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The Role of Modeling When Designing for Absolute Energy Use Intensity Requirements in a Design-Build Framework

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The Role of Modeling When Designing for Absolute Energy Use Intensity Requirements in a Design-Build Framework

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ABSTRACT

The Research Support Facility at the National Renewable Energy Laboratory is a 220,000-ft² office building designed to serve 822 occupants, to use 35.1 kBtu/(ft²·yr), to use half the energy of an equivalent minimally code-compliant building, and eventually to produce as much renewable energy annually as it consumes. These goals and their substantiation through simulation were explicitly included in the fixed price design-build contract. The energy model had to be repeatedly updated to match design documents and the final building, as it was built, to the greatest degree practical. Computer modeling played a key role in diagnosing the energy impacts of program and decisions and in verifying that the contractual energy goals would be met within the specified budget. The primary tool used was a whole-building energy simulation program. Other simulation tools were used to provide more detail or to complement the primary tool as required by the delivery schedule, including tools to calculate thermal bridging, daylighting, natural ventilation, data center energy consumption, transpired solar collectors, thermal storage in the crawlspace, and electricity generation by photovoltaic panels. Results were either fed back into the main whole-building energy simulation tool or used to post-process model output to provide the most accurate annual simulations possible. This paper details the models used in the design process and how they informed important program and design decisions from design to completion.

INTRODUCTION

The National Renewable Energy Laboratory's (NREL) mission is to advance the U.S. Department of Energy's and the nation's goals in the areas of energy security, environmental quality, and economic vitality. From the beginning, NREL recognized that its new Research Support Facility (RSF) represented a unique opportunity to demonstrate the state-of-the-art in energy-efficient, cost-effective commercial office design, construction, and operation. Today, buildings use roughly 40% of total primary U.S. energy consumption (22% residential, 18% non-residential); energy consumption in this sector is projected to grow by 25% in the next two decades[1]. The RSF is intended to prove that significant gains in energy efficiency can be realized cost effectively in commercial buildings with available technologies if careful attention is paid to project energy goals, the delivery process, and integrated design. We examine the details of how computer simulation tools were

[1] http://buildingsdatabook.eren.doe.gov/docs/xls_pdf/1.1.3.pdf

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used to help design the RSF and what capabilities the project required of those tools. We also present a portrait of how setting an absolute whole-building energy consumption target changes the role of energy modeling. Several teams were involved in the competition phase; however, we focus on the activities of the design-build team that was awarded the contract.

PROJECT OVERVIEW

The RSF project contains several novel features related to the delivery model, team structure, and Request for Proposals (RFP). Descriptions of how energy modeling was used in the design process follow.

Delivery Model

NREL decided early that to deliver the RSF, with its challenging performance requirements, on time and on budget, a traditional design-bid-build procurement process would not suffice. Rather, a performance-based "Best Value Design-Build/Fixed Price with Award Fee" delivery approach (Post 2010) was pursued to encourage innovation, reduce risk, expedite construction and delivery, control costs, make optimal use of team members' expertise, and establish measurable success criteria. The RSF procurement strategy provides an important context for understanding the design process and the use of energy modeling tools. By hiring a design-build team, NREL encouraged an integrated design process comprising architects, engineers, and builders working toward well-defined goals. This arrangement resulted in an iterative design pattern involving the entire team. Detailed computer simulations were used to assess whether the design as it evolved would meet performance requirements. It also required NREL to clearly define the scope and goals in the RFP and then allow the design-build team to find creative solutions. Having specific end-use and whole-building energy use goals necessitated that energy modeling be included in the design process from the beginning. The fixed budget for all work (conceptual design, preliminary design, final design, and construction) of $64 million, formulated by the U.S. Department of Energy, was determined before energy goals were established. This fixed budget, coupled with the energy goals, required that cost modeling be emphasized as much as energy modeling. The selected design-build team performed a great deal of conceptual phase energy modeling in the months leading to the submission of its design competition proposal in March 2008. Preliminary design occurred from July 2008, when the contract was awarded, through November 2008. Final design took place from January 2009 through July 2009. Construction began in February 2009 and lasted until June 2010, when it was turned over and ready for occupancy.

