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Renewable Energy Technologies for Designing and Constructing Low-Energy Commerical Buildings

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Renewable-Energy Technologies for Designing and Constructing Low-Energy Commercial Buildings

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Abstract

The Thermal Test Facility (TTF) at the National Renewable Energy Laboratory (NREL) in Golden, Colorado, was designed and constructed using a whole-building energy design approach. This approach treats a building as a single unit, not as a shell containing many separate systems. It relies on the use of energy simulation tools for optimization throughout the design process, and requires the involvement and commitment of the architect, engineer, and owner. It can produce a building that requires substantially less energy than a building designed and constructed with conventional means. TTF operating costs are 63% less than those of a code-compliant basecase building. These savings were achieved by implementing an approach that optimized passive solar technologies and integrated energy-efficient building systems. Passive solar technologies include daylighting, high-efficiency lighting systems, engineered overhangs, direct solar gains for heating, thermal mass building materials, managed glazing, and a good thermal envelope. The energy-efficient heating, ventilating, and air-conditioning (HVAC) system, designed to work with the building's passive solar technologies, includes ventilation air preheat, ceiling fans, indirect/direct evaporative cooling, and an automatic control system.

This paper focuses on the design features of the TTF and the results of tests conducted on the TTF since its completion in 1996. These results demonstrate the success of the whole-building approach.

Keywords

passive solar
whole building
whole-building
daylighting
energy efficiency
energy-efficient
energy efficient
building energy simulation

Introduction

The Thermal Test Facility at the National Renewable Energy Laboratory is an open-space laboratory building containing high-bay laboratory areas and office and conference room spaces. Design of the 929-m^2 (10,000-ft^2) building began early in 1994. Construction was completed during the summer of 1996. Energy performance monitoring efforts have been underway since that time. The TTF was designed using a whole-building approach, which considers how the building's systems, activities, and surrounding environment interact and exploits this interaction to maximize efficiency. Energy-related design decisions are optimized based on the results of computer simulations used throughout the design process.

The whole-building approach is based on the principle that the building must be designed and constructed as a single unit, not as a shell containing many separate systems. It follows that this approach works only when (1) the building team (building owner, architect, engineer, and energy consultant) establishes goals early in the project (during the predesign phase); (2) the building team is committed to achieving these goals; and (3) the individual contractors are responsible for ensuring that the systems within each discipline are installed according to specifications.

The TTF design team was composed of an architect, a mechanical engineer, an electrical engineer, a structural engineer, NREL facilities staff, and NREL researchers acting as energy consultants. At the onset of the TTF's conceptual design process, the team agreed on a clear goal of reducing energy consumption by 70% over a code-compliant building. Measured data has shown that TTF operating costs are 63% less than those of a code-compliant basecase building. The basecase is created using the U.S. Code of Federal Regulations (CFR) energy requirements. This code (10CFR435) is based on the ASHRAE 90.1 standard. The major difference between ASHRAE 90.1 and 10CFR435 is the lighting requirements for 10CFR435 are more stringent.

Although the TTF was designed as a laboratory building, the technologies discussed in this paper can be applied to other commercial buildings, such as retail buildings, office buildings, and warehouses.

Energy-Efficient Technologies

The TTF uses several technologies to achieve energy savings. These technologies work synergistically, thereby maximizing their effectiveness. The fundamental components are daylighting, the thermal envelope, and the HVAC system.

Daylighting

Researchers conducted extensive simulations and analysis to determine the optimal building orientation, window size, glazing type, and overhang size. This predesign work revealed a significant opportunity to save electricity by using natural daylight. Consequently, daylighting considerations were the driving force behind the design. With its long axis facing south, the rectangular building is about twice as long as it is wide. Eighty-five percent of the TTF's glazing faces south. Much of this glazing is in the form of clerestory windows positioned at higher elevations as the building stair-steps from south to north. Window overhangs were engineered to reduce unwanted thermal gains during the summer. All windows have low-e glazings. Clerestory windows have a high solar heat gain coefficient (SHGC=0.68) to allow passive solar energy to enter the building during the winter. Analysis showed that the office portion of the building had sufficient internal gains and, as a consequence, the windows have a gray tint and a SHGC of 0.45. Because the visible transmission is less, the glass blocks out some of the glare in the office portion.

The design incorporates few east and west windows because summer solar gain cannot be controlled with overhangs. Glare from these windows also is hard to control. North windows were designed to provide additional daylighting in the high-bay space. The benefits of the daylighting more than outweigh the thermal losses from the north glass. The building is completely daylit except for a minimal-use service core that includes restrooms and a small kitchen. In daylit areas, sensors turn electric lights on only when there is not enough daylight available. Occupancy sensors are installed on all light circuits. The TTF's electrical lighting system uses high-efficiency T-8 fluorescent lamps and compact fluorescent canned fixtures.

