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Authors
Robinson, Alastair
Regnier, Cindy
Settlemyre, Kevin
et al.

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MIT – Mighty Steps toward Energy Sustainability

Alastair Robinson, Cindy Regnier, Lawrence Berkeley National Laboratory; Kevin Settlemyre, Sustainable IQ, Inc.; Zorana Bosnic, HOK

Environmental Energy Technologies Division
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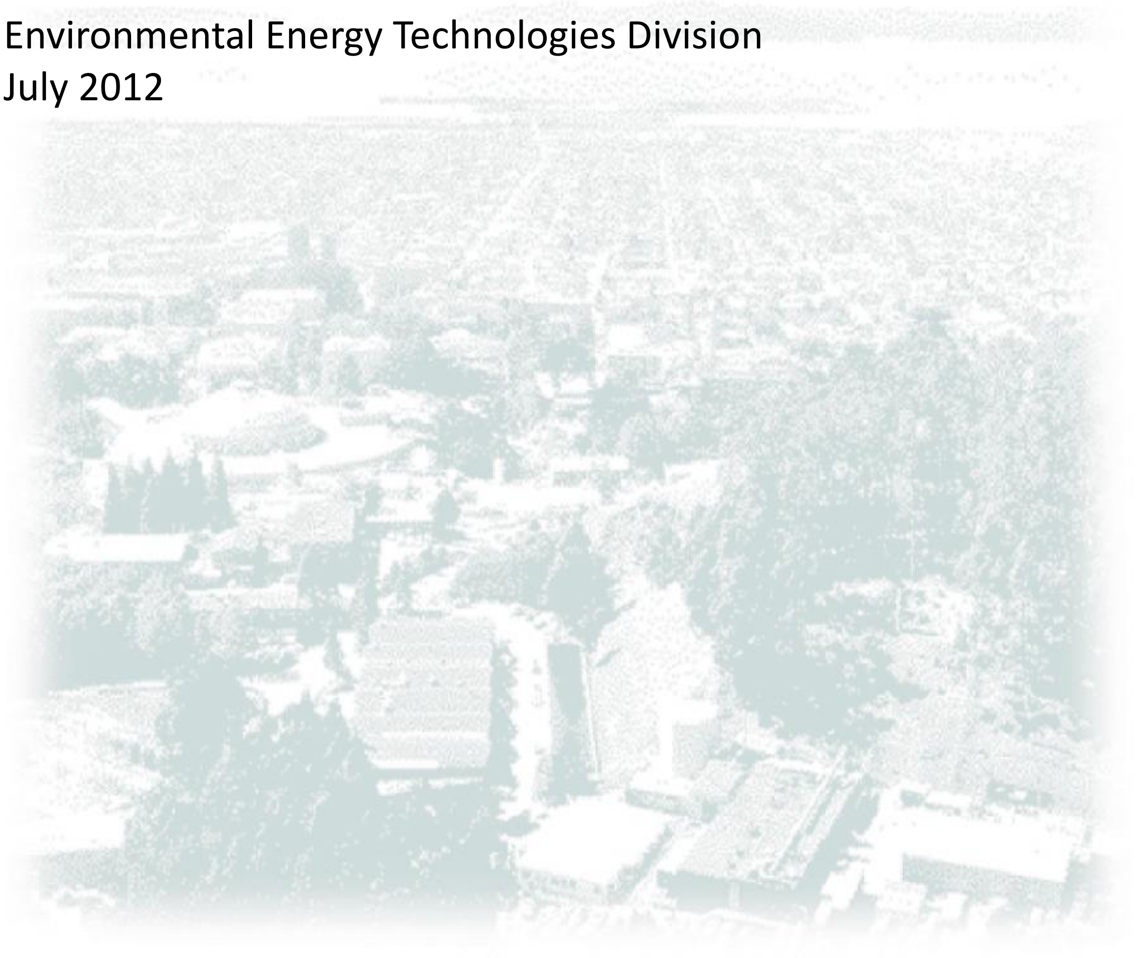

Disclaimer

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U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

