Using EnergyPlus to Simulate the Dynamic Response of a Residential Building to Advanced Cooling Strategies

Preprint

C. Booten and P.C. Tabares-Velasco

Presented at the 2nd International Conference on Building Energy and Environment
Boulder, Colorado
August 1-4, 2012

Conference Paper
NREL/CP-5500-55583
August 2012

Contract No. DE-AC36-08GO28308

Available electronically at http://www.osti.gov/bridge

Available for a processing fee to U.S. Department of Energy
and its contractors, in paper, from:

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone: 865.576.8401
fax: 865.576.5728
email: mailto:reports@adonis.osti.gov

Available for sale to the public, in paper, from:

U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
phone: 800.553.6847
fax: 703.605.6900
email: orders@ntis.fedworld.gov
online ordering: http://www.ntis.gov/help/ordermethods.aspx

Cover Photos: (left to right) PIX 16416, PIX 17423, PIX 16560, PIX 17613, PIX 17436, PIX 17721

Printed on paper containing at least 50% wastepaper, including 10% post consumer waste.

Topic 10. Intelligent buildings and advanced control techniques

Using EnergyPlus to Simulate the Dynamic Response of a Residential Building to Advanced Cooling Strategies

Chuck Booten[1,*], Paulo Cesar Tabares-Velasco[1]

[1]National Renewable Energy Laboratory

[*]*Corresponding email: chuck.booten@nrel.gov*

Keywords: Pre-cooling, energy savings, building energy simulation, control strategies, building envelope, EnergyPlus, modeling, simulation accuracy

SUMMARY

This study demonstrates the ability of EnergyPlus to accurately model complex cooling strategies in a real home with a goal of shifting energy use off peak and realizing energy savings. The house was retrofitted through the Sacramento Municipal Utility District's (SMUD) deep energy retrofit demonstration program; field tests were operated by the National Renewable Energy Laboratory (NREL). The experimental data were collected as part of a larger study and are used here to validate simulation predictions. The EnergyPlus model is based on detailed knowledge of building and equipment characteristics, but is otherwise not calibrated or adjusted to match the data. The cooling is provided by a heat pump using several control strategies, each of which is investigated to quantify the resulting hourly and daily peak load reduction and energy savings. The goals are to demonstrate the capability of EnergyPlus to accurately model cooling energy use in a house by comparing to empirical data and to investigate the potential impacts of these cooling strategies over an entire cooling season.

INTRODUCTION

Residential building air conditioning and electric heating play a major role in driving peak demand. Together with lighting, they can account for up to 40% of total peak load (Koomey and Brown 2002). Thus, a natural place to start addressing peak demand utility challenges is in the residential sector. Two primary strategies can be used to address peak demand: (1) demand reduction strategies via improved efficiency and onsite generation, and (2) demand shifting strategies via modified control strategies and onsite energy storage.

Researchers have made significant efforts to retrofit houses with energy efficiency measures that focus on utilizing existing thermal mass (distributed thermal storage) or hot water storage (concentrated thermal storage) in residential building along with strategies such as pre-cooling (Xu et al. 2004, Keeney and Braun 1997, Henze et al. 2005, Henze et al. 2007).

This study analyzes cooling strategies and uses building simulation models to extrapolate from experimental results and predict peak demand reduction and energy savings. Whole-house building models are valuable tools that can be used to estimate energy use impacts and cost-effectiveness of new building features or retrofit measures for a particular house and climate. For this study, a model of a heavily-instrumented house was validated against empirical cooling energy use data measured using different space conditioning strategies.

Short-term tests lasting from five days to two weeks were performed at the house to capture empirical hourly and daily data for comparison to simulations.

Figure 1: Floorplan of simulated house.