Thermal Envelope

Both the concrete slab and the north wall, which is tilt-up concrete, serve as thermal mass to reduce internal temperature swings. The north wall is insulated to R-1.8 $m^2 \cdot K/W$ (R-10 $hr \cdot ft^2 \cdot {}^\circ F/Btu$) with rigid polystyrene insulation on the outside. The other three walls consist of metal-stud framing with 3.34 $m^2 \cdot K/W$ (R-19 $hr \cdot ft^2 \cdot {}^\circ F/Btu$) fiberglass batts in the cavities and 3.75 cm (1.5 in.) of external rigid insulation for a total resistance of 4.0 $m^2 \cdot K/W$ (23 $hr \cdot ft^2 \cdot {}^\circ F/Btu$). Under the metal roof decking is 10 cm (3 in.) of polyisocyanurate, which provides an R-value of 4.0 $m^2 \cdot K/W$ (23 $hr \cdot ft^2 \cdot {}^\circ F/Btu$). Underground rigid insulation (R-1.8 $m^2 \cdot K/W$ [R-10 $hr \cdot ft^2 \cdot {}^\circ F/Btu$]) lines the external perimeter of the foundation. All of these insulation levels were determined by simulation.

As an essential part of reducing heat loss, the designers eliminated all thermal bridging between interior materials and the exterior environment; however, deviations from the design occurred during construction, resulting in some thermal bridging. Designers also reduced air infiltration to 0.10 air changes per hour (ACH) during unoccupied periods when the ventilation system is not operating.

HVAC System

The energy-efficient heating, ventilating, and air-conditioning (HVAC) system, designed to work with the building's passive solar technologies, includes ventilation air preheat, ceiling fans, indirect/direct evaporative cooling, and a computerized energy management control system. During the workday, the TTF is continuously ventilated. Air is simultaneously pulled into the building and exhausted by a heat recovery system. Inside the heat recovery units, incoming and outgoing air pass each other, separated by a thin-walled heat exchanger.

When the inside temperature becomes too cool, the air in the main air-handling unit picks up heat from coils filled with hot water (supplied by NREL's central heating plant). When the temperature becomes too warm, the air is cooled by an indirect/direct evaporative cooler. The cooling system operates in several stages to optimize efficiency. An economizer fan is first to come on, followed by the direct portion of the evaporative cooler and finally the indirect portion.

Building Performance Models

The design team used building energy computer simulation tools as part of the design process. Such tools give designers the opportunity to evaluate the interactions between building design aspects. Detailed evaluations of the TTF design were completed using hourly simulation tools. The thermal optimizations were completed using SERI-RES, a simulation tool that uses true thermal networks. Daylighting and HVAC system design were optimized using DOE-2.1e. Designers began optimizing the design during the conceptual design phase, when only building size, type, and location were known. They refined the simulations throughout all phases of the design process and then calibrated the simulations with actual data after the TTF was constructed.

Designers developed a basecase model to compare the energy savings derived from implementing energy conservation technologies. The basecase building satisfies Federal Energy Code 10CFR435. Forced ventilation at 7 liters per second per person ($l/s \cdot person$, [15 $ft^3/min \cdot person$]), was provided during occupied hours, and an infiltration rate of 0.25 ACH was used the remainder of the time. Lighting levels were set at 16.3 watts per square meter (1.4 watts per square foot) to be consistent with 10CFR435. All schedules and temperature set points between the basecase model and the design model remain the same.

Figure 1 shows the distribution of energy consumption in the basecase building. Plug loads are not included when calculating energy savings. These loads are determined by occupant use of equipment located within the building (e.g., laboratory equipment, computers, and appliances) and will occur regardless of how efficiently the building is designed and operated. Actual energy cost data shows that the TTF performs 63% better than the basecase model (Figure 2).

