

***ENERGYGAUGE@USA: A RESIDENTIAL BUILDING ENERGY SIMULATION DESIGN TOOL***

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**ABSTRACT**

The Florida Solar Energy Center (FSEC) has developed new software (*EnergyGauge USA*) which allows simple calculation and rating of energy use of residential buildings around the United States. In the past, most residential analysis and rating software have used simplified methods for calculation of residential building energy performance due to limitations on computing speed. However, *EnergyGauge USA*, takes advantage of current generation personal computers that perform an hourly annual computer simulation in less than 20 seconds. A simplified user interface allows buildings to be quickly defined while bringing the computing power and accuracy of an hourly computer simulation to builders, designers and raters.

**INTRODUCTION**

Easy to use residential building analysis software is desirable for builders, designers, home energy ratings and code compliance tools. Much of residential building energy software in the past has been based on simplified computational algorithms – use of variable based degree-day, bin or correlation methods. These methods often have significant limitations; for instance most cannot handle a changing internal heat gain schedule that may have large impacts on the best performing energy efficiency measures for the building. Evaluation of utility coincident peak impacts was similarly impossible.

With the recent speed increase in personal computers, hourly simulations become feasible even for mundane residential building energy rating or code compliance requirements. The *EnergyGauge USA* software was around the well-verified DOE-2.1E hourly simulation engine. The software uses the Borland Delphi 3.0 software to produce an easy-to-use front-end allowing users to conveniently describe the building in a project notebook. The notebook consists of three main “tabs” summarizing the energy related details of the project (Site / Envelope / Equipment) into which the 19 component input screens are arranged allowing the residential building to be defined in sufficient detail to make a full

building energy simulation. Defaults are available for all inputs so that useful results can be obtained with minimum effort.

The software features a number of enhancements to both improve the ease of inputs to describe houses as well as to utilize the power of an hourly simulation to examine impacts of varied schedules, ventilation rates, enthalpy-based controls and other important influences. Most importantly, the software also features a number of enhancements to the standard DOE-2.1E code that allows simulation of interactions between the building thermal distribution system and the building envelope. Research over the last five years at FSEC has shown that conductive gains or losses and leakage from distribution systems can represent as much as 30% of the building peak heating and cooling loads (Parker et al., 1998).

**INTENDED SOFTWARE CAPABILITIES**

A key objective for the software is bring the power of building energy simulations to Home Energy Rating System (HERS) scores, assessment of Model Energy Code (MEC) compliance along with evaluation of economics of improvements. Also unlike correlation or bin methods, calculation of hour-by-hour performance allows insight into peak period impact of efficiency and renewable technologies by utility system planners. For instance, *EnergyGauge USA* would allow users to find out how a changing daily thermostat schedule with a set-up from 9 AM to 5 PM (see the thermostat schedule screen from the software in Figure 1) will influence coincident peak loads. Further, since interior temperatures are calculated, the software would even allow designers to examine how passive design features influence comfort conditions in unconditioned buildings. Finally, the increasing concern with building air tightness and ventilation suggest the desirability of software able to model these aspects in a reasonably accurate fashion.

**SIMULATION**

The software uses the proven DOE-2.1E simulation engine to allow users to examine many different energy saving and/or renewable energy options,

The screenshot shows the 'EnergyGauge USA - Baltimore example' window. At the top, it displays 'Project ID: 17', 'Bldg ID: 1', 'Detailed Entry Mode', and '# of IA's: 10'. The main interface is divided into several sections:

- Thermostat Schedules:** Includes a 'Name' field with 'MyFavorite', a 'Comment' field, and checkboxes for 'Programmable Thermostat?' and 'Ceiling Fans'. A 'Change' button is also present.
- Schedule:** Features a 'Schedule Type' dropdown set to 'Cooling (WD)' and a 'Set All To Use:' field with the value '68'. Below this is a 24-hour grid showing temperature settings for AM and PM hours, with most cells containing '68'.
- Schedules:** A table listing the current schedule:
 

