Using Calibrated Engineering Models to Predict Energy Savings in Large-Scale Geothermal Heat Pump Projects

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ABSTRACT

Energy savings performance contracting (ESPC) is now receiving greater attention as a means of implementing large-scale energy conservation projects in housing. Opportunities for such projects exist for military housing, federally subsidized low-income housing, and planned communities (condominiums, townhomes, senior centers), to name a few. Accurate prior (to construction) estimates of the energy savings in these projects reduce risk, decrease financing costs, and help avoid post-construction disputes over performance contract baseline adjustments. This paper demonstrates an improved method of estimating energy savings before construction takes place. Using an engineering model calibrated to pre-construction energy-use data collected in the field, this method is able to predict actual energy savings to a high degree of accuracy. This is verified with post-construction energy-use data from a geothermal heat pump ESPC at Fort Polk, Louisiana. This method also allows determination of the relative impact of the various energy conservation measures installed in a comprehensive energy conservation project. As an example, the breakout of savings at Fort Polk for the geothermal heat pumps, desuperheaters, lighting retrofits, and low-flow hot water outlets is provided.

INTRODUCTION

It is well known that predictions of savings from energy conservation programs are often optimistic, especially for residential retrofits. Fels and Keating (1993) cite several examples of programs that achieved as little as 20% of the predicted energy savings. Factors that 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 may be the inaccuracy inherent in the engineering models 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 ESPC at Fort Polk were on the order of 40% of pre-retrofit electrical use; the evaluation has shown the true savings for the entire project to be about 32% (Shonder and Hughes 1997a).

The improved savings-estimation approach described in this paper 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 nonhousing loads on an entire electrical feeder at Fort Polk, Louisiana. 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). Analysis of pre- and post-retrofit data (Shonder and Hughes 1997a) indicates that the retrofits have saved 30.3% of pre-retrofit electrical energy consump-

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tion on the feeder modeled in this paper. The method outlined here predicts this savings within 0.1% of its measured value, using only pre-construction energy consumption data and post-retrofit data from one pilot test site.

Additional details on the Fort Polk project have been presented by Aldridge (1995). The methodology used in the evaluation is described by Hughes et al. (1997) and by Shonder and Hughes (1997b). Energy consumption data were collected on three levels: Level 1, which monitored energy supplied by the 16 electrical feeders serving Fort Polk's family housing areas; Level 2, which monitored total energy consumption and energy consumption by the HVAC system in a set of 42 housing units selected at random from a population of 4,003 units; and Level 3, which also monitored energy use by the water heaters and air-handling systems in a subset of 18 of the 42 Level 2 sites. Data at all three levels were collected at 15-minute intervals for approximately one year before and one year after the retrofits.

MODELING THE FEEDER

In order to test how well a calibrated model could predict energy consumption at the feeder level, a feeder serving 200 apartments located in 46 separate buildings on the North Fort was chosen. Figure 1 shows a site plan for the buildings located on the feeder. The area contains three unique building types: 12 buildings designated as Type 1, a four-plex; 18 buildings designated as 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 the carports. Since the roof design was expected to have an effect on space-conditioning loads, the two types were modeled separately. Table 1 lists the type and compass orientation of each building (south-facing buildings are at 0°; the orientation is measured counterclockwise from the south).

Among the three building types, there are only two unique apartment floor plans: apartment Type A, containing 1142 ft^2 of living space, and apartment Type B, containing 1114 ft^2. 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.

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.

