Creating Low-Energy Commercial Buildings through Effective Design and Evaluation

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ABSTRACT

This paper presents two case studies of passive solar commercial buildings that were designed and constructed at the National Renewable Energy Laboratory (NREL) in Golden, Colorado, as part of the U.S. Department of Energy's (DOE's) and NREL's Exemplary Buildings Program. These buildings use much less energy than equivalent code-compliant buildings and have remained within government-mandated budget constraints.

Performance predictions generated as an integral part of the design process, as well as actual measured energy and daylighting performance are presented. Also presented are lessons learned during the design, construction, and initial occupancy of the buildings.

Two *general* practices were tantamount—close communication between all team members from predesign through commissioning and occupancy, and a commitment to use of solar technologies and energy efficiency by all building design team members. It was found that, even when a team is committed to a low-energy goal, the actual energy savings can disappoint if there is lack of communication among team members.

Several more *specific* practices were also key—a whole-building energy design approach using computerized energy simulation tools during the entire design process, and frequent inspections during construction. Additionally, the building team, usually consisting of an architect, engineer, builder, and owner, should also include an energy consultant. Furthermore, the energy design process must begin in predesign as soon as location, size, and building type are known in order to determine the main energy issues. The team should continually work together to minimize the building's energy use.

Introduction

The DOE's Exemplary Buildings Program at NREL advocates low-energy buildings through whole-building design, using passive solar, renewable energy, and energy-efficient technologies. Program researchers work with teams of energy consultants, builders, developers, architects, and engineers to produce low-energy or "exemplary" buildings. The long-range goal for Commercial Exemplary Buildings is for solar technologies, including daylighting, to satisfy 75% or more of the building's energy demand, and for energy cost savings to exceed 70% of an equivalent building constructed to meet the Federal Energy Code 10CFR435 (based on the American Society of Heating, Refrigerating, and Air-Conditioning Engineers [ASHRAE] Standard 90.1). By using appropriate simulation tools with a whole-building approach that prioritizes the use of solar technologies and energy efficiency throughout the design, construction, commissioning, and operation processes, building teams can achieve large energy cost savings with minimal or no increase in construction costs.

The Whole-Building Approach

Using a whole-building design approach, a building team designs and constructs a building as a single unit, not as a shell containing many separate systems (see Figure 1). For the design to be successful, the team must understand how a building interacts with its systems, its activities, and its surrounding environment. The energy consultant uses computerized building energy simulation tools to evaluate the building's energy use and interrelated issues. The team must then employ the modeling results as a guide throughout the design and construction processes. Clear energy performance goals should be established during the preliminary design process and it is crucial that communication links between the energy consultant and the architect, engineer, and building owner are maintained from design through construction and commissioning.

