

LOW-RISK AND COST-EFFECTIVE PRIOR SAVINGS ESTIMATES FOR LARGE-SCALE ENERGY CONSERVATION PROJECTS IN HOUSING: LEARNING FROM THE FORT POLK GHP PROJECT

*John A. Shonder, Oak Ridge National Laboratory
Patrick J. Hughes, Oak Ridge National Laboratory
J.W. Thornton, Thermal Energy Systems Specialists, Inc.*

Background

Many opportunities exist for large-scale energy conservation projects in housing: military housing, federally-subsidized low-income housing, and planned communities (condominiums, townhomes, senior centers) to name a few. Energy savings performance contracting (ESPC) is now receiving greater attention, as a means to implement such projects. This paper proposes an improved method for prior (to construction) savings estimates for these projects. More accurate prior estimates reduce project risk, decrease financing costs, and help avoid post-construction legal disputes over performance contract baseline adjustments. The proposed approach to prior estimates is verified against data from Fort Polk, LA.

In the course of evaluating the ESPC at Fort Polk, Louisiana, we have collected energy use data - both at the electrical feeder level and at the level of individual residences - which allowed us to develop calibrated engineering models which accurately predict pre-retrofit energy consumption. We believe that such calibrated models could be used to provide much more accurate estimates of energy savings in retrofit projects, particularly in cases where the energy consumption of large populations of housing can be captured on one or a few meters.

The improved savings estimating approach described here is based on an engineering model calibrated to field-collected data from the pre-retrofit period. A dynamic model of pre-retrofit energy use was developed for all housing and non-housing loads on a complete electrical feeder at Fort Polk. The feeder serves 46 buildings containing a total of 200 individual apartments. Of the 46 buildings, there are three unique types, and among these types the only difference is compass orientation. The model included the heat transfer characteristics of the buildings, the pre-retrofit air source heat pump, a hot water consumption model and a profile for electrical use by lights and other appliances. Energy consumption for all 200 apartments was totaled, and by adjusting thermostat setpoints and outdoor air infiltration parameters, the models were matched to field-collected energy consumption data for the entire feeder. The energy conservation measures were then implemented in the calibrated model: the air source heat pumps were replaced by geothermal heat pumps (GHPs) with desuperheaters; hot water loads were reduced to account for the low-flow shower heads; and

lighting loads were reduced to account for fixture delamping and replacement with compact fluorescent lights (CFLs). Our analysis of pre- and post-retrofit data (Shonder and Hughes, 1997) indicates that the retrofits have saved 30.3% of pre-retrofit electrical energy consumption on the feeder modeled in this paper. Using the method outlined, we have been able to predict this savings within 0.1% of its measured value, using only pre-construction energy consumption data, and data from one pilot test site.

It is well-known that predictions of savings from energy conservation programs are often optimistic, especially in the case of residential retrofits. Fels and Keating (1993) cite several examples of programs which achieved as little as 20% of the predicted energy savings. Factors which influence the sometimes large discrepancies between actual and predicted savings include changes in occupancy, take-back effects (in which more efficient system operation leads occupants to choose higher levels of comfort), and changes in base energy use (e.g. through purchase of additional appliances such as washing machines and clothes dryers). An even larger factor, perhaps, is the inaccuracy inherent in the engineering models (BLAST, DOE-2, etc.) commonly used to estimate building energy consumption, if these models are not first calibrated to site-monitored data. For example, prior estimates of base-wide savings from the Fort Polk ESPC were on the order of 40% of pre-retrofit electrical use; our analysis has shown the true savings for the entire project (which includes 16 separate electrical feeders) to be about 32%.

It should be noted that the retrofits carried out at Fort Polk are unlike most utility programs in that all of the family residences at the site received the package of retrofits. Thus in this study we were not concerned with issues of free riders or free drivers. However, like most military family housing - and quite unlike the housing in most utility programs - the family housing at Fort Polk is not individually metered. The evaluation program upon which the present work is based relied on data collected from monitoring equipment installed at the site.

Site Description

The Fort Polk Joint Readiness Training Center is located in west-central Louisiana just outside of Leesville. The 200,000-acre facility contains military offices, training centers, equipment and storage warehouses, a hospital, and

housing for some 15,000 service members and their families. Approximately 12,000 people live in on-post family housing, which is the focus of the ESPC. Located in two distinct areas called North Fort and South Fort, the family housing stock consists of 4,003 living units in 1,292 buildings which were constructed in nine phases between 1972 and 1988. Units range in size from 1,073 to 2,746 square feet, with an average area of 1,393 square feet. Prior to the implementation of the ESPC, 3,243 (or about 81%) of the units were served by air source heat pumps and electric water heaters, while the remaining 760 had central air conditioners, natural gas forced-air furnaces, and natural gas-fired water heaters.

In January 1994, the U.S. Army awarded a 20-year ESPC of the shared savings type to an ESCO. Under the terms of the contract, the ESCO replaced the space conditioning systems in all of Ft. Polk's family housing with GHPs. The total capacity of GHPs is 6,593 tons, installed in heat pump nominal capacities of 1.5, 2, and 2.5 tons, with one heat pump per living unit at an average size across the entire project of 1.65 tons.

In those units which used natural gas, gas-fired water heaters were replaced with electric water heaters. Approximately 75% of the new GHPs included desuperheaters to supplement domestic hot water heating with energy recovered from the GHP when it is operating for heating or cooling. Additional energy conservation measures included low-flow shower heads and compact fluorescent lighting (all indoor and outdoor fixtures attached to housing) installed in all units, and attic insulation installed as needed. Further details of the ESPC have been presented by Aldridge (1995) and by Hughes et. al. (1997).

Site Data Collection

A four-level data collection plan was developed as part of an overall evaluation of the ESPC. Level 1 addressed the entire housing population: data on electrical demand and consumption were collected at fifteen minute intervals from submeters on fourteen of the sixteen electrical feeders that supply electricity to the family housing areas of the Fort (the original intent was to monitor all feeders, but the project's recording equipment could not be interfaced with existing metering on two feeders). Temperature and humidity data were also collected at fifteen-minute intervals at four different locations within the family housing area. Level 1 data allowed comparison of pre- and post-retrofit energy usage patterns on the aggregate of all loads served by each feeder.

Level 2 data collection focused on a sample of 42 individual housing units in 16 buildings. Total premise energy use and the energy use of the heat pump (or of the air conditioner/gas furnace combination in some of the pre-retrofit units) were collected at fifteen-minute intervals. Level 2 data allowed the determination of the coefficient of variation of savings across buildings and apartments.

In Level 3, more detailed energy use data were collected on a subsample of 20 of the 42 Level 2 units (7 of the 16 buildings). In addition to total premise and space conditioning energy, fifteen-minute interval data were collected to isolate the energy use of the hot water heater, the air handling system, and the furnace in the pre-retrofit condition. Again the subsample included buildings of varying floor areas and construction vintages. This technical sample is useful for understanding the relative importance of the weather-sensitive end-uses versus base loads, and supports analysis to determine the savings attributable to the various conservation measures.

