Global Ecology Center at Stanford University

Factor Ten Engineering Case Study

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Introduction

In 2002, the Carnegie Institution began planning a facility, called the Global Ecology Center (GEC), which would become known as one of the most energy-efficient laboratories in the nation. Located on the Stanford University campus, the 11,000-square-foot building was built to house the university's new Department of Global Ecology, a place for students and researchers to work at the cutting edge of their fields.

Research within the walls of the GEC focuses on sustainability and minimizing climate change, and designers saw fit to give researchers a building that reflects the GEC's mission.

The two-story building may call to mind a futuristic hybrid of a ski chalet and a pole barn—light-brown wooden façade, sloped metallic roofs, wall-sized windows and a silo-like tower. Many of the eye-catching design elements serve a functional purpose, be it to trap water, reflect sunlight, or capture wind. The goal was a design that offers both a comfortable office and lab space and one that conserves energy—using innovative systems to heat, cool and ventilate the building.

All told, the GEC achieved a 72 percent savings over a 2001 California Title 24-compliant building,[1] the strictest energy code in the nation, for a modest capital cost premium paid back between two and five years.[2]

But how?

The overarching success factors in this project were a client already convinced of the benefits of resource-efficient design and a design team experienced with and trained to deliver on that goal. Designers challenged conventional assumptions and design principles. Often, throwing out the old practices and starting afresh can bring improvements of ten times or more. RMI calls this approach 10×E[3] design.

This case study will highlight the differences between a "base case" and the 10×E design that was actually used in building the GEC. The case study will then spotlight the key design elements and how they played out in the design and building processes. Throughout, boxes explaining key 10×E principles accompany descriptions of how each principle was employed. It concludes with a discussion of barriers encountered and lessons learned.

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The Old Way and The 10×E Way

Typically, designers tend to focus on individual pieces and give little thought to those pieces' interactions with the other systems in a building. Similarly, their design processes include little interaction among stakeholders. The owner tells the architect what he wants, the architect produces a building design that responds to those demands, the engineers devise systems to serve that design, and the contractors build the facility. After the designers have moved on to the next project, the maintenance staff inherits the building.

The building may comply with building codes that don't necessarily provide occupants with details that define comfort and quality, for example, clean air in all parts of the building, glare-free daylight, low acoustic noise, and a thermally comfortable interior. The building's unnecessarily high capital and operating costs are due to energy-inefficient systems.

In sharp contrast, 10×E whole-system thinking makes connections between the different parts apparent and fosters integrative design. The following sections describe the 10×E design process and highlight several 10×E principles, indicated in both the colored text and a nearby box. Further information on 10×E is included in the Appendix. For a side-by-side comparison of the results of the two approaches, see the section "Summary of Principles and Project Results" later in the document.

[1]The 72% savings is for electricity only. See Appendix B for a complete breakdown of energy use and benchmarked energy performance.

[2]AIA/COTE Top Ten Projects, www.aiatopten.org/hpb/energy.cfm?ProjectID=809.

[3]10xE provides engineers with practical tools to achieve radical resource efficiency through integrative design, thereby saving their clients' money and helping solve some of the planet's most critical energy and climate problems. See Appendix A and www.10xE.org

Designing the Global Ecology Center

At the outset, the Carnegie Institution established ambitious goals for the project, such as a 50 percent energy reduction over California Title 24 requirements. Setting goals and communicating them at the start prompted the design team to invest more time up front in finding resource- and cost-saving opportunities.

A pre-design feasibility study found that the GEC's proposed size stretched the budget. At a pre-design workshop, players from all phases of the project explored ways to reduce construction costs and perhaps take advantage of other benefits.

The design process included a series of design workshops and consistent interdisciplinary communication—characteristics of an integrative design approach. Each member was responsible for thinking broadly about not just one design element but the whole building and site. As the team considered the benefits of various elements, the distinctions between elements' functions began to blur. Design team members began collaborating on specific elements.

Further, the design team established an early relationship with the contractor, who helped produce detailed design specifications and became equally invested in the success of the project. Construction practicalities thus informed design, and design intent carried over seamlessly into design execution. This created a relatively smooth construction process despite unconventional materials and innovative systems, which are explained in detail in the following pages.