	TYPE	HOUR_1	HOUR_2	HOUR_3	HOUR_4
1	Cooling (WD)	68	68	68	
- Seasonal Schedule:** A table with columns for 'Heat', 'Cool', and 'Vent' across the months of the year. Checkmarks indicate active settings:
 

	Heat	Cool	Vent
Jan	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Feb	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Mar	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Apr	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
May	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Jun	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>
Jul	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>
Aug	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>
Sep	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>
Oct	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Nov	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Dec	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

At the bottom, there are navigation buttons for 'Cooling(1)', 'Heating(1)', 'Ducts(1)', 'Hot Water(1)', 'Temperatures(4)', and 'Appliances+Lights(8)'. Below these are tabs for 'Site', 'Envelope', and 'Equipment'. A footer note reads: 'Right-click for page help, or place cursor in any field and press F1 for context-sensitive help.'

Figure 1. Temperatures and schedules input screen showing choice of programmable thermostat.

based on the power of a more versatile hourly calculation (BESG, 1981; Winkelmann et al., 1993). DOE-2 has been well validated against residential-scale test cell and test building data (Meldem and Winkelmann, 1995). The simulation calculates a six-zone model of the residence (conditioned zone, attic, crawlspace, basement, garage and sunspace) with the various buffered spaces linked to the interior as appropriate. Characterization of building foundation performance is based on a series of procedures recommended by Winkelmann (1998).

### UNIQUE FEATURES

There are a number of unique capabilities built into the software that are highlighted below. A key potential is the ability of the software to simulate the interaction of duct air distribution systems and their location (attic, interior, crawlspace, basement). Past research, both at FSEC and other energy research laboratories around the United States, has shown the large importance of duct leakage and duct heat transfer from unconditioned spaces in which the distribution systems are located (Parker et al., 1998). In Sunbelt states, such duct systems are often located in the unconditioned attic with a thermal environment that is significantly influenced by roof solar reflectance as well as radiant barriers, increased ventilation and roofing materials. Within the software, the duct system can be located in any of the available unconditioned or conditioned zones so that heat transfer to and from the duct system can be

Updated TMY2 weather data for the program are available for 239 locations around the U.S (Marion and Urban, 1995). These were processed for use by DOE-2: other TMY data such as for international sites can be added. The current software produces standard DOE-2 reports which summarizes annual heating and cooling energy use), although development will eventually produce customized reports and graphic representation of selected output.

explicitly modeled. Figure 2 shows the screen for the description of the thermal distribution system. Ductless systems or those with interior duct systems can also be modeled to show the thermal advantages of such configurations. Potential interactions, and improvement within the simulation are described below.

### ATTIC MODEL

The residential attic within DOE-2 is modeled as a buffer space to the conditioned residential zone. Various conventional construction are available depending on roofing system type (composition or wood shingles, metal, tile and concrete) The exterior roof surface has a set exterior infrared emissivity (set to 0.90) with the exterior convective heat transfer coefficient computed by DOE-2 based on surface roughness and window conditions. Convective and

**Figure 2.** Duct input screen. A key capability of EnergyGauge models the thermal distribution system both for leakage and thermal losses.

radiative exchange between the roof decking and the attic insulation was accomplished by setting the interior film coefficient according to the values suggested in the [ASHRAE Handbook of Fundamentals](#) depending on their slope and surface emittance. The attic floor was assumed to consist of a given thickness of fiber-glass insulation over 1.27 cm (1/2") sheet rock. Heat transfer through the attic floor joists were modeled in parallel to the heat transfer through the insulated section.

