

Air conditioning is practically ubiquitous across the United States and is becoming commonplace in most developed countries. The vapor compression cycle (the most common way of providing chilled air to an indoor environment) is run off electricity, making air conditioning especially energy intensive on a source energy basis. Residential air conditioning is also a major contributor to summer peak demand.

In the U.S. residential sector, air conditioning is now found in approximately 90% of new single-family homes (up from 75% in 1991). Heat pumps (HPs) have also been on a steady rise over the last 20 years. HPs as the primary heating system in new homes rose from 22% in 1991 to 37% in 2009 (EIA 2009). In 2008, residential air conditioning accounted for 9% of the site energy consumed and 14% of the source energy in the U.S. residential housing stock (EIA 2009).

The energy consumption of the equipment and the relative efficiencies of different pieces of equipment must be accurately quantified to recommend efficient designs and reduce the energy consumption of air conditioners (ACs) and HPs. The principal metrics used to quantify the energy efficiency of ACs and HPs are the seasonal energy efficiency ratio (SEER) and heating seasonal performance factor (HSPF), respectively. These metrics consist of a single value used to quantify the seasonal energy efficiency of a unit and do not vary with respect to climate, building type, or specific unit characteristics. The consensus from the research community is that these are convenient, yet inaccurate metrics for quantifying annual energy use (Courtney 2006, Fairey et al. 2004, Kavanaugh 2002). SEER and HSPF provide only very rough estimates of energy consumption and are meant only as ranking methods for different levels of efficiency (though even these rankings are inaccurate for different climates and different units (Courtney 2006, James J. Hirsch & Associates 2005).

An alternative approach to quantifying annual energy consumption is through whole-building annual simulation software. Programs such as EnergyPlus and DOE-2 can capture complex interactions between buildings, climate, and occupants. The simulation engines enable users to evaluate energy use trends across different equipment lines, buildings, and climates. Though manufacturers and the marketplace will not likely discard the SEER/HSPF metrics in lieu of annual simulation, the use of annual simulation tools can inform designers, policy makers, and future improvements to the SEER and HSPF rating procedures.

The Building Energy Optimization Tool (BEopt) is a residential-specific modeling program that provides a graphical user interface for EnergyPlus and DOE-2, an integrated cost database, and cost-based optimization capabilities for annual simulations. It enables users to model potential energy-saving technologies and to select the optimal package of energy efficiency measures based on either cost savings or energy savings.

BEopt enables users to evaluate energy consumed by ACs and HPs and to consider the complex interactions of all building/climate variables. The incumbent modeling approach in BEopt had two issues with AC and HP simulations:

- The “shipped” options (prepackaged options representing the SEER/HSPF families that were included in BEopt) did not always generate monotonically decreasing energy consumption for increasing SEER/HSPF. This begged the question of whether installing a SEER 14 over a SEER 15 (for example) should be recommended in certain climates.

- To effectively model a specific AC or HP using manufacturer data, large sets of complicated inputs (more than 35 inputs, including biquadratic curve fits of various performance metrics that are very difficult to compute) had to be generated.

Consistent results that are representative of the equipment in the marketplace are necessary to make informed recommendations on efficiency measures. This enables evaluation of the current equipment and its impacts on energy use across various climates and building types, and can help inform future efficiency and rating procedure improvements. It is also necessary to enable the simulation of units outside the shipped options in BEopt. This gives the energy modeler flexibility in an analysis.

The research described in this report takes an in-depth look at the data available to inform models used in simulation engines. These data are evaluated for consistency and reliability. The results of the extensive data evaluation are then used to propose a new method for modeling ACs and HPs that takes advantage of simplified inputs to provide more flexibility in modeling, while retaining or improving overall accuracy in simulations.

2 Background

When simulating AC (or HP) performance in the context of a whole building, several parameters should be accurately captured. For ACs, power, capacity, sensible heat ratio (SHR), and runtime must be accurately predicted as functions of outdoor dry-bulb temperature, indoor wet-bulb temperature, indoor air mass flow rate, and part load ratio (PLR) (cycling). For HPs, power and total capacity predictions are functions of outdoor dry-bulb temperature, indoor dry-bulb temperature, indoor air mass flow rate, and PLR.

Section 2.1 establishes several definitions that are necessary to understand the algorithms used to simulate AC and HP performance.

2.1 Definitions

2.1.1 Standard Rating Conditions

Air Conditioning, Heating, and Refrigeration Institute (AHRI) Standard 210/240 defines Standard Rating Condition as *rating conditions used as the basis of comparison for performance characteristics* (ANSI/AHRI 2008). Several standard rating conditions are used to evaluate the energy efficiency ratio (EER) and coefficient of performance (COP), which are used to calculate seasonal energy efficiency ratio (SEER) and/or heating seasonal performance factor (HSPF). However, industry has accepted two standard rating conditions (one for cooling and one for heating) for comparing product capacity and efficiency (see Table 1).

Table 1. Standard Rating Conditions for Cooling and Heating

AHRI Standard Rating Condition	Air Entering Indoor Unit				Air Entering Outdoor Unit			
	Dry-Bulb		Wet-Bulb		Dry-Bulb		Wet-Bulb	
	(°F)	(°C)	(°F)	(°C)	(°F)	(°C)	(°F)	(°C)
Cooling (A-Test)	80.0	26.7	67.0	19.4	95.0	35.0	75.0[1]	23.9[1]
Heating (H1 Test)	70.0	21.1	60.0^{max}	15.6^{max}	47.0	8.33	43.0	6.11

[1] Applies only if the unit rejects condensate to the outdoor coil

Source: AHRI 2008

For two-stage and variable-speed equipment, these conditions are tested only at the high stage and speed and are two of several operating conditions required to calculate the SEER and HSPF. However, manufacturers typically report performance at the standard operating condition for low stage and speed operation.

The conditions shown in Table 1 will be called the *rated operating point* and the performance at these conditions will be called the *rated performance*.

2.1.2 Net Versus Gross Performance Values

Typically the *net* capacity is reported and readily available. Net capacity takes into account heat produced by the fan motor in the airstream. *Gross* capacity is delivered by the refrigerant, which is equivalent to the airside capacity measured from the cooling coil inlet to the cooling coil outlet (fan heat not accounted for). The relationship between net and gross capacity is described in Eq. 1 as

$$\dot{Q}_{net} = \begin{cases} \dot{Q}_{gross} - \dot{P}_{fan} & \text{if in cooling mode} \\ \dot{Q}_{gross} + \dot{P}_{fan} & \text{if in heating mode} \end{cases} \quad (1)$$

Similarly,

$$\dot{P}_{net} = \dot{P}_{gross} + \dot{P}_{fan} \quad (2)$$

where the gross power ($\dot{P}_{gross}$) is equivalent to the power of the outdoor unit (compressor and outdoor fan).

Figure 1 depicts net and gross capacities. Net capacity is measured between points A and C; whereas gross capacity is measured between B and C.

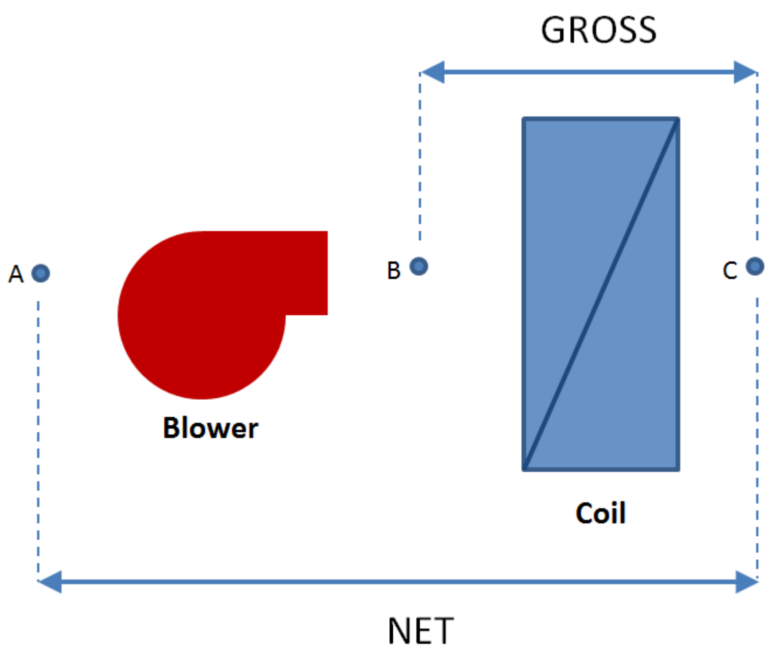

Figure 1. Net versus gross capacity for a blow-through fan configuration

The simulation engine used for this study modeled the cooling coil and fan separately. Thus, gross performance values were required.

2.1.2.1 Converting From Net to Gross

Net performance values often need to be converted to the corresponding gross value (published performance tables typically display net values and simulation engines generally require gross performance inputs). Unfortunately, the required fan performance is not often reported and assumptions often need to be made.

In cooling mode, starting with the following

$$COP_{net,cooling} = \frac{\dot{Q}_{net}}{\dot{P}_{net}} = \frac{\dot{Q}_{gross} - \eta_{fan} v' \dot{Q}_{gross}}{\dot{P}_{gross} + \eta_{fan} v' \dot{Q}_{gross}} \tag{3}$$

results in

$$COP_{gross,cooling} = \frac{COP_{net,cooling}}{1 - \eta_{fan} v' \left(1 + COP_{net,cooling}\right)} \tag{4}$$

where η_{fan} is the fan efficacy and v' the indoor volumetric flow rate per unit of gross cooling capacity. Several manufacturers state the assumptions used to determine net performance values. An assumed fan efficacy of 0.365 W/cfm and flow rate of 400 cfm/ton were used in Equation 4 when the necessary information could not be found (0.365 W/cfm is the AHRI default value for fan efficacy). Equation 4 can be manipulated to convert from a net EER to a gross EER if careful attention is paid to the units used in the equation.

A similar approach is used to determine the net COP in heating mode. Starting with

$$COP_{net,heating} = \frac{\dot{Q}_{net}}{\dot{P}_{net}} = \frac{\dot{Q}_{gross} + \eta_{fan} v' \dot{Q}_{gross}}{\dot{P}_{gross} + \eta_{fan} v' \dot{Q}_{gross}} \tag{5}$$

results in

$$COP_{gross,heating} = \frac{COP_{net,heating}}{1 + \eta_{fan} v' \left(1 - COP_{net,heating}\right)} \tag{6}$$

2.2 Split System Models

EnergyPlus and DOE-2 were both considered for this study. EnergyPlus was selected as the principal simulation tool for the following reasons:

- Simpler and more theoretically sound split direct expansion (DX) model
- Fewer and simpler inputs
- Improved documentation
- Position as the most current and advanced simulation engine with ongoing development.