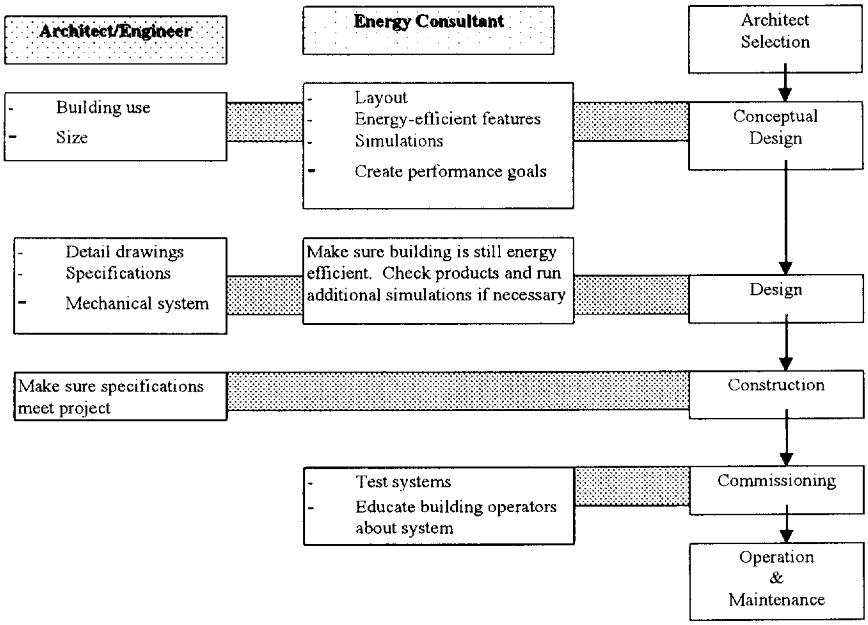


Figure 1. Design and construction process.

Predesign or Conceptual Design Process. A coordinated effort in determining building space use is the first vital step to ensuring building energy efficiency. After the team has agreed to the building's use and space allocation, the energy consultant analyzes the preliminary design using computerized design and energy analysis tools, such as Energy-10, DOE2.1E, SERI-RES, and ADELINE, to make recommendations for optimizing the orientation, basic geometry, and thermal envelope design.

These design tools bring all the architectural and engineering pieces together to predict how the building's components will interact. In other words, daylighting systems, thermal issues, and building control strategies may be addressed by different building disciplines, but successful low-energy performance can only be achieved by examining the interrelation between the components.

After the architect and engineer have incorporated the energy consultant's recommendations into a preliminary building design, the energy consultant returns to the analysis to provide alternatives and to fine-tune the architectural concepts.

Design Process. The team creates detailed drawings that accurately reflect the intent of the building during the design process. All component requirements should be clearly defined and system interactions considered. For example, if part of the building's heating load is designed to be met with passive solar gains, the windows specified must have a high solar heat gain coefficient. If daylighting is to be used, electric lighting must be effectively integrated with it.

Another consideration during the design process is cost. Low-energy buildings should not cost more to construct than conventional buildings. Although the predesign and design processes may increase the design cost by approximately 20%, compared to a non-optimized building design, the increased design cost is often balanced by plans with fewer errors and decreased mechanical system cost.

Construction Process. During construction, the design team must be available to explain details that are not clear. No matter how thorough the plans and specifications, details that affect the energy features of the building get overlooked. The design team must also watch the construction process to ensure the building is built according to plan. For example, insulation is often forgotten, pipes are misplaced, and glazing type is different than specified.

Commissioning Process. The commissioning process includes testing all subsystems in the building to ensure that they operate as intended and to ensure the systems are working together. In addition, the building owner and the maintenance staff must be educated to properly use the building systems as conceived by the design team. The building's energy performance can only be optimized if the people running the systems truly understand how the systems interact.

Case Studies

The following case studies describe two low-energy buildings at NREL, the Solar Energy Research Facility (SERF) and the Thermal Test Facility (TTF). Models calibrated with actual data show that the SERF and TTF incur 45% and 63% less energy cost respectively, for heating, cooling, lighting, and hot water than equivalent buildings complying with 10CFR435. Site energy use for the TTF was reduced by 50%.

Completed in 1993, the SERF was the first passive low-energy building to be constructed at NREL (see Figure 2). Table 1 shows the SERF achieved 45% energy cost savings for heating, cooling, lighting, and hot water compared to an equivalent code-compliant building based on a calibrated DOE-2.1E model.

Figure 2. The Solar Energy Research Facility at the National Renewable Energy Laboratory in Golden, Colorado.