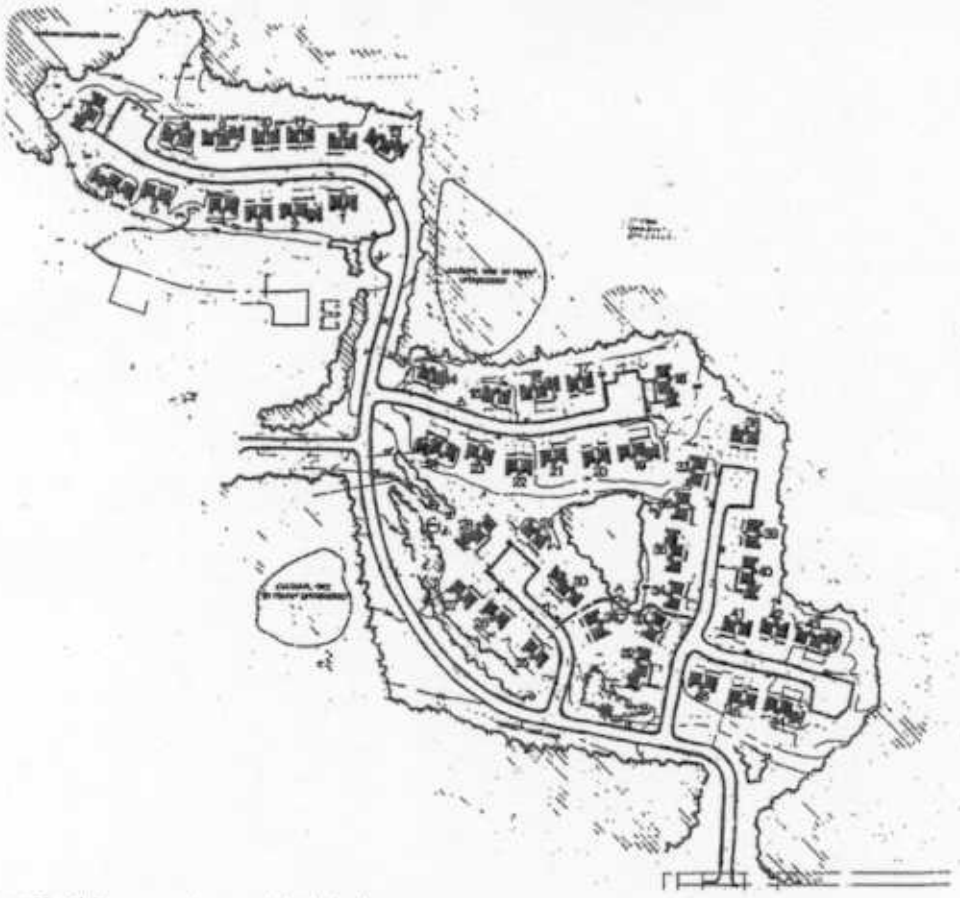


Figure 1 *Site map of buildings on the modeled feeder.*

TABLE 1
Building Types and Compass Orientations

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

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 vs. 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 change-point model to the data of Figure 2 gives the following relation between daily total energy use, E, and daily average temperature, T:

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

In the course of the evaluation of the Fort Polk project, equations like Equation 1 were developed for each feeder to correct for the varying weather conditions between the pre- and post-retrofit periods (Shonder and Hughes 1997a).

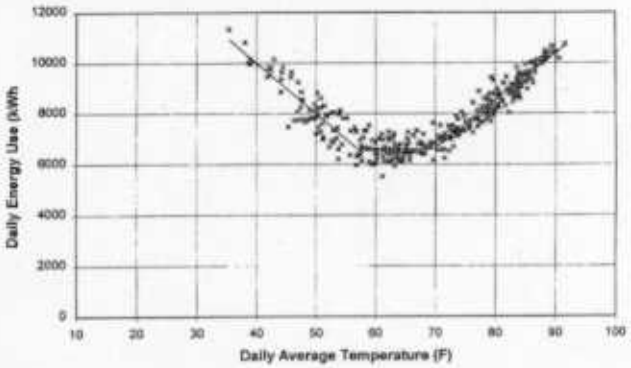


Figure 2 *Monitored daily electrical energy use for the feeder.*

Apartment-Level Energy Use Models

In order to model the energy used in space-conditioning equipment, controls, and water heating for the 200 apartments on the selected feeder, the TRNSYS (Klein et al. 1996) simulation software was employed. TRNSYS is a modular system simulation package in which the user specifies the components 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, such as 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. 1997a) 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, Texas, was used for the simulations, as Lufkin represents the closest inland TMY site to Fort Polk. Available weather data show slight differences in the long-term averages for Lufkin, Texas, and Alexandria, Louisiana, the closest location to Fort 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 overhang and wingwall shading effects, as each of the three buildings has many such features.

