SIDE-BY-SIDE TESTS OF A NET-ZERO ENERGY BUILDING

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Abastract

This paper presents the results of side-by-side tests of a net-zero energy building using various analysis approaches. The analysis includes an unadjusted measured energy use data of the both portions of the building, a weather-normalized change-point linear regression model to estimate annual energy savings, and calibrated simulation models. The results show savings of 37% to 50% for the renovated portion of the building (i.e., net-zero energy building) compared to the un-renovated portion.

Introduction

In recent years, there has been growing attention to the net-zero energy buildings in the US, because of decreasing costs for on-site renewable energy systems, and increasing concerns over climate change (Thomas and Duffy 2013). In addition, the US government has set a goal of net zero energy for 50% of commercial buildings by 2040 and for all commercial buildings by 2050 (Crawley et al. 2009). However, in the previous literature, very few authors have reported the actual measured performance and efficiency of net-zero energy building.

As part of an on-going energy efficiency effort, the US Army has designed and constructed a net-zero energy building, which is currently being tested as a prototype, at the Fort Hood Army Base in Texas. This net-zero energy building has a high efficiency envelope, a Variable Refrigerant Flow (VRF) HVAC system, and a photovoltaic (PV) system installed and metered for side-by-side testing with an adjacent structure.

In this paper, to verify the energy performance and efficiency of the net-zero energy building, various analysis methods were developed and applied, including: unadjusted measured energy use data analysis, change-point linear models to calculate weather-normalized annual energy savings using ASHRAE's Inverse Modeling Toolkit (IMT) (Haberl et al. 2003; Kissock et al. 2003), and calibrated building energy simulation models. This net-zero energy building has a renovated and un-renovated side, which have quite different thermostat setpoints for the indoor space. Therefore, to investigate the impact of the difference in thermostat setpoints on energy use of the building, calibrated building energy simulation models for both spaces were created and calibrated with measured data and information obtained from the site.

Methodology

The overall methodology of this study is described in Figure 1. As shown in this figure, to calculate the energy savings of the net-zero energy building (i.e., envelope upgrades plus new VRF HVAC system), four different analysis methods were used, and the results were compared. In Method 0, the unadjusted energy use measurements of both halves of the building were compared, while in Methods 1 through 3, change-point linear regression models and calibrated building energy simulation models were created and used. The results were normalized for weather and other conditions in order to analyze the different scenarios for evaluating the effectiveness of the net-zero energy building.

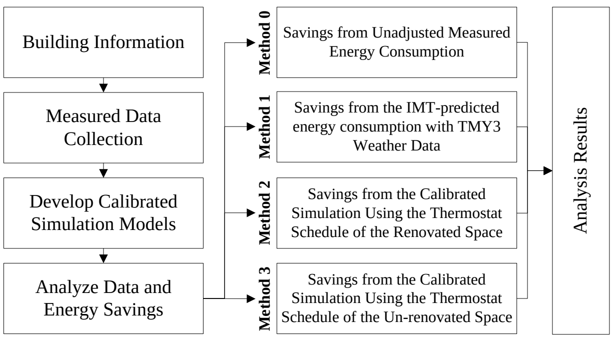

Figure 1: Overall research methodology.

Description of Net-Zero Energy Building

The net-zero energy building is located at the Fort Hood US Army Base in Fort Hood, Texas. Figure 2 shows an exterior view of the building. The building's total floor area consists of 409 m^2 and is divided into five separate conditioned zones: an un-renovated space; four renovated spaces. The un-renovated space is equipped with an air-source heat pump system, whereas the renovated space has a VRF HVAC system. An un-conditioned plenum is located above all five zones. A plan view of the building is shown in Figure 3.

Figure 2: Exterior view of the net-zero energy building.