BUILDING TECHNOLOGIES PROGRAM

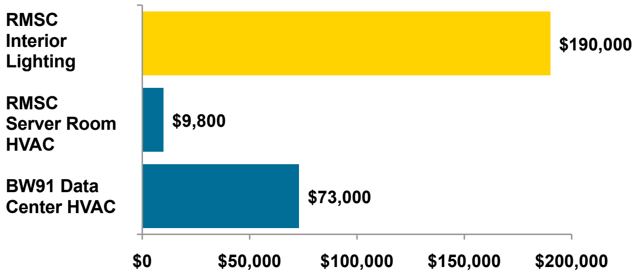
MIT–Mighty Steps toward Energy Sustainability

Massachusetts Institute of Technology (MIT) partnered with the U.S. Department of Energy (DOE) to develop and implement solutions to retrofit existing buildings to reduce energy consumption by at least 30% as part of DOE's Commercial Building Partnerships (CBP) Program.[1] Lawrence Berkeley National Laboratory (LBNL) provided technical expertise in support of this DOE program. MIT is one of the U.S.'s foremost higher education institutions, occupying a campus that is nearly 100 years old, with a building floor area totaling more than 12 million square feet. The CBP project focused on improving the energy performance of two campus buildings, the Ray and Maria Stata Center (RMSC) and the Building W91 (BW91) data center. A key goal of the project was to identify energy saving measures that could be applied to other buildings both within MIT's portfolio and at other higher education institutions.

The CBP retrofits at MIT are projected to reduce energy consumption by approximately 48%, including a reduction of around 72% in RMSC lighting energy and a reduction of approximately 55% in RMSC server room HVAC energy. The energy efficiency measure (EEM) package proposed for the BW91 data center is expected to reduce heating, ventilation, and air-conditioning (HVAC) energy use by 30% to 50%, depending on the final air intake temperature that is established for the server racks.

The RMSC, an iconic building designed by Frank Gehry, houses the Computer Science and Artificial Intelligence Laboratory, the Laboratory for Information and Decision Systems, and the Department of Linguistics and Philosophy.

Expected Energy Cost Reductions



Left: Exterior of the Ray and Maria Stata Center, showing the unconventional geometry of the building envelope. Source: MIT.
Right: Overhead view of BW91 Data Center with cooling towers visible on the roof. Source: Google Maps.

Project Type	Higher Education Classrooms and Offices, and Data Center, Retrofit
Climate Zone	ASHRAE Zone 5A, Cold and Humid
Ownership	Private
Barriers Addressed	• Existing energy management practices • Lower quality lighting environment of workspaces • Lack of measured energy use data to support more aggressive operational approaches
Square Footage of Project	300,000 (RMSC) 7,000 (BW91 Data Center)
Expected Energy Savings (vs. existing energy use)	~71% (RMSC Total) ~67% (RMSC lighting) and ~4% (RMSC Server Room HVAC) ~30% (BW91 Data Center HVAC) (30% min. to 50% max. based on final rack air-intake temperature)
Expected Energy Savings (vs. ASHRAE 90.1-2007)	RMSC Building: ~76% (Total) ~69% (RMSC Lighting) and ~7% (RMSC Server Room HVAC)
Actual Energy Savings (to be verified)	2,100,000 kWh / yr electricity
Expected Cost Savings	$270,000 (Total) $190,000 (RMSC Lighting), $9,800 (RMSC Server Room) and $73,000 (BW91 Data Center)
Project Simple Payback	~4 years (RMSC Lighting) ~3 years (RMSC Server Room) ~5 years (BW91 Data Center)
Actual Cost Reductions	To be verified
Expected Carbon Dioxide Emissions Avoided	~1,100 Metric Tons per year[2]
Construction Completion Date	2013 (Expected)

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[1] The Commercial Building Partnerships (CBP) program is a public-private, cost-shared initiative that demonstrates cost-effective, replicable ways to achieve dramatic energy savings in commercial buildings. Through the program, companies and organizations, selected through a competitive process, team with DOE and national laboratory staff, who provide technical expertise to explore energy-saving ideas and strategies that are applied to specific building project(s) and that can be replicated across the market.

[2] Calculated using the Greenhouse Gas Equivalencies Calculator.