Cutler (2012) provides an in-depth discussion of the EnergyPlus DX cooling coil and model; Kruis (2010) discusses the differences between the approaches used by DOE-2 and EnergyPlus to model air-conditioning equipment. Thus, only a brief overview of the EnergyPlus DX cooling coil model is provided here.

2.2.1 EnergyPlus Direct Expansion Cooling Model Overview

EnergyPlus uses a set of performance curves that scale rated performance values based on current operating conditions to simulate DX equipment. The required rated performance values include (DOE 2011):

- Total capacity
- SHR
- COP
- Indoor coil airflow rate.

Rated total capacity and COP inputs are gross values. The model uses the following set of normalized performance curves to scale the rated performance values for off-rated operating conditions:

- Total capacity—function of entering wet-bulb temperature (EWB) and outdoor dry-bulb temperature (ODB)
- Energy input ratio (EIR = 1/COP)—function of EWB and ODB
- Total capacity—function of flow fraction (flow rate/rated flow rate)
- EIR—function of flow fraction (flow rate/rated flow rate)
- Part load fraction (PLF)—function of PLR.

The total capacity and EIR curves that are a function of EWB and ODB are both biquadratic curve fits. Each takes the form

$$y = a + b \cdot T_{ewb} + c \cdot T_{ewb}^2 + d \cdot T_{odb} + e \cdot T_{odb}^2 + f \cdot T_{ewb} \cdot T_{odb} \tag{7}$$

where *ewb* is EWB and *odb* is OWB. The total capacity and EIR curves as functions of flow fraction (*FF*, defined as $\dot{m}/\dot{m}_{rated}$) are both quadratic curves and take the form

$$y = a + b \cdot FF + c \cdot FF^2 \tag{8}$$

The PLF as a function of PLR curve is a quadratic curve of the form

$$PLF = a + b \cdot PLR + c \cdot PLR^2 \tag{9}$$

PLR is defined as the ratio of sensible cooling load to total sensible capacity for the current time step in the simulation. The runtime fraction (RTF) is calculated as

$$RTF = {}^{PLR}\!/_{PLF} \tag{10}$$

Thus, if the output of the PLF curve is <1, it causes an increase in the runtime for that time step. This adjustment accounts for the unit's cycling losses. All the capacity and power calculations are assumed to be at steady state; therefore, part load is accounted for by extending the unit's total runtime (at steady state).

The power consumption for the time step is calculated as

$$\dot{P} = EIR \cdot \dot{Q}_{total} \cdot RTF \tag{11}$$

where EIR and $\dot{Q}_{total}$ are calculated as

$$EIR = EIR_{rated} \cdot EIR_{f(T)} \cdot EIR_{f(FF)} \tag{12}$$

$$\dot{Q}_{total} = \dot{Q}_{total,rated} \cdot \dot{Q}_{f(T)} \cdot \dot{Q}_{f(FF)} \tag{13}$$

In Equations 12 and 13, $EIR_{f(T)}$ and $\dot{Q}_{f(T)}$ are curves for normalized EIR and total capacity as a function of EWB and ODB; and $EIR_{f(FF)}$ and $\dot{Q}_{f(FF)}$ are curves for normalized EIR and total capacity as functions of flow fraction.

The preceding discussion describes how EnergyPlus evaluates total capacity and power. The sensible and latent performances of the unit are also evaluated for each time step. The rated SHR and the apparatus dew point (ADP)/bypass factor (BF) model are used to calculate the sensible and latent portions (DOE 2011). The EnergyPlus Engineering Reference provides additional information on the ADP/BF model.

Calculations for two-stage and multispeed ACs are quite similar to the single-speed model. In addition to specifying the number of speeds, the above set of inputs is required for each stage andspeed. Simply put, the two-stage and multispeed DX cooling coil models interpolate between speeds to calculate the performance of the given building's sensible load and operating conditions.

2.2.2 EnergyPlus Direct Expansion Heating Model Overview

The DX heating model is quite similar to the DX cooling model; albeit slightly simpler because the DX heating model needs to calculate only the sensible heat output. The model includes a set of algorithms to account for defrost operation. Those algorithms were not investigated during this study, but details about the defrost calculations can be found in DOE (2011).

Similar to the DX cooling model, the required rated performance values include:

- Capacity
- COP
- Indoor coil airflow rate.

The model uses the following set of normalized performance curves to scale the rated performance values for off-rated operating conditions:

- Capacity—function of entering dry-bulb and outdoor ODB
- Energy input ratio (EIR = 1/COP)—function of entering dry-bulb and ODB temperatures
- Capacity—function of flow fraction (flow rate/rated flow rate)
- EIR—function of flow fraction (flow rate/rated flow rate)

- PLF—function of PLR.

2.2.3 Summary of Model Inputs

The key required inputs for the EnergyPlus DX cooling and heating models are summarized in Table 2.

Table 2. Summary of EnergyPlus DX Cooling and Heating Model Inputs

	Cooling	Heating
Rated values	$\dot{Q}_{total,rated}$	$\dot{Q}_{total,rated}$
	COP_{rated}	COP_{rated}
	SHR_{rated}	$\dot{V}_{rated}$
	$\dot{V}_{rated}$	
Performance curves	$\dot{Q}_{f(T)}$	$\dot{Q}_{f(T)}$
	$EIR_{f(T)}$	$EIR_{f(T)}$
	$\dot{Q}_{f(FF)}$	$\dot{Q}_{f(FF)}$
	$EIR_{f(FF)}$	$EIR_{f(FF)}$
	$PLF_{f(PLR)}$	$PLF_{f(PLR)}$

2.3 Performance Data and Generating Model Inputs

The input parameters included in Table 2 must be acquired to simulate specific AC and HP units in the context of EnergyPlus. Published performance data are often the source for determining model inputs (direct testing is cost prohibitive) and three main data sources are available:

- AHRI Directory of Certified Product Performance (AHRI 2012)
- Manufacturer product data tables
- Manufacturer expanded performance tables (EPTs).

The AHRI Directory of Certified Product Performance is a source of accurate data. It has well-defined testing procedures and third-party oversight of the testing; however, only a small fraction of the required model inputs can be obtained from it. The directory contains the rated capacity, EER, and SEER, but does not include the rated SHR, cycling degradation coefficient (C_D—a metric describing part load degradation caused by cycling), flow rate, or sufficient data to generate the set of performance curves.

Manufacturer product data tables typically contain information about the rated performance of a particular unit, whereas manufacturer EPTs include performance data at various operating conditions and indoor airflow rates. EPTs are produced and made available for unit selection and sizing purposes, but also allow for the development of performance curves required for simulation. Table 3 shows common independent and dependent variables found in manufacturer EPTs.

Table 3. Common Independent and Dependent Variables Found in Manufacturer EPTs

	Independent Variables	Dependent Variables
Cooling	ODB	Total Capacity
	Indoor Dry-Bulb	Sensible Capacity
	Indoor Wet-Bulb	Total Power
	Airflow Rate	
Heating	ODB	Total Capacity
	Indoor Dry-Bulb	Integrated Capacity
	Airflow Rate	Total Power

EPTs are not without shortcomings. EPTs contain performance data at many operating conditions, yet there is no governing standard that dictates how the data are made available (PDF, spreadsheets, HTML, etc.) and what ranges and format are reported. This lack of standardization leads to a wide variety in reporting formats. It also leads to wide variations in the selected dependent variables and range of independent variables.

The EPTs generally report net capacity and power values, yet most manufacturers do not report the fan efficacy associated with the data. The energy model inputs require gross values, because the fan is modeled independently of the AC or HP unit. Therefore, fan power consumption must often be assumed to convert the EPT net values to the gross values required by EnergyPlus.

The EPTs are not representative of experimental test data, but are typically generated by manufacturers' in-house computer models. These models use test data from the AHRI test points and then predict performance at off-rated conditions. Therefore, although these are the best available data, they are only as good as the models produced by individual manufacturers.

When model inputs are generated, the temperature-based performance curves should be generated using data corresponding to the rated airflow rate only. These curves account for performance variations at various EWBs and ODBs; the flow fraction curves are responsible for adjusting for off-rated flow rates. Similarly, the flow fraction performance curves should be generated using data for the rated temperatures in Table 1.

An example EPT for a leading AC manufacturer is included in Table 4. Only a subset of outdoor temperatures is listed. Manufacturers typically include outdoor temperatures from approximately 75°F to 115°F in 10°F increments. The following process was used to develop a set of model inputs using these data. However, the process is quite similar for EPTs using different formats and containing different dependent variables.

1. Calculate net EIRs using total capacity and total system power.
2. Convert net total capacity and net EIR to gross values using Equations 1 and 4.

3. Select the rated airflow rate (this is often 400 cfm/ton, yet can also correlate to the middle fan jumper if tested with an indoor fan).
4. Normalize the data to the rated values by dividing by the capacity or EIR values at the rated conditions (95/80/67 in the case of the temperature cures, and the rated airflow rate as selected above for the flow fraction curves).
5. Perform linear least square regressions on the data corresponding to the rated airflow rate to generate temperature-based performance curves ($\dot{Q}_{f(T)}$ and $EIR_{f(T)}$) using Equation 7.
6. Perform linear least square regressions on the data corresponding to standard rating temperatures listed in Table 1 to generate flow fraction performance curves ($\dot{Q}_{f(FF)}$ and $EIR_{f(FF)}$) using Equation 8.