Table 1. The Solar Energy Research Facility Energy Costs and Savings

END USE	CODE BUILDING (10CFR-435)	SERF DESIGN PREDICTED	SERF ACTUAL CALIBRATED
Equipment/Plug Loads Energy Costs	$159,000	$159,000	$136,000
Lighting Energy Costs	$36,000	$14,000	$12,000
Cooling Energy Costs	$71,000	$11,000	$9,000
Heating Costs	$195,000	$111,000	$120,000
Domestic Hot Water Energy Costs	$1,000	$300	$300
Auxiliary Heating, Ventilation, & Air Conditioning (HVAC) Energy Costs	$102,000	$98,000	$83,000
Total Energy Costs (with equipment)	$565,000	$393,000	$360,000
Savings	N/A	$172,000 (30%)	$205,000 (36%)
Total Energy Costs (without equipment)	$406,000	$234,000	$224,000
Savings (without equipment)	$0,000	$172,000 (42%)	$182,000 (45%)
Building Size	10,799 m^2 115,200 ft^2	10,799 m^2	10,799 m^2

Energy-Saving Technologies. The SERF followed the guidelines for low-energy construction. The program required a 115,200 square-foot (10,799 square-meter building with highly specialized laboratory requirements. Zoning and geometric organization is a seldom-discussed, but vital part of low-energy design. These issues must be considered in the earliest stages of conceptual designs and are essential to creating a low-energy building The laboratories required controlled lighting with high outside air requirements. Office space was needed to support laboratory efforts. The building was therefore zoned with office pods on the south and laboratories on the north. This allowed for daylighting of the offices, and split off the special heating, ventilation, and air conditioning (HVAC) requirements of the laboratories from the rest of the building. The long axis of the building is north-south.

Daylighting plays an integral role in the design of the office pods. Stepped clerestory shelves (see Figure 3) separated by vertical glazings use the building's southern exposure to provide high-quality diffuse lighting for offices and adjoining corridors. Direct sunlight is shaded because it would create uncomfortable glare and heat gains. To control luminosity from the clerestory and east-west windows, a variety of glazings were selected for specific visual transmittance values. The east-west glazing surfaces are further protected from glare and heat gain with a motorized window blind system activated by an exterior sun sensor. Where the daylight is insufficient, high efficiency T-8 fluorescent fixtures with electronic ballasts provide electric light. Motion detectors are used throughout the building to keep the lights off when spaces are not occupied. These systems reduce both lighting electricity use and cooling loads.

Figure 3. The Solar Energy Research Facility's stepped clerestory shelves provide high quality lighting for its offices and adjoining corridors.

The HVAC system was optimized based on the Colorado climate and the energy loads for the building. The system incorporates direct and indirect evaporative cooling, which is well-suited for the dry Metro Denver-area climate. Direct evaporative systems use the heat of evaporation to lower air temperatures before distributing the air throughout the building. The indirect system uses the building cooling towers to produce chilled water through an intermediary heat exchanger. An oversized cooling tower provides more contact area between water to be cooled and the circulating airstream. Airflow pressure drop is reduced, and less fan horsepower is required to provide the same cooling tower performance. The chilled water is circulated through cooling coils to cool air streams without increasing humidity in the main air supply.

This type of system is often called a "waterside economizer." The waterside economizer provides enough cooling capacity for the SERF so that the building chillers operate less than 6 months out of the year. Direct and indirect evaporative cooling systems use far less energy than conventional air-conditioning systems, and resulted in energy savings of about $30,000 per year.

A special requirement of the labs was for 100% outside air. A heat recovery system employs heat exchangers to recover heat generated by equipment and uses it to preheat fresh, incoming air. This displaces 50% to 60% of the energy that would otherwise be required to heat incoming air. In addition, a thermal storage wall was incorporated into the building's shipping and receiving area to reduce heating costs and provide a radiant heat source in an area with frequent door openings. These strategies save about $30,000 per year.

Variable frequency drives operate the supply fans in the ventilation system and the HVAC pumps. These drives operate at the speed and power needed to meet demand. The HVAC system also uses high-efficiency motors that require 2% to 3% less electricity than standard motors to produce the same mechanical output.

Table 2 shows the incremental first cost, energy cost savings, and simple paybacks for the energy reduction strategies used in the SERF.

Table 2. Energy Costs, Savings, and Simple Payback for the Solar Energy Research Facility.

