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Development and use of the energy model of a research and demonstration house with advanced design features

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ABSTRACT

Advances on manufacturing processes and the use of new materials are increasing the efficiency and reducing the cost of energy efficient and renewable energy technologies to a point that their deployment will reach desired levels for the sake of energy security and environmental concerns. Along these advances, the demonstration of the cost-effectiveness of this technology is vital to educate people and promote deployment of these technologies. In this sense, at the University of Texas at Tyler, two research and demonstration houses were built. House #1 is a conventional design with some advanced features, and House #2 has more advanced design features. In this study, House #2 is considered, which has relevant characteristics such as net-zero energy with 7.4 kW of solar photovoltaic system, advanced wall framing with open-cell foam insulation (R-24), unvented attic with open-cell foam insulated roof deck (R-24), vinyl-frame windows with double-pane, low-E glass (U=0.33, SHGF=0.23), ducted single-split system in attic (19.0 SEER, 9.0 HSPF), and high solar reflectance shingles. Since building energy performance depends on many factors, different scenarios or design characteristics can be assessed by using an energy model. In this study, the software OpenStudio (version 1.7.0) is used to develop a model for House #2. The software, developed by the National Renewable Energy Laboratory, is a user interface for the well known whole building energy simulation engine EnergyPlus. This paper shows the more relevant steps on model development. As a means of validation of the model, energy consumption from the model is compared against monthly energy consumption data in a calibration approach that is available in the software. As an example of the use of energy models, since the house has high solar reflectance shingles, the model is used to evaluate solar absorptance of shingles as a design parameter that can reduce energy consumption during cooling season but increasing energy consumption during heating season.

INTRODUCTION

The energy performance of buildings is influenced by many factors, such as ambient weather conditions, building envelope characteristics, energy systems (lighting, HVAC, etc.), and occupancy. All these variables acting on the energy consumption output make it very difficult to accurately implement the prediction of building energy consumption. In attempts to estimate buildings energy consumption many approaches have been proposed. These approaches can be classified as statistical or black-box, hybrid or grey-box, and engineering or white-box (Fumo 2014). The accuracy of an approach depends on the information that is available for the purpose of the approach. Statistical approaches need measured data, but not buildings characteristics, while the engineering approaches need building characteristics but not data, at least when a calibrated model is the goal.

Engineering approaches have the shortcoming that most of the time building information is limited and much of the data needed by the model are filled by default values that do not necessarily match the building characteristics. Thus, the model produces results which over-predict or under-predict the real energy consumption. However, if

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building characteristics are known and energy consumption is available, a calibrated engineering model is the best option for analysis of energy-conservation and energy-efficiency measures (Reddy 2005, Raftery et al. 2011, Heoa et al. 2012, Mushtaq and Culp 2006, Yiqun et al. 2006).

Model calibration is the approach of modifying and adapting a model based on measured data to generate an updated model that can accurately reflect the actual building operation performance (Jian and Agami 2006). Error sources can be internal or external (ASHRAE 2009). Internal errors are associated to the whole-building energy simulation program itself, such as (1) differences between actual thermal transfer mechanisms in the real building and its HVAC systems versus the simplified model of those processes in the simulation, (2) errors or inaccuracies in the mathematical solution of the models, and (3) coding errors. Since the software used to develop the model presented in this paper has been widely validated, as well as used and accepted by the international community, its intrinsic validation supports that only external error types are to be considered. According to the National Renewable Energy Laboratory (ASHRAE 2009), the types of external errors are:

- Differences between actual building microclimate versus weather input used by the program.
- Differences between actual schedules, control strategies, effects of occupant behavior, and other effects from the real building versus those assumed by the program user.
- User error deriving building input files.
- Differences between actual physical properties of the building (including HVAC systems) versus those input by the user.