Finally, at one of the level 3 sites, additional data were collected on the operation of the vertical ground loop heat exchanger: inlet and outlet water temperatures, and water loop pump runtime. Data were also collected on domestic supply water temperature and indoor temperature and humidity. It was this "energy balance" data which allowed us to calibrate the ground loop model to determine actual soil heat transfer properties. Further details on the evaluation methodology have been presented by Hughes et. al. (1997).

Feeder Selected For Modeling

In order to determine how a calibrated model would predict energy consumption at the feeder level, we chose a feeder located on the North Fort which serves 200 apartments located in 46 separate buildings. Figure 1 shows a site plan for the buildings served by this feeder. The area contains three unique building types: 12 buildings designated as type 1, a four-plex; 18 buildings designated type 2, another four-plex; and 16 buildings of type 3, a five-plex. Although type 1 and type 2 buildings have identical floorplans, they differ in the design of the roof and in the location of carports. Since the roof design was expected to have an effect on space conditioning loads, the two types were modeled separately. Table 1 below lists the type and compass orientation of each building (south-facing buildings are at 0 degrees; the orientation is measured counterclockwise from south).

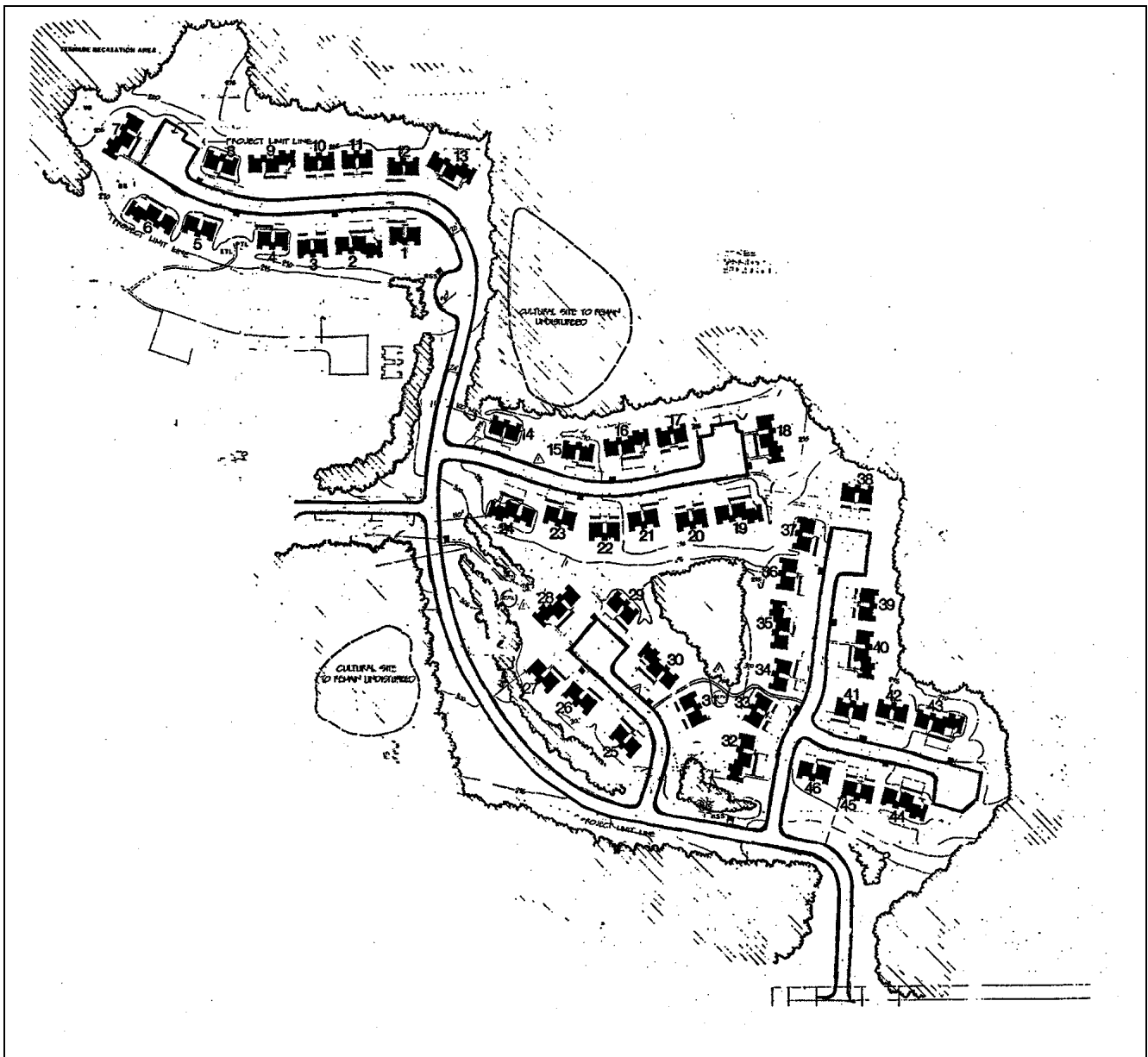


Figure 1: Site map of buildings on the modeled feeder.

Among the three building types there are only two unique apartment floorplans: apartment type A, containing 1142 square feet of living space, and apartment type B containing 1114 square feet. One apartment of type B exists in each of the five-plexes; the remaining apartments in both the five-plexes and the four-plexes are of type A. Thus in total there are 184 apartments of type A and 16 apartments of type B. As-built plans for all three building types were made available for use in modeling the building performance.

It should be noted that prior to the retrofits, the apartments on this feeder used electric, air-source heat pumps and electric water heaters. Since there was no natural gas use and the units do not contain fireplaces, the feeder meter captures all of the energy used in the 200 apartments.

Figure 2 presents the pre-retrofit electrical energy consumption on the feeder for a period of approximately one year, as monitored at the site. Each data point represents the total energy consumed on the feeder for one day; this value is plotted versus the average temperature for that day. It is seen that the energy use falls into three separate regimes: a heating regime, in which energy use is inversely proportional to daily average temperature; a cooling regime, in which energy use is proportional to daily average temperature; and a midrange in which energy use is approximately constant and does not depend on temperature. This is a common pattern for residential energy use. Fitting a dual changepoint model to the data of Figure 2 gives the

Building	Type	Orientation	Building	Type	Orientation
1	2	180°	24	3	200°
2	3	180°	25	2	230°
3	1	180°	26	2	220°
4	2	180°	27	2	220°
5	2	180°	28	3	320°
6	3	210°	29	2	50°
7	3	300°	30	3	50°
8	2	20°	31	1	60°
9	3	0°	32	3	280°
10	1	0°	33	1	300°
11	1	0°	34	2	280°
12	2	0°	35	3	280°
13	3	30°	36	2	280°
14	2	21°	37	2	280°
15	2	10°	38	1	10°
16	3	0°	39	1	100°
17	1	0°	40	3	100°
18	3	90°	41	2	10°
19	3	170°	42	1	10°
20	1	170°	43	3	10°
21	2	170°	44	3	190°
22	1	180°	45	1	190°
23	2	200°	46	2	190°

Table 1: Building types and compass orientations.

following relation between daily total energy use E , and daily average temperature T :

$$E = \begin{cases} 6595.20 - 200.65(T-56.95) & \{T < 57.0\} \\ 6595.20 & \{57.0 \leq T \leq 69.8\} \\ 6595.20 + 187.02(T-69.77) & \{T > 69.8\} \end{cases} \quad (1)$$

In the course of our evaluation, we used equations like (1) to correct for the varying weather conditions between the pre- and post-retrofit periods (Shonder and Hughes, 1997). Knowing daily energy use as a function of daily average temperature allowed us to normalize pre- and post-retrofit energy consumption to the same meteorological year.