Table 4. Example Manufacturer EPT (Subset of Data Displayed)

Evaporator Air		Condenser Air °F (°C)								
		75 (23.9)			95 (35)			105 (40.6)		
cfm	EWB °F (°C)	Capacity kBtu/h Total[1]	Capacity kBtu/h Sens[1,2]	Total Sys kW[3]	Capacity kBtu/h Total[1]	Capacity kBtu/h Sens[2]	Total Sys kW[3]	Capacity kBtu/h Total[1]	Capacity kBtu/h Sens[2]	Total Sys kW[3]
875	72 (22)	34.32	17.27	1.96	31.24	16.13	2.44	29.59	15.54	2.71
	67 (19)	31.45	21.21	1.96	28.59	20.05	2.43	27.04	19.44	2.71
	63 (17)	29.35	20.58	1.96	26.66	19.40	2.43	25.19	18.78	2.70
	62 (17)	28.82	25.13	1.95	26.24	23.94	2.43	24.86	23.29	2.70
	57 (14)	28.00	28.00	1.95	25.89	25.89	2.43	24.74	24.74	2.70
1000	72 (22)	34.88	18.05	2.01	31.66	16.90	2.48	29.96	16.30	2.76
	67 (19)	31.98	22.49	2.01	29.00	21.31	2.48	27.40	20.68	2.75
	63 (17)	29.88	21.78	2.00	27.07	20.58	2.48	25.55	19.95	2.75
	62 (17)	29.44	26.90	2.00	26.81	26.81	2.48	25.62	25.62	2.75
	57 (14)	29.10	29.10	2.00	26.85	26.85	2.48	25.62	25.62	2.75
1125	72 (22)	35.27	18.78	2.06	17.61	17.61	2.53	30.22	17.07	2.81
	67 (19)	32.36	23.68	2.05	22.50	22.50	2.53	27.66	21.88	2.80
	63 (17)	30.25	22.90	2.05	21.70	21.70	2.52	25.82	21.07	2.80
	62 (17)	30.02	28.49	2.05	27.62	27.62	2.52	26.32	26.32	2.80
	57 (14)	29.99	29.99	2.05	27.62	27.62	2.52	26.32	26.32	2.80

[1] Total and sensible capacities are net capacities. Blower motor heat has been subtracted.

[2] Sensible capacities shown are based on 80°F (27°C) entering air at the indoor coil. For sensible capacities at other than 80°F (27°C), deduct 835 Btu/h (245 W) per 1000 cfm (480 L/S) of indoor coil air for each degree below 80°F (27°C), or add 835 Btu/h (245 W) per 1000 cfm (480 L/s) of indoor coil air per degree above 80°F (27°C).

[3] System kilowatt is the total of indoor and outdoor unit kilowatts.

3 Manufacturer Performance Data Collection and Evaluation

Manufacturer EPTs were used to develop the simulation inputs for this study. The assortment of publishing formats and chosen dependent variables across the leading equipment manufacturers made the collection and processing procedure quite challenging. Data were collected from seven leading U.S. manufacturers responsible for 97% of the AC market (EIA 2009). The data provided by two of the manufacturers were not sufficient for full model input generation and were not incorporated into the analysis. The final dataset used for the study included data from five leading manufacturers that are responsible for 76% of the AC market.

Thousands of indoor and outdoor unit combinations are available. Collecting performance data for every mix-and-match combination from a given manufacturer was not feasible and data were collected for only the most common system combinations sold. As a result, data were collected for 260 ACs and 200 HPs. Performance and system data were read into a common format and stored in a SQLite database. SEER values for the collection ranged from 13–21 and nominal system capacities ranged from 1.5–5 tons. This database brought together performance data from each manufacturer into one usable format. The SQLite database format also used SQL-style queries to make the data fully searchable. The data and resulting simulation inputs were evaluated for quality and consistency before the generated sets of model inputs were used. Several methods were used to evaluate the data:

1. Visual inspection for data entry errors
2. Calculation of BF and ADP for each set of reported conditions
3. Comparison of ADP/BF algorithm predictions directly with manufacturer EPT data
4. Performance curve visualization and evaluation across manufacturers and models/capacities.

3.1 Data Visual Inspection

Visual inspection was limited because of the large quantity of data collected. It was used briefly during the creation of the database to ensure the data were processed and transferred to the database correctly. A certain number of errors were expected to be generated through the data parsing, but did not occur. The data transfer process proved to be quite robust and accurate.

Data inspection was most often precipitated by unexpected or suspicious results while model inputs or simulation results were being evaluated. These unexpected results required inspection of the database and the EPTs, and most often traced back to the EPTs. The errors encountered included decimal placement errors and identical fan speeds indicated for low and high speed data (for two-stage units). This type of data error was rare (only 5–7 cases in all the EPTs processed). The data were unusable for three units, which were discarded from the study.

3.2 Bypass Factor and Apparatus Dew Point Calculation and Verification

The BF was calculated for each indoor/outdoor condition listed in the EPTs. The BF is used in the EnergyPlus simulation algorithm to determine the sensible capacity of the unit at each time step. The sensible capacity determines the runtime of the unit, because ACs and HPs are generally controlled with thermostats, which are sensible-only devices (humidity control was not considered). The ADP/BF model played a central role in determining performance and energy consumption, so the BF was calculated for each point reported by the manufacturer.

Calculation of the BF led to some unexpected results. Many points could not be calculated, because the predicted exiting conditions were beyond the saturation curve on the psychrometric chart. This led to the calculation of a negative BF. The percent of total data points with a calculated negative BF ranged from 5% to 25% across the five manufacturers. These calculated exiting states are physically impossible, because supersaturated air states are not attainable at normal atmospheric pressures.

Discussion with one manufacturer indicated that the sensible capacities received limited attention during the manufacturer's model calibration because:

- EPTs are produced to aid in unit sizing and selection.
- SHR is important in unit selection in different climates, yet precision is not crucial.

Therefore, from the manufacturer's standpoint, the sensible capacities can be a few percentage points off and still be sufficiently accurate for system sizing. A discrepancy of a few percentage points in the sensible capacity can change the slope of the SHR line on the psychrometric chart enough to produce some of the physically impossible results that were observed. These results raised concerns about the overall accuracy of the manufacturer's models.

3.3 Apparatus Dew Point/Bypass Modeling Algorithm Comparison

For whole-building modeling, the BF is a function of airflow rate only in the EnergyPlus algorithm. It thus limits the impact of this data variability on the model. Therefore, the data points that were calculated as having a negative BF were retained in the dataset and the EnergyPlus BF factor algorithm was investigated.

Sensible capacities from the constant BF algorithm (used in Energy Plus) were compared with the reported sensible capacities listed in the EPTs. The predicted values were very close to EPT values (≈1-3% difference) for most units.

3.4 Performance Curve Visual Inspection

The final data evaluation was visualization of the performance curves that were generated from the data and comparison with the EPT data points. An example of the total capacity curves as a function of ODB (x-axis) and EWB (different series) is shown in Figure 2.

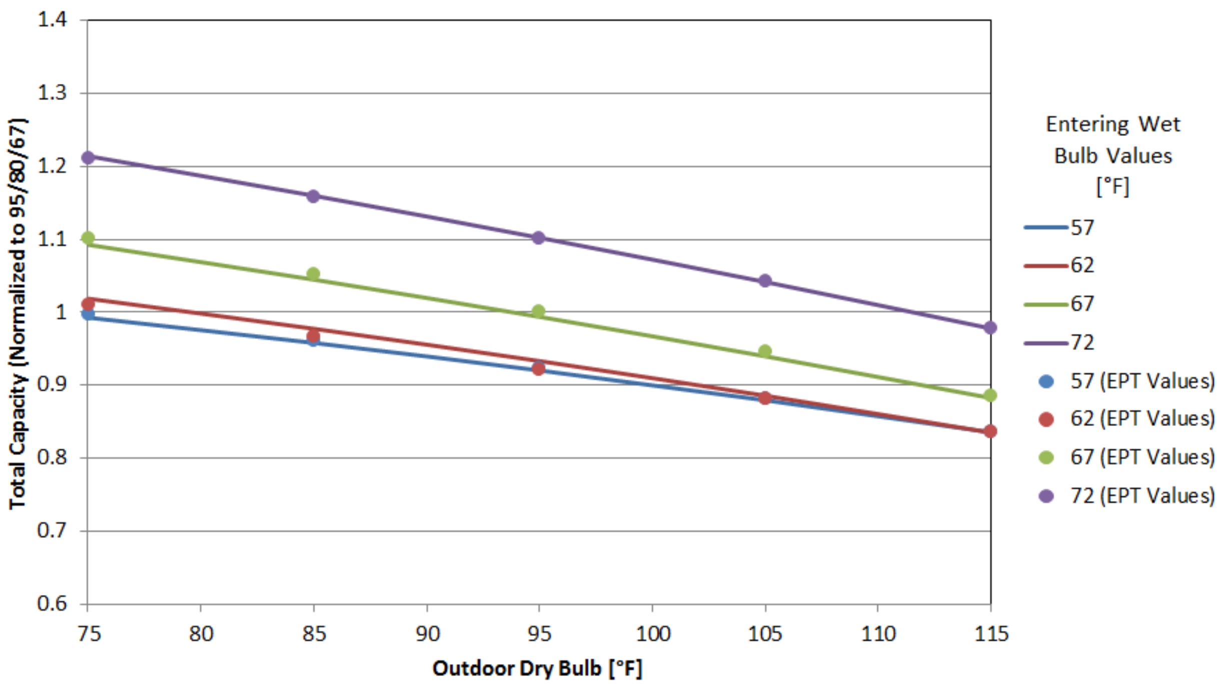

Figure 2. Comparison of total capacity performance curve to manufacturer EPT values

The only significant error encountered during this evaluation was a particular manufacturer's EPT data modified the rated point to maintain consistency with the AHRI test results. All other listed data points remained at the values predicted by the manufacturer's in-house model. An example of this adjustment is shown in Figure 3. The larger dot highlighted in the figure should be in line with the 67 EWB series, yet it has been shifted out of line with that series to attain the tested rated value at the A test point. The least squares regression generally ignores this point and fits to the remaining data.