First occupied in 2004, the building contains approximately 303,000 square feet of student classrooms, research labs, study areas, and faculty offices. The low-energy retrofit of RMSC focused on significantly upgrading much of the interior lighting and reducing HVAC energy use in a typical server room. Because of the irregular layout of the center's interior spaces (angled walls in plan and elevation) and the original fixture locations, developing a lighting solution that met occupant visual comfort requirements and provided significant savings presented a unique challenge. The RMSC server room occupies a small fraction (0.1%) of the building's floor area; however, it accounts for about 8% of the total building energy consumption. The server room retrofit aims to significantly reduce this energy use by means of strategies similar to those studied for BW91. Energy savings are estimated compared to the building's pre-retrofit energy use as well as to the Energy Standard 90.1-2007 of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), the American National Standards Institute (ANSI), and the Illuminating Engineering Society of America (IESNA).

The data center located in BW91 provides information technology (IT) services to portions of the MIT campus and houses dedicated office space for IT and other staff. The data center portion of the building is approximately 7,000 square feet with an energy use intensity (EUI) of approximately 917 kilo BTUs per square foot per year (kbtu/ft2/yr). A range of air-side and water-side HVAC EEMs were proposed for this building (discussed in further detail below). Energy savings are estimated compared to the pre-retrofit building's energy use.

The combination of EEMs for both buildings contributes to the campus-wide goal of reducing electricity by 34,000 megawatt-hours (MWh). This goal is the basis of a three-year partnership between MIT and the local utility, NSTAR. The designs selected for the CBP project reduce the most energy-intensive end use in each building area. The lighting design selected for RMSC includes new fixture layouts, high-efficiency luminaires, and a comprehensive lighting control system with occupancy and daylight harvesting sensors. The goal of the design was to improve interior lighting quality to meet the visual comfort requirements of students and staff in addition to saving energy.

For the RMSC server room, the design selected includes hot-aisle containment, increased rack supply air temperature, variable frequency drives (VFDs) on air handlers, and elimination of humidifiers.

The BW91 data center retrofit focuses on three areas:

1. Air Management – containing hot/cold-aisle air, increasing thermal set points (to 70°F, 80°F, or 90°F) and rack air-intake temperatures, increasing the humidity range, and adding VFDs to computer room air handler (CRAH) units
2. Plant Improvements – decommissioning CRAH humidifiers, adding VFDs to water pumps and cooling tower fans
3. Water-side Economizer – adding a direct water-side economizer (without a heat exchanger), separating water distribution loops, and elevating temperature of chilled water provided to data center

The retrofits are expected to significantly reduce lighting and HVAC energy use. Although the predicted energy reduction in the RMSC server room is relatively small, successful implementation of the measures for this space as well as for BW91 will open the door for these measures to be applied in multiple similar spaces at MIT, saving energy across the campus. The results presented in this case study are for proposed EEMs evaluated at the mid-design phase of the project.

Decision Criteria

Proposed EEMs for each of the MIT buildings had to be cost effective and have the potential to save energy, but several other criteria were important as well. These included visual comfort and occupant acceptance of the proposed lighting EEMs in RMSC, and maintaining operational reliability and efficiency of the data servers in RMSC and BW91 (relevant in particular to EEMs that increased interior temperature or modified humidity conditions in those areas). The EEMs selected to date went through several stages of review by the MIT facilities team as well as building occupants and end users. These stakeholders will continue to collaborate for the remainder of the project.

Economic

As a private institution, MIT's payback criteria are similar to those of other private-sector organizations. The target payback for efficiency measures was less than five years for the RMSC server room and BW91 and less than four years for the RMSC lighting retrofit. MIT will consider funding measures with a payback longer than their five-year criterion if there is potential for the measures to be applicable to multiple buildings in MIT's portfolio or there are incentives from the local utility. Thus, key economic criteria for EEMs included:

- Targeted simple payback period: five years as an initial filter (rebates were not included)
- First costs: significant effort to identify lower-cost items as alternatives to those perceived to be too expensive
- Cost effectiveness at scale: For data center EEMs, potential to implement similar strategies at other similar facilities within MIT's buildings portfolio

Occupant Acceptance

The criteria for evaluating RMSC energy efficiency measures were quality of lighting for the various types of spaces and activities in the building, and potential to save energy. When these objectives conflicted, it proved challenging to reconcile them.