Four Decisions That Cut Costs and Saved Energy

The integrative design approach required plenty of time and spirited discussion. But the process delivered four specific design elements that saved capital costs and energy:

Off-site freezers: During the workshop, the team explored ways to offer all the amenities occupants wanted with less floor space. Talking with the client, the team discovered that the laboratory freezers could be moved to an unconditioned warehouse nearby. Moving the freezers achieved the goals of reduced floor space and a smaller cooling load, cutting both capital and operating costs. Moving the laboratory freezers cut annual energy use in the GEC by 15 percent and, since the freezers were moved to an unconditioned building where a building cooling system did not have to remove the heat expelled from the freezers, total energy use on campus also decreased.

Two-story layout: The workshop also elicited a two-story design that offered additional benefits (e.g., lower construction and energy costs and a more comfortable environment) that far outweighed the added costs of stairways and elevators.

The two-story design offered other benefits: the GEC's smaller footprint provided more space outside the building and more interaction between researchers, students, and administrators inside; stacking the building on two floors allowed aggressive ventilation to be focused on the labs only, not the whole building, which is far more energy efficient; and the two-story layout reduced the size of the foundation and the rooftop area, a major maintenance and capital-cost concern for owners.

Upstairs carpet: There were competing ideas about how to finish the upstairs floor. This conflict and its resolution offer a specific example of the 10×E principle, "collaborate across disciplines." In order to reduce operating energy costs, cooling-system designers advocated that the concrete floor be left bare rather than carpeted. But other designers argued that carpet reduces noise and upfront capital costs, and that over its lifecycle carpet can be cheaper than finished concrete. In the end, the design team chose carpet in light of the client's willingness to accept a lower cooling capacity and the accompanying risk of occasional minor over-heating.

Unfinished ceiling: Team members also collaborated on the design for an exposed structural element in the ceiling. An unfinished ceiling is taller, enables better distribution of daylight and electric light, provides a more spacious feel, and saves significant capital costs by reducing finish labor. The architect and interior designer worked with the structural engineer to design the exposed structural element as an attractive architectural feature—yet another example of "wringing multiple benefits from single expenditures."

Getting Technical: Cooling, Heating, and Ventilating the Global Ecology Center

Typically, the mechanical-system design process for a building includes only mechanical engineers. After the architect determines the building's orientation on the site and its form, mechanical engineers design systems to keep the interior comfortable as specified in ranges of temperature and relative humidity established by the American Society of Heating, Refrigerating and Air-Conditioning Engineers. The mechanical engineers estimate the amount of cooling and heating required on the year's coldest and hottest days, often using imprecise assumptions. Then, they specify standard heating and cooling systems to meet those loads.

In contrast, the design of the GEC mechanical system included nearly everyone in the procurement process, led by mechanical engineers: the owner, occupants, project architect, landscape architect, interior designer, lighting designer, contractor (and sub-contractors), design engineers (electrical, plumbing, and structural), product suppliers and manufacturers, and facility maintenance staff. In addition, the team asked questions that might otherwise have been left unasked.

For example, rather than asking what the cooling and heating load of the building would be, they asked what thermal comfort the occupants would require—and whether or not they could eliminate the building's cooling and heating load. And, if the answer was no, they asked how close they could get to eliminating it.

Instead of asking what common system would meet a typical load for this building type, they asked what technologies could meet the actual load at least cost.

Collaborating with other design team members, mechanical engineers first evaluated such passive-design techniques as daylighting, solar thermal heating, and natural ventilation. Next, after determining that active (i.e., electricity-using) systems were also required, they sought the most efficient system that could supply the needed services. Finally, they assessed opportunities particular to the local climate to use natural ventilation and such semi-passive[4] cooling techniques as evaporative cooling.

Radiant Cooling and Natural Ventilation

The building's second floor includes office space and a conference room. Cooling the conference room was particularly challenging; its temperatures would likely fluctuate quickly and widely as people came and went. To meet varying cooling needs, designers chose a mix of natural ventilation and radiant floor cooling.

Perhaps the most innovative aspect of the design is the way water is chilled for the building's radiant-cooling system. The **night-sky cooling system** sprays water over the roof at night—making the roof part of the cooling system and thus deriving multiple benefits from it. On the roof, the water is cooled by both evaporation and radiation. The cooled water is then returned by gravity to a ground-level storage tank, from which it is pumped as needed to the hydronic slab and through fan coils.

In this case, the design team began by sizing a tank and pipes based on correlations with the roof area developed by the manufacturer of the "WhiteCap™ Roof Spray Cooling System."[5] Performance was estimated using an algorithm that correlates heat rejection from the roof with four temperatures: dry bulb, wetbulb, the night sky, and entering water.