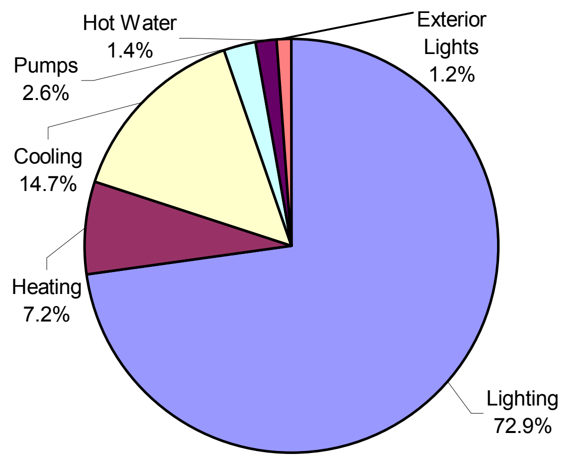

Fig. 1: Modeled operating cost breakdown in the basecase building

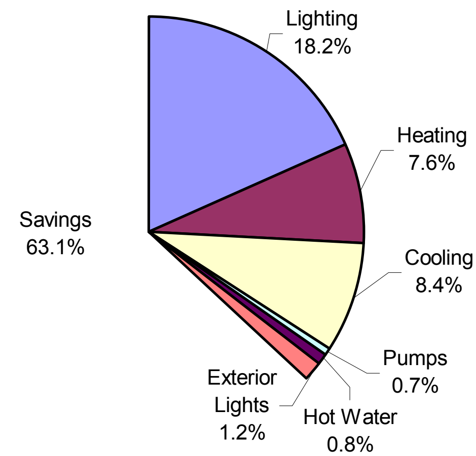

Fig. 2: Actual operating cost breakdown at the TTF

Sensors located throughout the TTF collect information on daylight levels, electrical lighting use, space temperatures, and equipment loads. Data collected by these sensors was used to calibrate the DOE2.1e model of the optimized building design. Actual weather data also was collected and used to calibrate the model weather files.

A Short-Term Energy Monitoring (STEM) test was conducted to predict the actual annual building performance. This test method allows researchers to extrapolate annual building performance from data collected over a short period of time (usually 4 days). One of the most useful results of a STEM test is the determination of the building load coefficient (BLC), an indicator of the efficiency of the building design. The TTF STEM tests showed that the actual BLC is greater than the originally predicted BLC. Inconsistencies between the building design and construction caused this difference (discussed in Analysis of Performance Data). When the building was modeled as actually constructed, the predicted BLC came to within 1% of the actual BLC determined by the STEM test.

The model was calibrated based on the STEM results in two steps; first according to the daylighting aspects, then according to the HVAC loads.

Analysis of Performance Data

Lighting

The largest savings experienced by the TTF resulted from implementing efficient electrical lighting and using daylighting strategies and occupancy sensors. The combined effects of these elements eliminated 75% of electrical lighting when compared to the basecase. Daylighting contributed the largest savings of the three techniques.

The building contains no security lighting. Interior lights turn on when the occupancy sensors detect motion within the building, eliminating the need for 24-hour security lighting. Savings of 2630 kWh/year are realized each year by not operating 10% of the electrical lighting 24 hours/day, a typical percentage of lighting dedicated to security lighting in commercial buildings.

Figure 3 shows the monthly cost comparisons for operating the lighting system at the TTF. Actual savings with respect to the basecase are provided. The figure shows that the daylighting savings are greater during the summer months when the days are longer. Figure 4 gives an example of the power consumed by the TTF lighting system during working hours on clear and cloudy days.

The daylighting/occupancy sensors for electrical lighting in the daylit spaces are on a single-step control system—the lights are either on or off. Dead-band set points and operating periods have been optimized to prevent excessive cycling during periods of partial cloud cover. These lighting step controls may be replaced with continuous controls. It is anticipated that continuous dimming controls will reduce lighting energy use by 6.5% beyond the savings already achieved with step controls. Continuous lighting controls were not implemented in the TTF because when the building was designed, these technologies were not readily available at a cost that resulted in a reasonable payback period.

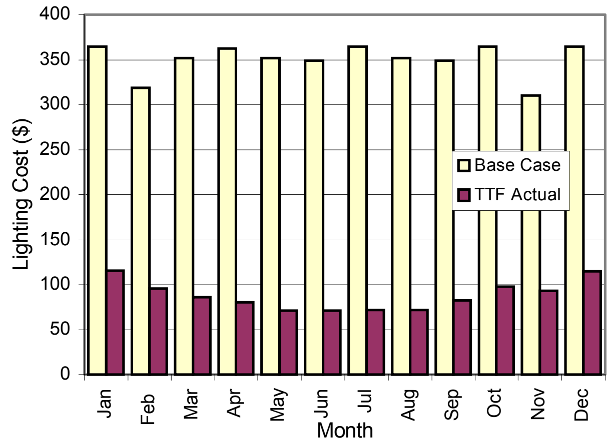

Fig. 3: TTF lighting cost comparison to basecase building

Heating Loads

In most commercial buildings, internal gains resulting from the operation of electric lights help to heat the building. Reducing the internal gains from the lighting system will increase the building heating loads and decrease the building cooling loads. Because of daylighting at the TTF, the contribution of the heating loads on the total building operating cost increased by 0.4%.