Lighting quality was assessed by both facilities representatives and end users (RMSC occupants). Lighting mockups allowed occupants to evaluate and provide comments on proposed products. Because of the building's unique combination of façade orientations, wall angles, and variety of interior space uses, ensuring that the design would satisfy the end users was a key criterion for advancing a lighting measure in the decision process. Lighting controls were evaluated in relation to the need for an overall quality lighting environment.

End Use Reliability

Energy modeling was used to identify a combination of HVAC EEMs for the RMSC server room and BW91 data center. Modeling also pinpointed pre-retrofit energy use that was not necessary for maintaining reliable server operation. However, in discussions over the EEMs, it became apparent that a key decision criterion was the operations staff's level of comfort regarding how the space would be operated. Staff had concerns about the impacts on server reliability and downtime of elevating the server racks' interior operating temperature (Tschudi, Mills, Greenberg, and Rumsey, 2006).

Project EEMs were evaluated for the risk they posed to server operation. Monitoring and analysis approaches were established to directly address these concerns and enable selection of EEMs based on monitored performance.

Policy

MIT's campus energy efficiency goals influence the institution's approach to projects. For example, as described above, MIT has partnered with the local utility to reduce electricity use. Therefore, projects take higher priority if they contribute significantly to this energy savings goal or if they demonstrate energy saving designs that could be replicated in other similar facilities within MIT's portfolio.

Energy Efficiency Measures Snapshot

The energy modeling and analysis for this project focused on selecting EEMs from a range of alternatives. The preferred package was a cost-effective investment that would significantly reduce energy use.

- Energy savings are shown for individual lighting EEMs. However, energy reductions from a combination of measures do not always equal the sum of energy reductions from the individual measures.
- Energy savings for the RMSC server room and the BW91 data center are presented as packages of EEMs.
- An electricity rate of $0.13/kWh was used in this analysis, reflecting the current rate paid by MIT.
- In selecting EEMs, MIT considered options for life-cycle cost reductions, such as rebates from the local utility or maintenance savings; however, these rebates are not reflected in the table below.
- The EEMS are presented ranked by their expected annual savings within each end use.

Energy Efficiency Measures

	Implementing in this Project	Will Consider for Future Projects	Expected Annual Savings		Expected Improvement Cost, $	Cost of Conserved Energy (CCE),[3] $/kWh	Simple Payback[4] (years)
			kWh/year	$/year			
Ray and Maria Stata Center (~71% Energy Savings)							
Lighting (~67% of Energy Savings)			1,500,000	190,000	754,000	0.23	~4
Install occupancy sensors and controls in the majority of space types (92% of the ~1,180 fixtures). Program lighting in common spaces to automatically be on when the space is occupied.	Yes	Yes					
Install daylight harvesting sensors and electronic dimming ballasts in perimeter and skylight spaces to control electric lighting in response to available daylight.	Yes	Yes					
Reduce lighting power density (LPD) by 89 kW, by replacing holophane glass globe luminaires with similar-looking LED high-bay fixtures and integral dimmable light-emitting diode (LED) driver.	Yes	Yes					
Use time-clock controls to deactivate lighting circuits according to scheduled building use.	Yes	Yes					
HVAC – Server Room (~4% of Energy Savings)			75,000	9,800	26,000	$0.15	~3
Implement air management with hot- and cold-aisle containment; increase rack supply air temperature to 70°F, with a 20°F air-side Delta T.*	Yes	Yes					
Eliminate humidification and active control of humidity levels.*	Yes	Yes					
Install VFDs on CRAHs.	Yes	Yes					
Building W91 Data Center (~30% Energy Savings)							
HVAC (~30% of Energy Savings)							
Water-side Economizer			560,000	73,000	330,000	0.26	~4
Add direct water-side economizer (without heat exchanger) between chilled water system and condenser water loop to enable direct free cooling capability.*	Yes	Yes					
Separate house and data center chilled-water distribution circuits (chilled water going to the CRAHs can be warmer because the discharge temperature can be higher – 54°F versus 44°F).	Yes	Yes					
Plant Improvement							
Decommission existing humidifiers within CRAHs. Handle humidity control with a single new humidifier (one vs. multiple) to be installed either in the existing fresh-air ventilation or as an independent room humidifier.*	Yes	Yes					
Install VFDs on chilled water pumps.	Yes	Yes					
Install VFDs on cooling tower fans.	Yes	Yes					
Air Management							
Improve air management and containment of hot aisles.	Yes	Yes					
Increase room temperature set point to 75°F versus the previous 68°F.	Yes	Yes					
Install VFDs on CRAHs (set point is 0.03 inches Water Column).	Yes	Yes					