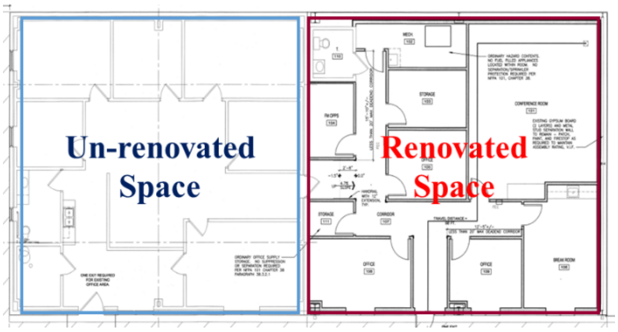

Figure 3: A plan view of the net-zero energy building.

Data Collection

Energy use data (i.e., electricity consumption) for both halves of the building was collected from the Utility Metering System (UMS) at the site for the period of January 2014 through December 2014. The 15-min interval data was converted to hourly and daily data intervals to use for the as-is energy savings analysis, regression analysis, and simulation model calibration.

Model calibration studies typically necessitate accounting for Actual Meteorological Year (AMY) conditions (Bhandari et al. 2012; ASHRAE 2014; Royapoor and Roskilly 2015; Yin et al. 2016). Therefore, a coincident AMY weather file for the building energy simulation models was created using both field measured and calculated data. The required weather variables for the building energy simulation program weather file include: dry-bulb temperature; wet bulb temperature; dew point temperature; wind speed; wind direction; global solar radiation; normal direct solar radiation; precipitation; station pressure. These variables, with the exception of solar radiation, were available from a nearby local government weather station from the National Climatic Data Center (NCDC) (NCDC 2014). The solar radiation data was measured at the site using a portable data logger for the same period.

The hourly indoor temperature for each thermal zone was measured using portable temperature data loggers to record actual thermostat setpoints of each thermal zone. These devices measured indoor temperatures that were used in the simulation models as thermostat setpoints for each thermal zone. Figure 4 and Figure 5 show the graphical summaries of the thermostat set points for the net-zero energy building in cooling and heating season, respectively. The methodology used to derive the thermostat set points is based on an analysis that uses percentiles, where 10th, 25th, 50th, 75th, and 90th percentiles are calculated for each hour of the day by day type (i.e., weekday, weekend). The 50th percentile values for each hour of the day were used as thermostat setpoints in the simulation. This statistical analysis method was used for ASHRAE Research Project 1093 (Abushakra et al. 2001; Claridge et al. 2004), and this was modified to calculate the thermostat set points in this study.

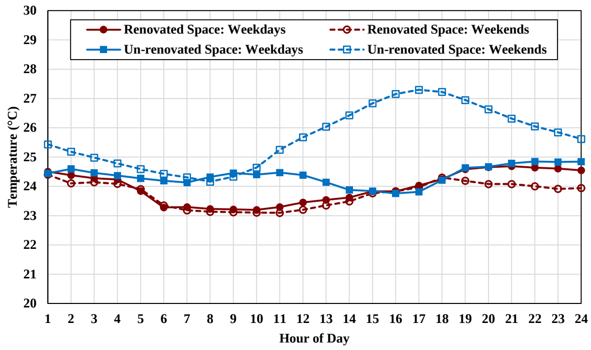

Figure 4: Indoor temperature profiles of the net-zero energy building in cooling season.

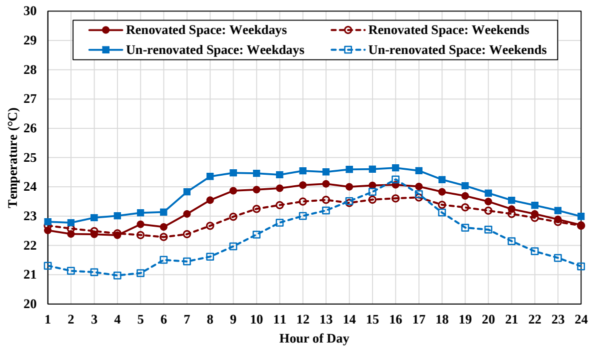

Figure 5: Indoor temperature profiles of the net-zero energy building in heating season.

Calibrated Simulation Model

The floor plan and building envelope geometry of the simulation models were developed from the original construction drawings and the information provided from the site. Figure 6 shows the 3D view of the simulation models for the renovated space and un-renovated space in the simulation program. Table 1 shows a summary of the building construction information for the simulation input data.