The ground temperature for the simulations was modeled with the Kusuda correlation (Kusuda and Archenbach 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, Louisiana, 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 airflow 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.

At the 18 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, it was necessary to derive 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, the non-HVAC, non-DHW electrical energy use will be referred to as the "lighting/appliance load," which, in addition to residential lighting, 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 18 Level 3 residences over the 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 floor space, the profiles were normalized by dividing each value by the total average daily energy use.

While the appliance use per day per apartment was highly variable (with a standard deviation of 7.5 kWh per day), there

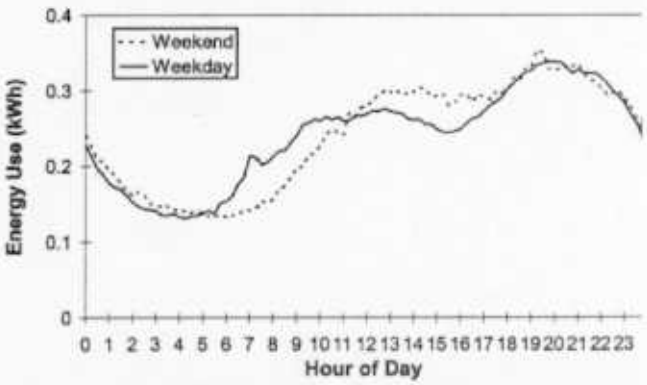


Figure 3 *Daily lighting/appliance electric load profile for apartments on the modeled feeder.*

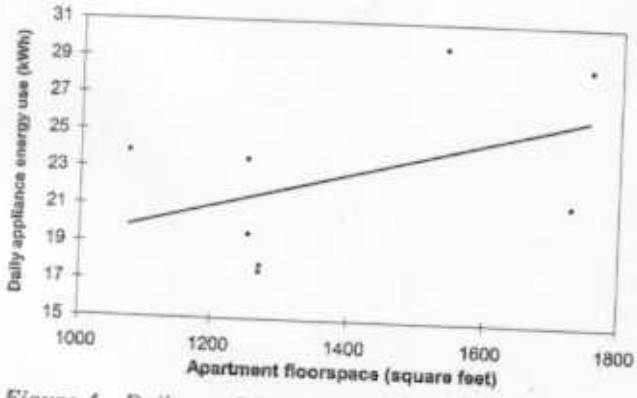


Figure 4 *Daily total lighting/appliance electric use vs. apartment floor space.*

was a slight positive correlation between total daily energy use and apartment floor space. These data are 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 seen in the data. Thus, to determine the daily appliance electrical profile for the modeled apartments, the normalized profile based on all the Level 3 apartments was used, with each 15-minute value multiplied by a constant that was dependent on the apartment floor area.

The weekday and weekend electrical lighting/appliance load profile of Figure 3 was used as 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.

As with the appliance energy use, the daily hot-water draw profile used in the modeled apartments is an average of data collected at 18 Level 3 sites, adjusted by apartment floor space. However, the data collected at the Level 3 sites were hot-water tank electrical energy use rather than hot-water draw. In order to convert electrical use into hot-water use, it was 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, the hot-water use during every 15-minute interval could be determined. For the apartments on Feeder 1, the average daily pre-retrofit hot-water use was determined to be 36.2 gal. For comparison, ASHRAE (1995) reports an average daily use of 42 gal for apartment buildings of 20 units or less. The lower figure derived from the Fort Polk data may be due to less than full occupancy in the apartments monitored. 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.