3. CCE calculated with 3% discount rate for 25 years (Meier, 1984)
4. Calculated using MITs electricity price of $0.13 / kWh
* Climate-dependent EEM.

Energy Use Intensities by End Use

The EEMs for RMSC and BW91 were identified and analyzed by the technical team, including Bovis Lend Lease and Kling Stubbins. The RMSC energy models were created to analyze design concepts and estimate energy savings from efficiency measures. The models simulated occupancy and daylight availability and provided energy results for various lighting conditions and control strategies. An inventory of the building's lighting fixtures and spaces identified areas where energy efficient design was a priority, which informed the energy modeling. Lighting system redesign focused on providing a quality light environment for users and incorporating energy saving lighting controls that were not part of the system's original design. It was discovered that lighting power density (LPD) needed to increase in some locations to provide the targeted light quality, but even with these increases, significant savings would be realized from use of lighting controls. After this discovery, lighting retrofits were separated into two categories: 1) contributing to energy efficiency and improved lighting quality; 2) contributing to improved lighting quality only. Only the first category was included in the CBP project. Overall, the LPD was reduced by approximately 0.3 watts per square foot.

Energy modeling for the RMSC server room and BW91 data center was based on equipment schedules, relevant information from construction drawings, and site visits. Metered energy and weather data collected from the site were used to calibrate the existing building model. Also, to encourage the MIT facilities team to examine all potential energy solutions, the project team utilized an environmental and energy monitoring package to actively capture current energy use and temperature distributions within the BW91 data center. These data were used to inform computational fluid dynamics (CFD) calculations evaluating the proposed EEMS. The output showed the temperature distributions resulting from the EEMs as well as the effects on servers. This analysis and visualized results were invaluable in providing the MIT staff with a means to assess impacts on server performance and reliability, especially where EEMs involved an increase in ambient operating temperatures. This analysis method also provided an energy heat map of the data center, which highlighted particular areas where additional improvements were possible.

Graphic results from several models show the impact to date of both projects. Models 1 through 3 are for the Stata Center project:

Models 1 to 3 were created to evaluate the performance of each of the proposed lighting system and server room HVAC options for RMSC. Model 3 – (Proposed Design) was then compared to two baselines, Model 1 – Code Baseline (ASHRAE) and Model 2 – Pre-retrofit Design, to estimate energy savings. For consistency, energy use intensity for the server room was calculated using the serviced Stata Center building floor area rather than the computer room floor area, which shows the relative significance of lighting and server room energy consumption.

Model 1 – RMSC Code Baseline (ASHRAE 90.1-2007)

The first model represents the ASHRAE standard baseline for only the RMSC server room and the portion of the building's lighting that was targeted for retrofit. This model has an annual energy use intensity (EUI) of about 29.5 kBtu/ft^2.

Model 2 – RMSC Pre-retrofit Design

Model 2 represents the pre-retrofit operation of the RMSC server room and the lighting targeted for retrofit, calibrated using metered energy use data. The pre-retrofit lighting system included manually operated light switches. This model has annual EUI of approximately 24.4 kBtu/ft^2.

Model 3 – RMSC Proposed Design

Model 3 includes new lighting fixtures and an overall lighting redesign including a new control system with occupancy and daylight harvesting sensors. Four EEMs are assumed for the server room: an increase in rack intake temperature, hot- and cold-aisle containment, VFDs on the CRAHs, and deactivation of the humidifiers. This model has an annual EUI of about 7.12 kBtu/ft^2.