METHODS

The modeling approach incorporated detailed information about the physical characteristics of the house, local weather and measured thermostat setpoint temperatures. This information was used to generate the model and run simulations. The model was calibrated only to estimate thermostat setpoints based on the measured interior air temperatures when the heat pump cycled on. This was necessary because point measurements cannot accurately reflect bulk temperature changes throughout the house. Thus, the setpoint used in the simulations was the average of the five thermocouples installed in center of the bedrooms and living room when the heat pump turned on.

The physical characteristics of the house including wall construction and insulation, window area, orientation, shading characteristics, and attic and ceiling construction (which was vaulted in some areas) were modeled in EnergyPlus v7.0. The floor plan is shown in Figure 1; the house is a ranch with slab-on-grade construction and a total floor area of 1732 sq. ft.

When validating simulations against empirical data the environmental conditions must be simulated as accurately as possible. Therefore, TMY3 or similar generic weather data are inadequate. For this study, local weather data collected by the weather station on the roof (dry bulb temperature, dew point, relative humidity, wind speed and direction, insolation and local pressure) were substituted over existing data in the TMY3 for Sacramento, CA. The simulated weather thus matched experimental conditions as closely as possible. However, since not all parameters in the TMY3 format were measured, it is possible that using this technique there could be a degenerate case where some remaining TMY3 conditions are incompatible with measured weather on particular days (such as rain in the TMY3 and low humidity in measured data) but that did not happen in this study.

During the experiments the home had simulated occupancy using heaters and lighting to simulate occupant's behaviour and appliance usage. No occupants were in the house during the testing period and the simulated occupancy was based on the standard occupants assumptions defined in the Building America House Simulation Protocols (Hendron and Engebrecht 2010). The exceptions to the Building America House Simulation Protocols are the nominal thermostat set points used in the space conditioning experiments. These were chosen to match Title 24 recommendations from the California Energy Commission (2008) as closely as possible as these recommendations are of particular importance to SMUD.

This house was intended to showcase new and effective energy efficiency and renewable energy measures such as a heat pump rated at SEER 16/EER 13 HSPF 9.75, a heat pump water heater (COP=2.11) with an integrated solar water collector, and a 2.3 kW photovoltaic system. These measures, as well as high efficiency windows, exterior blinds, dissimilar wall insulation levels on exterior and interior walls and complicated cooling strategies make this a challenging building to model accurately. Detailed information about the retrofit measures can be found in (Sparn et al 2012).

The initial building model was developed using the Building Energy Optimization (BEopt) software, which generated an EnergyPlus input file for the home containing occupant usage profiles consistent with the Building America House Simulation Protocols. The more complicated features, such as the heat pump model, multiple wall insulation levels, exterior shades on the west wall, and the finished garage were added directly in EnergyPlus because it offers greater flexibility. All simulations used 1-minute time steps. For each cooling strategy, the house was modeled for several days prior to the day used for data comparison to allow for transient simulation start-up effects to diminish before comparing results to field data. The results presented here are representative for each test and comparisons are limited to single days for simplicity.

Cooling Strategies

Three cooling strategies were tested: a constant thermostat setpoint, a simple pre-cooling strategy and a more complex cooling strategy. The goal of the two pre-cooling strategies is to keep cooling energy use at zero during SMUD peak hours of 4-7pm. Particular days during each test were simulated in EnergyPlus for comparison. Each test is described briefly below. As noted earlier, the thermostat setpoints for EnergyPlus simulations were estimated to be the room temperature at which the heat pump turned on and off.

- Baseline - The thermostat was kept at a constant temperature of 24.1 °C
- Simple Pre-cooling - The house was pre-cooled to 21.0 °C between 10am and 4pm. The heat pump was turned off at all other times.
- Advanced Pre-cooling - The thermostat was set to 21.1 °C between 10am and 4pm, 26.0 °C between 4pm and 8pm and 24.1 °C all other times. This provided additional cooling during the evening to attempt to reduce the cooling load during the morning and early afternoon.

RESULTS

The modeling results and field test data presented here are limited to the room temperatures and HVAC energy (heat pump and air handler energy use). The results shown compare EnergyPlus predictions to test data from individual test days.