Raftery et al. 2011 described a five steps approach for calibration: (1) preparation (initial model, historical weather data, calibration data, documentation), (2) obtain readily accessible data and information, (3) update model inputs (zone-typing, constructions, HVAC and plant, internal loads), (4) error check, and (5) iterative calibration process (test model for acceptance, review outputs using visualization techniques, investigate possible further sources of information, update model). Using this approach in this study results of the development of an energy model for a research house is presented.

RESEARCH FACILITY

The research facility has two research houses with conditioned area of 137 m² (1,470 ft²) (TxAIRE 2015). These two houses have been designed to serve as realistic test facilities for developing and demonstrating new technologies related to energy efficiency, indoor air quality, and sustainable construction materials and methods. House #1 ("Tyler House"), on the right of Figure 1 and on the left of Figure 2, demonstrates a wide range of energy efficiency renovation features that result in a house that consumes only 50% of the energy used by an average home. House #2 ("Patriot House"), on the left of Figure 1 and on the right of Figure 2, through the use of a wide array of components, is capable of generating all of the energy that it requires over the course of the year – a "net-zero energy" home. Both houses are unoccupied and all energy systems are electric.

Figure 1 Front view of the TxAIRE Houses.

Figure 2 Back view of the TxAIRE Houses.

House #2 is the house used to develop the model for this paper and a more detailed specification is as follows:

- Energy-efficient (HERS 52) and air-tight (0.08 ACH)
- Net-Zero Energy (HERS -11) with 7.4 kW (25,250 Btu/hr) of solar photovoltaic system
- Advanced wall framing with open-cell foam insulation (R-24)
- Unvented attic with open-cell foam insulated roof deck (R-24), 152.4 mm (6") thick
- Attic above the garage is vented (house attic and garage attic separated by R-30 insulated wall)
- Vinyl-frame windows with double-pane, low-E glass (U=0.33, SHGF=0.23)
- Ducted Air Source Heat Pump (2 ton, 19.0 SEER, 9.0 HSPF) with advanced air cleaning
- Energy Recovery Ventilation (ERV) (ducted independently of the Heat Pump ducts)
- Heat pump water heater in house
- High solar reflectance shingles
- Walls brick with hardieplank lap siding on walls facing patio
- Solar light tube in master bath
- Low-maintenance landscaping & rain water recovery
- Bore holes for future ground-coupled heat pump installation

Data is recorded every 5 minutes but for this study the data is compiled to generate hourly and monthly data. For illustration purposes and for the sake of some further explanations, Figure 3 shows the plot of the hourly total energy consumption of the house.

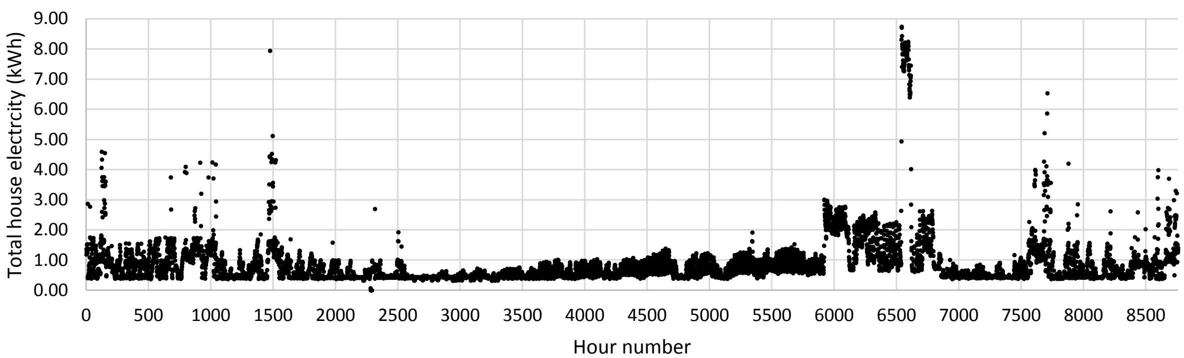


Figure 3 Measured hourly total house electricity.