STRATEGY	ADDED COST	ANNUAL SAVINGS	SIMPLE PAYBACK
Heat Recovery	$174,000	$28,000	6 years
Indirect/Direct Evaporative Cooling	$69,000	$30,000	2 years
Efficient Lighting	$54,000	$9,000	6 years
High Efficiency Motors	$4,000	$2,000	2 years
Variable Frequency Drives	$6,000	$2,000	3 years
Upsize Cooling Towers	$6,000	$1,000	6 years
Daylighting/Zoning/ Geometry/Orientation	N/A	$110k	N/A

It is not possible to assign a precise incremental cost to the daylighting, zoning, geometry, and orientation modifications. All buildings have a certain "aesthetic cost." This is the cost associated with the architecture of the building. A building like the SERF would never be a rectangular pre-fab metal building and was never conceived as such. In this case the aesthetic cost was applied in such a way as to also reduce the need for lighting, heating, and cooling energy. In other words, the architecture works with the building's energy needs.

Performance Analysis. A post-construction analysis of the SERF's energy-saving features completed in 1997 revealed additional savings opportunities within the lighting and HVAC systems. The office pods were designed with a permanent security lighting system that remained on 24 hours a day (there were no controls beyond the electrical panel that allowed operators to turn off the security lights). In addition, the daylight and motion detectors throughout the building were not adjusted correctly, allowing some of the electric lights to remain on throughout the day. This is a common problem in lighting controls, and was even more prevalent in the generation of controls available when the SERF was constructed.

Simulations were completed to predict the energy savings from calibrating the SERF's daylighting and occupancy sensors using DOE2.1e, an hourly building energy simulation software tool. According to DOE2.1e, calibration of the daylighting sensors could provide an additional annual energy savings of $1,800 and calibrating the occupancy sensors could provide an additional annual energy savings of $1,100. However, when these problems were corrected, some occupants complained that the space seemed too dim. Light measurements in the space showed adequate ambient light levels. This discrepancy indicates that there is a psychological aspect to the lighting that may not be well understood at this time. The SERF daylighting system diffuses almost all the daylight, and bounces much of the light off the ceiling. Also, the furniture and partition wall colors (shades of gray) were specified by an interior designer who had not been part of the design team, and those surfaces may be the wrong color or too dark. Some occupants seem to be more satisfied when at least some ambient electric lighting is used to add a warmer color to the space, even though the electric lighting does not add appreciably to the measurable ambient light levels.

The HVAC system was undersized for heating the office pods. Most commercial buildings are internally load dominated such that cooling costs usually outweigh heating costs; however, in a carefully designed passive daylit building, waste heat from lights and unwanted solar gains are greatly reduced. Thus, the quality of the thermal envelope and the windows become very important to maintain comfort for occupants located at the perimeter. The energy analysis, however, did not show a good payback for increased insulation or low-e windows, so they were not incorporated into the building. Unfortunately, perimeter occupants did experience an uncomfortable chill on very cold days, so it was necessary to retrofit electric resistance heaters to maintain comfort on those days. Table 3 shows the envelope and window thermal properties. These complied with code, and exceeded code for the low-e east and west windows. Payback analysis is not always appropriate when determining energy features.

Table 3. Envelope and Window Thermal Properties for the Solar Energy Research Facility.

ELEMENT	CONSTRUCTION	U-VALUE or R-VALUE	SOLAR HEAT GAIN COEFFICIENT (SHGC)
East and West Windows	double-pane, 3/8", Low-e, aluminum frame	U-0.31	0.38
All others	double-pane, 3/8" aluminum frame	U-0.48	0.38
South Walls	Frame, R-19 batt	R-21.6	N/A
East, West, North Walls	concrete, R-19 batt	R-22.5	N/A
Stepped Roof	Lukabond R-30 batt	R-35.27	N/A
Flat Roof	Polyisocianurate, metal deck	R-20.71	N/A

Lessons Learned. Overall, the SERF annual energy cost for heating, cooling, and lighting is approximately 45% less than an equivalent code-compliant building. This is remarkable for a laboratory building that houses very specialized functions and the building should therefore be considered a success. For the future, however, the important lessons are:

- Diffuse ambient daylighting is required to avoid glare problems; however, there appears to be a psychological need for some warm light and "sparkle" in the light mix.
- The interior designer must be included in the design team and fully indoctrinated into daylighting design so that interior surface colors for carpets, furniture, and partitions are appropriately specified. This is in addition to a functional team consisting of the design engineers, the building owner, and the architect.
- The thermal envelope and windows should be specified to ensure comfort at the perimeter, even though an energy analysis will not show cost justification. These specifications include thermally broken frames and low-E glass.
- Motion and photo-sensors are improving and becoming more cost effective, but there are still frequent calibration and control problems.
- More guidance and tools are needed for building operators to optimize the control strategies in the building according to how it is actually used. Designers cannot know this in advance, and the usage patterns will change over time.

The Thermal Test Facility (TTF)

When researchers began designing the TTF (Figures 4 and 5) in 1994, they took a strong approach to whole-building design. The first strategy researchers employed for the 10,000-square-foot facility was to establish a clear goal of 70% energy cost reduction from a code-compliant building at the onset of the conceptual design process. Designers then began optimizing the building design with detailed evaluations, using hourly simulation tools. The thermal optimizations were completed using

SERI-RES, a simulation tool that uses thermal network solved with finite difference routines. Daylighting and HVAC system design were optimized using DOE-2.1e.

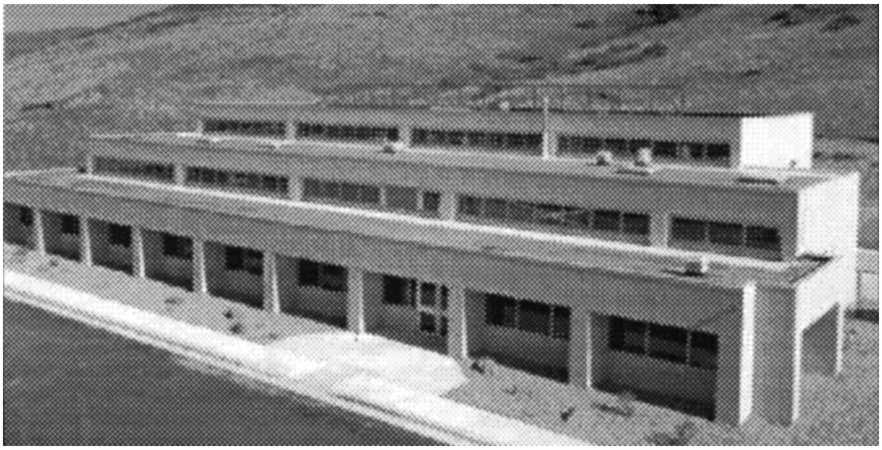


Figure 4. NREL's Thermal Test Facility energy costs are 63% less than an equivalent code-compliant building.

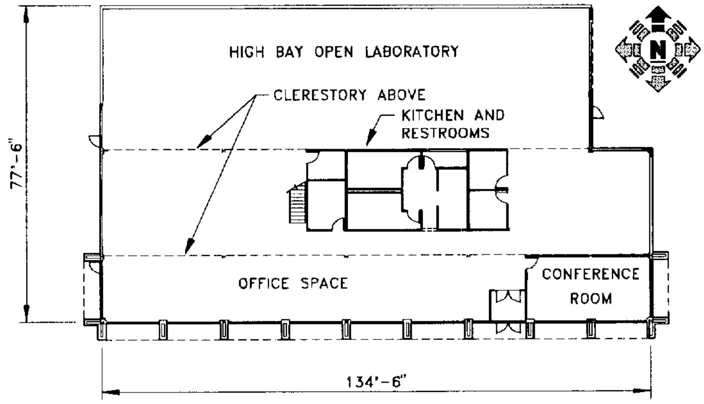


Figure 5. Thermal Test Facility floor plan.