10×E Principle:
Define shared and aggressive goals.

10×E Principle:
Collaborate across disciplines.

Using a 12,000-gallon storage tank, the building's night-sky cooling system distributes water throughout the building at 55–60 °F using only 0.07 kW per ton of cooling for water pump power. A standard chiller uses nearly 1.0 kW per ton for refrigerant compression.

In addition, the night-sky system loses half as much water as a chiller system does in a cooling tower, cutting water consumption in half. To back up the night-sky system, the team chose an old, unused air-cooled chiller that was discovered elsewhere on the campus through ongoing interactions with the client and architect.

The **radiant cooling system** exploits the fundamental but often forgotten fact that the comfort sensation is the average of air temperature and mean radiant temperature. A cool radiant element subtending a large solid angle, such as the floor slab, can be a far more effective and efficient way to help people feel cool than blowing cold air at them.[6] Also, such systems usually use less energy than forced-air systems. Additionally, since part of the cooling system is also the floor, the client pays only once for three benefits (i.e., comfort, less energy cost, and structural support), another example of "wringing multiple benefits from single expenditures."

To ensure that the slab would meet peak loads in the conference room, the designers created a computer

10×E Principle:
Wring multiple benefits from single expenditures.

[4] Semi-passive cooling techniques rely in large part on natural phenomena, such as the removal of sensible heat from air through water evaporation (the addition of latent heat to water until the point of evaporation), and they require a small amount of electricity (such as pumping water into a position where it will more quickly evaporate). Completely passive cooling strategies do not require electricity.

[5] "WhiteCap™ Roof Spray Cooling System." Federal Energy Management Program. http://www1.eere.energy.gov/femp/pdfs/WhiteCapTechInstall.pdf

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model that depicts the slab's performance. The model estimated the thermal comfort of the occupants and accounted for the transfer of energy from the occupants to the slab and, in turn, to the chilled water.

The building energy model evaluated the conference room with various occupancies for various durations. In some scenarios, the radiant slab proved inadequate, requiring an energy-intensive fan coil unit—outdoor air is blown across a mechanically chilled coil and into the room.

However, since this was a very common and inelegant solution, the team looked for other ideas. For example, they could moderate the assumed peak-cooling load with such measures as eliminating late-afternoon summer solar radiation, and raising the ceiling so heat could stratify above the occupants.

In addition, the designers considered how passive design comfort standards might apply since they regarded cooling as an occupant amenity rather than a way to meet thermal comfort standards. The team decided to let the conference room's temperatures float beyond the specified range by a few degrees Fahrenheit.[7]

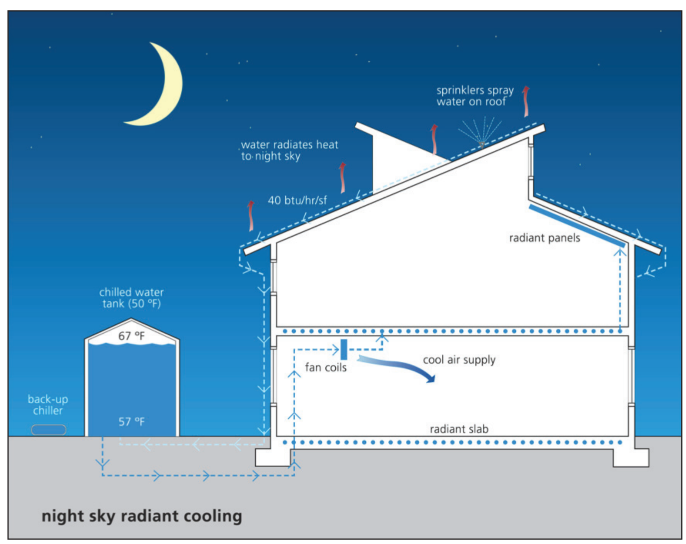
Despite the team's efforts, it was not entirely clear that the occupants would be comfortable on the warmest days. The team expressed this concern to the client, who was willing to accept that risk.

Laboratory Ventilation

The primary use of energy in the building's labs is removing hazardous vapors from spaces occupied by people. The exhausted air must be replaced with clean conditioned air to maintain the integrity of the testing environment.

In a base-case building, "dirty air" is removed by large exhaust systems, which typically operate 24 hours a day and do not have on/off switches. Such exhaust systems require an enormous amount of energy both for fan power and for makeup air conditioning. Thus a wet laboratory can commonly use four to five times more energy than a normal office the same size.