Objectives

In the conceptual documents of the original RFP (dated February 6, 2008), the objectives were prioritized and then divided into three groups: Mission Critical, Highly Desirable, and If Possible. Competing design-build teams were judged based on their ability to meet as many objectives as possible while meeting the overall budget constraint. A subset of those goals related directly to energy modeling and the low energy design process includes:

1. Mission Critical
    a. LEED™ Platinum designation
    b. ENERGY STAR® appliances, unless another system outperforms
2. Highly Desirable
    a. 800 staff capacity
    b. 35.1 kBtu/(ft^2·yr)[2]
    c. Measurable 50% energy savings versus ASHRAE 90.1-2004
3. If Possible

[2] Absolute energy goals of 25, 32, and 35.1 kBtu/(ft^2·yr) all appear at certain points in the project documents; 25 kBtu/(ft^2·yr) assumes 650 occupants and data center energy use prorated to reflect that only a portion of the data center services are consumed in the RSF; 32 kBtu/(ft^2·yr) assumes 822 occupants and prorated data center energy; 35.1 kBtu/(ft^2·yr) includes the entire data center energy consumption.

a. Net zero energy building approach
b. LEED Platinum Plus
c. Exceed 50% savings over ASHRAE 90.1-2004 baseline

The absolute site energy consumption, net zero energy balance, and LEED Platinum goals in particular influenced the modeling tools and design process. The RFP also specified parameters such as temperature and humidity set points, nighttime setback, maximum U-value of windows, and compliance with elements of ASHRAE 55 that have energy impacts.

Energy Goal Setting

The absolute energy consumption target was chosen based on analysis done as part of a sector-wide energy efficiency modeling study (Griffith et al. 2006). As part of that study, energy models of all the buildings in the 2003 Commercial Building Energy Consumption Survey were created using EnergyPlus. These models were then modified to make them minimally compliant with ANSI/ASHRAE/IESNA Standard 90.1-2004 requirements. Tables containing these results are available online[3] for the industry at large to facilitate energy goal setting. An absolute energy use intensity goal was chosen to correspond to half the average energy use of the simulated office/professional buildings in ASHRAE climate zone 5B, which includes Golden, Colorado. This goal was in line with the measured performance of several high-performance office buildings analyzed in detail by the Commercial Buildings group at NREL (Torcellini et al. 2006). Further feasibility studies carried out in 2007 indicated that this target should be achievable for an office building in the Denver area if special attention were paid to optimizing glazing area to maximize daylighting yet minimize thermal losses; emphasizing the building's east-west axis to facilitate the daylighting goal (daylight is easiest to control and harness from the north and south); and minimizing plug and process loads. The modeling study used NREL-developed design optimization software to explore design options that could lower end-use energy consumption. The optimization modeling begins with an initial baseline whole-building energy model then systematically alters the design features, at each stage selecting the most cost-effective energy saving design options.

MODELING IN CONCEPTUAL AND PRELIMINARY DESIGN PHASES

The project team engineers conducted early feasibility studies to assess whether the absolute energy goal set in the RFP was realistic and how the form of the building needed to reflect the energy goals. Even before the internal design-build charettes began, initial simulations showed that daylighting and natural ventilation would be critical for success. The building form quickly came to reflect these strategies, with two 60' wide (north-south dimension) office wings, connected by a central core of conference spaces in the shape of a "lazy H," spaced to minimize self-shading. At this early stage of conceptual design, self-shading was studied using a 3-D modeling software package; energy modeling was performed with a whole-building energy analysis tool. Hydronic radiant heating and cooling in the ceiling slab and daylighting (with continuous dimming lighting controls) were included in these runs. Numerous design features were not included in the proposal concept energy model, but were incorporated in subsequent design phases, such as winter ventilation preheating (using a double skin façade design), summer, occupancy sensors, natural ventilation, daylight redirection, and demand control ventilation. The radiant heating and cooling system is modeled in the whole-building analysis as a fan coil unit with nearly zero fan energy; however, the comfort and control implications of the radiant slab conditioning were still carefully considered.