Pre-Retrofit Energy Use

Electrical energy on the feeder can be categorized into four end-uses: space conditioning (i.e. heating and cooling), water heating, residential lighting and other electrical appliances, and streetlights. The sections below detail how each of these uses was modeled.

Space Conditioning Loads

In order to model the buildings, space conditioning equipment, controls, and water heating for the 200 units on the selected feeder, the TRNSYS (Klein, 1996) simulation software was employed. TRNSYS is a modular system simulation package in which the user specifies the compo-

nents that constitute the system and the manner in which these components are interconnected. In TRNSYS, components may be physical pieces of equipment such as pumps or controllers, or utility modules like occupancy forcing functions, shading effects due to overhangs and wingwalls, and weather data readers. The TRNSYS software was chosen for three primary reasons:

- 1) The program is modular, which allowed both existing components from the standard library of models and new components that were added or developed for this study to be used simultaneously;
- 2) An earlier study (Thornton et. al., 1997 [1]) had used the software to integrate existing and newly added/developed component models to represent one “energy balance” apartment and the geothermal heat pump system serving it, and to calibrate each of those components to data;
- 3) The software allows modeling of the true transient response of the building to the conditioning equipment.

TRNSYS simulations run at user-defined time steps, iterating at each time step until the system of equations created by the interconnection of the component model inputs and outputs is solved. In this study, a time step of 15 minutes was chosen after considering accuracy, stability requirements, typical equipment cycle times and simulation speed.

For this study, each of the three building types was treated as a separate simulation. The component models were chosen to be the building and its associated forcing functions (weather, occupancy, infiltration, water draw), heat pumps for each apartment (air-source heat pumps for the pre-retrofit simulations and geothermal with desuperheaters for the post-retrofit simulations), thermostats for each apartment, domestic hot water storage tanks, and pumps and fans for each apartment.

Although the ambient temperature and relative humidity were measured at the site, these values were not used in the simulations due to the lack of solar radiation measurements. Instead, Typical Meteorological Year (TMY) weather from Lufkin, TX was used for the simulations, as Lufkin represents the closest inland TMY site to Ft. Polk. Available weather data shows slight differences in the long-term averages for Lufkin, TX and Alexandria, LA, the closest location to Ft. Polk with published bin data.

The TMY weather, which is a monthly best-fit average of 30-years of weather data, contains ambient temperature, relative humidity, incident solar radiation, and wind speed values at hourly increments for a year. The incident solar radiation on each of the exterior surfaces of the apartment buildings was processed and subject to over-

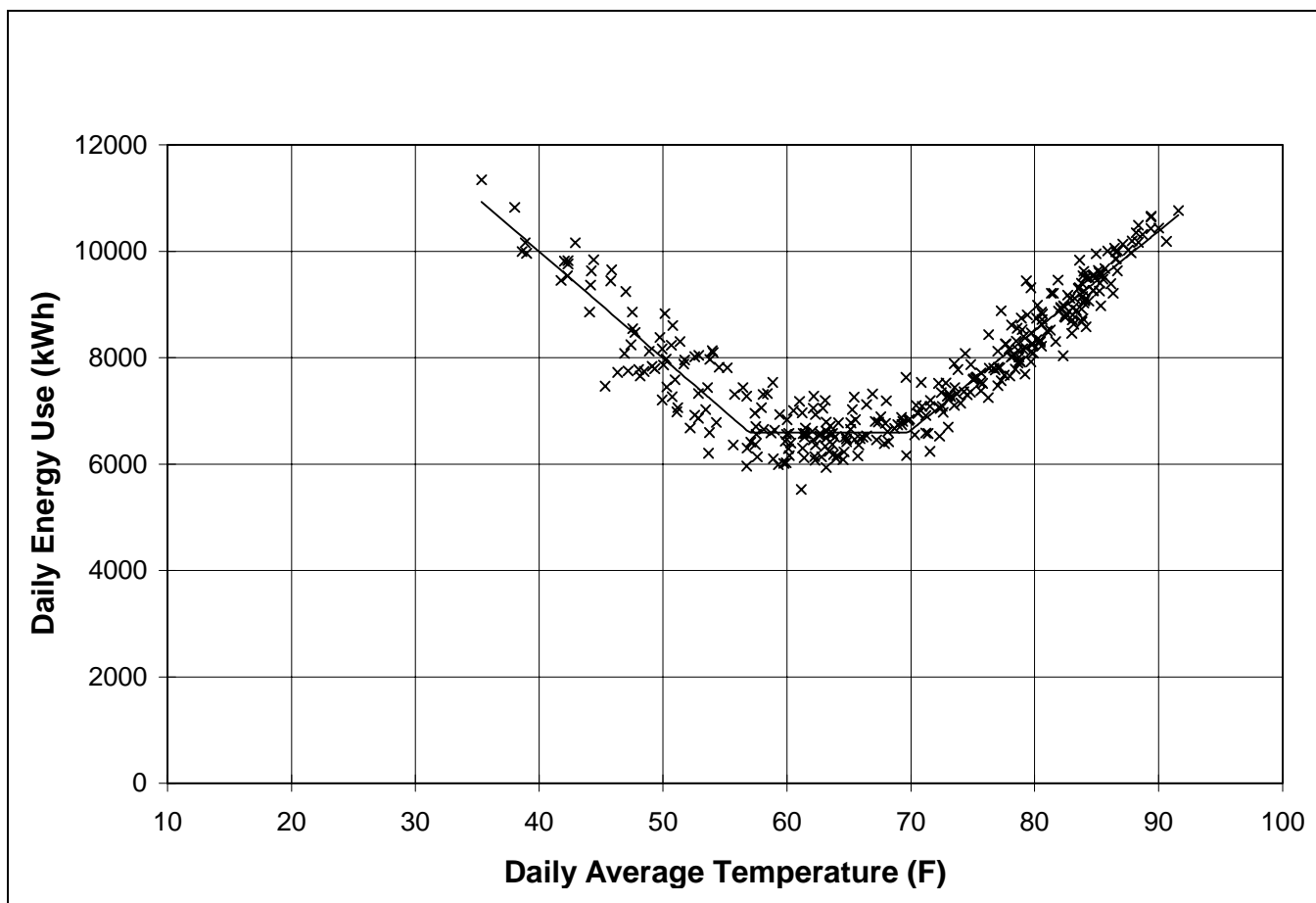


Figure 2: Monitored daily electrical energy use for the feeder.

hang and wingwall shading effects as each of three buildings have many such features.