- To decrease laboratory energy use, building designers focused on ventilation end-use, removing "dirty air;" not providing air changes.
- Lab and office ventilation systems were separated in order to reduce total floor space needing strong ventilation.
- Instead of using 20-inch diameter ducts for ventilation, the labs use larger 24-inch low-pressure-drop ducts to reduce fan power from ¾ hp to ¼ hp for 3000 cfm. A one-fifth-larger duct diameter needs two-thirds less fan power because friction drops as the fifth power of duct diameter.
- Outside air is blown first through the dry lab, where there are no hazardous chemicals, *then* to the wet lab, which houses hazardous chemicals. By eliminating a fresh-air intake in the wet lab, this "cascading"



Courtesy of EHDD Architecture.

[6] Radiant ceilings are also highly effective, and common in Europe. One must be careful to avoid condensing conditions.

[7] Extensive field data shows that people in a naturally ventilated office report the same comfort at air temperatures about 3 °C higher than in an air-conditioned office. Also, ASHRAE Standard 50-81 explicitly allows significant hour-long excursions beyond the comfort zone because they're imperceptible—it takes longer than that for the body's thermal mass to heat up and for the nervous system to report discomfort.

of the airflow reduces the need for outside air, hence fan power and conditioning, by 20 percent.[8]

- In addition to turning off lights, occupancy sensors also reduce the ventilation rate in areas that are not in use—another example of the 10×E principle, "meet minimized peak demand; optimize over integrated demand." Also, linking the sensors to both the lights and ventilation offers multiple benefits from single expenditures.
- Fume hoods were reduced to the number needed for the hazardous-chemical experiments actually intended, not estimated using a rule-of-thumb based on floor space—another example of "using measured data and explicit analysis, not assumptions and rules." Fewer fume hoods greatly reduced capital cost.
- Standard hoods run all the time and have no on/off switch. The GEC hoods were given switches so a trained building manager can turn off unused hoods when, and only when, conditions warrant.

Use of the Building and Follow-up With Users

Because of the unconventional systems in the GEC, especially the night-sky cooling system, the design team ensured that the facilities staff was trained to maintain and operate the building's systems and remained available for questions years after the building was occupied. In addition, the team ensured that the staff fully understood the design intent.

The building's engineers continue to download data on the GEC's energy performance and they continue to compare their design calculations to reality, illustrating the 10×E principle, "use measured data and explicit analysis, not assumptions and rules." After nearly a year, occupant satisfaction was surveyed to tell the team how well its design had met the occupants' needs, with the unusually favorable results in *Figure 2* below.

Barriers and Success Factors

Some challenges encountered by GEC designers merit fuller discussion.

The mechanical engineers couldn't accurately predict the building's performance with standard energy-modeling software due to the unusual systems in the GEC. For instance, the lab has a variable-air-volume ventilation system and a cooling slab, each of which reduce energy consumption in the lab. The variable-air-volume system reduces fan power when the space is unoccupied and

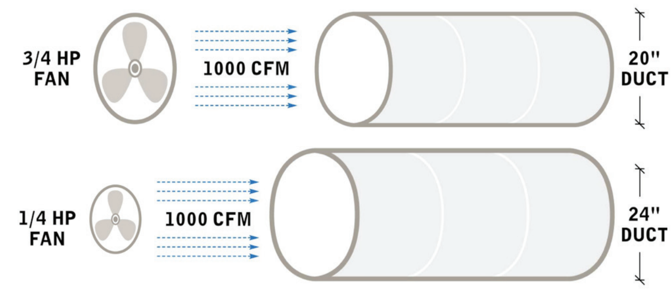


Figure 1: Larger ducts require less fan power to move te same airflow. See also: The Interface Case Study.
Courtesy of Rumsey Engineers

the cooling slab reduces energy required for air-based cooling. However, the energy-modeling software could not model both of these energy savings—the modeler had to choose just one.

Limited time and budget for life-cycle-cost analysis presented another challenge: when the team debated the layout of the piping that would carry water from the roof to the tank, the most energy-frugal layout was not compatible with architectural design and landscaping goals. Eventually, architecture won and a less energy-efficient layout was adopted.

High-volume fly-ash (HVFA) concrete halved the project's concrete carbon footprint,[9] but its different curing time and different installation techniques required educating the contractors and adjusting the construction schedule.