The TTF usually requires heating only during the early morning hours to compensate for the nightly temperature setback (Figure 5). Although the temperature is set back to 13°C (55°F) every night, the temperature rarely drops that low. During the morning warm up, the temperature is increased to 21°C (70°F). After the morning warm up, passive solar heating and internal gains in the building meet most of the building's heating requirements.

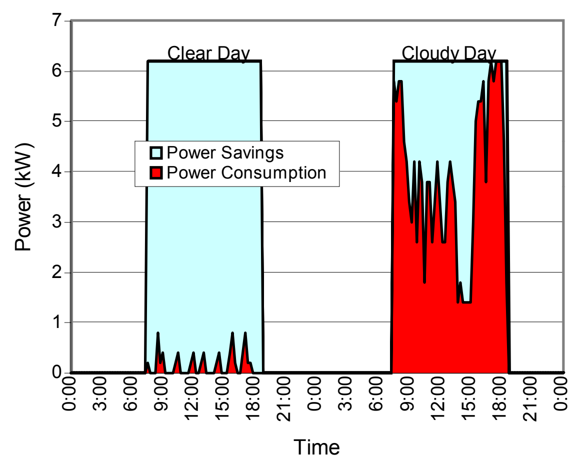

Fig. 4: Energy demand for a non-daylit building and the TTF for typical clear and cloudy days

The primary heat loss paths (or thermal bridges) through the building envelope have been identified. Using infrared imaging thermography, it was discovered that the specified window and door frames with thermal breaks were not installed. Compared to the basecase model, it is estimated that 2985 kWh/year (13.6 MMBtu/year) is lost because there are no thermal breaks.

During construction it was decided that the internal slab insulation had to be removed for structural purposes. As a result, 15 cm (6 in.) of insulation was removed. This decision was made on site, so by the time researchers were aware of the situation, it was too late to change without adding significantly to the cost of the project. The thermal bridge is approximately 119 m (390 ft) long by 15 cm (6 in.) wide. In addition, a thermal bridge occurs where the retaining wall connects to the building. These two thermal bridges result in approximately 1260 kWh/year (4.3 MMBtu/year) of adverse energy effects compared to the basecase building. Even though the energy savings amounts are small, the cold exterior surfaces have caused some comfort concerns.

Cooling Loads

Cooling loads were reduced by approximately 43% compared to the basecase building. Incorporating daylighting into the building design reduced the internal gains placed on the building from operating electrical lighting. Engineering the window overhangs to prevent direct solar gains from entering the building during the cooling season also reduced cooling loads.

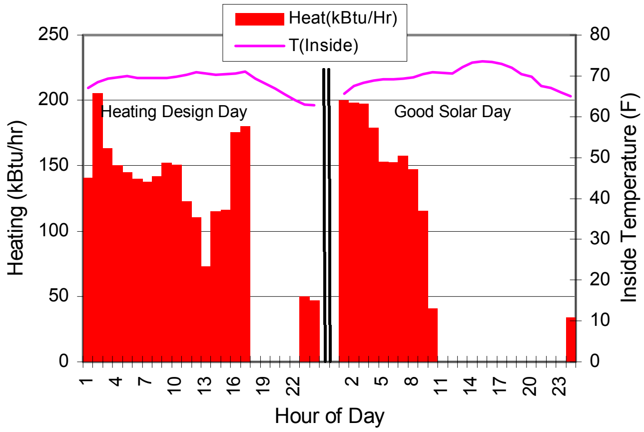

Fig. 5: TTF heating load on typical heating design days (with temporary setback at 18°C [64°F])

The energy required to cool the building was reduced by using a two-stage evaporative cooling system instead of a conventional chilled-water or direct-expansion system. The worst (2.5%) condition Denver design day dry bulb (DB) and wet bulb (WB) temperatures are 35°C DB/15°C WB (95°F DB/59°F WB). Under these conditions, the indirect portion of the evaporative cooler is able to supply air at 21°C DB/9°C WB (70°F DB/49°F WB). Operating the direct portion of the evaporative cooler reduces the supply air temperature further to 13°C DB/9°C WB (56°F DB/49°F WB).

Another option for cooling the building was with chilled water from a chilled water plant. Because this system was not used, the chilled water distribution pumps were not needed. The total building pump energy was then reduced by 73% compared to the basecase. (The remaining pump energy is for the hot water coils.)

Fan energy increased by implementing the evaporative cooling system versus a more conventional system; however, the savings from the evaporative cooling system far outweighed the increased fan energy requirements.