Early concept design drawings for the winning proposal showed a double skin façade. This approach was later eliminated based on multi-disciplinary design coordination, thermal analysis (using a second whole-building analysis package with more detailed thermal modeling capabilities), and cost modeling in favor of an approach using a single façade and transpired solar collectors. Producing timely energy modeling projections was a constant challenge for the design-build team because of the compressed design and construction schedule. Rather than relying solely on one tool, the team used a constellation of models to provide detailed analysis of building components (Figure 1). The results were then either fed back

[3] http://apps1.eere.energy.gov/buildings/publications/pdfs/commercial_initiative/energy_use_intensity_targets.pdf

into the main whole-building energy model or used to post-process its output to provide an integrated picture of whole-building energy use. For example:

- Daylighting calculations were performed with detailed lighting simulation tools, including window shading and light redirection; the daylight performance and correlated electric lighting dimming and switching responses were fed into the whole-building energy model;
- Thermal effects of natural ventilation strategies were analyzed using a separate whole-building energy modeling tool with more advanced thermal analysis capabilities and used to post-process the results of the main energy analysis model;
- Data center energy use, including electricity consumed by information technologies equipment, cooling energy, fan energy, and heat recovery, was modeled outside of the main energy model and added to its energy projections;
- A separate model of air heating by transpired solar collectors on the south face of the building was used to post-process the energy modeling results;
- Ventilation preheating benefits of the crawlspace during the heating season, with inputs from the data center and transpired solar collector models, were modeled using a separate finite-difference thermal model and combined with the energy model output;
- Renewable energy generation by PV panels was modeled separately.

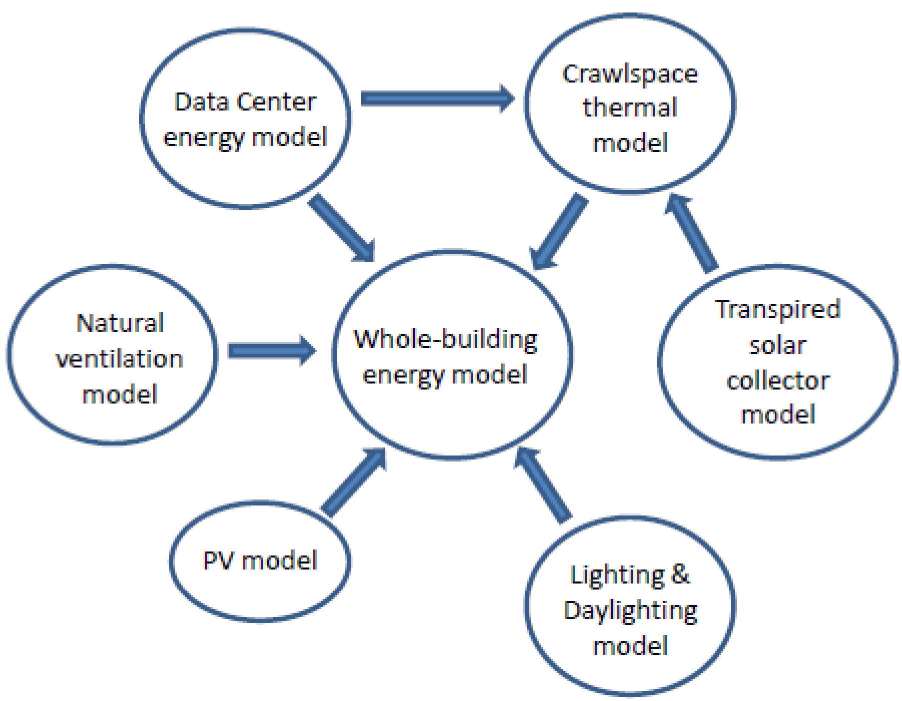

Figure 1 *Modeling information flows*

More details of each module in the energy modeling suite follow.