Framing, recessed lighting cans, junction boxes and other insulation voids are assumed to comprise a less insulated fraction of the gross attic floor area which can be input. Ventilation to the attic is specified in the model as the free ventilation inlet area to the attic. Common attic spaces are assumed to have soffit and ridge ventilation such that it meets the current code recommendation for a 1:300 ventilation area to attic floor area ratio. However, within the simulation, this simulation, this value can be varied to examine impact of attic ventilation of predicted performance. The rate at which ventilation air enters the attic space is modeled using the Sherman-Grimsrud air infiltration. This model takes into account the effects of wind and buoyancy on the computed ventilation. Local wind-speeds in the model for calculating attic ventilation and house air infiltration are estimated assuming typical suburban terrain and shielding factors as described in the DOE-2 manuals.

### THERMAL DISTRIBUTION SYSTEM

A large weakness of the DOE-2.1E simulation is the inability to appropriately simulate the interaction between duct systems located in attics and building cooling energy use. Attic mounted duct systems are very popular in sun-belt homes with slab on grade construction. The authors developed a very detailed simulation of heat transfer to thermal distribution system that was used to guide the development of a function with DOE-2.1, which can simulate this interaction (Parker et al., 1993). Duct leakage estimates are based on defaults or duct integrity test results with the performance impact of return air leakage based on zone enthalpy conditions where the return is located.

The duct heat transfer model was implemented as a function within the systems simulation module in DOE\_2.1E for RESYS. The following parameters are input:

$$\begin{aligned} \text{Supply}_{\text{area}} &= \text{Supply Duct Area} \\ \text{Return}_{\text{area}} &= \text{Return Duct Area} \\ R_{\text{duct}} &= \text{Duct thermal resistance} \end{aligned}$$

Heat gain to the duct system is proportionate to the duct system thermal conductances, the involved temperature differences and the modified machine run\_time fraction:

$$\begin{aligned} UA_{\text{supply}} &= \text{Supply}_{\text{area}} / R_{\text{duct}} \\ UA_{\text{return}} &= \text{Return}_{\text{area}} / R_{\text{duct}} \end{aligned}$$

The default areas for the duct system are 6.4 m<sup>2</sup> for the return side and 34.4 m<sup>2</sup> for the supply ducts although specific values are readily input. The supply air temperature and that of each zone containing the ducts is available within systems as is the average temperature of the return air to that of the interior (e.g. 25°C). The ducts can be located in any of the available unconditioned zones (attic, crawlspace, basement, garage) or located on the interior to simulate ductless systems or those with interior placement. The heat gain to the duct system is then:

$$Q_{\text{duct}} = (T_{\text{zone}} - T_{\text{supp}}) * UA_{\text{supply}} + (T_{\text{zone}} - T_{\text{int}}) * UA_{\text{return}}$$

The fraction of the heat gain to the duct system in an individual hour depends on run time fraction, which depends on the capacity ( $Q_{\text{cap}}$ ) of the machine (e.g. 10.5 kWt) and its coefficient of performance (COP) (2.9 Wt/We): 3.6 kW at full run\_time fraction. The air conditioner electric demand ( $AC_{\text{kW}}$ ) is directly available as output from the systems section in DOE\_2:

$$\text{RTF} = (AC_{\text{kW}} / (Q_{\text{cap}}/\text{COP}))$$

A correction term is added to the initial estimate to account for the fact that the machine must run longer to abate the duct heat gains and that the ducts continue to absorb heat in between cycles:

$$\text{RTF}' = \text{RTF} + Q_{\text{duct}} / Q_{\text{cap}}$$

The addition to the AC electrical load from the duct system is then:

$$\text{Duct}_{\text{kW}} = Q_{\text{duct}} * \text{RTF}' / \text{COP}$$

The cooling load in SYSTEMS (QC) is then increased by the product of the duct system heat gain and the cooling system runtime fraction. If heating, the heating load, QH, is increased in a similar fashion. The above simulation was compared with the more detailed implementation within the finite element simulation that is being used as the reference estimation within ASHRAE SPC152P. Calculations using the DOE-2 function showed the simple model within 5% of the prediction for the impact of the duct system on the building loads.