Baseline Cooling Strategy

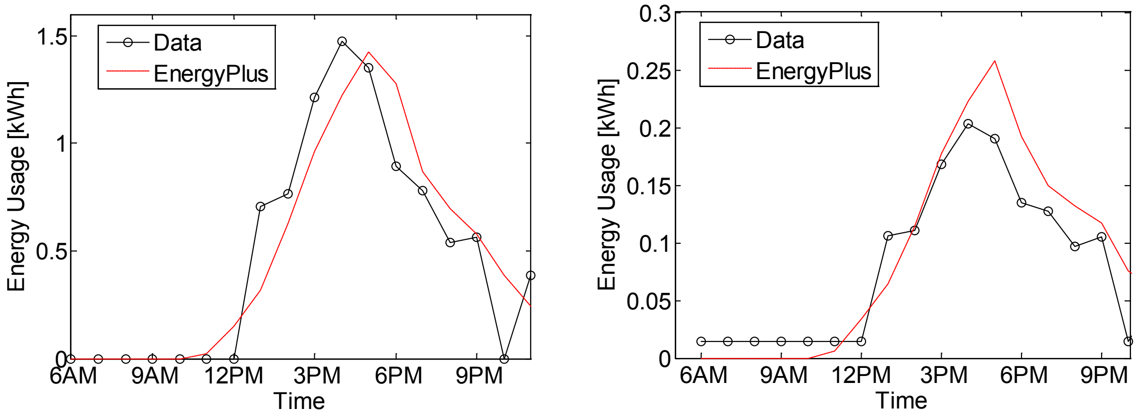

Figure 2: Baseline HVAC data and modeling results for July 20, 2010: cooling energy (L) and air handler energy (R)

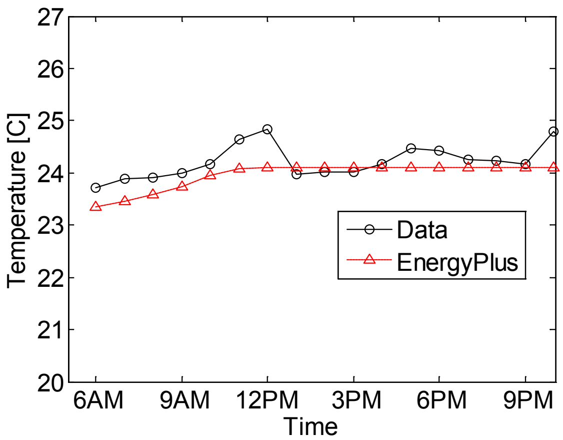

Figure 3: Baseline average house temperatures for July 20, 2010

Figure 2 and Figure 3 show the hourly energy use and temperature for the Baseline cooling strategy for one day in July. The temperature profile is the average of the 5 temperature sensors located in the center of each room in the house. However, room to room temperature varied up to ±2°C. The predicted hourly profile captures the important characteristics for both the cooling energy and air handler energy. Predicted energy use started and stopped consistent with measured data; the peak load also matched within 4% for the cooling energy and 27% for air handler energy and within 1% for total peak energy. Certain features in the data such as non-monotonic behavior in energy use from 8 to 10pm are not captured in the model. This can be due to the internal thermostat control algorithms or to air flow patterns within the house. The result is temperature variations from the setpoint that can be seen in Figure 3, most notably from 10am to 12pm and also at 9pm. These temperature variations are correlated to heat pump operation and can also result in the non-monotonic behavior seen in Figure 2. The air handler also had a minimum power draw of 14 W for continuous operation of the control board that is not captured in the EnergyPlus model.