HVAC System Operation

Figure 6 shows the cost for operating both the basecase building HVAC system and the TTF HVAC system. Trends shown in this figure include:

- The cooling costs are reduced as a result of evaporative cooler efficiency and the reduction of internal and solar gains.
- Pump operating costs are reduced because the basecase chilled water pumps were eliminated and because lower heating loads required less pumping.
- The total heating load is increased slightly because the electric lights no longer heat the building. The benefits from the passive solar strategies are the greatest in December and January.

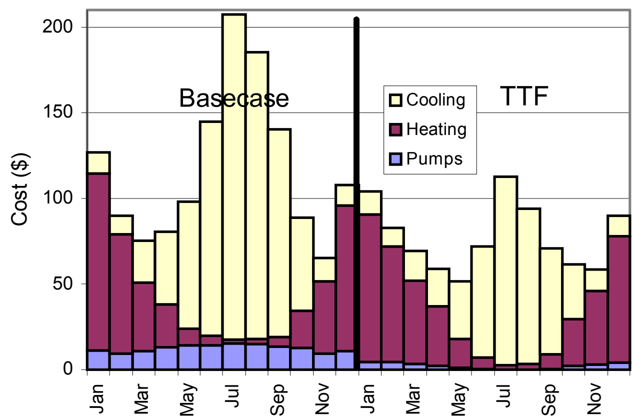

Fig. 6: Monthly HVAC costs for both the basecase and TTF

Figure 7 shows the total daily building energy consumption versus daily outdoor average dry bulb temperature for the basecase building and the actual building. This figure shows that the passive solar design of the building requires less energy to operate at all ambient temperatures. It also shows that the building is skin-dominated and not load-dominated. The balance point for the solar building increases from 14°C to 22°C (57°F to 72°F) because the building is not being heated with the lights.

Conclusions

The success of designing and constructing the low-energy TTF building was the result of the whole-building design approach. Members of the design team worked together to ensure that the building envelope, internal systems, activities within the building, and the environment in which the TTF is located all work together as a single unit. Designers used computer simulations throughout the design process to optimize the energy performance. Designers also were required to stay within a certain budget, so the TTF was constructed for about the same price as a conventional energy code-compliant building.

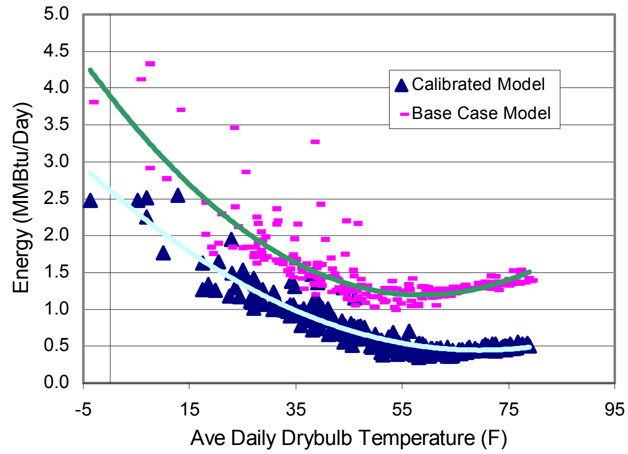

Fig. 7: Building energy use characteristics

Incorporating daylighting strategies contributed to the largest energy savings. Reducing the use of electrical lighting also decreased the internal gains in the building. The cooling load decreased and the heating load increased. Passive solar heating helped to offset the reduction of heating by the lights. Cooling energy savings also were achieved through use of an indirect/direct evaporative cooling system. Finally, optimizing building overhangs reduced the cooling load that results from solar gains. Reducing the cooling load had the second largest impact on the total building energy savings after daylighting measures.

The goal for the TTF energy performance was to be 70% less than a basecase building designed to meet Federal Energy Code 10CFR435. After monitoring the building performance, the actual operating cost savings were found to be 63% compared to the basecase building. The actual performance of the TTF is less than predicted primarily for the following reasons:

- Thermally broken window and door frames were not installed.
- A thermal bridge exists at the foundation and slab and at an exterior retaining wall.

If these elements had been included during construction, the original goal could have been met. This is an example of the importance of quality control during construction.

Some other observations have been made about the operation of this low-energy building:

- 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 for long time constant systems. Although ambient zone air temperature recovery can be easily achieved, comfort issues can still arise due to the radiative, conductive, and convective effects inherent in building components with a large thermal mass.

Buildings can be designed and built to use significantly less energy. To achieve the full potential of the design, the building must adhere to the construction specifications and be operated according to the design intent. Research to optimize the mechanical control strategies in low-energy buildings has the potential to produce even more energy savings.

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