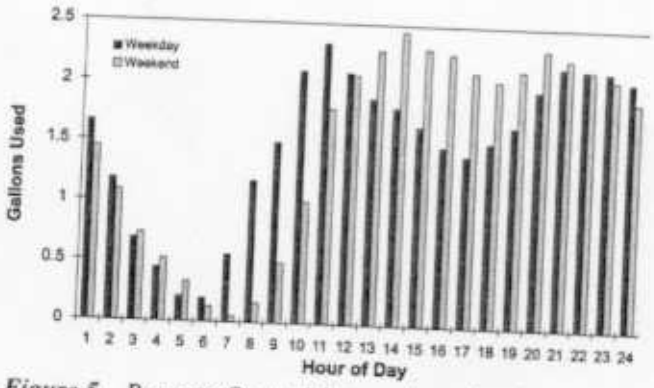


Figure 5 *Pre-retrofit weekday and weekend hot water draw profiles for apartments on the modeled feeder.*

The weekday and weekend hot-water draw profiles of Figure 5 were used as input to the TRNSYS models. Each apartment is assumed to contain a standard 52 gal electric hot-water heater with two 3300 W heating elements.

Street Lights And Other Nonhousing 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 that 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 kWh 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 no information on these losses was available, they are expected to be small, in the range of 1% to 2%. This loss was not modeled; since the models were calibrated to feeder-level data, the energy consumption predicted for the apartments may be 1% to 2% higher than their actual energy consumption.

Model Calibration to Pre-Retrofit Data

The floor plans, construction details, and compass orientation of each of the 46 buildings, as well as the average 15-minute hot-water draw and appliance electrical loads, provided sufficient information for the energy use to be modeled. Nevertheless, several unknowns still remained. No information was available for the occupancy (number of occupants per apartment) or vacancy rate. Since the population of family housing at Fort Polk is 12,000 for the 4,003 housing units, the average occupancy was assumed to be three individuals per apartment, even though the modeled apartments are slightly smaller than the average family housing unit at the base. Thermostat setpoints were also unknown.

The TRNSYS software allows the adjustment of numerous other parameters affecting energy use: occupancy schedules, shading schedules for windows by curtains and blinds, moisture capacitance of furnishings, etc. Aside from thermostat setpoints, the single parameter that perhaps has the largest effect on energy consumption is outdoor air infiltration. Since the rate of outdoor air infiltration was unknown for the modeled apartments, it was decided that the feeder model would be calibrated to the monitored pre-retrofit feeder energy-use data by varying outdoor air infiltration. Thus, in this simulation, the outdoor air infiltration likely captures the effect of a number of other parameters and probably does not represent the true infiltration rate of the apartments.

In order to reduce the number of computer runs required, the building compass orientations were run at intervals of 45°. Table 2 presents the building types and the number of each type at each 45° increment. 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.

TABLE 2
Building Type and Orientations Simulated

	Building Type		
Orientation	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

A constant of 0.05 air changes per hour was originally used to calibrate the model to the actual data. The output matched the monitored data 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 the room and ambient temperatures. Thermostat setpoints were fixed at 72°F in heating and 76°F in cooling, which agrees with monitored data from other apartments at the site. 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 with the actual pre-retrofit energy consumption of the feeder. For a TMY, the model predicts energy consumption of 3.02 million kWh, or an average of 41.4 kWh per apartment per day. The monitored data, when normalized to a TMY, give an annual energy use of 2.87 million kWh, or about 39.4 kWh per apartment per day. Thus, on an annual basis, the calibrated TRNSYS model is able to predict energy consumption within about 5% of the monitored data.