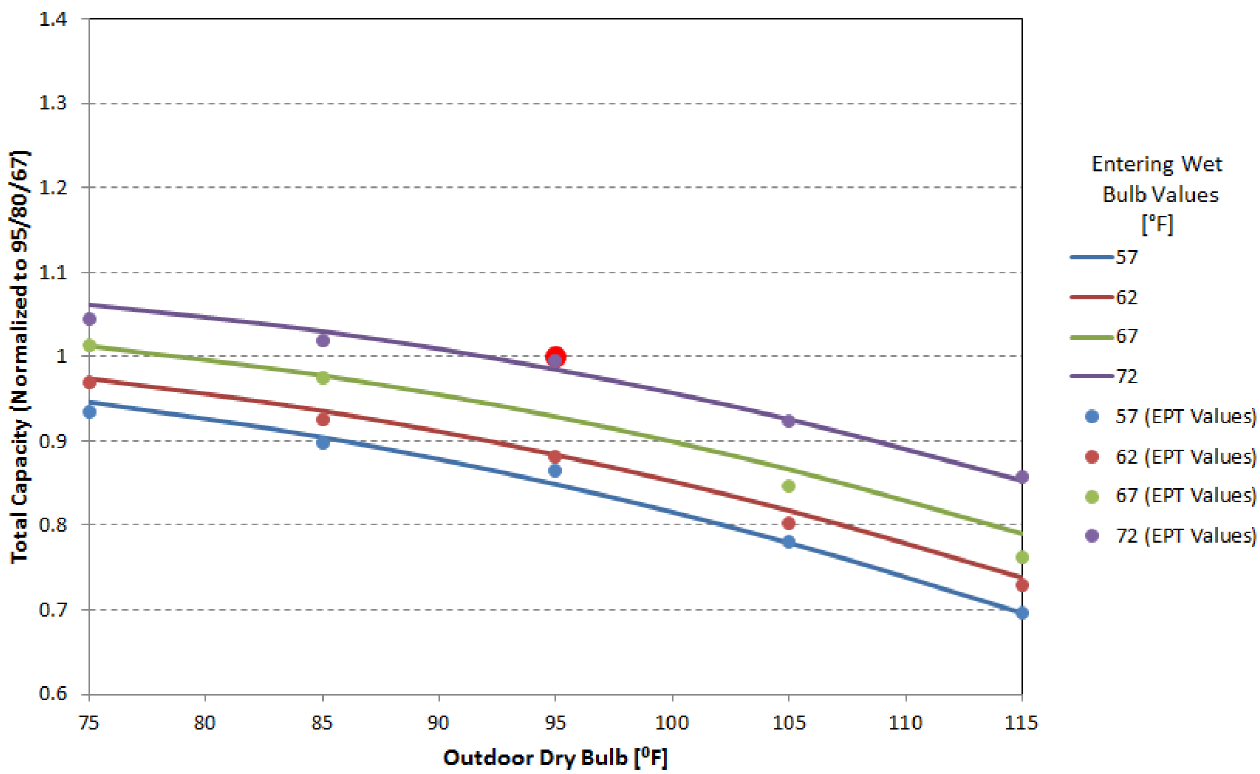

Figure 3. Comparison of total capacity curve to manufacturer data with an adjusted rating point (shown in red)

This section has described the EPT data evaluation process. The database was used to generate full sets of EnergyPlus inputs for each unit in the database

The data issues described in this section raise the following important questions:

- Which inputs are the most sensitive to errors and variations?
- How will the errors in the available data affect the predicted performance of AC and HP units?
- What would be the best approach to limit the effects of data variability and capture the crucial aspects of the unit's performance?
- Which set of model inputs will best predict unit performance?

The answers to these questions are addressed in the following sections.

4 Simulation of Specific Air Conditioner Units

4.1 House Description

The house simulated for this study was a two-story, 2,500-ft^2 design compliant with International Energy Conservation Code 2009 building codes (ICC 2009). The house was simulated in four cities (Houston, Phoenix, Atlanta, and Chicago), representing hot-humid, hot-dry, mixed-humid, and cold Building America climate regions (PNNL and ORNL 2007) in accordance to the Building America House Simulation Protocols (Hendron and Engebrecht 2010). The chosen foundation type was based on common construction practice for the given region—slab-on-grade for Houston and Phoenix, crawlspace for Atlanta, and unfinished basement for Chicago. The equipment (AC or HP) was sized according to Manual J for each climate (Rutkowski 2006).

4.2 Modeling Assumptions

Air leakage and conduction losses associated with ductwork were neglected to prevent the selected duct characteristics from impacting modeled equipment performance. The purpose was to improve AC and HP models through a comparative study. The complicated interaction between ducts and equipment would have made the comparison more difficult without adding insight.

Part load effects were neglected by setting the part load curves to unity, effectively modeling steady-state performance only. This was done for two principal reasons:

- **The cycling performance data are not published for individual units.** This was the most significant reason. Any part load performance curves introduced into the simulations would thus be based on estimates. This was not desirable, because it would mask some impacts of the inputs generated from manufacturer data on the results.
- **To eliminate the impact of the sizing routine on the annual simulation results.** Without part load losses, the simulated size of the unit would not have an impact on the performance. The goal of these runs was to evaluate performance variation as influenced by the inputs generated for specific AC and HP units.

Fan efficiencies are not reported, so values had to be assumed. Most single-stage units use permanent split capacitor motors, whereas two-stage units contain brushless permanent magnet motors. Thus, a fan efficiency of 0.365 W/cfm was assumed for single-stage ACs and 0.14 W/cfm was used for two-stage units.

4.3 Performance/Comparison Metric

A metric was developed to evaluate the performance of the units in the various climates simulated. An annual average, steady-state, net COP calculated using Equations 14 and 15 for cooling and heating, respectively, was used to compare units. The metric is steady state because part load effects were eliminated.

$$\overline{COP}_{net,ss,c} = \frac{\sum_{n=1}^{8760}\left(\dot{Q}_{cool,n} - \dot{P}_{fan,n}\right)}{\sum_{n=1}^{8760}\left(\dot{P}_{outdoor,n} + \dot{P}_{fan,n}\right)} \forall n : \dot{Q}_{cool,n} > 0 \tag{14}$$

$$\overline{COP}_{net,ss,h} = \frac{\sum_{n=1}^{8760}\left(\dot{Q}_{heat,n} + \dot{P}_{fan,n}\right)}{\sum_{n=1}^{8760}\left(\dot{P}_{outdoor,n} + \dot{P}_{fan,n}\right)} \forall n : \dot{Q}_{heat,n} > 0 \tag{15}$$

This metric allows for clear comparison across climates and nominal capacities without the confusion that an annual energy metric might introduce. Some variation is expected between climates because of different sensible and latent load profiles and different ambient conditions, but with significantly less discrepancy compared to an absolute number.

4.4 Air Conditioner Simulation Results

Figure 4 shows simulation results for all 260 AC units in Houston. Results from the other cities were similar. Results have been grouped by the nominal (product-line) SEER value. Within a nominal SEER grouping, units are plotted from left to right in order of increasing nominal capacity (starting with 1.5 tons and increasing to 5 tons in 0.5-ton increments). The Manufacturer E, SEER 15 product line and SEER families 16 and above (for all manufacturers) are two-stage ACs. In several instances, multiple product lines from a single manufacturer are plotted. However, for clarity, only a single point is displayed if different product lines yielded similar results (resulting in fewer than 260 individual points).

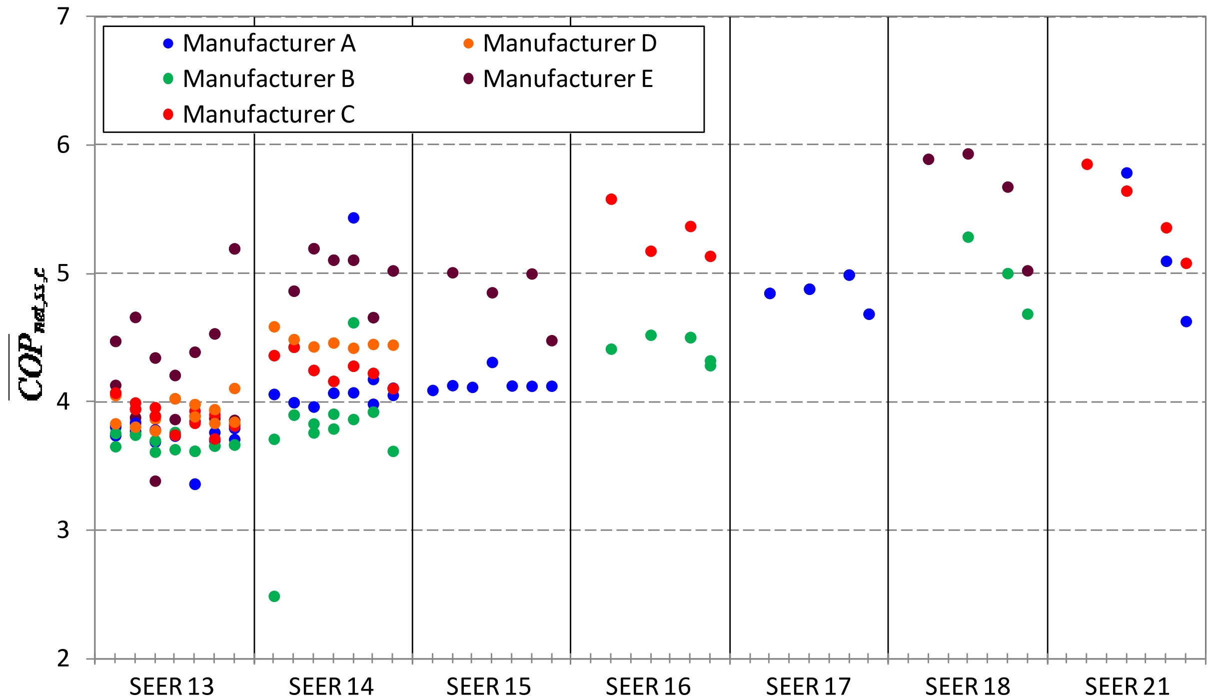

Figure 4. Simulation results for ACs evaluated in Houston (individual capacities of 1.5, 2, 2.5, 3, 3.5, 4, and 5 tons shown in ascending order within each SEER family, when available)

Several interesting trends and issues were immediately apparent after this initial set of runs:

- Variation in $\overline{COP}_{net,ss,c}$ within a model line without a consistent trend (see Manufacturer C, SEER 14)
- Significant outliers for most manufacturers (see minimum value for Manufacturer B, SEER 14)
- Differences in $\overline{COP}_{net,ss,c}$ for the same nominal SEER rating for a given manufacturer (see range for Manufacturer E, SEER 13)
- Differences in $\overline{COP}_{net,ss,c}$ for the same nominal SEER rating across manufacturers (see range for SEER 14 units)
- Minimal increase in $\overline{COP}_{net,ss,c}$ for increasing nominal SEER values for a given manufacturer (see Manufacturer A, SEER 14 versus SEER 15)
- Lack of consistent trend $\overline{COP}_{net,ss,c}$ with nominal SEER value
- Decreasing $\overline{COP}_{net,ss,c}$ as nominal tonnage increases for SEER 18 and SEER 21 product lines.

5 Performance Curve Sensitivity Study

An initial two-part question was: Can we provide more accurate modeling through a full database of inputs that represent all current makes and models? Or are we better served by using the database to inform a model with reduced complexity and better overall accuracy? The data issues that were outlined in Section 3 brought this question to the forefront. To answer it, a sensitivity study had to be performed on the EnergyPlus model inputs to determine whether a generalized approach was possible.