Models 4 and 5 focus on the Building W91 data center HVAC system. Model 4 represents the pre-retrofit building HVAC energy use against which the Proposed Design (Model 5) is compared in order to estimate energy savings.

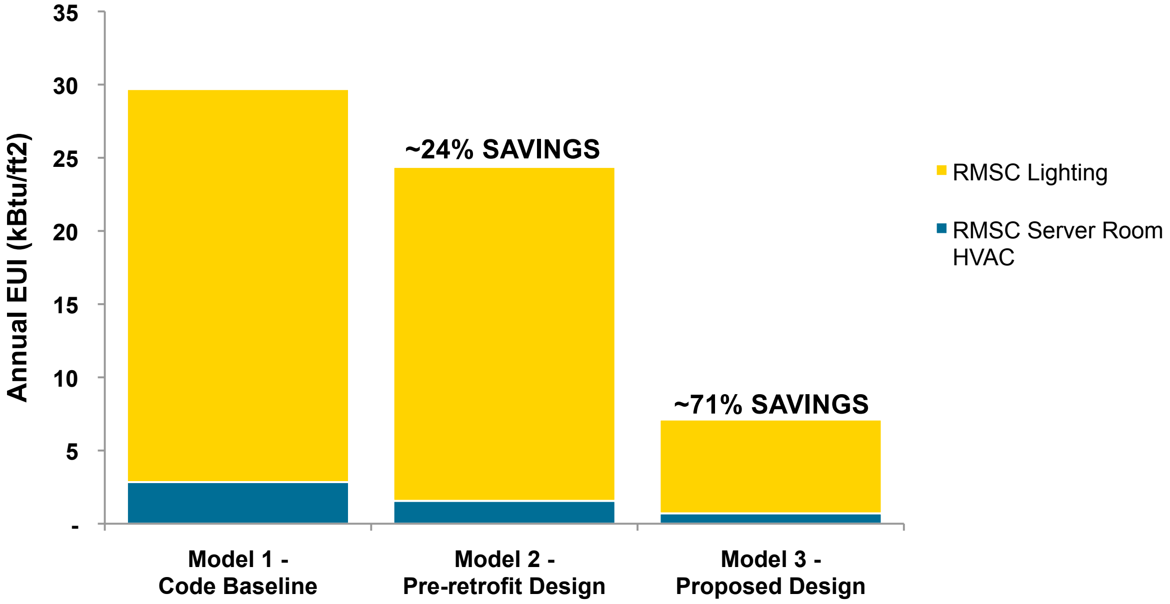
Model 4 – BW91 Pre-retrofit Design

Model 4 represents the pre-retrofit data center's HVAC performance. This has an annual energy use intensity (EUI) of about 914.9 kBtu/ft^2.

Model 5 – BW91 Proposed Design

This model represents the proposed BW91 HVAC design, incorporating all of the proposed HVAC EEMs, including air management improvements, a direct water-side economizer, a dedicated chilled-water loop for the data center, a chilled-water temperature reset to reduce the load on the chiller compressor, and an additional chilled-water pump in the return. The model results presented below also reflect a data center interior operating temperature of 75°F, resulting in 30% overall energy savings with an annual EUI of about 637.5 kBtu/ft^2. Design modifications to increase the interior operating temperature to 80°F are also being considered, which would result in up to 50% energy savings.

Comparing EUI of Code Baseline, Pre-retrofit Design, and Proposed Design for RMSC Building