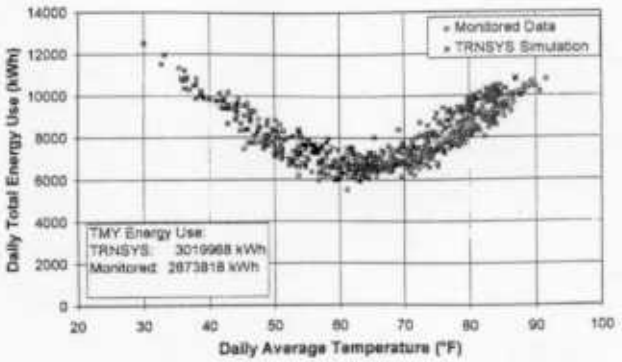


Figure 6 Pre-retrofit daily energy use: monitored data and calibrated engineering model.

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

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

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 temperatures, air infiltration factors, and other parameters, it would have been possible to match the monitored pre-retrofit heating data to a higher degree of accuracy. But the intent is to demonstrate that reasonably accurate prior estimates of savings are possible after only modest efforts to calibrate the model. An error of just 5% was obtained by varying only one parameter (air infiltration).

IMPLEMENTATION OF ENERGY CONSERVATION MEASURES

Once the TRNSYS model was calibrated to the pre-retrofit data, the energy conservation retrofits were implemented in the model. Air-source heat pumps were replaced with geothermal heat pumps including a desuperheater to provide 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 following sections describe how each of these measures was implemented in the model.

Geothermal Heat Pump Model

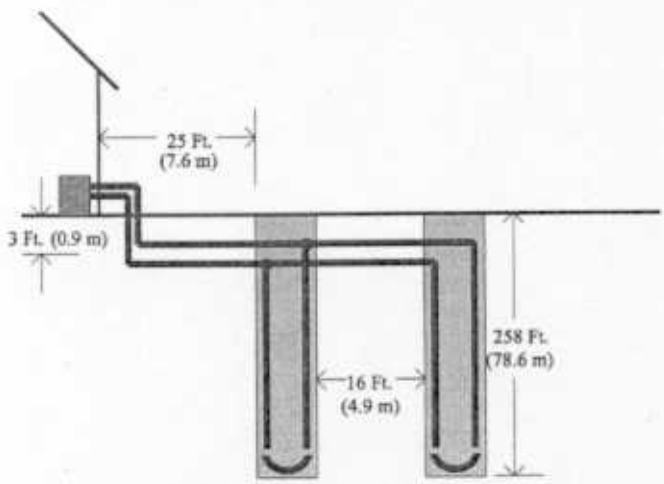
As part of the energy conservation retrofit, each of the 200 apartments on the feeder was equipped with a nominal one-and-a-half-ton geothermal (ground-source) heat pump (GHP) with 17,300 Btu/h total cooling capacity and 15.4 EER at ARI 330 rating conditions and an 11,800 Btu/h heating capacity and 3.5 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 in. (0.10477 m) in diameter and varying depth based on apartment type and orientation (on this feeder, the average bore length was 360 ft per apartment, or 240 ft per nominal ton of installed heat-pump capacity). These boreholes were typically spaced 16 ft (4.88 m) apart, 25 ft (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 composed of 1 in. nominal (0.0254 m) SDR-11 polyethylene pipe (1.08 in. ID, 1.31 in. OD) with a nominal center-to-center spacing of 2.565 in. (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 ft (0.914 m), with outbound and return legs in separate trenches. Figure 7 presents a diagram of a typical ground heat exchanger configuration.

A geothermal heat pump model, written for TRNSYS in a previous study (Thornton et al. 1997b), was used for the post-retrofit simulations. The geothermal 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 geothermal heat pumps ensure that the results from the model at each time step are reasonable.

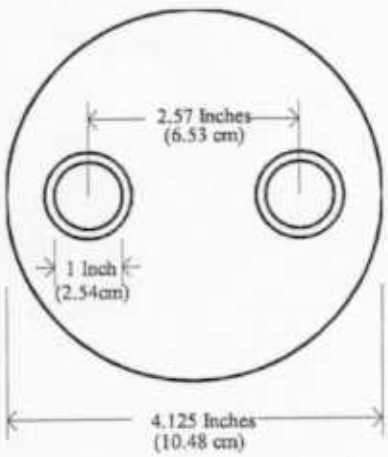
For geothermal heat pump system simulations, the most important component model is the ground heat exchanger. Although several ground heat exchanger models were available, the duct ground heat storage model (Hellstrom et al. 1996) developed at a university in Sweden was chosen for this study because it is well documented, is validated, and considers multi-bore interactions and long-term (multi-year) effects. In an earlier paper (Thornton et al. 1997a), the same model was utilized to predict ground heat exchanger performance against measured data with excellent results.