The ground temperature for the simulations was modeled with the Kusuda correlation (Kusuda, 1965). This correlation requires the average annual surface temperature, the amplitude of the surface temperature, and the phase delay and calculates the hourly distribution of ground temperature with depth. For reference, the published values of these properties (ASHRAE, 1977) for Alexandria, LA are:

- Mean soil surface temperature: 69 °F (20.6 °C)
- Amplitude of surface temperature: 17 °F (9.4 °C)
- Day of minimum surface temperature: February 1

Prior to the retrofits, each of the apartments was equipped with a nominal one-and-a-half ton stand-alone air-source heat pump. The heat pumps were manufactured in 1981. An air-source heat pump model was written for this study so that the manufacturer's catalog data for the installed heat pumps could be read from a look-up table and interpolated, based on operating conditions, to provide the heating and cooling capacities and system power. Inputs to the model include the ambient and zone conditions (temperature and humidity), the conditioned air flow rate

(assumed constant at its rated value of 650 CFM), and the control signal from the thermostat. Outputs from the model include the calculated values of exiting air temperature and humidity, and the equipment capacity and power draw.

Lighting/Appliance Electrical Load Profile

At the 20 level 3 residences included in the evaluation (none of which, incidentally, were located on the modeled feeder), data were collected at 15-minute intervals for the total residence electrical use, the energy used by the HVAC system, and the energy used by the water heater. Because the simulation would determine HVAC and hot water energy use from the building and equipment characteristics, we required an electrical load profile for the other appliances. This was obtained by subtracting the energy used by the HVAC system and the water heater from the total apartment energy use in each 15-minute interval. Hereafter, we will refer to the non-HVAC, non-DHW electrical energy use as the "lighting/appliance load". In addition to residential lighting it includes such things as clothes washers, clothes dryers, hairdryers, stereos, radios, televisions, etc.

The lighting/appliance load data was used in two ways. First, average weekday and weekend daily profiles were developed for the 20 residences over the approxi-

mately one-year pre-retrofit monitoring period (since construction was ongoing during data collection, and the sites were randomly distributed across the base, the length of the pre-retrofit period varied by apartment). On each weekday in the pre-retrofit period, an average was taken of the electrical energy use in each 15-minute period, for each apartment. The same average was taken for each weekend day. These average profiles are shown in Figure 3. Since it was assumed that lighting/appliance energy use would be a function of the apartment floorspace, the profiles were normalized by dividing each value by the total average daily energy use. Interestingly, while there is a difference in shape, the total appliance energy consumption on weekdays and weekend days was virtually the same.

While the appliance use per day per apartment was highly variable (with standard deviation of 7.5 kWh per day), there was a slight positive correlation between total daily energy use and apartment floorspace. The data is presented in Figure 4. Note that each data point in the figure represents the average daily appliance energy use of several apartments with the same floor area. Although the correlation coefficient (r^2) was only about 0.2, it was decided to use the regression equation to determine total daily appliance draw for the modeled apartments. In the absence of demographic data, apartment floor area was the only way to account for the variability we saw in the data. Thus to determine the daily appliance electrical profile for our modeled apartments, we used the normalized profile based on all the level 3 apartments, and multiplied each 15-minute value by a constant which depended on the apartment floor area.

The weekday and weekend electrical lighting/appliance load profile of Figure 3 was used as an input to the TRNSYS models. In order to approximately account for exhaust fans and porch/entry lighting, only 90% of the electrical energy was returned to the building as a heat gain.

Hot Water Draw Profile

As with the appliance energy use, the daily hot water draw profile used in the modeled apartments is an average of data collected at 20 level 3 sites, adjusted by apartment floorspace. However, the data collected at the level 3 sites was hot water tank electrical energy use rather than hot water draw. In order to convert electrical use into hot water use, we assumed that the lowest energy use during the day represented standby losses. Then assuming an inlet temperature of 68°F (the average value seen at the “energy balance” site) and a tank setpoint temperature of 130°F, we could determine the hot water use during every 15-minute interval. For the apartments on Feeder 1, the average daily pre-retrofit hot water use was determined to be 36.2 gallons. For comparison, ASHRAE (1995) reports an average daily use of 42 gallons for apartment buildings of 20 units or less. The average weekday and weekend day water draw profiles for the modeled apartments are presented in Figure 5. They compare well with the ASHRAE profile (1995) for a typical residence. As with appliance electric load, there was no apparent difference in total daily draw between weekdays and weekend days; only the shape of the profiles is different.

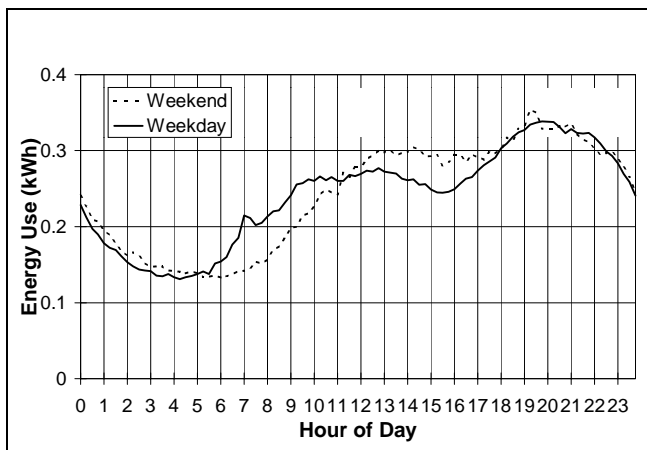


Figure 3: Daily lighting/appliance electric load profile.

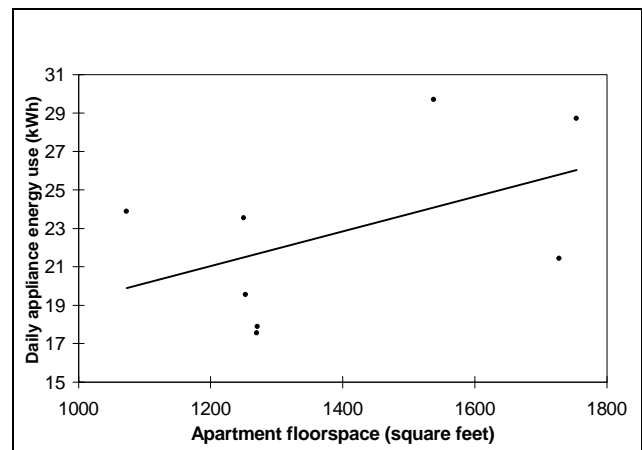


Figure 4: Daily total lighting/appliance electric load vs. apartment floorspace

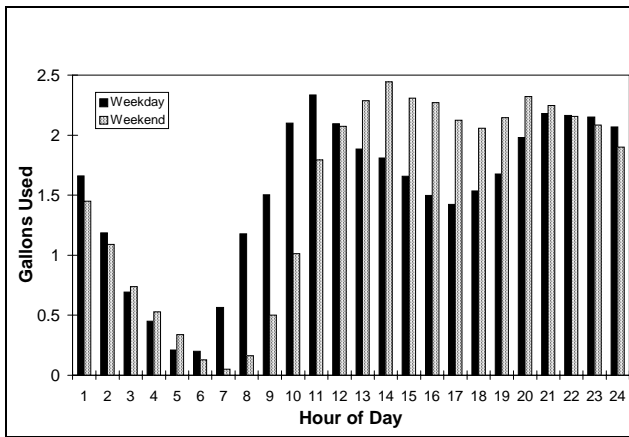


Figure 5: Pre-retrofit weekday and weekend hot water draw profiles.