Daylighting/Lighting Modeling

A lighting simulation tool was used to quantify annual daylighting characteristics and to establish optimal photosensor placement for energy savings. It is driven by a physically based, backward ray-tracing simulation designed to provide accurate quantitative and qualitative daylight and electric lighting predictions, even when considering complex fenestration systems such as daylight redirection devices. The lighting tool was initially employed in the design competition phase in the context of the LEED daylight credit iEQ8.1, mandated in the RFP. Analysis of the workplane illuminance under clear skies at noon on the equinox – a metric for assessing compliance with this criteria – showed that even with best practices of separating view glass and daylight glass and using a daylight redirection device to reflect incoming sunlight deeper into the building, a maximum floor depth of 60' could be daylit sufficiently to satisfy the requirements. This consideration effectively set the building's footprint. For the energy modeling, the lighting analysis tool was able to provide an 8,760 hour schedule of the lighting power fraction for an electric lighting system with dimming and switching controls to match the specified office illuminance set point. This schedule can be passed seamlessly to the whole-building energy model. For this analysis, the typical office space was divided into a south perimeter zone, a core zone, and a north perimeter zone. Other daylit spaces were simulated using the built-in continuous dimming sensor and daylighting calculations available in the energy model. Installed lighting power density in open office areas is very low – only 0.62 W/ft^2, facilitated by the open office structure (no obstructions), highly reflective room surface finishes, ability to use a regular grid, and efficient electrical lights.

Natural Ventilation Modeling

Window configurations and control strategies for natural ventilation were analyzed by modeling the building in a separate whole-building energy analysis tool to enable explicit modeling of the thermal effects of natural ventilation and thermal mass effects, which the main energy modeling software cannot do. The natural ventilation modeling was performed without including mechanical systems, so results represent passive conditioning. Then, on days when the as-designed window arrangement and natural ventilation controls yield temperatures that do not exceed 78°F or fall below 69ºF, the thermostat cooling set point was set to 100ºF (turned off) in the main office wing spaces. Preliminary modeling showed that night purging to cool the office spaces would be a promising strategy to save energy. Natural ventilation modeling made an impact on the preliminary building design in the form of low-level motorized windows being added to enhance stack effect ventilation and allow better night cooling.

Data Center Cooling and Heat Recovery Calculations

Data center equipment was modeled as a continuous 24/7 load of 65 W per person (this does not include energy consumption by cooling equipment), based on a survey of typical data center configurations. The owner selected temperature and humidity criteria consistent with the 2008 ASHRAE Environmental Guidelines for Datacom Equipment (ASHRAE, 2008). Complete hot and cold aisle separation was assumed. The cooling system was simulated with and without airside economizers, with appropriate adjustments made to the fan system pressure drops. The TMY3 climate data were analyzed to understand the psychrometric processes that could be used to achieve the required supply air temperatures. We found that an economizer and direct evaporative cooling could be used to cool the data center for 99.5% of hours with no mechanical cooling, partly because of its assumed broad acceptable supply dry bulb temperature range (66.4-77ºF), as recommended by the ASHRAE Datacom guidelines. At this stage, the economizer and direct evaporative cooling strategies were predicted to save substantial energy, but were not included in the actual design because the incremental capital cost was estimated to be too high. Eventually, these strategies were included in the design, with the ability to cool mechanically for the limited number of hours when analysis of TMY2 data suggests dehumidification will be required. Energy savings by the servers were not included; this is a conservative assumption, as the NREL Information Technologies department will probably use equipment that is more efficient than the industry standard.