Lighting Retrofits

Lighting retrofits in the 200 apartments included delamping of some conventional fixtures and replacement of lamps in other fixtures with CFLs. The retrofits are described in Table 3. In order to determine the reduction in electrical energy use, the average pre-retrofit electrical energy profile, which accounts for all electrical use exclusive of the HVAC and water-heating systems, was adjusted to correspond to the retrofits. In the apartments under consideration, the total daily consumption for lighting/appliance use is 20.5 kWh. According to a reference from the U.S. Department of Energy (DOE 1994), lighting should account for 24.2% of this total, or about



Vertical heat exchangers



Borehole

Figure 7 *Typical ground heat exchanger installation.*

TABLE 3
Lighting Retrofits

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**

5.0 kWh/day, leaving 15.5 kWh/day for other uses, such as cooking, refrigeration, radios, televisions, etc.

In each apartment, lighting power was reduced from 1845 W to 458 W. If lighting is to account for 5.0 kWh in the pre-retrofit period, then on average, these 1845 W 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 W)(2.71 h) = 1.2 kWh/day. Assuming the 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. Since lights are used mostly in the morning and the evening, it would have been possible to develop a lighting schedule. However, considering that the pre-retrofit profile was developed by averaging one year's worth of daily profiles for 18 different apartments inhabited by occupants with varying work schedules, it was decided to simply multiply each 15-minute consumption in the pre-retrofit lighting/appliance profile 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, the starting point was the pre-retrofit hot-water draw profile, 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 (DOE 1994), hot water use for showers accounts for about 59% of total residential hot water use on a national basis. Thus, it is assumed that the average residence at Fort Polk uses approximately 21.4 gal per day for showers and 14.8 gal for other uses. Calculations made by the ESCO show that the shower heads installed will reduce water use per shower from 9.6 gal to 6.0 gal. This accounts for an average of 2.2 showers per day in the modeled apartments. If the number and length of showers per day remains constant after the retrofits, hot water use for showers should drop to 13.4 gal per day; the total post-retrofit hot water use is then 28.2 gal per day, or about 78% of its pre-retrofit value.

Again, since 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. However, considering that the pre-retrofit profile was developed by averaging daily profiles of 18 apartments over one year, it was decided to simply multiply each 15-minute draw in the pre-retrofit hot-water draw 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, but additional insulation was not added. Since no information was available either on the number of apartments that received these repairs, or on the quantity of insulation replaced, no attempt was made to model this retrofit.

POST-RETROFIT ENERGY USE

Total Energy Savings

With all of the energy conservation measures implemented in the apartment models, the energy use was determined for each apartment on each day of a TMY. 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 plots 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 Fort Polk's climate. For a typical meteorological year, the calibrated TRNSYS model predicts annual energy use of 2.11 million kWh, or 28.9 kWh per apartment per day. The monitored post-retrofit data, when normalized to a TMY, predicts an annual energy consumption of 2.00 million kWh, or 27.4 kWh per apartment per day. 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 TMY, the retrofits result in a savings of 872,000 kWh for this feeder, which is about 30.3% of the pre-retrofit annual consumption. Comparing the pre- and post-retrofit annual consumption predicted by the calibrated TRNSYS simulations, the model presented here would have predicted a savings of 912,000 kWh, or 30.2% of the predicted pre-retrofit consumption. Applying this savings to the pre-retrofit monitored energy consumption data, the model 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.