The rated values (especially COP) had the largest impact on the variations noted in Figure 4. Therefore, a sensitivity study was performed on the curve inputs. This process is discussed in detail in Cutler (2012) and will not be repeated here. The results showed the difference between using unit-specific performance curves and selected standard curves were very small. The standard set of curves was selected from the manufacturer that had consistently shown the highest quality data and, when applied across all units, the average error was ±2%–5%. The selection process used for choosing the standardized curves, and the results from using the selected curves, are presented in Section 5.1.

5.1 Air Conditioner Simulation Results

The curve sensitivity study showed that a single set of curves could be used for all single-stage AC units. Two sets of curves could be used for the two-stage units (one for low-stage and one for high-stage operation). This was also demonstrated for HPs (Cutler 2012). The set of curves was selected by minimizing the difference between the unit-specific $\overline{COP}_{net,ss,c}$ and the average of the $\overline{COP}_{net,ss,c}$ across all simulated units. This process resulted in a standard set of curves that represented the average performance at off-rated conditions across all units and introduced the least discrepancy (from the unit-specific curves) into the simulations.

The results for all manufacturers using the standard set of curves are shown in Figure 5. The error bar denotes the difference between using specific unit performance curves (indicated by the dot) and fixed, representative curves.

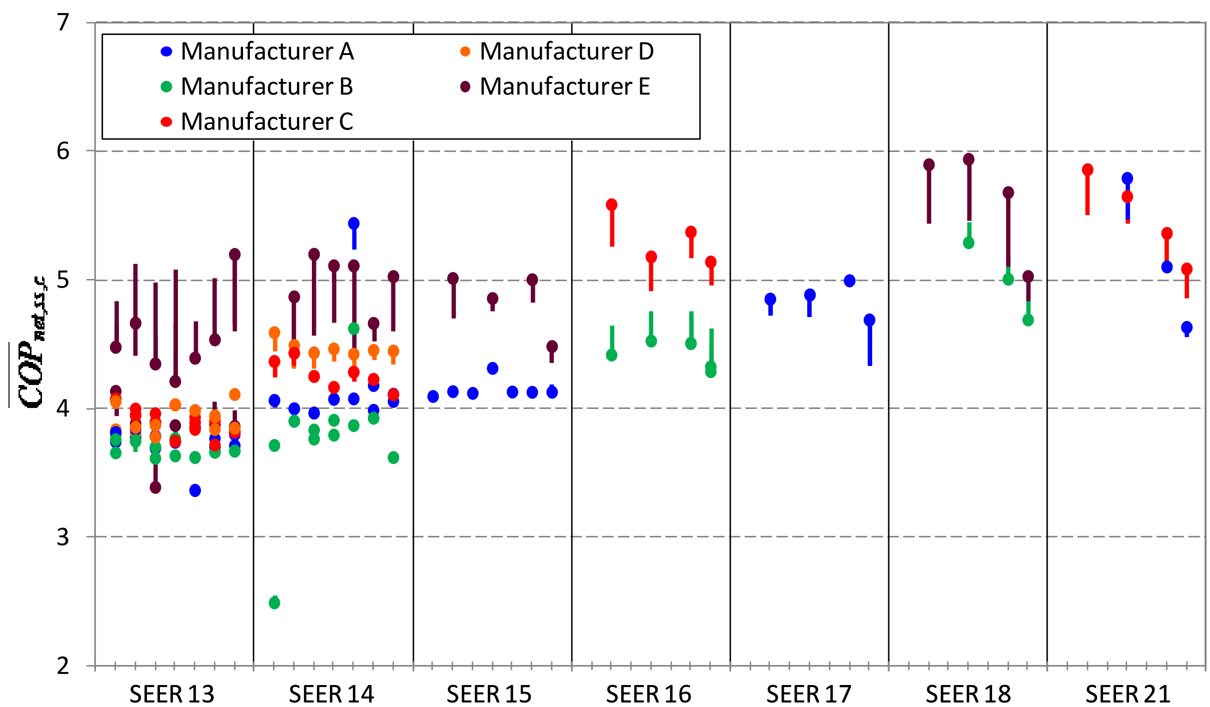

Figure 5. Variations in simulation results attributed to using a fixed set of performance curves (individual capacities of 1.5, 2, 3, 4, and 5 tons shown in ascending order within SEER values)

Most units showed very little variation. The noticeable exception was Manufacturer E, which had significant error in the EPT data throughout the study; its simulation inputs were not considered reliable.

High SEER, two-stage units had noticeably more discrepancy with a standardized set of performance curves than did single-stage units. This trend likely results from the uniqueness of two-stage units, whereas single-stage units are very common across manufacturers. Nevertheless, the assumption of using a standardized curve set was appropriate for comparing energy use across SEER families.

The full set of simulations was run in four climates at four fan speeds to bound the possible inaccuracy that could be generated from using a standard set of curves. These simulations exercised the temperature-related and the flow fraction curves and bound the total expected errors.

Table 5 shows results for a fan speed of 400 cfm/ton for all four cities. Other fan speeds yielded similar results. Although this variation is denoted “error” here (because it is a deviation from the manufacturer’s data), it is not necessarily a less accurate answer, because some of the manufacturer’s data are variable (see Section 3).

Table 5. Calculated Error in Annual Average COP Attributed to Using Fixed Curves

	Manufacturer	A	B	C	D	E
Houston	Average error	–0.3%	–5.1%	–3.6%	3.3%	3.2%
	95% confidence interval (± around average	1.8%	2.2%	2.1%	3.2%	12.8%
Atlanta	Average error	–0.3%	–5.5%	–3.8%	0.6%	3.4%
	95% confidence interval (± around average	1.9%	2.3%	2.3%	3.7%	13.1%
Phoenix	Average error	0.9%	5.8%	–2.3%	0.6%	1.5%
	95% confidence interval (± around average	1.6%	2.5%	1.7%	3.7%	13.6%
Chicago	Average error	0.4%	–8.3%	–2.2%	4.3%	2.7%
	95% confidence interval (± around average	2.5%	2.2%	3.0%	5.0%	13.5%

A similar study on HPs (operating in cooling and heating modes) was conducted and presented in Cutler (2012). HP data provided by the manufacturers were very limited in scope. Only three manufacturers provided data at multiple airflow rates (necessary to generate the flow fraction curves) and only two provided data on both entering dry-bulb temperature and ODB (for the biquadratic curves). The lack of these curves would not allow EnergyPlus to evaluate the HP performance at various airflow rates or indoor temperatures. All possible comparisons (given the scarcity of data) were performed for HPs. The results indicated very limited error because of the curves that were evaluated (similar to the AC analysis presented earlier). Of the two manufacturers providing sufficient data to generate all inputs, one was Manufacturer E, which had the most questionable data evaluated in this research. Therefore, a single set of curves was selected from the remaining manufacturer that provided sufficient, high-quality data.

6 Importance of Rated Value Inputs

The results presented in Section 5 did not resolve all issues observed in Figure 4. The observed variation when modeling individual units was not resolved by the selection of representative performance curves; these just simplified the problem and indicated the real source of the variation—the rated values. Therefore, the rated values from the database of EPT data were evaluated.

AHRI (2012) was used to evaluate the validity of the rated values that were generated from the database. The AHRI data were used during this section of the analysis because:

- They represent laboratory test data (not the manufacturer model generated data that are in the EPTs).
- AHRI reports data that facilitate the comparison with manufacturers' rated values.

Data published by AHRI are representative of laboratory test data, where the test procedures are clearly defined and monitored by AHRI (ANSI/AHRI 2008). This allows the values gathered from the manufacturer's performance tables to be validated against certified data. This would be a relatively simple evaluation if AHRI published the results for all the tests required in the SEER rating process; however, the directory includes only results of the A-test point. Publishing the unrounded SEER values along with the A-test point (second bullet) would facilitate the inference of some other testing points for further comparison.

To compare the EPT data to the AHRI data, it was necessary to quantify the uncertainty in AHRI data and its testing procedures. ANSI/AHRI (2008) describes the acceptable tolerance in Section 6.5 as follows: "To comply with this standard, measured test results shall not be less than 95% of Published Ratings for performance ratios and capacities." This indicates that AHRI accepts error of <5% in both the performance ratios (SEER and rated EER values) and rated capacities. Therefore, agreement to ≈95% of the AHRI data is expected. Conclusions drawn about results with <5% error are within the uncertainty of the data and cannot be conclusive. This margin of error also further supports the selection of the single set of curves described in the previous section where average error was <5% for all but one manufacturer, which had >6% error in only one location tested.

6.1 Single-Stage Rated Values

The single-stage rated values were evaluated in two ways: (1) direct comparison of rated EER values reported in the certified AHRI data and EPT values; and (2) evaluation of off-rated EER (EER_B) and cycling degradation coefficient (C_D) values using the SEER calculation procedure and the AHRI-reported SEER values.

Figure 6 compares the AHRI-certified rated EER to the rated EER determined using manufacturer EPT data. The figure clearly shows a significant discrepancy. Based on these results, the manufacturer-reported EPTs are not a reliable data source for rated input values and the AHRI-certified data should be used when possible.