For the renovated space, detailed information was obtained from the construction drawings, which is reflected in the model. For the un-renovated space, however, limited information was available, so input values represent the best available information from site visits. According to the information obtained from the site, the building typically is occupied on weekdays by eight staff members in the un-renovated space, and three staff members in the renovated space. Lighting fixture power was calculated using information from the lighting system floor plan for the renovated space, and assumed for the un-renovated space. To obtain calibrated simulation models, the outputs from the models were compared with the measured data until they were based on the criteria from ASHRAE Guideline 14 (ASHRAE 2014). Using the calibrated simulation models with an AMY weather file, annual energy savings were calculated for the net-zero energy building.

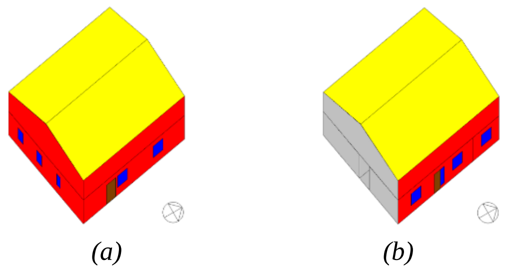

Figure 6: 3D view of the simulation models: (a) the renovated space; (b) the un-renovated space.

Table 1: A summary of simulation model inputs.

Parameters	**Un-renovated space**	**Renovated space**
Floor area	204 m^2 (2,200 ft^2)	204 m^2 (2,200 ft^2)
Number of floors	1	1
Occupancy	8	3
Lighting type	Fluorescent	LED
Infiltration rate	3.13 ACH (0.47 cfm/ft^2)	0.8 ACH (0.12 cfm/ft^2)
Number of thermal zones	1	4
Wall U-value	0.5 W/(m^2·K)	0.3 W/(m^2·K)
Ceiling R-value	3.8 W/(m^2·K)	3.8 W/(m^2·K)
Glazing U-factor	3.2 W/(m^2·K)	1.8 W/(m^2·K)
SHGC	0.76	0.37
Roof R-value	0.4 W/(m^2·K)	0.1 W/(m^2·K)
System type	Air-source heat pump	VRF
System efficiency	SEER 13.0 EER 11.0	SEER 17.0 EER 9.25

Regression Analysis

The regression analysis used the ASHRAE Inverse Modeling Toolkit (IMT) (Haberl et al. 2003; Kissock et al. 2003) developed from the ASHRAE Research Project RP-1050 under the guidance of Technical Committee 4.7, Energy Calculations.

In this study, the whole-building electricity data and outdoor dry-bulb temperature data were used for the regression models. To accomplish this, the 15-min interval data collected was converted to hourly and daily data to use for regression analysis. The data was modeled with change-point linear models (Figure 7) for weekdays and weekends, separately.