The heat from the data center available for recovery was modeled for several scenarios. First, an "economizer" case was modeled assuming direct discharge of the hot aisle air into the crawlspace, where it would warm the mass during nonoccupied hours and be used during occupied hours to preheat ventilation air. A “no-economizer” case was also modeled employing a runaround loop to transfer heat from the data center hot aisle to preheat domestic hot water and ventilation air. More efficient data center equipment would reduce the amount of heat available for ventilation preheating; however, future efficiency gains were assumed to be matched by increased data center us,e so the overall load would remain the same.

Transpired Solar Collector Air Heating Calculations

Delivery of hot air from the transpired solar collectors to the crawlspace during the heating season was modeled separately using manufacturer data, making simple assumptions about airflow through the transpired solar collectors, an appropriate value of cfm/ft^2, absorptivity of the collector, fan efficiency, and fan pressure drop. Ambient air temperatures and solar radiation (direct and diffuse) were taken from TMY3 weather data, with appropriate adjustments made based on sun angle relative to the collector surface. An 8,760 hour schedule of outlet temperatures was passed along to the crawlspace thermal calculations.

Crawlspace Energy Calculations

The first floor of the RSF had to be constructed above grade because the site has expansive soils. Early in the design process the team conceived that the below-grade crawlspace formed by the foundational piers could be used to precondition ventilation air – storing heat from the transpired collectors and data center and delivering it when needed in the heating season and removing heat in the cooling season after nighttime precooling (Torcellini et al. 2010). This crawlspace is referred to as a *remote-mass labyrinth* because of its maze-like appearance. To model energy savings, it was divided into sections defined by the piers and finite difference heat transfer nodes defined to represent the slab perimeter, slab center, perimeter walls, and the grade beam. Nodes representing the earth below the slab and outside the perimeter walls were also included, and in turn were connected to boundary conditions of the undisturbed ground surface temperature for the perimeter and constant deep ground temperature below the slab. Air nodes were included to complete the energy balance. The energy flows were then calculated using a spreadsheet program for 8,760 hours of the year to characterize the heat exchange between concrete and air (neglecting the heat capacitance of the air nodes). The separate data center and transpired collector calculations provide a schedule of available temperature and flow rate from those two heat sources. The ventilation system is designed to deliver space-neutral air, so the flow rate from the data center and transpired collector and the mixing with outdoor air can be controlled to deliver 68ºF air at the volume needed to meet ventilation requirements.

MODEL EVOLUTION AND INCREASING DETAIL IN SUBSEQUENT DESIGN PHASES

The main whole-building energy model developed in the preliminary design phase contains 247 zones to account for the loads in every typical space. This level of modeling is indicative of the attention to detail required by the absolute energy goals. It quickly became clear- that accurate assumptions about the data center energy use and miscellaneous plug and process loads would be at least as important as the thermal modeling. Early modeling substantiation showed server electricity use representing one-third of the building’s total annual energy consumption and miscellaneous plug loads another 23%. Energy use by office and exercise equipment, audiovisual equipment in the telepresence room, the security system, elevators, the fire alarm system, and even a coffee cart was carefully tabulated and included. Eventually exit lighting, sump pump energy, and parasitic losses in the lighting panels would all be incorporated. Occupancy and equipment schedules were repeatedly updated to reflect owner modifications. The eventual plug load density, including a constant 0.35 W/ft^2 demand by the data center, was modeled to be 0.85 W/ft^2 during occupied hours and 0.54 W/ft^2 during unoccupied hours (Lobato et al. 2010).

Lighting, Daylighting, and Natural Ventilation

During the core and shell design development, a limitation was discovered in the number of input files that could be taken from the daylighting simulation and incorporated into the whole-building energy model. Although 22 files were developed to modify lighting schedules for typical RSF office spaces, only 4 could be added before the energy model code reached its maximum length. As a workaround, lighting files representing south perimeter and core spaces in both wings were used to model all those spaces, and the energy model's built-in daylighting controls were used for the north perimeter spaces in both wings. Layout and fixture changes in the electrical lighting design were incorporated into the energy model as they occurred. For the final round of energy modeling, seven lighting files were incorporated into the model as other schedules were combined.