### HEATING AND COOLING EQUIPMENT PERFORMANCE

DOE-2 includes several correlation curves that

predict how furnace, air conditioner and heat pump performance varies under part load conditions. These curves generally have been completely reassessed within the development of *EnergyGauge USA* with significant impact on measures that effect sensible loads. The development of the new correlations is described in Henderson (1998a) and is based on empirical assessment of current generation heating and cooling equipment. These curves estimate much lower levels of part load performance degradation than the default RESYS DOE-2 curves. Significantly, the revised PLR curves increase the magnitude of savings estimates for widely evaluated residential measures such as increased insulation or window improvements (Reilly and Hawthorne, 1998).

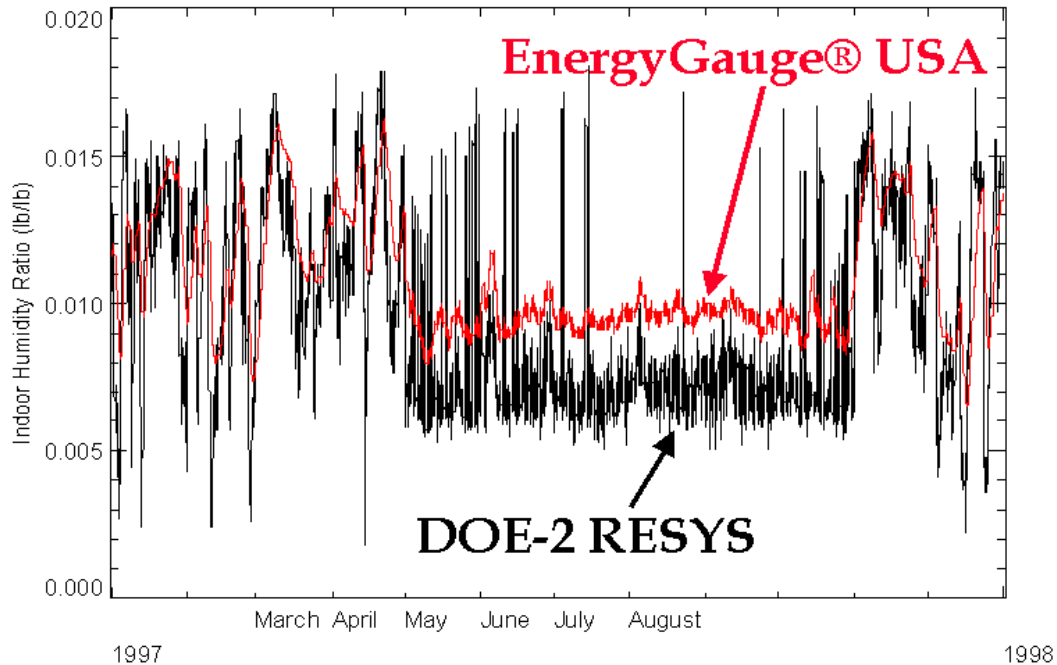
Further improvements have been made to the residential air-conditioning model (RESYS) in terms of its calculations of its latent performance. The adaptation involves adding a simple lumped moisture capacitance model for the simulation to damp out unrealistic variations in air enthalpy that were observed with the current model. The model, described in Henderson (1998b) assumes that the building has a moisture capacitance that is twenty times the air mass of the interior air – a value that has shown good agreement with empirical results. This results in superior prediction of the air conditioner cooling coil entering conditions compared with a model without moisture capacitance. Figure 3 shows the difference in predicted hourly zone humidity conditions with standard RESYS against the moisture storage approach.