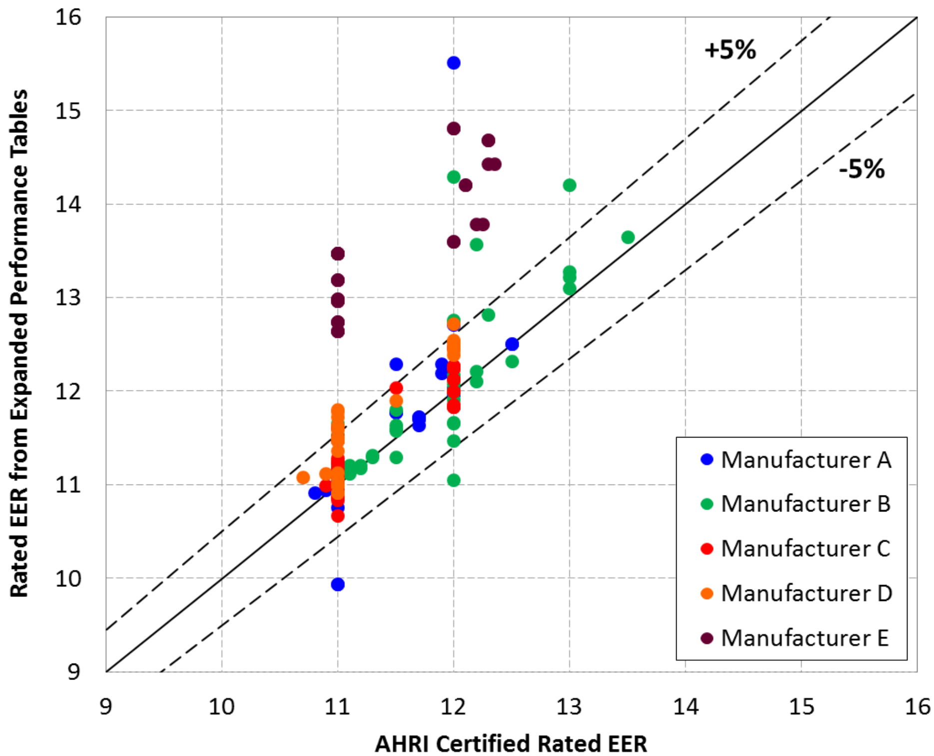

Figure 6. Comparison of AHRI-certified EER to manufacturer EPT data for single-stage ACs

The equation to calculate SEER for single-stage equipment is

$$SEER = PLF(0.5) \cdot EER_B \tag{16}$$

where $PLF(0.5) = 1 - 0.5 \cdot C_D$. To evaluate the rated values from the database of manufacturer EPT data, C_D values were back-calculated using Equation 16 with EER_B values generated from manufacturer data, and certified SEER values obtained from AHRI. The back-calculated C_D values for each single-stage air-conditioning unit, by manufacturer, are shown in Figure 7. The EER_B values used in calculating C_D are net values that were evaluated by interpolating between listed values in the EPTs (EPTs do not generally contain data at 82°F outdoor dry-bulb). The fact that these are net values obviates any need for assumptions about fan power. This evaluation resulted in a large number of units with negative C_D values or C_D values >0.25 (the upper limit default defined by ANSI/AHRI [2008]). Both values are impossible. This cast further doubt on the validity of acquiring the rated values from manufacturer's data. Refer to Cutler (2012) for further discussion of the C_D evaluation process.

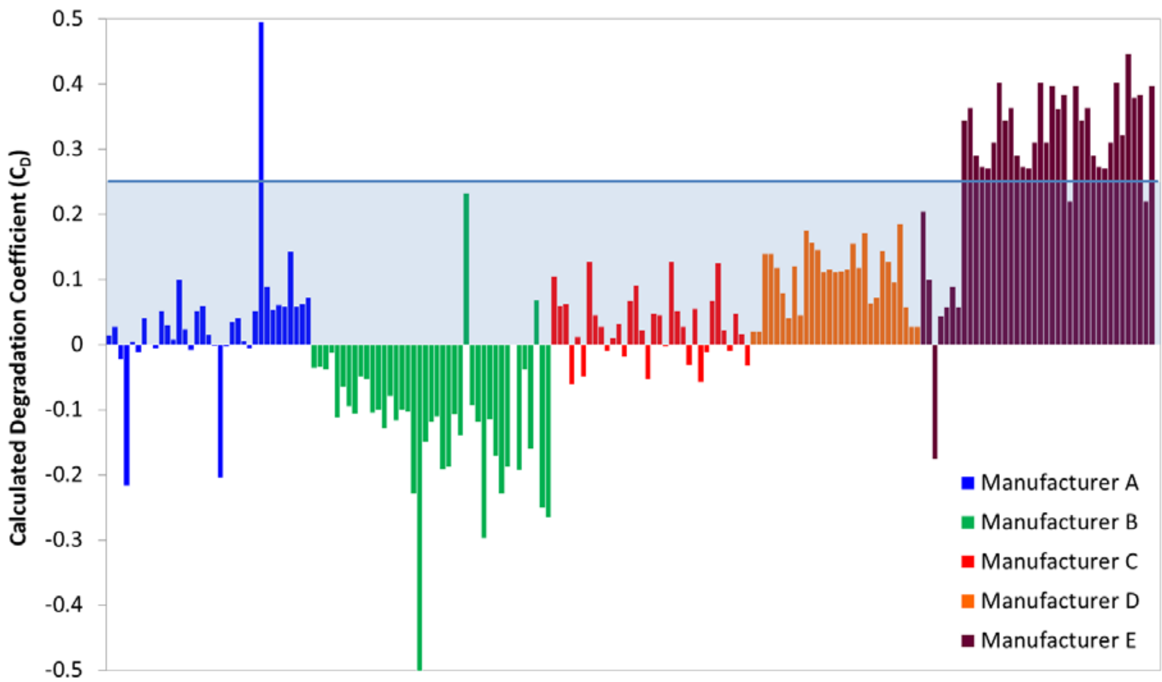

Figure 7. Back-calculated C_D values for single-stage ACs using AHRI SEER values and manufacturer EPT data

6.2 Two-Stage Rated Values

Similar to the single-stage case, a direct comparison was made between the rated efficiency from the AHRI data and that in the EPTs. This metric was able to show only half the picture for two-stage ACs, because AHRI publishes only high stage-rated performance. Figure 8 shows the comparison between the AHRI-rated efficiencies and efficiencies listed in manufacturer EPT data for two-stage ACs.

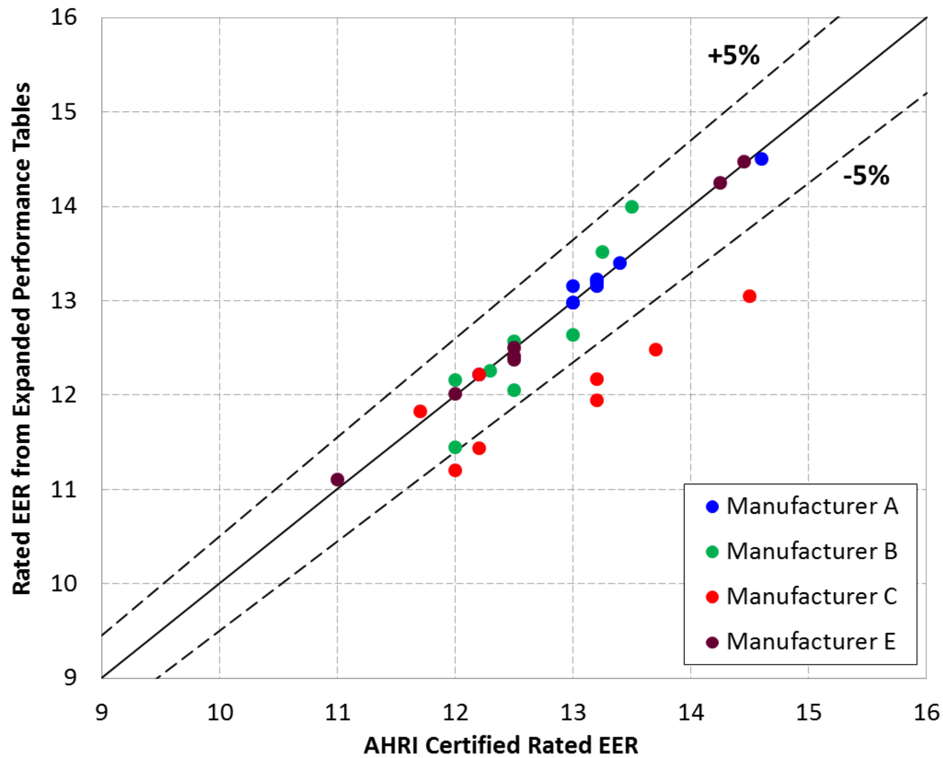

Figure 8. Comparison of AHRI-certified EER to manufacturer EPT data for two-stage ACs

For a more complete picture of the other rated values for two-stage units, comparisons were made between the SEER values obtained from AHRI (2012) and those calculated using data from the manufacturer EPTs. This comparison provided a clearer picture of the discrepancies between the two data sources, and a picture of how the different sets of rated values would theoretically compare (on an annual energy basis).

The two-stage SEER calculation requires knowledge of four operating points (A_2, B_2, B_1, F_1) and the C_D value. The regression curves were evaluated to determine the performance at all four operating points. Because of the complexity inherent in the two-stage SEER calculation, it was necessary to assume a C_D when using manufacturer data to calculate a SEER value. The C_D was assumed to be 0.1—considered a conservative estimate for two-stage ACs. The impact of C_D on the calculated SEER values is shown in Figure 9 by the shaded band around the calculated SEER values representing calculated SEER at C_D equal to 0.01 and 0.25 (upper and lower bounds given by AHRI on the C_D value). A sensitivity to fan efficiency was not necessary, because net values are used in the SEER calculation procedure and are provided in the EPTs. This is similar to the calculated C_D values shown in Figure 7; the capacity and efficiency values used in calculating the SEER values shown here are essentially interpolations in the EPT tables.

The results are shown in Figure 9, presented in blocks of three to five units. Each block represents a particular manufacturer's specific model line (labeled A–E); each point represents a different size unit within the model line (in ascending order of capacity, i.e. 2–5 tons). The figure has three series: (1) $SEER_{AHRI}$ (SEER values listed in AHRI [2012]); (2) $SEER_{CALC}$ (calculated from manufacturer EPTs assuming a C_D of 0.1); and (3) the nominal/family SEER value for the particular model line.