Simple Pre-Cooling Strategy

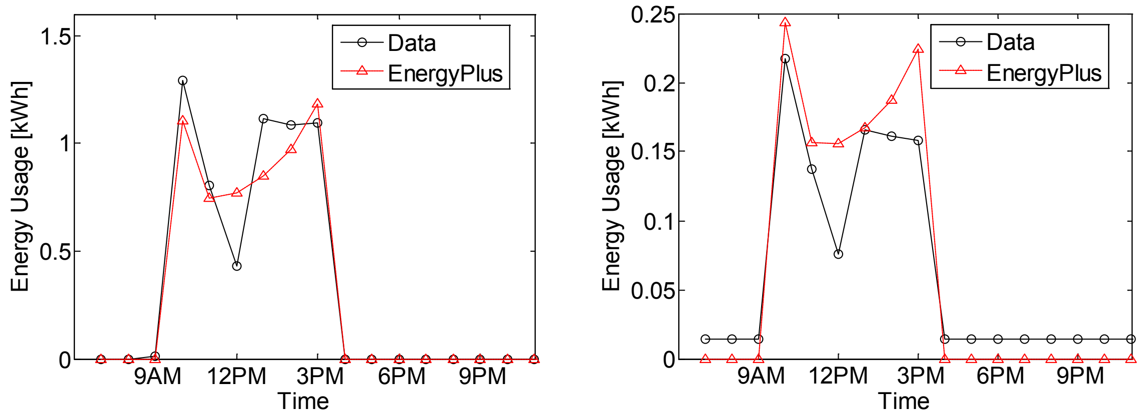

Figure 4: Simple pre-cooling modeling results for September 15, 2010: cooling energy (L) and air handler energy (R)

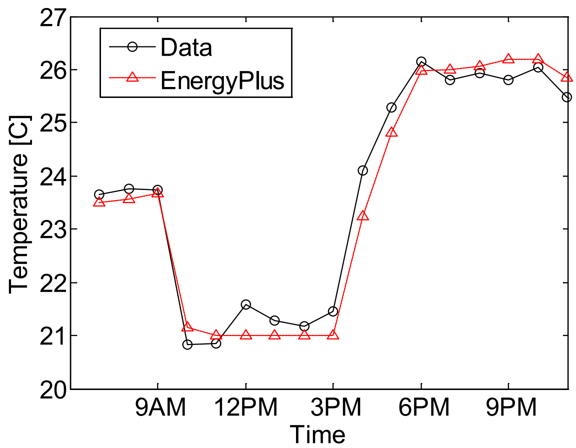

Figure 5: Simple pre-cooling average house temperature for September 15, 2010

The simple pre-cooling comparison is shown in Figures 4 and 5. The important features in Figure 4 are A) the large spike in energy use when the heat pump is initially turned on in the morning followed by B) a large decrease in energy use after the house has been cooled to the new setpoint temperature and C) the subsequent increase in cooling energy in early afternoon as the cooling load increases. EnergyPlus captures these features qualitatively but does not match peak power. This can be explained by the living room temperature in Figure 5. The measured living room temperature overshoots the setpoint temperature in EnergyPlus and has a damped oscillating behavior. When the measured temperature exceeds the predicted temperature, the measured energy use is less than the predicted use and vice versa. The difference between the measured and simulated temperatures from 9-11am is consistent with the difference in cooling energy usage in Figure 4.

Predicted energy use was qualitatively consistent with measured data; the peak load matched within 9% for the cooling energy and 13% for air handler energy and within 7% for total peak energy.