Energy-Saving Technologies. Like the SERF, the form of the building followed the functionality and was designed for minimizing energy use. To maximize the building's daylighting potential, the design team created a stepped building that accommodated clerestory windows for its mid- and high-bay laboratory areas. Daylighting meets all the TTF lighting needs except in the minimal-use areas of the building (restrooms, electrical rooms, etc.). Daylighting-occupancy sensors control operation of the electric lighting in the daylit areas, maintaining 50 foot-candles (538 lux), and occupancy sensors govern electric lighting use in other areas. The daylighting-occupancy sensors for the electric lighting in the daylit spaces are on a single-step control system; the lights are either on or off. Controls have been optimized to prevent short cycling during periods of partial cloud cover.

Electric lighting needs are met by high-efficiency T-8 bulbs with electronic ballasts and compact fluorescent fixtures. Solid-state 2-watt exit signs also contribute to the building's reduced lighting energy requirements. The building contains no security lighting. The interior lights turn on when the occupancy sensors detect motion occurring within the building, eliminating the need for 24-hour security lighting. Researchers estimate 2,630 kWh/year are saved by not operating 10% of the electric lighting 24 hours per day; the typical percentage of lighting dedicated to security lighting in commercial buildings.

Maximizing daylighting also led to the opportunity to passively heat and cool the building. Simulations revealed a large heating demand during the winter. Therefore, overhangs for the clerestory windows were engineered to allow direct solar gain during the winter and eliminate solar gains during the summer. Heating loads in the low-bay portion of the building are less than in the remainder of the building due to internal gains. As a consequence, oversized overhangs were placed around low-bay (office and conference room) windows to prevent direct solar gains almost year-round. The density of internal gain is higher in this area. The oversized overhangs also minimize direct glare onto work surfaces and computer equipment in these office areas.

The rear wall of the building is tilt-up concrete. The exterior side of the tilt-up concrete wall is covered with 2 inches (5 centimeters) of polystyrene insulation, which has an R-value of 10 $hr{\cdot}ft^2{\cdot}{}^{\circ}F/Btu$ (1.8 $m^2{\cdot}K/W$). The exterior stud walls are insulated with 1.5 inches (3.75 centimeters) of polystyrene with an Exterior Insulated Finishing System (EIFS) finish and fiberglass batt insulation (19 $hr{\cdot}ft^2{\cdot}{}^{\circ}F/Btu$ [R 3.3 $m^2{\cdot}K/W$]) between the metal studs. The total R-value of the stud walls is 23 $hr{\cdot}ft^2{\cdot}{}^{\circ}F/Btu$ (4.0$m^2{\cdot}K/W$).

Approximately a 4-foot (1.2-meter) length of R-10 $hr{\cdot}ft^2{\cdot}{}^{\circ}F/Btu$ (R-1.8 $m^2{\cdot}K/W$) insulation exists around the perimeter of the slab. The roof is a metal decking over a steel structure. Three inches (10 centimeters) of polyisocyanurate insulation is built up on top of the roof for a total R-value of R-19 $hr{\cdot}ft^2{\cdot}{}^{\circ}F/Btu$ (3.34 $m^2{\cdot}K/W$). Designers were careful to eliminate all thermal bridging between envelope components and the ground or outside environment. For example, thermally broken door and window frames were specified. The glazing for both view windows and clerestories is composed of insulating units having a U-value of 0.33 $Btu/hr{\cdot}ft^2{\cdot}\ {}^{\circ}F$ (1.87 $W/m^2{\cdot}K$) and a low-e coating. The clerestory windows have a high solar heat gain coefficient (SHGC of 0.68) for passive solar heating. The coefficient of the office and conference room windows is less (SHGC of 0.45) to help manage solar radiation and provide a gray tint for aesthetic purposes. Eighty-five percent of the glazing area faces south. Glass on the east and west faces was minimized because this glass cannot be effectively managed with overhangs and shading devices. North-facing glazing areas were sized to provide balanced daylighting. The energy saved with daylighting (by not using the lights) outweighs the heat loss through the north-facing fenestration.