SOFTWARE AND WEATHER FILE

The software used to develop and run the simulations is a collection of software tools to support whole building energy modeling that uses the well-known EnergyPlus software as the simulation engine. The model geometry is developed using a graphical interface. The software used, as an interface for the simulation engine, is in constant development and at this moment is not able to handle all the simulation capabilities of the simulation engine. In this sense, in this paper, the Energy Recovery Ventilator (ERV) system existent in the house could not be simulated as actually is installed, which is explained in the section on model development.

For any simulation, a weather file (weather data) is needed. For compatability with the the simulation engine, the weather file must be of the format/extension EPW that is the format recognized by the software. A review on weather data can be found on (Fumo 2014). However, for this study an Actual Meteorological Year (AMY) must be used because of the calibration approach available from the software and used in this study. The AMY weather file used in this study was bought from (Weather Analytics 2015) and corresponds to the closest weather station to the research site that is located in the city of Tyler, Texas (Climate Zone 3A).

MODEL DEVELOPMENT

Geometry. Figure 4 shows screenshots of the Front and Back views of the house; while Figure 5 shows screenshots of ISO (from felf and right) views of the house.

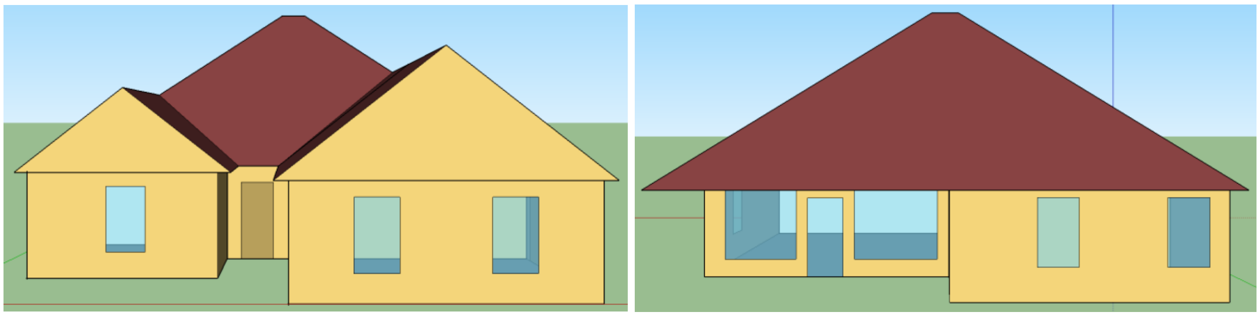


Figure 4 Front and Back standards views of the TxAIRE House #2 on SketchUp.

One of the challenges for the development of the geometry of the house was the roof because it has gables and hips. Using the 'Follow Me' tool and a method similar to the one that can be seen at (YOUTUB 2015) the roof with hips was developed. To create the gables on the front façade, the vertices of the front hips were moved to the front to create the gables as seen in the ISO views (Figure 5).

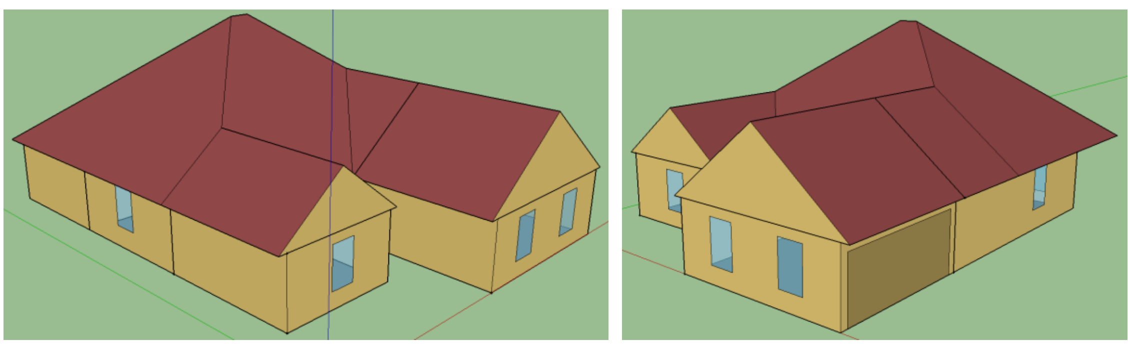


Figure 5 ISO views of the TxAIRE House #2 on SketchUp.