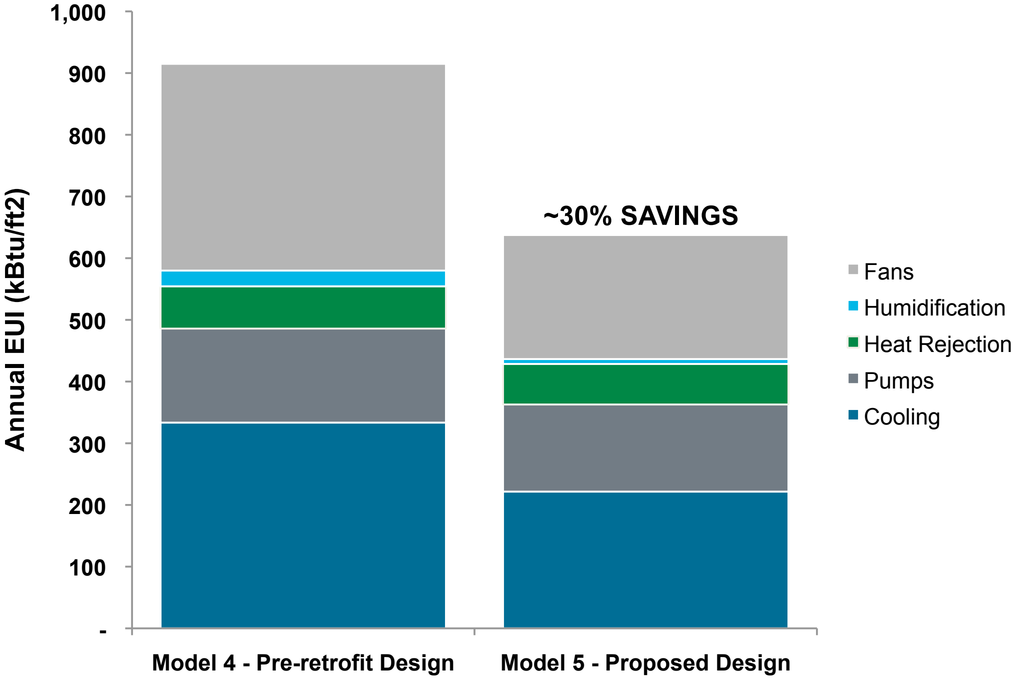
Expected Annual Energy Use and Percentage Savings by End Use

End Use Category (electricity)	Model 1 – Code Baseline	Model 2 – Pre-retrofit Design	Model 3 – Proposed Design	
	Annual EUI (kBtu /ft^2)	Annual EUI (kBtu /ft^2)	Annual EUI (kBtu /ft^2)	Percent Savings over existing
🟨 Lighting	26.9	22.8	6.4	72%
🟦 Server Room HVAC	2.8	1.6	0.7	55%
Total Energy	**29.7**	**24.4**	**7.1**	**~71%**

Expected Building Energy Savings from Implemented EEMs by End Use

Electricity End Use Category	Energy Savings
🟨 Lighting	1,500,000 kWh
🟦 Server Room HVAC	75,000 kWh
Total Electricity Savings	**~1,600,000 kWh**

Comparing Estimated EUI of Pre-retrofit Design and Proposed Design for Building W91



Expected Annual Energy Use and Percentage Savings by End Use

End Use Category (electricity)	Model 4 – Pre-retrofit Design	Model 5 – Proposed Design	
	Annual EUI (kBtu /ft^2)	Annual EUI (kBtu /ft^2)	Percent Savings over existing
Fans	335.1	201.1	40%
Humidification	25.5	7.9	69%
Heat Rejection	68.5	65.7	4%
Pumps	152.4	141.3	38%
Cooling	333.5	221.6	34%
Total Energy	**914.9**	**637.5**	**~30%**

Expected Building Energy Savings from Implemented EEMs by End Use

Electricity End Use Category	Energy Savings
Fans	270,000 kWh
Humidification	36,000 kWh
Heat Rejection	6,000 kWh
Pumps	23,000 kWh
Cooling	230,000 kWh
Total Electricity Savings	**~560,000 kWh**

Lessons Learned

From CBP work on the MIT campus, the project team (MIT, LBNL, Bovis Lend Lease, Kling Stubbins, and DOE) all learned lessons that could be applied to large campuses in the future.

Assign a Key Decision Maker

Having a key decision maker as the main point of contact for the project was invaluable. This person interfaces with the CBP team and the individual retrofit project teams and has the "larger picture" of campus priorities and initiatives. They can lay the groundwork for identifying opportunities elsewhere on the campus where EEM assessments and lessons learned from current or past projects can be incorporated into those of the future. In addition, having a key decision maker engaged in discussions with occupants and end users promotes comfort and consistency, minimizing the chances that competing views will arise and impede a resolution.