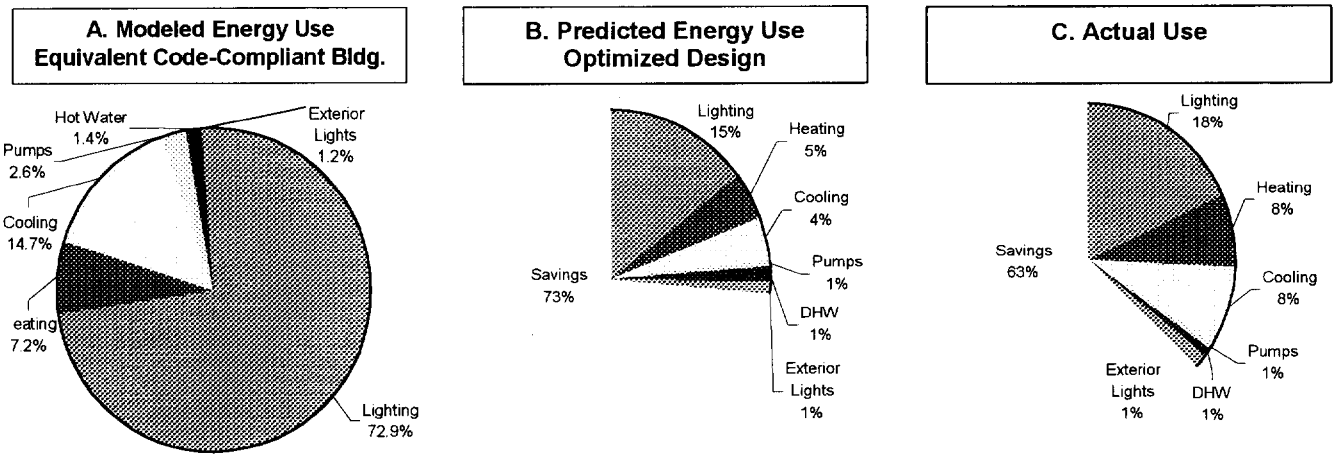
Thermostatically controlled ceiling fans distribute heated or cooled air throughout the building. Fan-powered, make-up air units with water heating coils operate if building heating loads cannot be met by passive solar heating. The main air handling units (AHUs) contain a water heating coil and a direct/indirect evaporative cooler. A central heating plant serving the NREL campus supplies hot water to the make-up air units and main AHU heating coils. When cooling is needed, the indirect section of the evaporative cooler operates first to avoid adding moisture to the building. A conventional economizer operates when outside conditions are right for supplying unconditioned air to the building. All duct runs in the building are as short and straight as possible to minimize static pressure losses through the ducts. Lower static pressure loss reduces energy consumption by the fans for air distribution. Air-to-air heat exchangers precondition ventilation air. These units operate during both the heating and cooling seasons, except when the economizer or evaporative cooler is operating.

One of the objectives of this design was to create a building requiring minimal HVAC equipment and minimal run-times for equipment. The building and the HVAC system were designed together as a single package to meet this objective. The building Energy Management System (EMS) optimizes the HVAC system operation. Table 4 outlines the operation sequence.

Table 4. Equipment Operation Sequence Based on Inside Temperature

COMPONENT	LESS THAN 71°F	71°F	72°F	73°F	MORE THAN 73°F
Central Fan	Off	Off	Off	Economizer on	Evaporative cooler on
Evaporative Cooler (Direct)	Off	Off	Off	Off	On, if dew point less than 65°F
Evaporative Cooler (indirect)	Off	Off	Off	Off	On
Make-up Air Unit Box Fans (w/ heating coil)	Modulates hot water valve to maintain zone temperature	Off	Off	Off	Off
Heat Exchange (HX)	Runs continuously except when economizer or direct evaporative cooler are operating or when the building is unoccupied				
Ceiling Fans	Operates on a 5°F temperature difference from ceiling to floor to minimize stratification. Direction of fan blades determined by heating or cooling mode.				