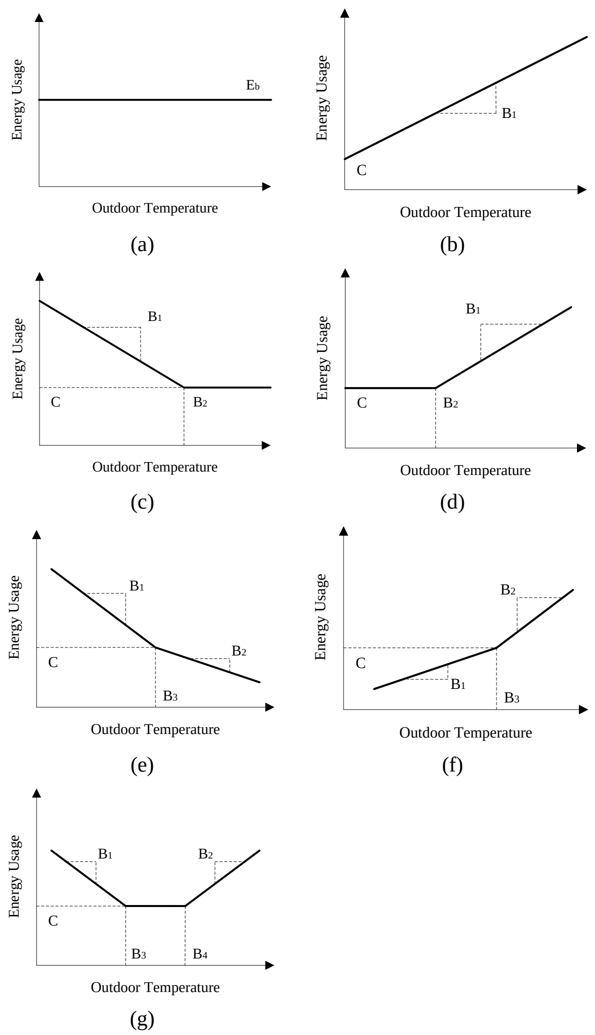

Figure 7: ASHRAE IMT Change-Point Models: (a) mean or 1P model; (b) 2P model; (c) 3P heating mode; (d) 3P cooling model; (e) 4P heating model; (f) 4P cooling model; and (g) 5P heating and cooling model.

Table 2: A summary of analysis methods.

	Method 0	**Method 1**	**Method 2**	**Method 3**
Analysis method	Empirical	Regression analysis	Calibrated simulation models	Calibrated simulation models
Source of weather data	Not used	AMY, TMY3	TMY3	TMY3
Source of data	Measured whole building energy use data	Measured whole building energy use data	Measured whole building energy use data and indoor environmental conditions	Measured whole building energy use data and indoor environmental conditions
Thermostat schedule	Not applicable	Not applicable	Renovated space setting used for both spaces	Un-renovated space setting used for both spaces

Results and Discussion

To calculate the energy savings of the net-zero energy building, four different analysis methods were used, and the results compared. The four different methods are:

- **Method 0** - Energy savings from unadjusted, measured energy use of the renovated and un-renovated space were used.
- **Method 1** - Used ASHRAE's Inverse Model Toolkit (IMT) a change-point linear model with measured energy use data and AMY weather data. Then, using the IMT coefficients from the measured data and the AMY weather data, the annual energy consumption of the renovated and un-renovated space was calculated using TMY3 weather data.
- **Method 2** - Used calibrated DOE-2 simulation models with the thermostat schedule and occupancy condition of the renovated space for both spaces and TMY3 weather data.
- **Method 3** - Used calibrated DOE-2 simulation models with the thermostat schedule and occupancy condition of the un-renovated space for both spaces and TMY3 weather data.

Table 2 shows a summary of each analysis method.

Method 0: Savings from the Unadjusted Energy Consumption Comparison

Figure 8 shows a time series plot of daily total energy consumption data for the renovated and un-renovated halves of the net-zero energy building along with the coincident air temperature outside for the period January 2014 to December 2014. In the figure, energy consumption of un-renovated space is clearly much higher than the renovated space especially during the winter season. However, the energy use of the un-renovated space is lower on the weekends than the renovated space. The calculated energy savings from the comparison of the unadjusted energy consumption are summarized in Table 3. The results showed that the renovated space used 37% less than the un-renovated space. However, these unadjusted results do not take into account differences in the occupant behaviour (i.e., turning lights and receptacles on/off) or thermostat settings.

Table 3: Unadjusted energy consumption and savings of the net-zero energy building (Method 0).

	Cooling (Jun-Sep)	**Heating (Nov-Feb)**	**Total (Jan-Dec)**
Renovated space (kWh)	5,701	6,141	16,853
Un-renovated space (kWh)	7,575	12,633	26,775
Energy savings (kWh)	1,874	6,492	9,921
Energy savings (%)	24.7	51.4	37.1

Method 1: Savings from the Weather-adjusted Energy Consumption using TMY3 Weather Data