HVAC. The model HVAC used was the 'Unitary – DX Heat Pump (Two Speed Cooling) – Cycling – Elec reheat' as illustrated in Figure 6 as part of the air loop of the thermal zone of the house (conditioned space). Since the heat pump has no outdoor air because it is handled/provided by the ERV, to ensure zero ventilation at the Unitary DX Heat Pump, the ventilation for the house thermal zone and the fraction of outdoor air at the AirLoopHVAC:OutdoorAirSystem object were set as zero.

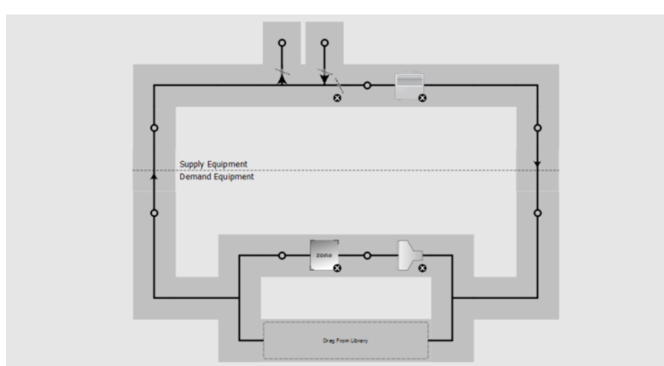


Figure 6 Screenshot of the air loop for house thermal zone.

The ERV installed at House #2 has an independent duct system and the outdoor air for ventilation is introduced directly to the house without being conditioned by the heat pump. This situation cannot be modeled because the software used does not allow having two air loops connected to the same thermal zone. This outdoor air is adding a thermal load for cooling and heating that cannot be modeled using an electric plug-in load. To overcome this situation, a dummy thermal zone was created beneath the house. The heat transferred between the house and the dummy space through an air wall was used to simulate the thermal load imposed by the outdoor air.

Loads and Schedules. The house is unoccupied and its use is for academic purposes (teaching and research). The internal loads, which are associated to electric plug-ins, were estimated based on the data recorded at the house. A typical set (month of February) is shown in Figure 7. The average load was estimated at 300 W (1,023 Btu/hr) and a schedule of a constant load during the whole year was created.

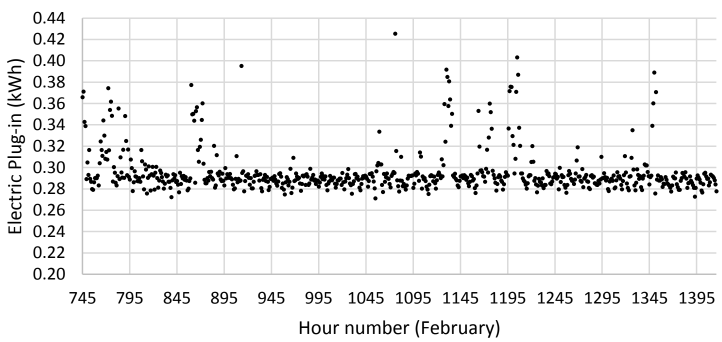


Figure 7 Example of electric plug-in loads for the TxAIRE House #2.