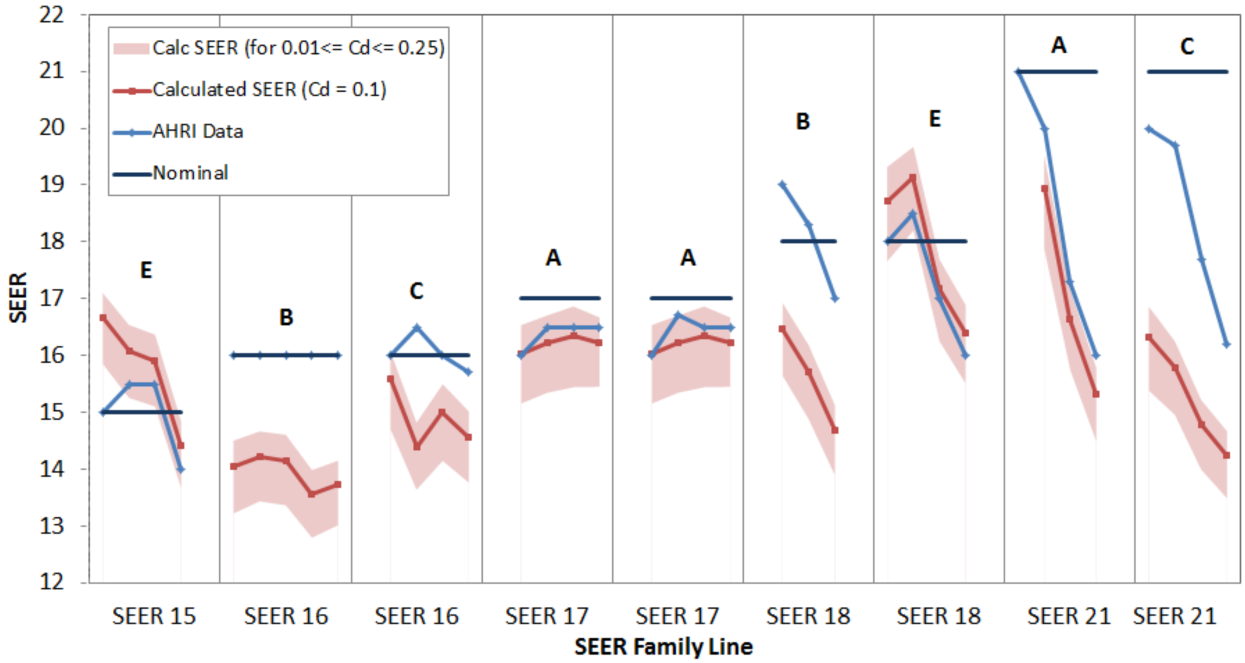

Figure 9. SEER calculated using manufacturer data compared to AHRI reported SEER values for two-stage ACs (letters A, B, C, and E denote manufacturer; capacities of 2, 3, 4, and 5 tons shown in ascending order within a product line)

These results showed interesting issues with the two-stage models:

- The large discrepancies between $SEER_{CALC}$ and $SEER_{AHRI}$ for most units evaluated were most significant. The differences ranged from 0 to >3.5 SEER points. In some cases the trend in $SEER_{CALC}$ did not match the trend in $SEER_{AHRI}$ values.

  These results demonstrate the significance of the various rating points when evaluating the annual efficiency of two-stage units. Figure 8 demonstrates improved agreement (over the single-speed results) for the A_2 rating points, yet evaluation of the other rating points (B_2, A_1, and F_1) through the SEER rating comparison demonstrated a significant discrepancy between manufacturer data and the data gathered from the AHRI directory.

- Figure 9 identifies a correlation between SEER and capacity for the highest SEER model lines. Both the $SEER_{CALC}$ and the $SEER_{AHRI}$ demonstrated significant degradation of the SEER value for large capacities in the SEER 18 and SEER 21 model lines. The 2-ton capacities for the high (nominal) SEER lines had SEER values that were 3–5 points higher than the 5-ton unit of that same model line.

6.3 System Tonnage Impact on High SEER Air Conditioners

Figure 9 displays a clear trend in the SEER values for high SEER (SEER 18 and 21 product lines) ACs—the SEER decreases as the nominal system tonnage increases. This trend is apparent in the simulation results, the calculated SEER results, and the SEER values listed in AHRI (2012).

This decrease in efficiency needs to be accounted for when simulating high SEER ACs in whole-building simulation tools. For example, when evaluating the potential energy savings of a SEER 21 AC in a large home, the unit cannot be modeled as SEER 21 equipment. The SEER for this unit (as reported by AHRI) is approximately 16 and must be modeled as such. The procedure used to take this trend into account is explained in Section 8.

The decreasing trend in ratings for larger capacity ACs can be explained by the extremely large outdoor heat exchanger areas, which would be required to achieve these high SEER ratings for large-capacity ACs. At least three of the four product lines plotted in Figure 9 use the same outdoor heat exchanger design across all or several system capacities. Thus, it is not surprising that the efficiency drops as the compressor and indoor heat exchanger increase in size to achieve the rated nominal capacity, while the outdoor heat exchanger size remains constant.

7 Standard Library Development

The principal goal of this research was to improve energy use predictions for ACs and HPs through accurate energy modeling with whole-building simulation tools. Section 6 showed that unit-specific performance curves have a minimal impact on predicted annual efficiency and selected standard performance curves for each type of DX unit (single- and two-stage ACs and HPs) achieved acceptable accuracy. Almost all the unexpected variations seen in unit-specific simulation results were due to variations in the rated value inputs. Section 6 evaluated the rated values in manufacturer EPTs through comparison with AHRI (2012). This comparison demonstrated limited agreement between the certified rating values in the AHRI directory and the rated values gathered from the EPTs.

The results from these two sections are combined in this section to provide consistent and accurate modeling in the residential modeling software BEopt (providing simulation capability in EnergyPlus or DOE-2). This same methodology can be implemented directly into EnergyPlus, if desired. It was desirable to have representative models for each SEER and HSPF efficiency family in the BEopt library. This allows for effective cost and energy comparisons between SEER and HSPF values.

This section presents the rated value inputs for the BEopt library and the curve coefficients for the standard curves (discussed in Section 5) for ACs and HPs.

The use of the standard set of performance curves significantly reduced the number of required modeling inputs. Remaining inputs were total rated capacity, rated EER, rated SHR, rated airflow rate, and a part load curve. Rated total capacity is a function of the building and is determined by BEopt using Manual J procedures (Rutkowski 2006). The rated airflow rate (the value the flow rate curves are normalized to) is inherently tied to the performance curves and cannot be changed. The remaining inputs (rated COP, rated SHR, and the degradation coefficient) need to be specified in the built-in library or defined by the user.

This modeling approach provides the shipped options in the standard BEopt library that are presented in this section. It also allows for more customized use. The user who wants to model a specific make or model can find the unrounded SEER value in the AHRI directory (and at least one of the rated EER values), and then select the rated values that will result in that exact SEER value. This allows the advanced user to model ACs and HPs that are representative of the officially tested data inherent in the data published by AHRI. The required SHR can be obtained from the EPTs on that model.

7.1 Air Conditioner Library Inputs

Table 6 shows the model inputs for the eight AC options included in BEopt. Rated EER values were determined using the nominal (rounded) SEER value and C_D values provided by a particular manufacturer. Two-stage units require the rated values inputs for each stage and the capacity ratio (defined as the rated total capacity of the low stage divided by the rated total capacity of the high stage). Manual J calculations are used to define the high stage capacity of the unit; the capacity ratio is used to calculate the lower stage. The selected capacity factors were representative of the two-stage units studied. Derate factors scale the rated EER to capture the efficiency degradation for larger units (described in Section 6.3).

Table 6. BEopt AC Rated Value Inputs

SEER	Rated EER (low, high)	C_D	Rated SHR (low, high)	Capacity Ratio[1]	EER Derate Multiplier (2, 3, 4, 5 tons)
13	11.1	0.05	0.73	–	–
14	12.0	0.05	0.73	–	–
15	13.0	0.07	0.73	–	–
16 (1)	14.0	0.12	0.73	–	–
16 (2)	13.5,12.4	0.10	0.71,0.73	0.72	–
17	14.4,13.2	0.10	0.71,0.73	0.72	–
18	15.2,14.0	0.10	0.71,0.73	0.72	1, 1, 0.94, 0.88
21	17.7,15.3	0.07	0.71,0.73	0.72	1, 0.95, 0.82, 0.76

[1] The rated capacity of the low stage divided by the rated capacity of the high stage

7.2 Air Conditioner Performance Curve Coefficients

Coefficients for the representative performance curves are included in Tables 7–10. Appendix A includes corresponding coefficients as a function of operating temperature in SI units, which can be directly input into EnergyPlus. Total capacity and EIR performance curves that modify performance for off-rated flow rates are nondimensional. Thus, these flow fraction coefficients can be used in EnergyPlus without modification.

Table 7. AC Total Capacity Coefficients as a Function of Operating Temperatures (°F)

	Single-Stage Units	Two-Stage/Speed Units	
		Low	High
a	3.670270705	3.940185508	3.109456535
b	–0.098652414	–0.104723455	–0.085520461
c	0.000955906	0.001019298	0.000863238
d	0.006552414	0.006471171	0.00863049
e	–0.0000156	–0.00000953	–0.0000210
f	–0.000131877	–0.000161658	–0.000140186

Table 8. AC EIR Coefficients as a Function of Operating Temperatures (°F)

	Single-Stage Units	Two-Stage/Speed Units	
		Low	High
a	–3.302695861	–3.877526888	–1.990708931
b	0.137871531	0.164566276	0.093969249
c	–0.001056996	–0.001272755	–0.00073335
d	–0.012573945	–0.019956043	–0.009062553
e	0.000214638	0.000256512	0.000165099
f	–0.000145054	–0.000133539	–0.0000997

Table 9. AC Total Capacity Coefficients as a Function of Flow Fraction

	Single-Stage Units	Two-Stage/Speed Units	
		Low	High
a	0.718605468	0.65673024	0.690334551
b	0.410099989	0.516470835	0.464383753
c	–0.128705457	–0.172887149	–0.154507638

Table 10. AC EIR Performance Curve Coefficients as Function of a Flow Fraction

	Single-Stage Units	Two-Stage/Speed Units	
		Low	High
a	1.32299905	1.562945114	1.31565404
b	–0.477711207	–0.791859997	–0.482467162
c	0.154712157	0.230030877	0.166239001

7.3 Heat Pump Library Inputs

Table 11 shows the model inputs for the seven HP options in the BEopt library. These are very similar to the AC inputs, except both rated EER (for cooling) and COP (for heating) values are required. A separate C_D is also required for heating mode.

Table 11. BEopt HP Rated Value Inputs

SEER, HSPF	Rated EER (low, high)	Rated COP (low, high)	C_D (cool, heat)	Rated SHR (low, high)	Capacity Ratio[1]	EER Derate Multiplier (2, 3, 4, 5 tons)
13, 7.7	11.4	3.05	0.08, 0.10	0.73	–	–
14, 8.2	12.2	3.35	0.07, 0.10	0.73	–	–
15, 8.5	12.7	3.5	0.01, 0.10	0.73	–	–
16, 8.6	13.1, 11.7	3.6, 3.2	0.12, 0.10	0.71, 0.72	0.72	–
17, 8.7	13.9, 12.8	3.6, 3.3	0.13, 0.10	0.71,0.72	0.72	–
18, 9.3	14.5, 13.3	4.0, 3.5	0.09, 0.10	0.71,0.72	0.72	1, 1, 0.93, 0.90
19, 9.5	15.5, 13.8	4.1, 3.6	0.10, 0.10	0.71,0.72	0.72	1, 0.95, 0.88, 0.81

[1] The rated capacity of the low stage divided by the rated capacity of the high stage

7.4 Heat Pump Performance Curve Coefficients

Coefficients for the representative HP curves are included in Tables 12–15. Cooling and heating coefficients are listed. Appendix A includes coefficients for the corresponding curves using SI units.