Advanced Pre-Cooling Strategy

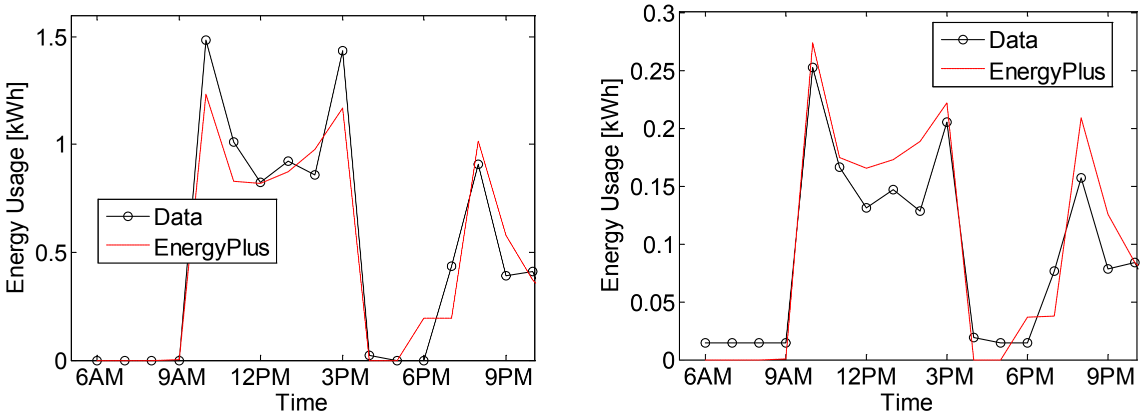

Figure 6: Advanced pre-cooling modeling results for August 11, 2010: cooling energy (L) and air handler energy (R)

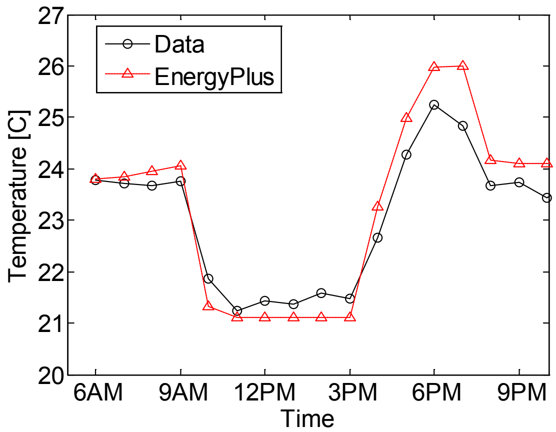

Figure 7: Advanced pre-cooling average house temperatures for August 11, 2010

The advanced pre-cooling energy use comparison is shown in Figure 6. This cooling strategy is similar to the Simple pre-cooling but with additional cooling in the evening. The multiple rapid changes in setpoint temperatures and the associated thermal transients make this very challenging to model accurately. The important characteristics of the measured data are reflected in EnergyPlus. However, the prediction of the spikes in energy use at 9am and 3pm are lower than the measured data. The peak load matched within 17% for the cooling energy and 9% for air handler energy and within 13% for total peak energy.

Daily Comparison

Table 1 shows the total daily energy use for each cooling schedule and compares that to measured data. The comparisons are for the cooling load, air handler and total cooling energy (which is the sum of the two). The agreement with data for the total energy use is within 4% for all three strategies. The cooling energy comparisons are generally in better agreement than for the air handler, which could indicate the need for improved air handler model assumptions; for example steady state and minimum power required or purge time. Predictions of energy consumption were generally more accurate than peak load predictions. EnergyPlus under predicted peak loads by 4% – 26%; the Baseline case having the best prediction and the Advanced pre-cooling had the worst.

Table 1: Single day cooling energy comparison between EnergyPlus and field data for all three cooling strategies.

Cooling schedule		Cooling Energy (kWh)		Difference (%)
		Field Data	EnergyPlus	
Baseline	Cooling Load	8.68	8.83	-1.7
	Air Handler	1.52	1.60	5.4
	Total	10.20	10.43	2.2
Baseline Pre-cooling	Cooling Load	5.84	5.68	-3.6
	Air Handler	1.17	1.13	-3.2
	Total	7.01	6.76	-3.5
Advanced Pre-cooling	Cooling Load	9.09	8.89	-2.2
	Air Handler	1.69	1.83	8.4
	Total	10.78	10.72	-0.5

DISCUSSION

As utilities move towards time-of-use pricing, more homeowners will be interested in ways to shift their cooling load away from the peak hours and/or reduce their total energy use. Utilities that can control cooling loads will also be looking for optimal control strategies for peak shifting. This study is a step toward demonstrating modeling capabilities that will allow investigation of energy saving and peak shifting strategies from individual homes up to grid-scale. Further work can be conducted to determine how to improve models to capture rapid changes in cooling load and peak load and to investigate other strategies or technologies for reducing energy and peak loads.