The weekday and weekend hot water draw profiles of Figure 5 were used as an input to the TRNSYS models, which included standard 52 gallon electric hot water heaters, each with two 3300 Watt heating elements.

Street Lights And Other Non-Housing Loads

In addition to the 200 apartments, the feeder under consideration also provides electrical energy for 68 streetlights: 52 lamps rated at 116 W and 16 lamps at 302 W. In order to include these loads in the total energy use of the feeder, a separate TRNSYS model was developed which simply turned on all of the streetlights each day at dusk and turned them off at dawn, using the value of solar radiation from the TMY file to determine the time of sunrise and sunset. Between 109 and 152 kWh per day are added to the total housing load, depending on the length of the day throughout the year.

In general, the sum of the electrical energy in the 200 apartments will not equal the electrical energy as monitored at the feeder - even when streetlights are considered - due to line losses and transformer losses. Although we had no information on these losses, we expected them to be small, in the range of 1-2%. We did not model this loss; since we calibrated our models to feeder-level data, the energy consumption predicted for the apartments is likely to be 1-2% higher than their actual energy consumption.

Pre-Retrofit Feeder Modeling

Given the floor plan, construction details, and compass orientation of each of 46 buildings, as well as the average 15-minute hot water draw and appliance electrical loads, we were able to begin modeling the feeder. In order to reduce the number of runs required, the building compass orientations were run at intervals of 45 degrees. Table 2 below presents the building types, and the number of each type at each 45° increment.

Orientation	Building type		
	1	2	3
0°	5	5	3
45°	1	1	2
90°	1	0	2
135°	0	0	0
180°	4	6	4
225°	0	3	1
270°	0	3	2
315°	1	0	2

Table 2: Building type and orientations simulated.

Thus building type 1 was simulated at orientations of 0°, 45°, 90°, 180° and 315°, etc. This reduced the number of cases run to 17. Each of the 17 cases was then weighted according to the number of buildings it represented. The daily streetlight energy use was added to this weighted sum to determine the energy use for the entire feeder.

Nevertheless, several unknowns still remained. In general we had no information about occupancy (number of occupants per apartment) or vacancy rate. We did not know the thermostat setpoints for the apartments. Also, while TRNSYS allowed us to model the building heat transfer characteristics fairly accurately, the rate of outdoor air infiltration was unknown. These three variables then - occupancy, thermostat setpoints and infiltration - allowed us to calibrate the TRNSYS output to the monitored feeder level data.

Since the population of family housing at Ft. Polk is given as 12,000 for the 4,003 housing units, the average occupancy should be about 3 individuals per apartment. For the purposes of this study we assumed an occupancy of three individuals, even though the apartments are slightly smaller than the average family housing unit at the base.

In order to model outdoor air infiltration, a constant of 0.05 air changes per hour was originally used. With indoor temperature setpoints of 72°F heating/76°F cooling, the output of the simulation matched the monitored data quite well in the cooling season, but simulated energy use was low in the heating season. For this reason, a separate infiltration model was used for the heating season. The model assumed a constant of 0.05 air changes per hour plus a separate factor of 0.02 multiplied by the temperature difference between room and ambient temperatures. Selecting temperature setpoints and infiltration models is an interactive process; we chose values which seemed reasonable based on actual indoor air temperatures monitored at the “energy balance” site. It is recognized that 0.05 air changes per hour is at the low end of the range of values typically seen in residences. This indicates that the average occupancy is probably lower than the three occupants per apartment we chose.

Figure 6 compares the modeled data for the entire feeder, pre-retrofit, with the feeder-level data collected on-site. Visually, the calibrated TRNSYS model appears to agree quite well with the actual pre-retrofit energy consumption of the feeder. For a typical meteorological year, the model predicts energy consumption of 3.02 million kWh; the monitored data, when normalized to a typical meteorological year, predicts 2.87 million kWh. Thus on an annual basis, the calibrated TRNSYS model is able to predict energy consumption within about 5% of the monitored data.

When fitted to a dual changepoint model of daily energy use vs. daily average temperature, the TRNSYS model gives the following equation:

$$E = \begin{cases} 7007.50 - 209.27(T-54.1) & \{T < 54.1\} \\ 7007.50 & \{54.1 \leq T \leq 70.6\} \\ 7007.50 + 237.10(T-70.1) & \{T > 70.6\} \end{cases} \quad (2)$$

Comparison with equation (1) shows that the “base load” constant derived from the TRNSYS simulations is about 8% higher than the constant derived from the monitored data. Also, the breakpoint for the heating region is about 3 °F lower than the breakpoint derived from the monitored data. With further adjustments of setpoint tem-

peratures and infiltration factors in our model, it would have been possible to match the monitored pre-retrofit heating data to a higher degree of accuracy.

Implementation of Energy Conservation Measures

With the TRNSYS model calibrated to the pre-retrofit data, we were ready to implement the energy conservation retrofits into the model. We replaced the air source heat pump with a geothermal heat pump including a desuperheater which provides additional heat to the hot water tank. The lighting load was reduced to account for fixture delamping and replacement of existing fixtures with CFLs. Finally the hot water load was reduced to account for the low-flow shower heads. The sections below describe how each of these measures was implemented in the model.

Geothermal Heat Pump Model

As part of the energy conservation retrofit, each of the 200 apartments on the feeder was equipped with a nominal one-and-a-half ton geothermal (ground-source)