Natural ventilation modeling analysis of the fitness center, connector wing, and information commons (library) was also performed in the core and shell design development, implementing the lessons learned in the preliminary modeling. The effectiveness of night purging was analyzed for different window arrangements to identify the best configuration of manual and automatic windows and their control for effective cooling. We found that natural ventilation would likely be ineffective in the connector wing, mainly because of high transient internal loads (for example, densely occupied conference rooms) relative to the amount of perimeter façade available for ventilation. Also, the full exterior building geometry (rather than that of a typical wing) was eventually included in the natural ventilation model to more realistically capture shading. The technique for quantifying the cooling savings for natural ventilation was changed from adjusting the thermostat set point on select days to post-processing cooling energy results on select days. The design team also tried to capture the influence of occupant behavior vis-a-vis window operation by halving the potential energy savings from natural ventilation to reflect the possibility that it would be suboptimal.

Thermal Bridges

In the same way small details have a large impact on simulated energy use, small architectural details can affect the energy use bottom line by compromising the envelope's thermal properties. Two-dimensional heat transfer analysis and fin heat transfer formulas were used to study thermal bridging in the balconies at the east and west ends of the RSF. A detailed 2-D heat transfer model was used to derate the U-values of the constructions used in the energy model for the whole-building energy model, to investigate design strategies to minimize the bridging, and identify likely areas of problematic condensation. Areas initially studied included the connection of the superstructure to the substructure and balcony attachment points. In all cases the design-build team adopted mitigating measures. Later this analysis was used to evaluate the insulation required between the radiant ceiling slabs and the adjacent supply air floor plenums and prove the necessity of avoiding a specific standard detail for mounting photovoltaics (PV) to the roof. This drove a complete change of the roofing system to a standing seam strategy to avoid penetrations. The standing seam structure was affixed to the roof membrane; the funds came from the project contingency.

Photovoltaic Panel Electricity Generation

A software tool originally developed at NREL was used to size and calculate expected PV output to match the demand-side energy goal. The modeling of PV to match the demand side pushed the design team to maximize the amount of roof area available for PV, ensure the 14 degrees of south orientation for the north wing did not significantly degrade the optimal output, and optimize the roof tilt to balance the need to maximize output with the additional cost of building structure at the optimal tilt. A 10-degree roof tilt angle was determined to provide an optimal balance between PV output degradation and additional roof and building costs for the tilt. A total of 1.7 MW of PV will eventually be required to offset annual energy consumption.

Baseline Simulation

The project RFP included an absolute energy use intensity target for energy consumption, a net zero energy balance target, and a minimum 50% energy savings versus a minimally code-compliant equivalent building with the same unregulated loads and program. This requirement necessitated construction of a baseline building model, built according to the requirements laid out in Appendix G of ASHRAE 90.1-2004, which include distributing glazing in equal bands around the building, eliminating shading devices, modeling a standard HVAC system type with airside economizers and screw chillers with a coefficient of performance of 4.9, and using standard lighting power densities per space type. U-values of the opaque envelope and glazing assemblies were taken from ASHRAE 90.1-2004 Table 5.5-5. In the baseline case, computer workstations were assumed to consume 120 Watts versus the 65 Watts in the low energy case.

Closeout Modeling

As construction neared completion, the energy model was again updated to reflect minor modifications and new information available from the construction. Changes include pump and fan power as balanced, revised assumptions for plug load equipment, and in some cases measured parasitic power draws of specific components.

LESSONS LEARNED

One of the most important lessons of the RSF modeling effort is the degree to which unregulated plug and process loads can dominate energy use, and the degree to which these loads must be understood and controlled to meet a stringent absolute whole-building energy use target. Energy modeling typically focuses on envelope properties, mechanical systems, and regulated internal loads, but for the RSF great attention was paid to details such as schedules and the energy use of individual items ranging from telephones and task lights to lighting control systems (a constant 728 Watts in the case of the latter), distribution transformer losses, white noise generators, and sump pumps. Architectural details such as thermal bridging in window mullions (which might typically be ignored) were also important considerations. When detailed calculations of window performance were done instead of taking overall U-values from ASHRAE Fundamentals (Chapter 15 table 4), expected U-values were found to be 30% greater.