In general, outdoor temperature is one of the most important factors that heavily influence the heating and cooling energy use of buildings (Yin et al. 2016). In order to normalize the energy consumption to an average weather year, change-point linear models were calculated for both halves of the buildings. The change-point linear models were calculated using the energy use data of the building for the period of January 2014 to December 2014, and the corresponding measured weather data. To accomplish this, the hourly data collected from the renovated and un-renovated spaces were converted to daily data and then modelled with five-parameter, change-point linear models for weekdays and weekends

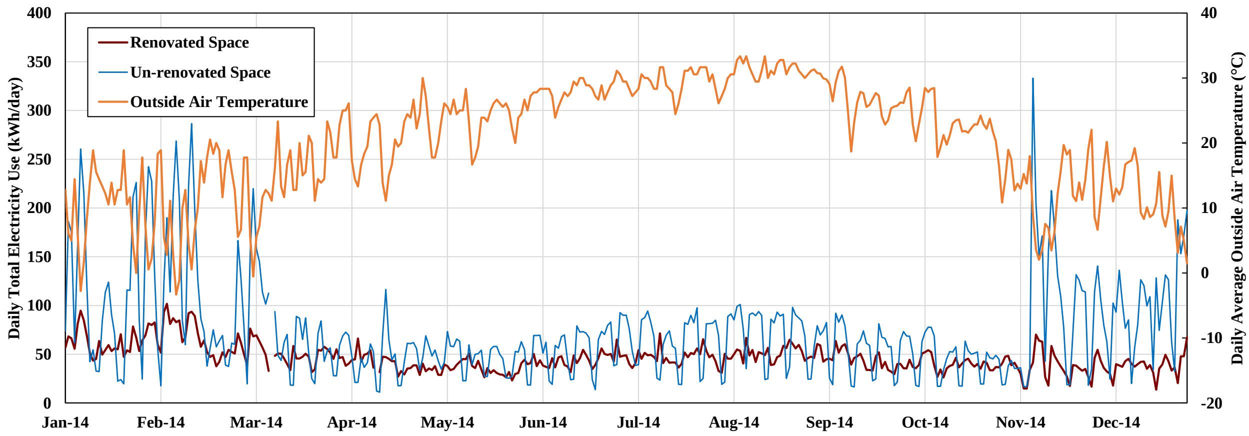

Figure 8: Daily energy consumption of both halves of the net-zero energy building and the coincident daily outdoor temperature (Method 0).

separately for the un-renovated and renovated spaces as shown in Figure 9. Energy savings from weather-normalized consumption using the 5P model and the outside temperature from the TMY3 weather file are shown in Table 4. The results show the renovated space used 40% less than the un-renovated space. In this analysis, the building's energy use is normalized to the TMY3 weather conditions. However, difference in the thermostat setting and occupant behaviour are not normalized.

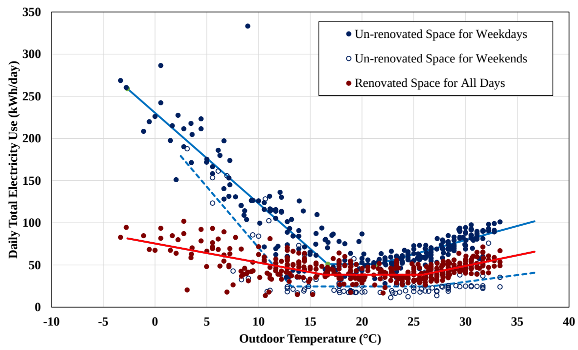

Figure 9: Daily energy use vs. outdoor temperature, with 5P change-point linear models, for the net-zero energy building (Method 1).

Table 4: Energy consumption and savings of the net-zero energy building (Method 1).