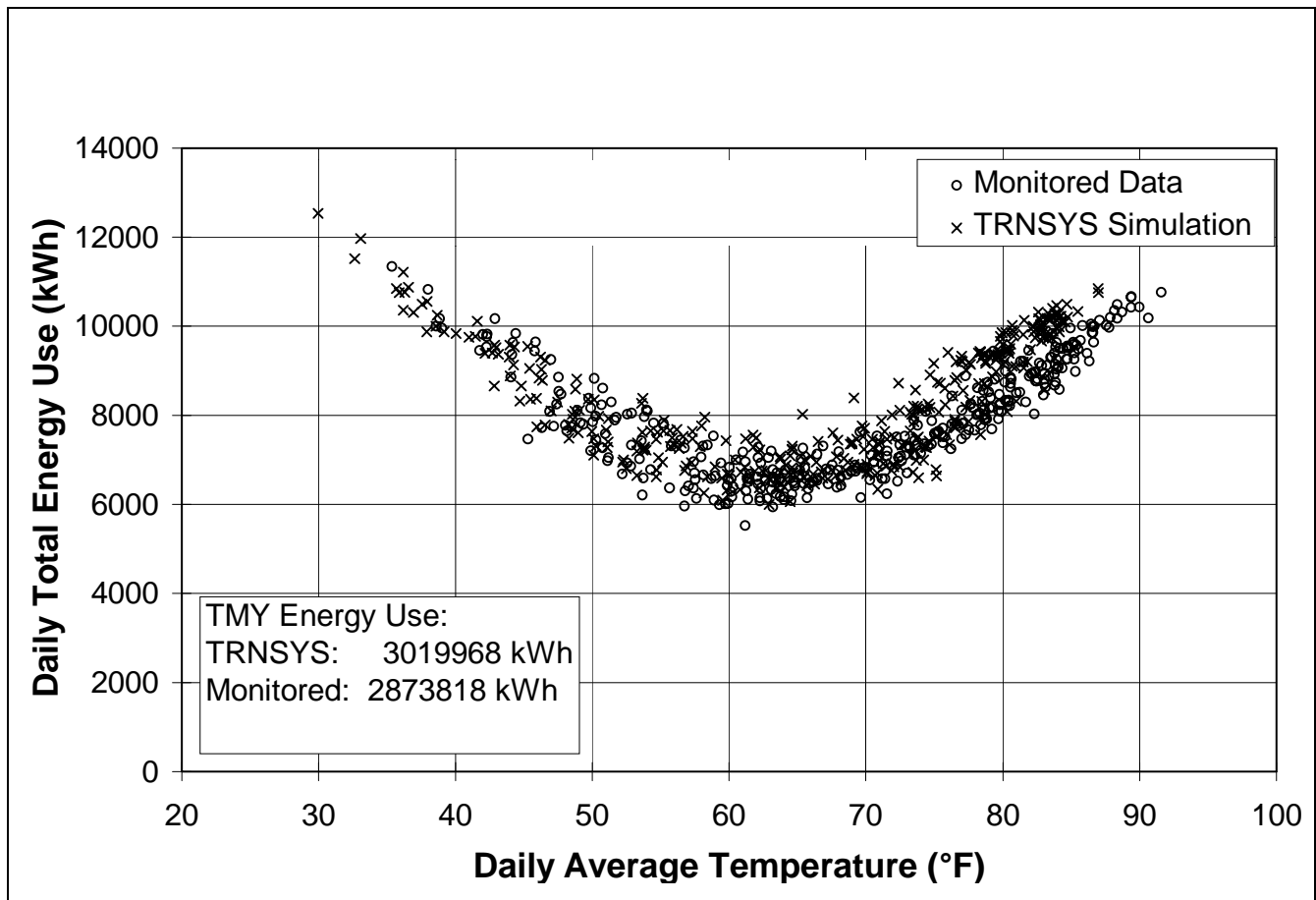


Figure 6: Pre-retrofit daily energy use: Monitored data and calibrated TRNSYS simulation.

heat pump (GHP) with 17,300 btuh total cooling capacity and 15.4 EER at ARI 330 rating conditions, and an 11,800 btuh heating capacity and 3.5 COP at ARI 330 rating conditions. The GHPs used water as the ground loop working fluid and came equipped with a desuperheater for supplying domestic hot water to the apartment. Two vertical U-tube ground heat exchanger circuits connected in a parallel arrangement were used to reject/absorb heat to/from the earth. Each of the vertical U-tube circuits was placed in a vertical borehole of approximately 4.125 inch (0.10477 m) diameter and varying depth (based on apartment type and orientation). These boreholes were typically spaced 16 feet (4.88 m) apart, 25 feet (7.62 m) from the exterior wall and were backfilled with a bentonite-based grout after the installation of the U-tubes. The U-tubes themselves are comprised of 1 inch nominal (0.0254 m) SDR-11 polyethylene pipe (1.08 inch ID, 1.31 inch OD) with a nominal center-to-center spacing of 2.565 inches (0.065 m). The center-to-center U-tube spacing exists at the bottom of the U-tube heat circuit (the bottom of the bore). No extraordinary measures were taken to maintain this spacing along the length of the bore. The horizontal runouts to the boreholes, and the horizontal piping between the bores, are typically buried at a depth of 3 feet (0.914 m) with outbound and return legs in separate trenches. Figure 7 presents a diagram of a typical ground heat exchanger configuration.

A water source heat pump model, written for TRNSYS in the previous study (Thornton et al., 1997 [2]), was used for the post-retrofit simulations. The ground-source heat pump model uses a look-up table approach in both heating and cooling mode to determine the manufacturer's published catalog data for capacity, power, and water heat transfer. Inputs to the model include the entering water temperature and flow rate, the entering air temperature, humidity ratio, and flow rate, and the control signal from the thermostat. Outputs from the model include the calculated values of leaving water temperature and flow rate, exiting air temperature, humidity ratio, and flow rate, and the equipment capacity and power draw. Energy balance and psychrometric calculations at each iteration for both the air-source and ground-source heat pumps assure that the results from the model at each time step are reasonable.

For ground-source heat pump system simulations, the most important component model is the ground heat exchanger. Although several ground heat exchanger models were available for this study, the duct ground heat storage model (Hellstrom et al., 1996) developed at the University of Lund, Sweden was chosen for this study because it is well documented, validated, and considers multi-bore interactions and long-term (multi-year) effects. In the earlier paper (Thornton et al., 1997 [1]) the same model was utilized to predict ground heat exchanger performance against measured data with excellent results. The average bore depth was 360 ft per apartment, or 240 feet per nominal ton of installed heat pump capacity.

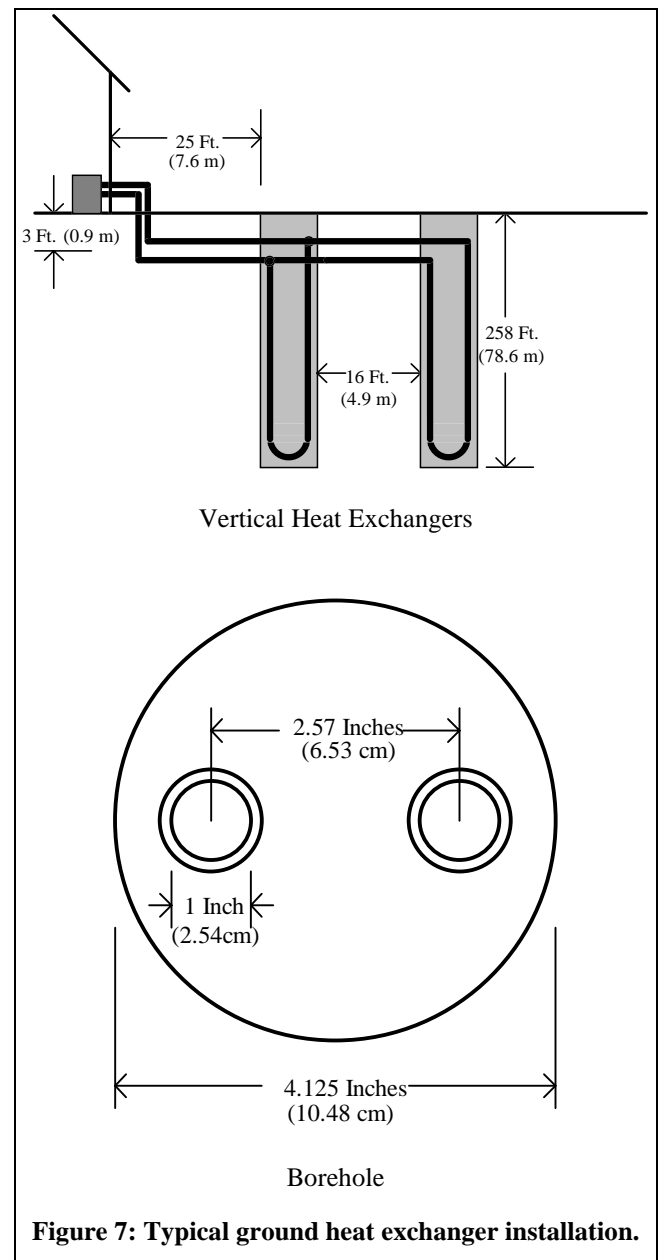


Figure 7: Typical ground heat exchanger installation.