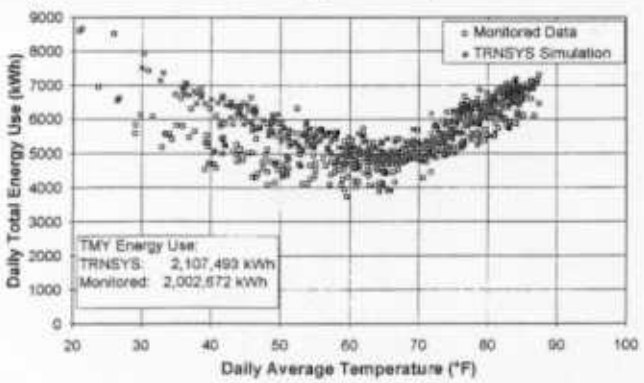


Figure 8 Post-retrofit daily energy use: monitored data and calibrated engineering model.

Energy Savings by Energy Conservation Measures

With the output from the calibrated TRNSYS model, it is possible to determine the relative impact of each of the four energy conservation measures installed on the housing units. Table 4 presents a breakdown of the average energy use per apartment per day for space conditioning, hot water heating and lighting/appliances, pre- and post-retrofit, based on the simulation of the entire feeder. The results indicate that due to the retrofits, energy use for lighting and other appliances was reduced by 18%. Energy use for water heating was reduced by 71%, and energy use for space conditioning was reduced by 27%.

TABLE 4
Average Daily Load Per Apartment in kWh for Space Conditioning, Water Heating, and Lighting/Appliances for All 200 Apartments on the Modeled Feeder

	Space Conditioning	Water Heating	Lighting/ Appliance	Total
Pre-Retrofit	13.81	7.08	20.52	41.40
Post-Retrofit	10.03	2.05	16.82	28.90

It was recognized, however, that there are interactions between the various conservation measures installed in these apartments. For example, the 71% reduction in energy use for water heating was due to both the desuperheater and the low-flow shower heads. To account for these interactions, the calibrated feeder model was used to determine the change in energy consumption for each end-use when the conservation measures were added one by one. The results are given in Table 5 and presented graphically in Figure 9. It is seen that including the geothermal heat pumps (measure "A") reduces

TABLE 5
Daily Average Energy Use Per Apartment (kWh) for Three End-Uses as Retrofit Measures are Added Successively*

	Space Conditioning	Water Heating	Lighting/ Appliance	Total
Pre-Retrofit	13.81	7.08	20.52	41.40
A	10.20	7.08	20.52	37.80
A+B	10.34	2.39	20.52	33.25
A+B+C	10.34	1.78	20.52	32.63
A+B+C+D	10.03	2.05	16.82	28.90

* A = Geothermal Heat Pumps; B = Desuperheaters; C = Low-flow Showers; D = Lighting Retrofits

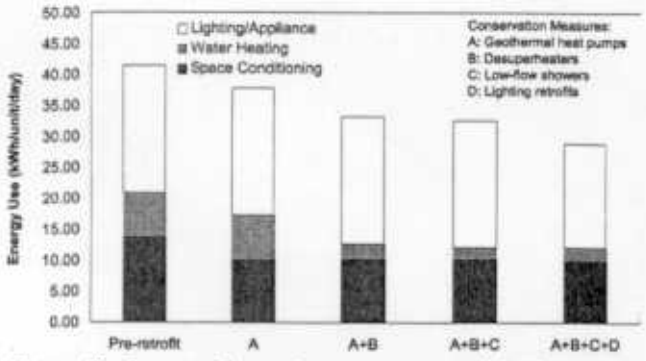


Figure 9 Impact of retrofits on space conditioning, water heating, and lighting/appliance loads.

the average daily energy consumption for space conditioning by 3.61 kWh per apartment. Addition of the desuperheaters (measure "B") reduces the average daily energy use for water heating by 4.69 kWh per apartment. Adding the low-flow showers (measure "C") reduces energy use for water heating by an additional 0.61 kWh/day; however, adding the lighting retrofits increases the energy use for water heating by 0.27 kWh/day. This is because the lighting retrofits reduce the amount of time the heat pump runs on an annual basis (cooling hours decrease more than heating hours increase), and the energy not provided by the desuperheater must be made up by the tank heating elements. On the other hand, the energy use for space conditioning drops by 0.31 kWh/day as a result of the lighting retrofits.