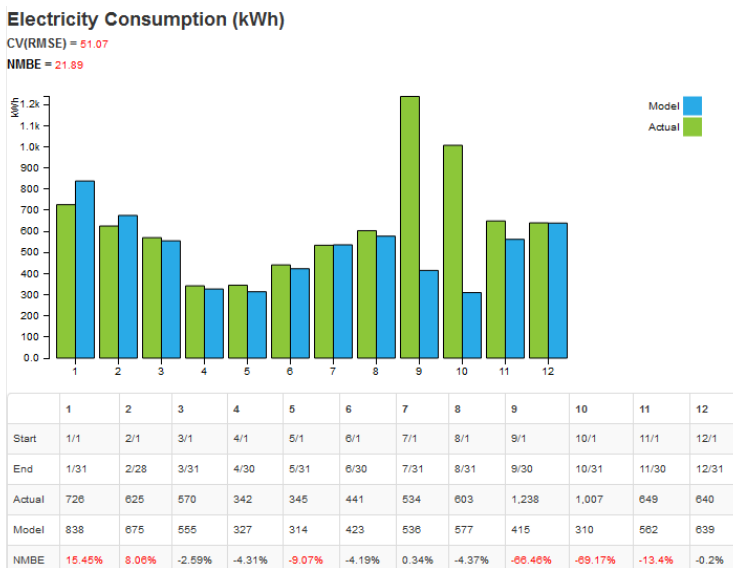
SIMULATION RESULTS AND DISCUSSION

Table 1 shows the simulation results and Figure 8 shows the calibration results. From Table 1 it can be noted that a dominant heating load is present, as well as the expected total energy distribution along the months according with the seasons. However, Figure 8 illustrates that the months of September and October are off by more than 50%. The differences in these months can be explained by looking at the electric plug-ins data for September (hour numbers 5833 to 6552) and October (hour numbers 6553 to 7296) on Figure 9. The electric loads were increased more than 5 times for most of this period but with values of even 20 times for hour numbers 6542 (September) and 6616 (October). These high values of electric loads were not implemented in the model because they are not normal.

The accepted Normalized Mean Bias Error (NMBE) and Coefficient of Variation of the square Root of the Mean of the Squares of the Deviations CV(RMSD) for the ASHRAE 14-2002 calibration method are 5% and 15% of the monthly data, respectively. Six months satisfy the 5% NMBE criterion. For the other months, the off condition can be justified by considering (1) teaching and research activities at the house that cannot or have not been implemented in the model; (2) differences between the actual weather conditions and the weather file used due to inaccuracies of the weather file and microclimate effects; and (3) the inability of the software to model the ERV as explained previously. Most of the differences can be explained by looking at the measured data shown in Figure 3. The month of September and October that are the months with the largest errors have been discussed. Other differences can be justified by the scattered data points above 2.0 kWh (68,243 Btu) which are the result of not normal operating conditions or weather conditions nor captured by the weather file used.

Table 1. Simulation Results (kWh)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Heating	559.9	423.5	300.7	83.4	20.6	0.1	0.5	—	3.3	27.7	312.3	375.4	2,107.4
Cooling	—	—	—	16.6	58.1	175.7	265.2	300.6	166.7	48.6	—	—	1,031.5
Interior Equipment	223.2	201.6	223.2	216.0	223.2	216.0	223.2	223.2	216.0	223.2	216.0	223.2	2,628.0
Fans	55.0	50.2	31.4	11.2	11.9	30.7	47.0	52.8	29.2	10.9	33.7	40.1	404.2
Total	838.2	675.4	555.2	327.3	313.7	422.5	535.8	576.7	415.2	310.4	562.0	638.7	6,171.1



	1	2	3	4	5	6	7	8	9	10	11	12
Start	1/1	2/1	3/1	4/1	5/1	6/1	7/1	8/1	9/1	10/1	11/1	12/1
End	1/31	2/28	3/31	4/30	5/31	6/30	7/31	8/31	9/30	10/31	11/30	12/31
Actual	726	625	570	342	345	441	534	603	1,238	1,007	649	640
Model	838	675	555	327	314	423	536	577	415	310	562	639
NMBE	15.45%	8.06%	-2.59%	-4.31%	-9.07%	-4.19%	0.34%	-4.37%	-66.46%	-69.17%	-13.4%	-0.2%

Figure 8 Screeshot of Calibration Results.