Lighting Retrofits

Lighting retrofits in the 200 apartments included delamping of some conventional fixtures and replacement of other fixtures by CFLs. The retrofits are described in Table 3 above. In order to determine the reduction in electrical energy use, we began by considering the average pre-retrofit electrical energy profile, which accounts for all electrical use exclusive of the HVAC and water heating systems. In the apartments under consideration, the total daily consumption for lighting/appliance uses is 20.5 kWh. According to a reference from the U.S. Department of Energy (1994), lighting should account for 24.2% of this total, or about 5.0 kWh/day, leaving 15.5 kWh/day for other uses such as cooking, refrigeration, radios, televisions, etc.

Room	Fixture type	Lamps per fixture	Watts per lamp	Number of fixtures	Pre-retrofit Watts	Retrofit type	Post-retrofit Watts
Kitchen	Ceiling, fluor.	2	48	1	96	delamp	68
Kitchen	Range hood	1	25	1	25	CFL	13
Dining	Ceiling surface	5	100	1	500	CFL	65
Family	Pendant, fluor.	2	66	1	132	delamp	66
Bath	Wall, fluor.	1	46	1	46	CFL	26
Closets	Ceiling, keyless	1	60	1	60	CFL	13
Bedrooms	Ceiling surface	2	60	3	360	CFL	78
Kitchen	Under cab., fluor.	1	25	2	50	delamp	25
Hall	Ceiling surface	1	60	2	120	CFL	26
Hall	Wall bracket	1	60	1	60	CFL	13
Utility	Ceiling, fluor.	2	48	1	96	CFL	13
Patio	Wall bracket	1	60	1	60	CFL	13
Ext. entry	Wall bracket	1	60	2	120	CFL	13
Carport	Ceiling, keyless	1	60	2	120	CFL	26
Total per apartment:					1845		458

Table 3: Lighting retrofits.

In each apartment, lighting power was reduced from 1845 Watts to 458 Watts. If lighting is to account for 5.0 kWh in the pre-retrofit period, then on average these 1845 Watts must have been in use for 2.71 hours per day. Assuming lights are in use for the same number of hours after the retrofits, then post-retrofit lighting use will account for $(458 \text{ W})(2.71 \text{ hr}) = 1.2 \text{ kWh/day}$. If electrical use for other appliances remained constant, then the daily lighting/appliance electrical use in the post-retrofit will be 16.7 kWh/day, or about 81% of the pre-retrofit use.

Our pre-retrofit lighting/appliance electrical use profile gives energy use during each 15-minute period of the day. Considering that lights are used mostly in the morning and the evening, we could have assumed a lighting use schedule, and developed the post-retrofit energy use profile by subtracting the effect of the CFLs from the pre-retrofit according to the schedule. However, considering that the pre-retrofit profile was developed by averaging one year's worth of daily profiles for 20 different apartments inhabited by occupants with varying work schedules, we decided to simply multiply each 15-minute consumption in the pre-retrofit by 0.81 to obtain the post-retrofit energy use.

Low-Flow Shower Heads

In order to determine the effects of the low-flow shower heads, we began with our pre-retrofit hot water draw profile, which was developed from the hot water tank energy use profile. The draw profile indicates that the average residence on this feeder uses about 36.2 gallons of hot water per day. According to a reference from the U.S. Department of Energy (1994), hot water use for showers accounts for about 59% of total residential hot water use on a national basis. Thus we assume the average residence at Ft. Polk uses approximately 21.4 gallons per day for

showers and 14.8 gallons for other uses. Calculations made by the ESCO show that the shower heads installed will reduce water use per shower from 9.6 gallons to 6.0 gallons. If the number and length of showers per day remains constant after the retrofits, hot water use for showers should drop to 13.4 gallons per day; the total post-retrofit hot water use is then 28.2 gallons per day, or about 78% of its pre-retrofit value.

Again, knowing that most showers are likely to occur in the early morning and late evening, it would have been possible to develop a schedule and adjust the pre-retrofit water draw accordingly. Again however, considering that the pre-retrofit profile was developed by averaging daily profiles of 20 apartments over one year, we decided to simply multiply each 15-minute draw in the pre-retrofit profile by 0.78 to obtain the post-retrofit hot water draw.

In the post-retrofit simulations, water is also heated by being drawn from the bottom of the storage tank and sent to the desuperheater of the geothermal heat pump when it is operating. The heated water is then returned to the top of the tank. The desuperheater in the geothermal heat pump is modeled with a constant UA which was calculated from the manufacturer's catalog data. Desuperheater refrigerant temperatures in heating and cooling mode were established based on conversations with the manufacturer.

Attic Insulation

According to the subcontractor who performed the retrofits, degraded attic insulation was repaired on a small number of upper-floor apartments on this feeder. Since no information was available either on the number of apartments which received these repairs, or on the quantity of insulation replaced, no attempt was made to model this retrofit.

Post-Retrofit Energy Use

With all of the energy conservation measures implemented in the apartment models, we once again determined the energy use for each apartment on each day of a typical meteorological year. The parameters for occupancy, infiltration and thermostat setpoints were the same as those used to model the pre-retrofit energy consumption. The same 17 cases were run; the streetlight energy use was added to the weighted sum of the cases to determine the total load on the feeder.

Figure 8 is a plot of daily energy use vs. daily average temperature as predicted by the calibrated TRNSYS model. Also plotted is the actual post-retrofit data monitored from the feeder. While the TRNSYS model predicts higher energy use in heating, there appears to be excellent agreement with the monitored data in cooling, which is the dominant operating mode in Ft. Polk's climate. For a typical meteorological year, the calibrated TRNSYS model predicts annual energy use of 2,107,493 kWh; the monitored post-retrofit data, when normalized to a TMY, predicts an annual energy consumption of 2,002,672 kWh. As in the pre-retrofit, the TRNSYS simulation is about 5% higher than the monitored value.

Analysis of the monitored pre- and post-retrofit data for this feeder shows that for a typical meteorological year, the retrofits result in a savings of 30.3%. Comparing the pre- and post-retrofit annual consumption predicted by the calibrated TRNSYS simulations, we would have predicted a savings of 30.2%. Applying this savings to the pre-retrofit energy consumption data, we would have predicted an annual post-retrofit consumption of 2,005,502 kWh on this feeder for a typical year. This is in excellent agreement with the normalized post-retrofit data collected at the site.