Table 12. HP Total Capacity Coefficients as a Function of Operating Temperatures (°F)

	Cooling			Heating		
	Single-Stage Units	Two-Stage/Speed Units		Single-Stage Units	Two-Stage/Speed Units	
		Low	High		Low	High
a	3.68637657	3.998418659	3.466810106	0.566333415	0.335690634	0.306358843
b	–0.098352478	–0.108728222	–0.091476056	–0.000744164	0.002405123	0.005376987
c	0.000956357	0.001056818	0.000901205	–0.0000103	–0.0000464	–0.0000579
d	0.005838141	0.007512314	0.004163355	0.009414634	0.013498735	0.011645092
e	–0.0000127	–0.0000139	–0.00000919	0.0000506	0.0000499	0.0000591
f	–0.000131702	–0.000164716	–0.000110829	–0.00000675	–0.00000725	–0.0000203

Table 13. HP EIR Coefficients as a Function of Operating Temperatures (°F)

	Cooling			Heating		
	Single-Stage Units	Two-Stage/Speed Units		Single-Stage Units	Two-Stage/Speed Units	
		Low	High		Low	High
a	–3.437356399	–4.282911381	–3.557757517	0.718398423	0.36338171	0.981100941
b	0.136656369	0.181023691	0.112737397	0.003498178	0.013523725	–0.005158493
c	–0.001049231	–0.001357391	–0.000731381	0.000142202	0.000258872	0.000243416
d	–0.0079378	–0.026310378	0.013184877	–0.005724331	–0.009450269	–0.005274352
e	0.000185435	0.000333282	0.000132645	0.00014085	0.000439519	0.000230742
f	–0.0001441	–0.000197405	–0.000338716	–0.000215321	–0.000653723	–0.000336954

Table 14. HP Total Capacity Coefficients as a Function of Flow Fraction

	Cooling			Heating		
	Single-Stage Units	Two-Stage/Speed Units		Single-Stage Units	Two-Stage/Speed Units	
		Low	High		Low	High
a	0.718664047	0.655239515	0.618281092	0.694045465	0.741466907	0.76634609
b	0.41797409	0.511655216	0.569060264	0.474207981	0.378645444	0.32840943
c	–0.136638137	–0.166894731	–0.187341356	–0.168253446	–0.119754733	–0.094701495

Table 15. HP EIR Performance Curve Coefficients as a Function of Flow Fraction

	Cooling			Heating		
	Single-Stage Units	Two-Stage/Speed Units		Single-Stage Units	Two-Stage/Speed Units	
		Low	High		Low	High
a	1.143487507	1.639108268	1.570774717	2.185418751	2.153618211	2.001041353
b	–0.13943972	–0.998953996	–0.914152018	–1.942827919	–1.737190609	–1.58869128
c	–0.004047787	0.359845728	0.343377302	0.757409168	0.584269478	0.587593517

7.5 Air Conditioner Library Simulation Results

The standard BEopt options were simulated and plotted with the set of AC units in the manufacturer’s database (see Figure 10). The shipped options attain a clear progression of increasing annual average efficiency over increasing SEER families. The efficiency degradation for larger units in high SEER families was also captured effectively through the EER derate multiplier.

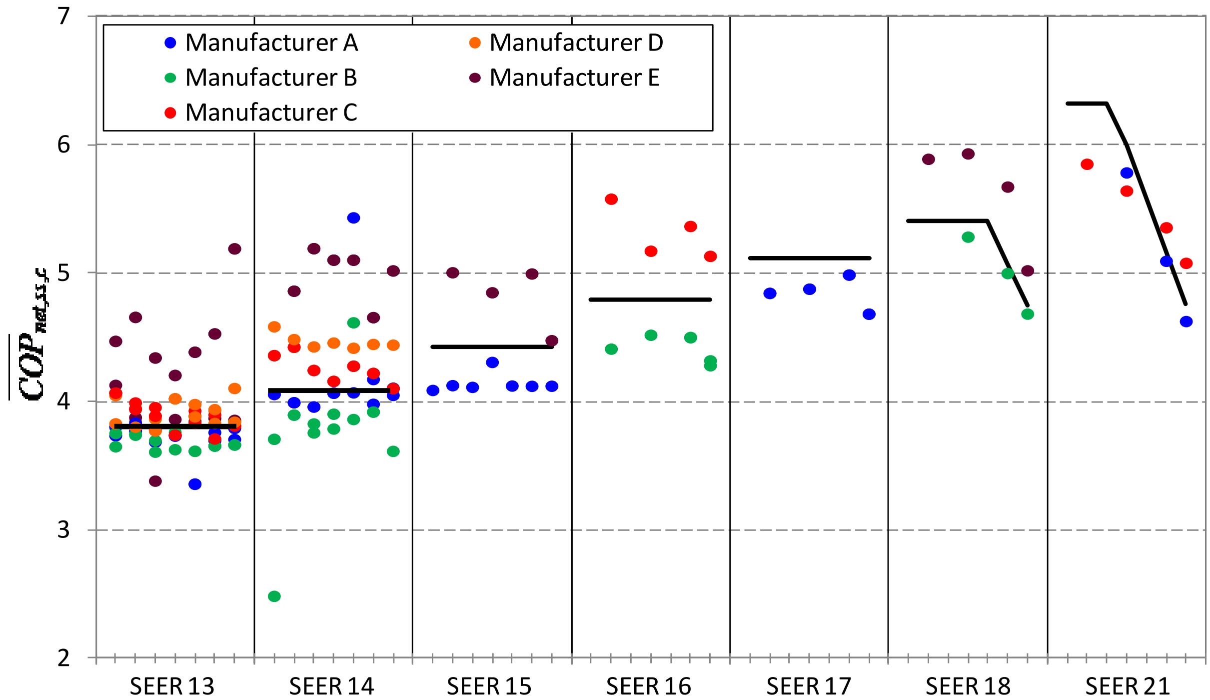

Figure 10. Simulation results for the AC library (shown in solid black lines) compared to individual AC units (individual capacities of 1.5, 2, 3, 4, and 5 tons shown in ascending order within SEER values)

The BEopt library represents the intent of the AHRI rating procedure and provides an average performing unit at varying efficiency levels. The simplified set of required inputs can be used to simulate a specific AC or HP unit to reflect the AHRI data for that unit.

8 Conclusions

When simulating AC and HP energy use in the context of whole-building simulation tools:

- Unit-specific performance curves do not significantly impact the predicted energy use. The standardized set of curves included in this report for single- and two-stage ACs and HPs offers comparable accuracy and significantly reduces the number of modeling inputs.
- The assumed rated value inputs are the key drivers in the predicted energy use; the data source chosen to determine these inputs is also important. Rated values from the manufacturer EPTs did not always match AHRI (2012). Rated values should be selected to represent the SEER and HSPF ratings for the specific unit being modeled.
- A standard AC and HP library containing inputs consistent with SEER and HSPF rating procedures is useful for making energy and cost comparisons. This was made possible by the combination of rated inputs and curve coefficients presented in Section 7. Simulating specific AC and HP units is also facilitated by using the standard curves with unit-specific rated values.

Further improvements to AC and HP modeling would be facilitated by more complete data reporting by AHRI and the individual manufacturers. More detailed performance maps are required than are currently provided. Of particular use would be the cycling degradation coefficient (C_D, verified by AHRI in its testing process), and the fan efficacy (W/cfm) value that corresponds to the reported net testing data.

The modeling procedures presented in this report provide improved consistency and agreement with the SEER and HSPF ratings and are recommended for current simulations in whole-building energy simulation tools.

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Appendix A—Performance Coefficients in SI Units

The coefficients in Tables 16–19 for AC and HP performance can be directly used in EnergyPlus. Coefficients for total capacity and EIR as function of operating temperatures are displayed below in SI units. Flow fraction curve coefficients can be found in Section 5.

Table 16. AC Total Capacity Coefficients as a Function of Operating Temperatures (°C)

	Single-Stage Units	Two-Stage/Speed Units	
		Low	High
a	1.55090	1.66458	1.36788
b	–0.07505	–0.08039	–0.06257
c	0.00310	0.00330	0.00280
d	0.00240	0.00124	0.00504
e	–0.00005	–0.00003	–0.00007
f	–0.00043	–0.00052	–0.00045

Table 17. AC EIR Coefficients as a Function of Operating Temperatures (°C)

	Single-Stage Units	Two-Stage/Speed Units	
		Low	High
a	–0.30428	–0.42738	0.04232
b	0.11805	0.14191	0.07892
c	–0.00342	–0.00412	–0.00238
d	–0.00626	–0.01406	–0.00304
e	0.00070	0.00083	0.00053
f	–0.00047	–0.00043	–0.00032

Table 18. HP Total Capacity Coefficients as a Function of Operating Temperatures (°C)

	Cooling			Heating		
	Single-Stage Units	Two-Stage/Speed Units		Single-Stage Units	Two-Stage/Speed Units	
		Low	High		Low	High
a	1.557360	1.658788	1.472738	0.876825	0.846130	0.818223
b	–0.074448	–0.083453	–0.067222	–0.002955	–0.002279	0.001981
c	0.003099	0.003424	0.002920	–0.000058	–0.000047	–0.000203
d	0.001460	0.002433	0.000052	0.025335	0.026703	0.028703
e	–0.000041	–0.000045	–0.000030	0.000196	0.000201	0.000207
f	–0.000427	–0.000534	–0.000359	–0.000043	–0.000079	–0.000071

Table 19. HP EIR Coefficients as a Function of Operating Temperatures (°C)

	Cooling			Heating		
	Single-Stage Units	Two-Stage/Speed Units		Single-Stage Units	Two-Stage/Speed Units	
		Low	High		Low	High
a	–0.350448	–0.582916	–0.488196	0.704658	0.551837	0.815840
b	0.116810	0.158101	0.099162	0.008767	0.020380	–0.006150
c	–0.003400	–0.004398	–0.002370	0.000625	0.000546	0.001021
d	–0.001226	–0.020335	0.019503	–0.009037	–0.009638	–0.001301
e	0.000601	0.001080	0.000430	0.000738	0.000785	0.001083
f	–0.000467	–0.000640	–0.001097	–0.001025	–0.001250	–0.001487