This analysis shows that while interactions do occur between the various conservation measures, in this case their effect is not significant. Thus, it is reasonable to conclude that of the 872,000 kWh reduction in annual electrical energy use for the housing on this feeder, approximately 576,000 kWh is due to the geothermal heat pump (259,000 kWh for space conditioning and 317,000 kWh for water heating); 253,000 kWh is due to the lighting retrofits, and 43,000 kWh is due to the low-flow shower heads. This is presented graphically in Figure 10.

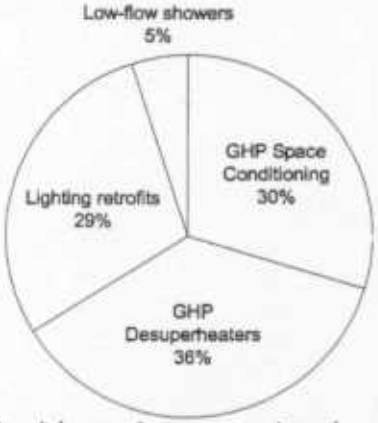


Figure 10 Breakdown of energy savings by conservation measure.

Comparison with Monitored Data

Pre- and post-retrofit data were available for one of the buildings on the modeled feeder; the data included total electrical use and energy used by the HVAC system. When normalized to a TMY, the data show good agreement with the TRNSYS model for this building (note that the TRNSYS model was matched to pre-retrofit data for the entire feeder and not for this particular site). As shown in Table 6, TRNSYS is able to predict total energy and energy used by the HVAC system within 5% of the monitored values for both the pre- and post-retrofit conditions.

TABLE 6
Average Daily Total Energy Use and Energy Use for Space Conditioning Per Apartment, Pre- and Post-Retrofit for One Building on the Modeled Feeder

		Monitored	TRNSYS
Pre-Retrofit	Total	38.2	40.5
	HVAC	13.7	13.2
Post-Retrofit	Total	27.3	28.0
	HVAC	9.5	9.4

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 TMY. 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 (including desuperheaters), installation of low-flow shower heads, and lighting retrofits, which included fixture delamping and replacement of other fixtures with compact fluorescent lights. The resulting model was able to predict 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 with the 30.3% savings based on monitored data. The model was also used to determine the breakdown of energy savings due to the various retrofits. It was found that the geothermal heat pumps, including the desuperheaters, were responsible for 66% of the energy savings achieved. Lighting retrofits accounted for 29%, and the installation of low-flow shower outlets accounted for about 5%.

The results obtained depended on the existence of several data sets. First, in order to calibrate the TRNSYS model, pre-retrofit data on daily energy use vs. daily average temperature for the entire feeder were required. While about one year's data were available for this study, the 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 an important contribution to the accuracy of the model. This profile was developed using one year of 15-minute interval data from 18 separate apartments. The profile—presented in Figure 3 with suitable corrections for apartment floor space—could be used for other projects in military family housing. The figure presents the kWh used during every 15-minute period for the typical Fort Polk residence during a typical day. 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 the profile developed for this paper was suitable.

The hot-water draw profile presented in Figure 5 compares 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 this profile 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, it is recognized that the calibrated ground heat exchange submodel was perhaps the most important factor in the accuracy of the model. The calibration to monitored site data produced soil heat transfer properties that were quite different from those measured at the site using standard short-term testing methods available at the time the Ft. Polk project was developed. In future projects involving geothermal heat pumps, it may be necessary to use improved short-term soil property tests or to collect at least six months of 15-minute interval data from at least one pilot test site.

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