Conclusions

Using the TRNSYS software, a model of the energy use on an electrical feeder containing 200 separate apartments in 46 buildings was developed and calibrated to data monitored at the site. The model predicted annual energy use on the feeder within about 5% for a typical meteorological year. The model was then used to implement several energy conservation retrofits in each of the apartments: replacement of air-source heat pumps with geothermal heat pumps, installation of low-flow shower heads, and lighting retrofits which included fixture de-lamping and replacement of other fixtures with compact fluorescent lights. The resulting model was able to predict

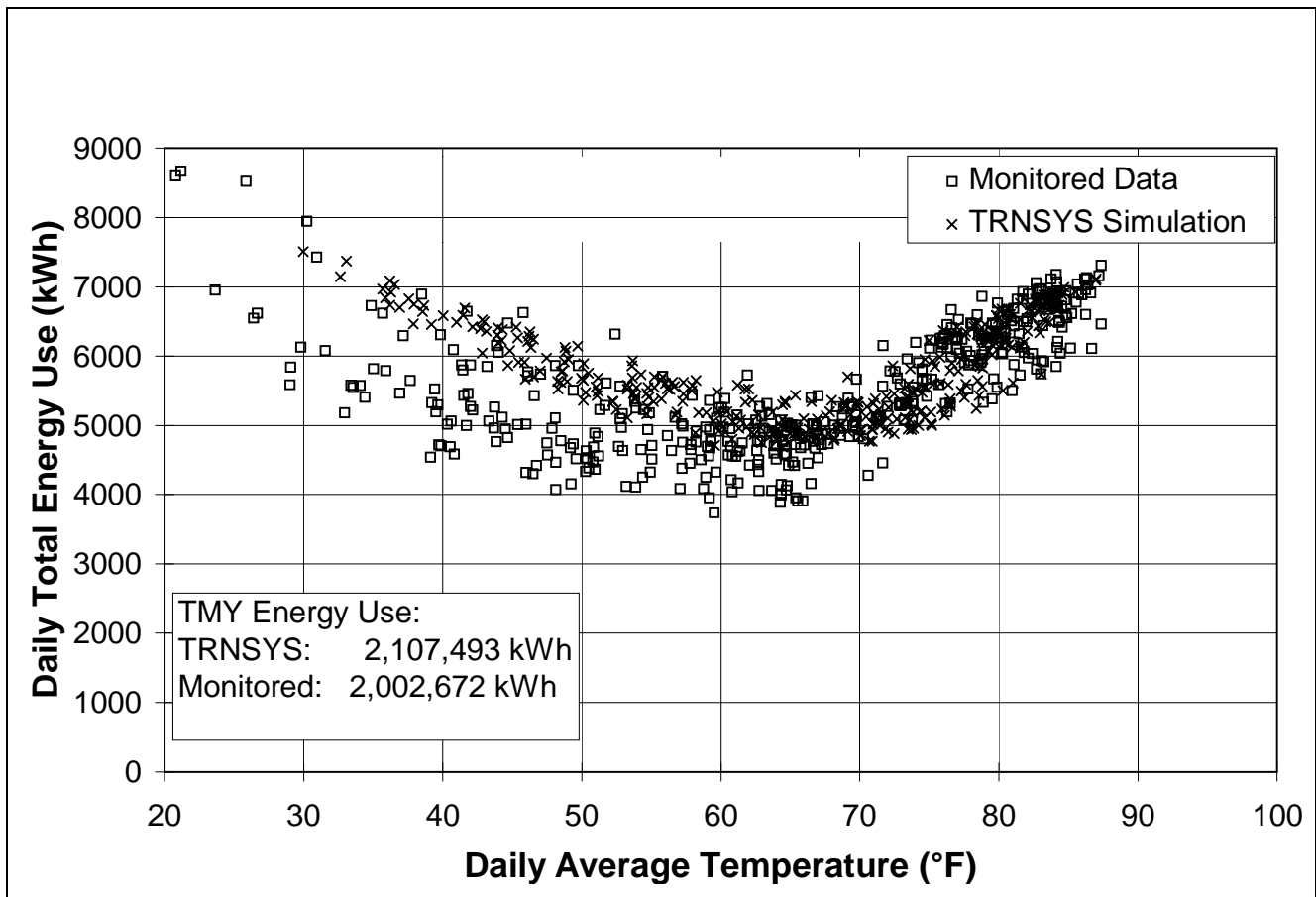


Figure 8: Post-retrofit daily energy use: monitored data and calibrated TRNSYS simulation.

post-retrofit annual energy consumption within 5% of its monitored value. The model also indicated that the retrofits would save 30.2% of pre-retrofit energy, which agrees well with the 30.3% savings actually achieved.

The results we obtained depended on the existence of several data sets. First of all, in order to calibrate the TRNSYS model we required pre-retrofit data on daily energy use vs. daily average temperature for the entire feeder. While about one year's data was available to us, in fact our experience at Fort Polk suggests that the feeder energy use profile can be characterized with as little as six months of data; however this may not be the case in all climates.

Since the lighting/appliance loads account for about 46% of the pre-retrofit electrical use on the feeder, the 15-minute interval profile of daily lighting/appliance energy use was also important in the accuracy of our model. This profile was developed using one year of 15-minute interval data from 20 separate apartments. We suggest that the profile we have developed - with suitable corrections for apartment floorspace - could be used for other projects in military family housing. In other housing types, it would be necessary to examine the number and type of electric lights and appliances in a representative number of apartments to determine whether our profile was suitable.

The hot water draw profile we developed compares well with published values, and could likely be used in future military housing projects. For other housing types, it may be necessary to monitor DHW tank energy consumption in a representative number of apartments to determine whether the profile we developed is suitable. Factors such as climate may have an impact on hot water use. Nevertheless, since water heating accounts for only about 15% of energy use on the feeder, an incorrect hot water draw profile will have a correspondingly small effect on total energy use.

Finally, we recognize that the calibrated ground heat transfer submodel was perhaps the most important factor in the accuracy of our model. Our calibration to monitored site data produced soil heat transfer properties which were quite different from those measured at the site using standard short-term testing methods. In future projects involving geothermal heat pumps, we would recommend collecting at least six months of 15-minute interval data, from at least one pilot test site. This recommendation may change if ongoing efforts to improve short-term soil property tests bear fruit.

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instrumental in determining the feasibility of the ESPC, developing the request for proposal, and awarding the contract. The selected energy services company, Co-Energy Group (CEG), was responsible for designing, financing and building the energy conservation retrofits in return for a share of the energy savings; and is responsible for maintaining the installed equipment for the duration of the 20 year contract. Applied Energy Management Techniques, under subcontract to CEG, was responsible for surveying the family housing, developing the energy consumption baseline from historical data, and developing the retrofit designs and prior cost and savings estimates. Oak Ridge National Laboratory (ORNL) carried out an independent evaluation of the ESPC with sponsorship from the U.S. Department of Defense (DoD), the U.S. Department of Energy (DOE), and Climate Master, Inc. Under subcontract to ORNL, field data collection was provided by Science Applications International Corporation and TRNSYS modeling was provided by Thermal Energy Systems Specialists.

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