> "Through these projects, MIT recognized that key buy-ins from occupants and users were necessary to ensure success. MIT and the CBP team evolved our design process to include analysis and mockups that directly addressed the needs and interests of these groups, enabling critical decision making to move forward."
>
> — Peter L. Cooper
>
> Manager of Sustainable Engineering and Utility Planning, MIT

Target Analysis to Address Decision Criteria

"One size fits all" does not apply to energy performance analysis! Energy modeling can identify key issues and establish recommendations, but if the analysis results do not provide information that relates to key decision criteria, there is a real chance those recommendations might not be implemented. One issue of concern for the BW91 data center IT staff revolved around the data center's operational temperature set points and environmental conditions. Substantial savings were possible if the ambient temperature in the space was increased from 68°F. A number of projects were presented to the staff demonstrating that increased temperatures had been successfully implemented elsewhere. However, the MIT team was very reluctant to move forward with these EEMs because of a concern that increased temperatures in combination with the air circulation in the space might cause hot spots that could affect server performance and/or cause server failure. Through a series of discussions with ideas contributed by the collective team, the group realized that if data were obtained to establish an existing temperature map for the server racks at different heights as well as for the overall space, then everyone could better understand the existing conditions. These data could also be used to calibrate a CFD model, which could then be used to simulate and investigate energy scenarios reflecting the proposed range of internal thermal conditions. Through this data gathering and modeling, it was confirmed that there was significant opportunity to relax the set points and turn off certain units without compromising operation of the equipment (ASHRAE, 2011). Ongoing collaboration and an openness to adapt the analysis approach provided the results and information needed to address the specific decision criteria and barriers and to empower decision making on this key issue (Greenberg, Tschudi, and Weale, 2006).

Provide for Occupant Input and Decision Making

Occupants can become fatigued when a building system or space is changed or adjusted multiple times to address design issues. In the potentially stressful top-level research environment at MIT, occupant acceptance can be a significant barrier to the success of EEMs. A particular contest for the RMSC project was the building's colorful lighting history. As one project team member described it, the building had gone from a challenging lighting design to a challenging but more energy efficient lighting design, and now the CBP project was trying to implement a quality and energy efficient lighting design. The initial approach to occupant input was to install sample fixtures so that occupants could experience them and provide feedback on which a decision could be based. However, a combination of the original lighting design, the unique nature of the building, issues in getting the sample fixtures installed with the right components (bulbs and controls) in a timely manner, and occupant fatigue led to a longer decision making process than anticipated. The lesson learned is the desirability of an integrated process for occupant feedback and decision making. Such a process utilizes multiple approaches in parallel, such as mockups, messaging describing the project intent and benefits, and tools such as lighting satisfaction surveys before, during, and after retrofits, to enable timely and productive occupant input.

Empower Decision Making Through Data

A first step toward improving a building's performance is to understand how it is performing now, so increasing the number of metered buildings should be one of the priorities for any large campus or owner of numerous unmetered facilities. Many metering and software products are now available for continuously measuring and monitoring buildings' energy usage. These products offer additional benefits, such as analysis of building energy use for reporting purposes, identification of energy trends, and assistance with fault detection and diagnostics to identify where system repair, retrofit, or recommissioning is required. Once performance data are available, they must be used effectively. A useful tool for designing how performance data can be effectively collected and used is the *Energy Information Handbook* (Granderson, Piette, Rosenblum, and Hu, 2011).

Consider Future Expansions

At the beginning of the BW91 data center retrofit analysis, only about 30% of total rack server rack space was being utilized. In evaluating the analysis results for the EEMs for this space, the team observed some payback periods that appeared longer than would normally be anticipated. An additional sensitivity analysis showed that if the capacity of the data center increased, the energy savings from the EEMs would increase, bringing them closer to MIT's target payback period. Near the end of the preliminary design stage of the project, a private-sector tenant expressed interest in using a portion of the data center capacity, which would increase server rack utilization to approximately 65%. The lesson learned was to explore the sensitivity of EEMs to gain insight into whether changes in building usage patterns or loading could have notable impacts on cost effectiveness.

Several of the lessons learned from this project can be applied not just to the system or building type from which they emerged but more broadly across the higher education and commercial buildings sector.

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