Performance Analysis. The HVAC system design and system operation in the TTF matches the load profile of the building. Figure 6, Chart A shows the distribution of energy costs for an equivalent code-compliant building developed by the simulation tools to compare the energy savings derived from implemented energy design strategies and technologies. This code-compliant building satisfies minimum standards of Federal Energy Code 10CFR435 and is solar neutral (windows are equally distributed on all four sides). Lighting watt densities are set at 1.4 w/ft^2 (15.1 w/m^2). Figure 6, Chart B shows the predicted operating costs in the optimized building design, and Figure 6, Chart C shows the TTF's actual energy use. The reasons why the actual operating costs differ from the predicted operating costs are listed under Lessons Learned.


A. Modeled Energy Use Equivalent Code-Compliant Bldg.

B. Predicted Energy Use Optimized Design

C. Actual Use

Figure 6. Energy use in the Thermal Test Facility.

Lessons Learned. The goal for the TTF energy cost performance was to be 70% less than an equivalent conventional building designed to meet the Federal Energy Code 10CFR435. After monitoring the building performance, researchers found the actual savings to be 63% compared to the code-compliant building.

The TTF's actual performance is less than was predicted, primarily for the following reasons.

- Through infrared imaging thermography, researchers discovered thermally-broken window and doorframes were not installed.
- A thermal bridge exists between the building foundation and an exterior retaining wall. A decision was made during construction to relocate the foundation insulation for structural reasons. By the time the researchers were made aware of the situation, the error could not be corrected without adding significantly to the project's cost.
- Fixtures provide direct lighting to the work areas. Stepped controls cause some distraction. Using continuous dimming would further save energy while improving user satisfaction. When the building was designed, the cost of this equipment prevented this level of lighting sophistication.
- Direct gain in the winter has caused some glare issues in the workplace. Light shelves and blinds can reduce this effect.
- The TTF has minimal air flow when heating and cooling are not required. Because of this, temperature stratification occurs, especially in the early morning hours. Ceiling fans need to be carefully placed to break up stratification without causing drafts.
- Temperature setback recovery times need to be carefully programmed because smaller equipment requires additional time. Optimal start programs tend not to work well because they can not predict recovery times.
- Heat loss through the slab-on-grade floor is more than the simulation models predicted.

Although an energy consultant-researcher was involved throughout the TTF's building process, window and slab insulation specifics were missed. Had these elements been included during construction, the original energy-conservation goal could have been met. This oversight shows the level of communication it takes between the energy consultant and other team members to ensure that all energy saving features are incorporated and functioning properly from design through commissioning.

Conclusions

The success of the TTF and SERF designs demonstrates that by closely following the steps of a whole-building approach, a low-energy building can be constructed for nearly the same cost as a code-compliant building. Designers were required to stay within a certain budget, and the buildings were constructed for about the same price as a typical building. Using the whole-building approach, members of the design team first established clear energy performance goals and conducted detailed simulations. Team members then worked together using the modeling results as guides through the design, construction, and commissioning processes. By working together, members of the building team ensured that the building envelope, internal systems, activities within the building, and the environment in which the buildings are located all work together as a single unit to operate more efficiently to conserve energy. In addition, the following should be noted.

- An energy consultant must be involved in the entire design process to help establish goals, brainstorm solutions, and provide analytical expertise.
- Two-stage evaporative coolers require different maintenance than traditional refrigerant-based systems.
- Daylighting can provide large savings. In addition, maintenance costs from bulb replacement is significantly reduced. Control of light fixtures and glare must be considered as an integral part of the design.
- Each design stage must incorporate commitment to energy efficiency. Lack of a "watchful eye" can cause a decrease in savings.
- Low-energy buildings are similar in cost to traditionally built buildings.

Acknowledgements

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