	Cooling (Jun-Sep)	**Heating (Nov-Feb)**	**Total (Jan-Dec)**
Renovated space (kWh)	5,295	6,404	17,000
Un-renovated space (kWh)	6,933	13,614	28,522
Energy savings (kWh)	1,638	7,210	11,523
Energy savings (%)	23.6	53.0	40.4

Method 2: Savings from the Calibrated Simulation Using the Thermostat Schedule of the Renovated Space

Using the calibrated simulation models (Shin et al. 2015), the annual energy savings of the net-zero energy building were calculated using the TMY3 weather file. In the analysis, both calibrated models had the same thermostat setting, which represented the average 24-hour setting of the renovated space. Figure 10 shows the time series plot of the simulated daily total energy consumption data for the renovated and un-renovated spaces of the net-zero energy building using the TMY3 weather file. As shown in the figure, the energy consumption of the un-renovated space was much higher than the renovated space especially during winter season. Table 5 shows the summary of annual energy consumption and savings from the calibrated simulation model using the TMY3 weather file. The results show the annual energy use of the renovated space was 45% less than the un-renovated space. In this analysis and in Method 3, the energy use is normalized to the TMY3 weather file and the thermostat schedule, and occupant influenced energy use are normalized.

Table 5: Energy consumption and savings of the net-zero energy building (Method 2).

	Cooling (Jun-Sep)	**Heating (Nov-Feb)**	**Total (Jan-Dec)**
Renovated space (kWh)	6,449	6,314	17,966
Un-renovated space (kWh)	9,683	13,705	32,677
Energy savings (kWh)	3,234	7,391	14,711
Energy savings (%)	33.4	53.9	45.0

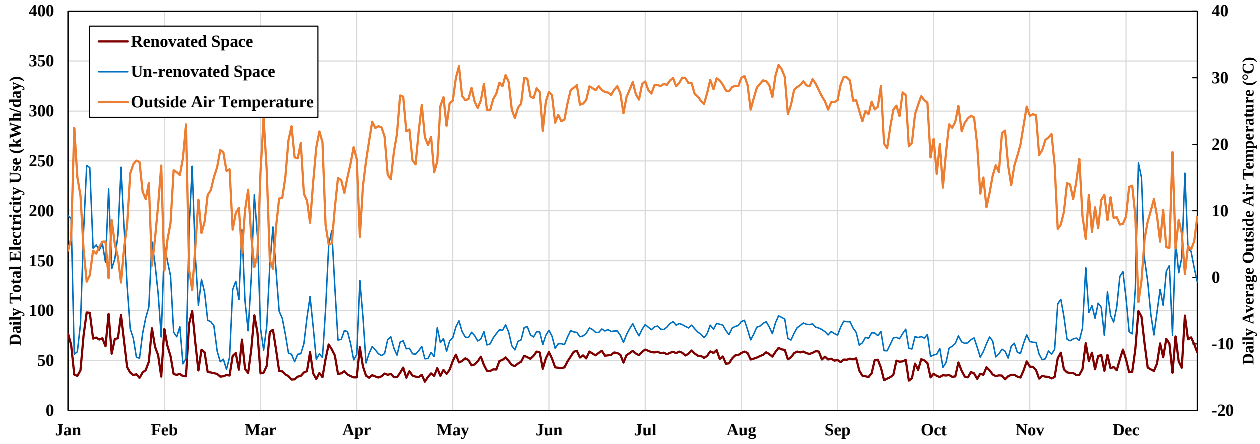

Figure 10: Daily energy consumption of the building and the corresponding TMY3 daily outdoor temperature (Method 2).