CONCLUSIONS

In this study, EnergyPlus was used to model cooling energy usage during summer days at hourly and daily resolution for three cooling strategies in an actual home in Sacramento, CA. The goals were to demonstrate the capability of EnergyPlus to accurately model cooling energy use in a house by comparing to empirical data and to investigate the potential impacts of these cooling strategies over an entire cooling season. The three cooling strategies investigated were Baseline cooling with a constant thermostat setpoint, Simple pre-cooling with the house cooled from 10am-3pm, and Advanced pre-cooling which added evening cooling to the Simple pre-cooling schedule. Simulation results predicted total cooling energy uses that differed from measured energy by less than 5% over an entire day for all three strategies. Hourly comparisons showed very good agreement; EnergyPlus captured the important features, such as when the cooling system was operating, and predicted peak load within 1% for the Baseline cooling, 7% for the Baseline pre-cooling and 13% for the Advanced pre-cooling.

Rapid changes in cooling load, such as a large change in thermostat setpoint, result in differences between the model predictions and measurements. Further work is needed in this area, such as investigating EnergyPlus setpoint determination and understanding sensitivity of the model to difficult-to-measure parameters such as thermal mass, interior temperature variations and room to room air flow patterns.

ACKNOWLEDGEMENT

This work was funded by the Sacramento Municipal Utility District (SMUD) and the US Department of Energy.

The authors wish to acknowledge other NREL employees and contractors who contributed to this project: Bethany Sparn (lead researcher for data collection and analysis), Lieko Earle, Kate Hudon, Ed Hancock (Mountain Energy Partnership), Lee Magnusson (formerly of NREL), Dave Roberts, Stacey Rothgeb, Cheryn Engebrecht, and Paul Norton (formerly of NREL). Also, this work would not have been possible without the support of Jim Bayless (Greenbuilt Construction) and Mike Keesee (SMUD). Lastly, the authors wish to thank Dan Roberts (Mountain Energy Partnership) for being our local assistant for a number of tests.

REFERENCES

1. Hendron, R.; Engebrecht, C. (2010). “Building America Research Benchmark Definition” NREL/TP-550-47246, Golden, CO. National Renewable Energy Laboratory.
2. California Energy Commission (2008). “2008 Building Energy Efficiency Standards for Residential and Commercial Buildings.” California Code of Regulations, Title 24, Part 1 CEC-400-2008-001-CMF
3. Sparn, B. et al. “Greenbuilt Retrofit Test House Final Report” NREL technical report, to be published 2012.
4. Koomey, J. and Brown R. (2002). "The Role of Building Technologies in Reducing and Controlling Peak Electricity Demand," Energy Analysis Department, Environmental Energy Technologies Division, Ernest Orlando Lawrence Berkeley National Laboratory, LBNL-49947
5. Xu, P et al. (2004). “Peak Demand Reduction from Pre- Cooling with Zone Temperature Reset in an Office Building” *Proceedings of 2004 ACEEE Summer Study on Energy Efficiency in Buildings*, Pacific Grove, CA, August 23-27, 2004.
6. Keeney, K. and Braun, J. (1997). “Application of Building Precooling to Reduce Peak Cooling Requirements”, *ASHRAE Transactions*, vol. 103, no. 1, pp. 463-469.
7. Henze, G. et al. (2005). “Experimental analysis of model-based predictive optimal control for active and passive building thermal storage inventory” *HVACR Research*, vol. 11, no. 2, pp. 189-213.
8. Henze, G. et al. (2007). “Sensitivity analysis of optimal building thermal mass control” *Journal of Solar Energy Engineering*, vol. 39, no. 2, pp 221-235.