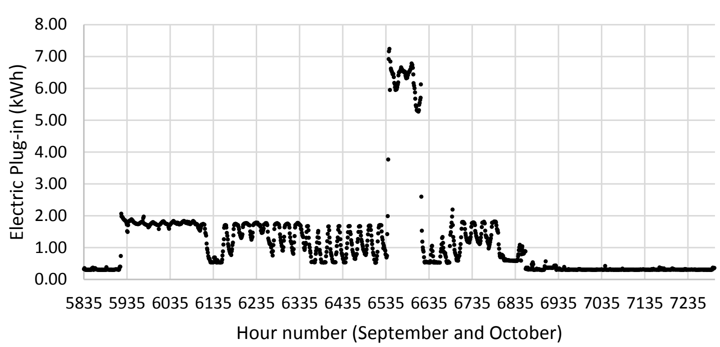


Figure 9 Electric plug-in loads for the research house.

USE OF THE MODEL FOR ANALYSIS

Energy models are used to predict the energy performance of buildings. Although a calibrated model is ideal, the importance of a model is its use to compare scenarios/cases. In this sense, the relative variation is more important than the absolute variation. For example, if a model follows satisfactorily the trend of the energy consumption along the year, the absolute variation is not relevant because in the analysis of two scenarios/cases the difference in energy consumption cancels out the reference value. It is like having a bias error in the model that will be removed when the difference in energy consumption is performed. Since the source of the main differences between the results of the model and the measured data are understood, the developed model is considered acceptable and can be used for the analysis of energy-conservation and energy-efficiency measures.

At the TxAIRE research houses, House #1 has regular shingles and House #2 has high solar reflectance shingles. In order to compare the effect of shingles reflectivity, for the asphalt Shingles – 3.18 mm (1/8") used in the model the absorptance was varied between 0.4 and 0.9 and the simulation results are shown in Table 2. As expected, as the absorptivity increases, the energy consumption decreases during heating season and increases during cooling season. Using an absorptance value of 0.7 for a regular roof shingle, the last column on Table 2 illustrates the relative change of total energy consumption changes with absorptance values.

Table 2. OpenStudio Simulation Results for Shingles Absorptance (kWh)

Absorptance	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	%
0.4	846.0	681.4	563.2	329.0	308.2	405.4	513.4	555.1	399.1	309.3	569.2	643.6	6122.8	-0.78
0.5	845.5	681.1	562.8	328.9	308.5	406.1	514.2	555.9	399.7	309.5	568.8	643.3	6124.3	-0.76
0.6	841.3	678.4	559.0	328.7	311.8	413.2	524.5	565.7	406.7	310.9	565.3	641.0	6146.5	-0.40
0.7	838.2	675.4	555.2	327.3	313.7	422.5	535.8	576.7	415.2	310.4	562.0	638.7	6171.1	0.00
0.8	833.0	673.2	551.8	328.7	318.8	427.2	544.8	585.0	420.6	314.0	558.5	636.5	6192.1	0.34
0.9	828.9	670.6	548.4	328.9	322.4	434.2	554.8	594.5	427.4	315.8	555.1	634.3	6215.4	0.72

CONCLUSION

An energy model was developed for a research house using a software that can be used free of charge. Capabilities of the software allowed accurate recreation of the geometry of the building, as well as define appropriate construction sets and schedules. The house has an ERV that has a duct system independent of the duct system of the heat pump. The ERV introduces ventilation air 24 hours a day without following the intermittence of the heat pump. This arrangement cannot be modeled with the software and a dummy space was used to create a thermal load without affecting the electricity consumption. Using the ASHRAE 14-2002 calibration method for monthly data available on the software, the results illustrate that the model does not satisfy the recommended errors of the method but the differences can be explained by understanding the measured hourly total energy consumption of the house. The model follows appropriately the monthly energy consumption which makes the model useful for the analysis of energy-conservation and energy-efficiency measures. As an example of the use of the model, simulations were run to investigate the impact of the absorptance of the roof shingles on the annual energy consumption, finding that high solar reflectance shingles may reduce the annual energy consumption by less of 0.8%.

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