With a whole-building absolute energy use goal, plug and process loads cannot be assumed to be the same between baseline and low-energy models and therefore "fall out" of the analysis when the two models are compared. They must be carefully modeled before construction and measured when the building is occupied. A corollary to this lesson is that the building owner, who controls the building program, must be committed to the energy goals and monitor end use energy consumption over time to make building performance match design and to sustain those energy savings. A design team cannot deliver a building that automatically reaches aggressive whole-building energy use targets; the building must emerge from an integrated design team that places energy use intensity at the top of the checklist throughout and uses rigorous simulation to verify the design's performance at every milestone.

The energy modeling process required close coordination between the engineering and design teams because of the expedited design-build process and the RFP's strict substantiation requirements. There was a constant tension between the model detail required for accuracy and the compressed design-build schedule. In retrospect, the energy modeling process should have been included as significant constraint instead of being squeezed into a schedule that was based primarily on design documentation and construction. This would likely have resulted in fewer design changes, a more streamlined decision making process, and a more integrated building. The workaround calculations, such as the heat budget of the labyrinth, were critical to the energy modeling process, but were significantly more time consuming than originally anticipated. When approaching these types of calculations in the future, the team would be much more likely to model these in an existing energy model with detailed heat transfer simulation capabilities rather than completely from scratch. Modeling uncertainties led the team to build an energy-use contingency into its design to provide a cushion should some assumptions fail. The RSF closeout energy modeling report cites a final energy use of 33.3 kBtu/(ft^2·yr), 5.9% better than NREL's goal of 35.1 kBtu/(ft^2·yr).

Energy modeling played a dramatically different role in this project versus a project where energy modeling is required only for code compliance or voluntary certification programs. The team had to model early and often at a high level of detail, to gain confidence that the building as constructed would meet its energy use goals. Energy modeling fundamentally influenced the design of the building, including the narrow floor plate; the size and performance of windows; architectural detailing to avoid thermal bridging; the data center cooling approach; and office equipment.

CONCLUSION

Energy modeling helped the RSF design-build team to assess from the outset whether the design would be able to accomplish NREL's ambitious energy efficiency goals. The modeling process pushed the team's available energy modeling toolkit to, and perhaps past, the limit of its capabilities. Separate models were required for daylighting, natural ventilation, data center energy use, crawlspace heat recovery and storage, and renewable energy generation. The team successfully knit these outputs together; ultimately, however, a tool that could simulate the RSF from start to finish more seamlessly and with a reasonable learning curve would have been advantageous. Detailed monitoring of the RSF operational energy use has begun and the building is now partially occupied. These data will be used to verify model assumptions, calibrate a more detailed EnergyPlus model, and quantify operational energy use across days, seasons, and years.

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14. ABSTRACT *(Maximum 200 Words)*

The Research Support Facility was designed to use half the energy of an equivalent minimally code-compliant building, and to produce as much renewable energy as it consumes on an annual basis. These energy goals and their substantiation through simulation were explicitly included in the project's fixed firm price design-build contract. The energy model had to be continuously updated during the design process and to match the final building as-built to the greatest degree possible. Computer modeling played a key role throughout the design process and in verifying that the contractual energy goals would be met within the specified budget. The main tool was a whole building energy simulation program. Other models were used to provide more detail or to complement the whole building simulation tool. Results from these specialized models were fed back into the main whole building simulation tool to provide the most accurate possible inputs for annual simulations. This paper will detail the models used in the design process and how they informed important program and design decisions on the path from preliminary design to the completed building.

15. SUBJECT TERMS

research support facility; rsf; computer simulation; energy simulation program

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