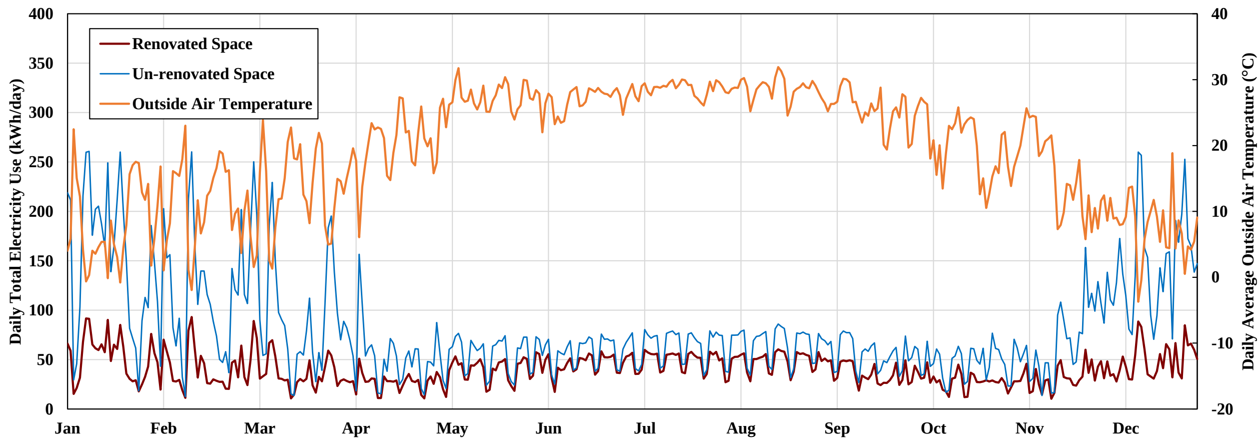

Figure 11: Daily energy consumption of the building and the corresponding TMY3 daily outdoor temperature (Method 3).

Method 3: Savings from the Calibrated Simulation Using the Thermostat Schedule of the Un-renovated Space

Using the calibrated simulation models, the annual energy savings of the net-zero energy building were calculated. In the analysis, both calibrated models had the same thermostat setting, which is the represented the average 24-hour halves of the un-renovated space. Figure 11 shows the time series plot of simulated daily total energy consumption data for the renovated and un-renovated spaces of the net-zero energy building using the TMY3 weather file. In a similar fashion, the energy consumption of the un-renovated space is much higher than the renovated space especially during winter season. Table 6 shows the summary of annual energy consumption and savings from the calibrated simulation model using the TMY3 weather file. The results show the annual energy use of the renovated space was 50% less than the un-renovated space.

Table 6: Energy consumption and savings of the net-zero energy building (Method 3).

	Cooling (Jun-Sep)	**Heating (Nov-Feb)**	**Total (Jan-Dec)**
Renovated space (kWh)	5,497	5,179	14,743
Un-renovated space (kWh)	7,480	14,364	29,776
Energy savings (kWh)	1,983	9,185	15,033
Energy savings (%)	26.5	63.9	50.5

Conclusion

In summary, the annual energy savings were calculated using four different analysis methods for the net-zero energy building at the Fort Hood Army Base. These four methods include: unadjusted measured energy data (Method 0); regression model analysis with the TMY3

Table 7: Annual total energy consumption and savings of the net-zero energy building.

	Method 0	**Method 1**	**Method 2**	**Method 3**
Energy consumption of the renovated space (kWh)	16,853	17,000	17,966	14,743
Energy consumption of the un-renovated space (kWh)	26,775	28,522	32,677	29,776
Energy Savings (kWh)	9,921	11,523	14,711	15,033
Energy Savings (%)	37%	40%	45%	50%

weather file (Method 1); and calibrated building energy simulation models with the TMY3 weather file (Method 2, Method 3) as shown in Table 7.

The results from the analysis using Method 0, which compared the unadjusted energy consumption for the period January 2014 to December 2014 for the renovated and un-renovated portions of the building showed an annual energy reduction of 37%. The results of the five parameter, inverse model regression analysis (Method 1) using the TMY3 weather file showed an annual, weather normalized savings of 40% for the renovated versus un-renovated halves of the building.

The results from the calibrated simulation that adjusted for differences in thermostat settings showed weather normalized savings of 45% to 50% for the renovated portions of the building compared to the un-renovated portion (i.e., Method 2 and Method 3). In Method 2, the average thermostat setpoints of the renovated space were used for the thermostat settings of the un-renovated space, which resulted in energy savings of 45%. In Method 3, the thermostat set points of the un-renovated space were used for the thermostat settings of the renovated space, which resulted in energy savings are 50%. This implies there could be additional savings if the renovated space has the thermostat setpoint schedule of the un-renovated space, especially during the weekend when the un-renovated HVAC system was mostly turned-off.

On-going work is being conducted to determine additional features of the net-zero energy building including: the impact of the building orientation, the envelope improvements, and the HVAC systems upgrade using the calibrated simulation models.

Acknowledgement

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