An improved air conditioner/heat pump model, DOE\_AC, was added to RESYS (Henderson, Rengarajan and Shirey, 1992) for use in *EnergyGauge USA*. The DOE\_AC model is a direct expansion air conditioner model that uses the bypass factor concept to estimate the apparatus dew point (ADP). This function was added to take advantage of its better ability to determine the entering wet bulb temperature to the coil, which has large impact on cooling system performance. Also, the addition of these capabilities allow explicit evaluation of the impact of reduced coil air flow on the performance of residential heat pump and air conditioning systems which has been documented to impact space conditioning requirements by 10% or more (Parker et al., 1997).

### OTHER CAPABILITIES

In interest of brevity, we list a number of unique capabilities of the software calculation:

- Explicit evaluation of light colored building surfaces on annual cooling and heating



**Figure 3.** Comparison of predicted main zone humidity conditions with and without moisture storage (simple shade planes can be located around the building geometry).

- performance and indirect impacts on duct systems when located in the attic space.
- Assessment of performance of advanced glazing products and interaction with interior and exterior shading
- Explicit modeling of duct system leakage based on test results.
- Assessment of the energy impacts of various building ventilation approaches (exhaust, supply, balanced, with and without heat recovery).
- Characterization of appliance and lighting loads along with interactions with space heating and cooling.
- Assessment of the sizing and auxiliary strip heat on heat pump performance.
- Estimation and modeling of air handler location on thermal performance.

#### COMPARISON WITH METERED DATA

A recurring question with building energy software, regardless of the calculation rigor, is the relative accuracy of the estimates, particularly for cooling loads. To address this question, the software was

used to estimate the hourly air conditioning electrical demand in three homes extensively monitored in Apopka, Florida. Each of the homes were unoccupied, and were identical in layout and orientation, yet contained different efficiency measures (Chandra and Fuehrlein, 1999). A conventional concrete block homes served as the project control while a second had better insulated walls (autoclaved aerated concrete) and double-glazed windows. The third home, constructed with wood frame walls, had solar-control windows and an attic radiant barrier.

Building geometry, construction and features were entered into the software with measured values being used for critical inputs. Monitored meteorological data was used to create weather files for the simulation and measured interior temperatures were input for each building. The resulting hourly simulation predictions for air conditioning power were then compared to the monitored values for September 1998.

#### RESULTS

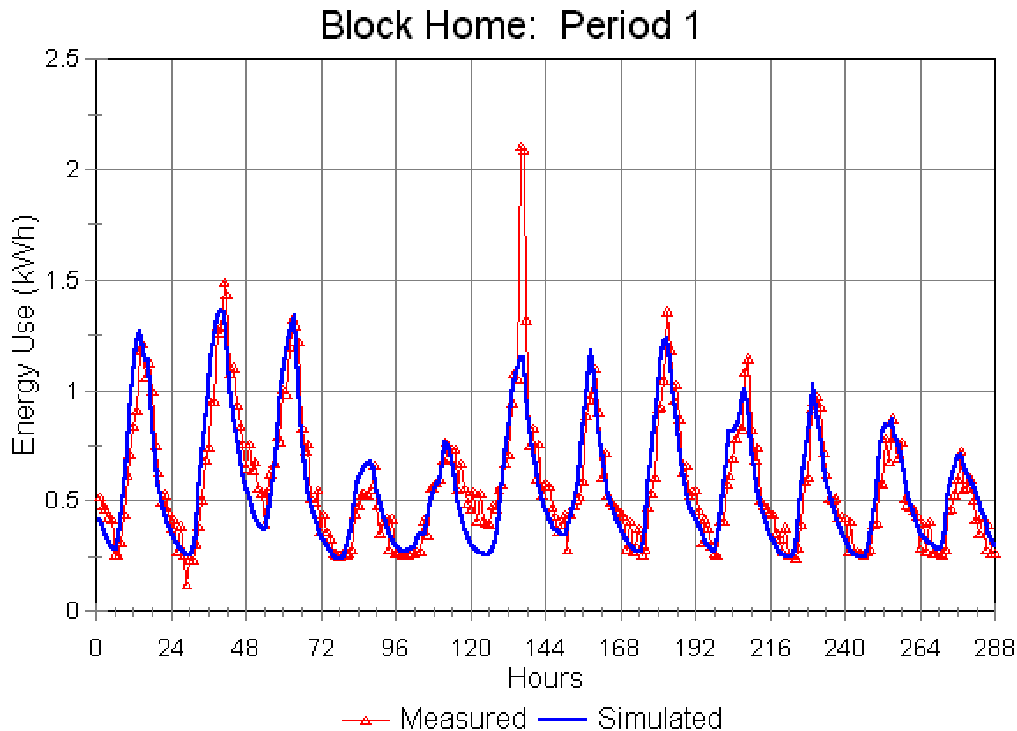
This experiment served as a comprehensive test of the EnergyGauge USA software. The variables in this experiment were the following: 1. Three different home constructions representing base case, energy efficient and improved IAQ homes. 2. Three

different periods of thermostat settings that are input into the software. These variables were tested in three periods for each house. Period one represented a warm thermostat setting and periods two and three represented a cooler thermostat setting. By testing a total of nine periods these variables were isolated.

Since many variables are being controlled, if the outputs (i.e. predicted hourly a/c energy use) of the simulation match closely with the measured data, for all three homes, for all three periods, the simulation can be considered valid for entry-level homes. Other conclusions will be drawn depending on which parts of the simulation do not match the measured data.

Figure 4 shows the energy consumption of the Block house during monitoring period one. This plot is very representative of the other two houses during

this period. For space limitation reasons only one set of plot results is shown for each monitoring period – a different home for each period. There is an excellent relationship between the simulated and the predicted indoor temperatures. There was, however, an anomaly near hour 140 on day six. The measured energy consumption was really high for several hours for all three homes. This was the day that FSEC researchers performed the SF<sub>6</sub> test on the homes. When performing the SF<sub>6</sub> test the air handlers were on for the duration of the test. This was what caused the sharp increase in energy consumption during those few hours. This was something that the simulation would not and should not predict. These bad data points were ignored during the data analysis section. Also, the AAC house was missing data for several days during this period. This data was also ignored.

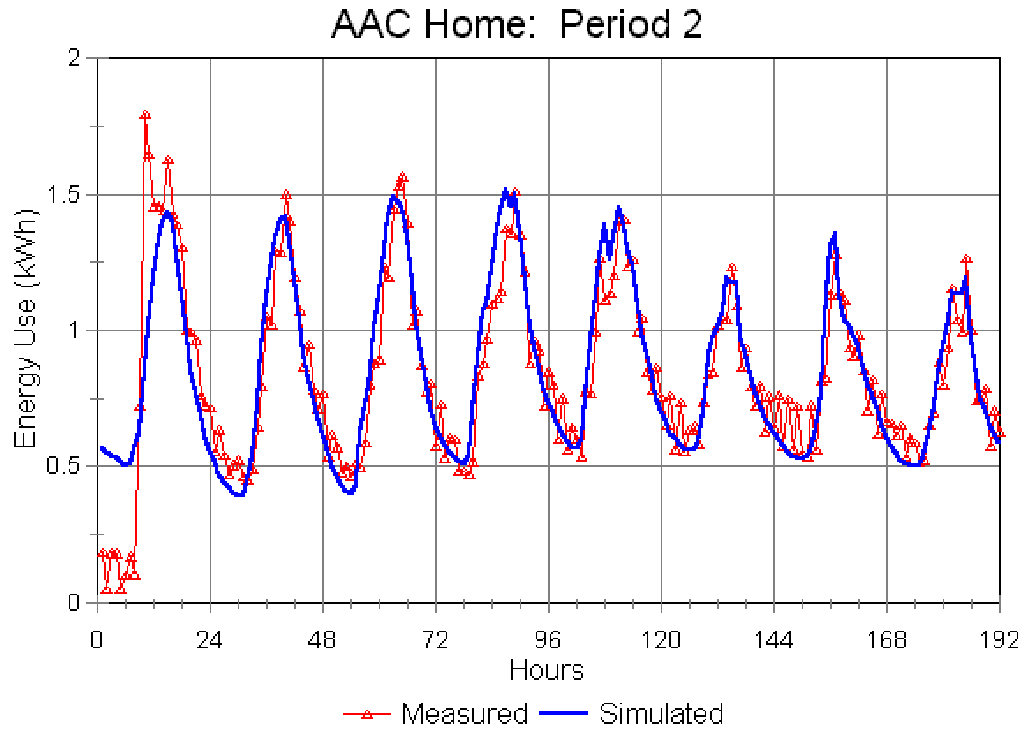


**Figure 4.** Predicted and measured interior temperatures for Block house during monitoring Period 1

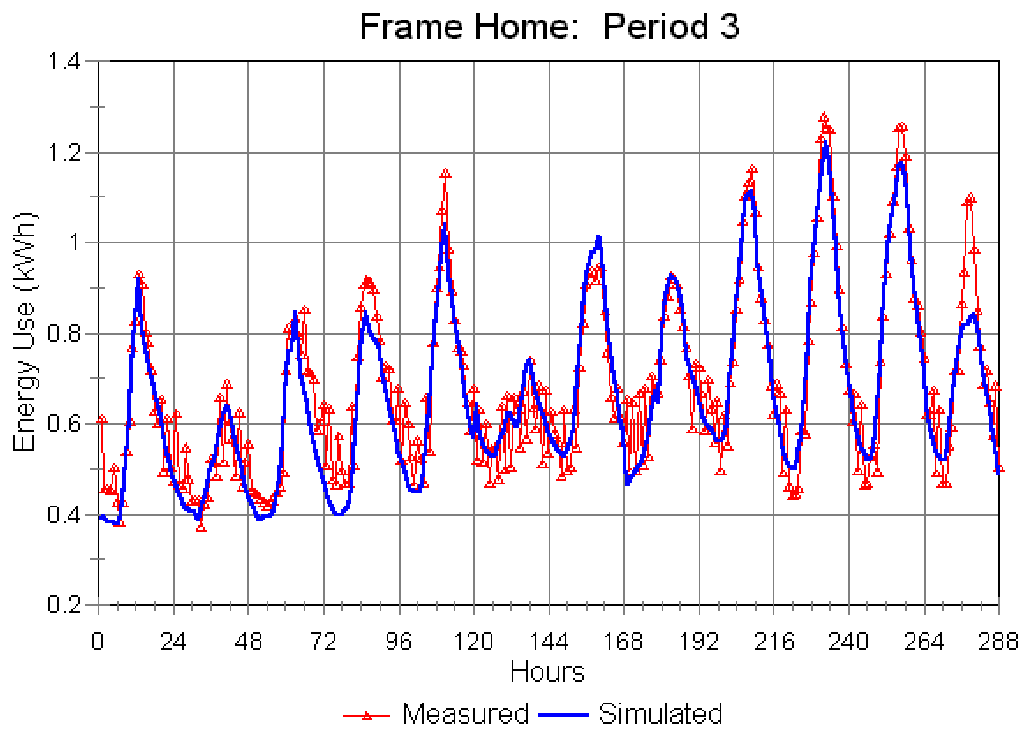
Figure 5 (following page) shows the hourly energy consumption for the AAC House for period two. Again, results from the other two homes are similar. The thermostats for the houses were set near 78 degrees the last day of period one and near 72 degrees for the first day of period two. For the first day of the colder setting the air conditioner not only has to meet the steady state cooling loads but also load from cooling down the thermal mass of the house itself. In the simulation, the warm up period has to be the same thermostat setting as the period of interest. There is no way to accurately simulate a

sudden thermostat change to 72 degrees from 78 degrees. This is the reason that the measured energy consumption was more than the simulated energy consumption. The first day of data from period two was not included in the data analysis.

Figure 6 (following page) shows the energy consumption of the Frame house for period three. Again, results from the other two homes are similar. Since the thermostat change was very small for all three homes between period two and three, the warm-up period will be ignored.



**Figure 5.** Predicted and measured interior temperatures for AAC house during monitoring Period 2



**Figure 6.** Predicted and measured interior temperatures for Frame house during monitoring Period 3

Period averages were looked at in an effort to draw initial conclusions about the difference between the predicted data and the measured data. Period averages for the overall simulation, for each house, for the high thermostat and for the low thermostat settings are presented in Table 3. Table 4 shows the period averages broken down individually for each house.

The overall averages were practically the same showing a strong overall accuracy of the software. Isolating each building technique and thermostat setting as variables, the period average error did not exceed four percent.

Table 4 shows a detailed look at all nine sets of data. The high thermostat setting represents period one for all three houses and the low thermostat setting represents periods two and three for all three houses. Again, regardless of thermostat setting, the simulation model is very accurate with error never exceeding nine percent.

A second analysis was conducted to test the simulation accuracy during peak cooling load periods. In the summertime in Florida, peak cooling occurs between the hours of four and six p.m. Data points for the four o'clock and five o'clock hours were isolated from the data sets and then the error between the measured and predicted was calculated. Similar to Table 4 above, the data is broken down by period and by construction technique so all nine data sets are presented.

Table 5 shows that even under extreme cooling load conditions the EnergyGauge USA software is accurate. The error only exceeded ten percent once and all other times was consistently below six percent.

Analysis showed excellent correspondence between the simulated and actual. Average error was less than 4 percent for average hourly as well as peak hour air conditioning usage. Maximum errors were about 10 percent.

**Table 3.** Overall Period Averages

	Overall	Block	Frame	ACC	High T'stat	Low T'stat
Predicted	0.69	0.75	0.55	0.79	0.51	0.80
Measured	0.69	0.75	0.57	0.76	0.51	0.79
Error	0.00%	0.00%	-3.51%	+3.95%	0.00%	+1.27%

**Table 4.** Individual averages for each home during each monitoring period

	Period 1			Period 2			Period 3		
	Block	Frame	AAC	Block	Frame	AAC	Block	Frame	AAC
Predicted	0.57	0.40	0.57	0.87	0.61	0.87	0.85	0.67	0.89
Measured	0.57	0.41	0.58	0.95	0.64	0.86	0.81	0.69	0.84
Error	0.00%	-2.44%	-1.72%	-8.42%	-4.69%	+1.16%	+4.94	-2.99%	+5.95%

**Table 5.** Peak load error for each home during each monitoring period

	Period 1			Period 2			Period 3		
	Block	Frame	AAC	Block	Frame	AAC	Block	Frame	AAC
Predicted	0.82	0.65	0.83	1.20	0.87	1.19	1.11	0.88	1.15
Measured	0.82	0.64	0.81	1.36	0.91	1.22	1.08	0.89	1.09
Error	0.00%	+1.56%	+2.47%	-11.76%	-4.40%	-2.46%	+2.78	-1.12%	+5.50%

## SOFTWARE DEVELOPMENT

A number of enhancements to the software are under development. The most anticipated is the inclusion of an hourly calculation of photovoltaic (PV) system performance. The PV module will allow direct examination of interactions between building loads and solar electric system performance. Other planned software enhancements are as follows:

- Characterization of solar hot water (SHW) performance against hourly loads
- Formatted output for HERS, MEC and Energy Efficient Mortgage program
- Graphic output for comparison of selected data



ACKNOWLEDGMENTS

Special thanks to the Florida Energy Office for their sponsorship of the development of the software. We are also appreciative to the many individuals who have tested the initial versions, or otherwise provided suggestions.

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