Located in the ceiling throughout the facility, standard chilled-water-control valves leaked. Normally this would require a routine visit by a plumber. However, because leaking water might pickup impurities (e.g., bird droppings) when sprayed on the roof, the unconventional cooling-system created a potential liability situation for the mechanical engineers. After extensive and expensive investigation into water chemistry and pollutants, they found their design was not the problem; the leaks were due to a common error in manufacturing the valves. This illustrates how unconventional design can require more attention for anticipating unexpected consequences.

Cost barriers and conventional value engineering[10] were encountered but overcome through whole-system design, making the building less expensive but no less efficient.[11] The whole-system design and costing process stressed both energy and economic efficiency throughout the process, making the design more resistant to being picked apart by budget-cutters.

[8] AIA/COTE Top Ten Projects, www.aiatopten.org/hpb/energy.cfm?ProjectID=809.

[9] For more information on HVFA concrete and its effect on the carbon footprint of the GEC, see http://dge.stanford.edu/about/building/.

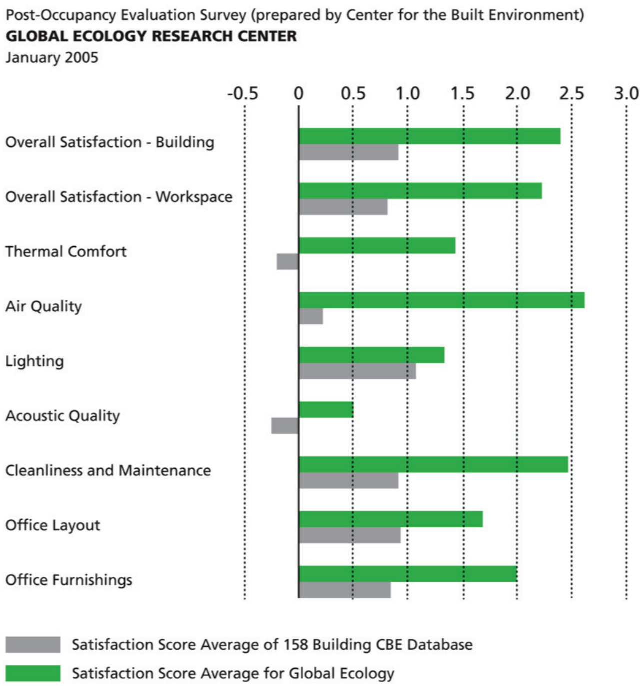


Figure 2: Results from occupant satisfaction surveys. The University of California at Berkeley developed these results for the Built Environment in January 2005 (nearly a year after project completion). The survey was based on a scale of –3 (highly dissatisfied) to +3 (highly satisfied), with 0 representing a neutral opinion. Source: Carnegie Department of Global Ecology website, http://globalecology.stanford.edu/about/building/.

10xE PRINCIPLE:
Seek systemic causes and ultimate purpose.

10xE PRINCIPLE:
Use measured data and explicit analysis, not assumptions.

10xE PRINCIPLE:
Seek radical simplicity.

10xE PRINCIPLE:
Define the end-use.

However, value engineering did compromise some of the building's resource-efficiency potential. A tank could have been installed to increase the amount of rainwater used on site, and rainwater could have been integrated into the night-sky system, providing more water for cooling and irrigation. But it was omitted to reduce capital costs, which increased operating costs due to greater water consumption.

Summary of Principles and Project Results

The team used the following 10×E principles *before beginning design* to ensure an integrative design process:

1. Define shared and aggressive goals: One of the first things the team did together was discuss their goals for the project. In this case, the client challenged the team to achieve high levels of resource efficiency.
2. Collaborate across disciplines: Team members agreed to think not only about the particular aspect of building design or operation for which they were responsible but also its relationship to other systems. Each would contribute to the other's work and vice-versa.

The team took the following *design steps* that included 10×E principles.

1. Define the end-use (a 10×E principle): the client wanted a comfortable, productive, healthy workspace. The team focused on what that means for occupants.
2. Minimize loads: the team reduced energy loads through strategic choices related to envelope, lights, and plug loads.
3. Seek radical simplicity (a 10×E principle): the team created comfort through solar heat gain, shading, natural ventilation, and daylighting.
4. Use waste-energy streams: the team examined how to recover energy from active and passive systems (e.g., exhaust air or water) to further boost efficiency.
5. Meet the remaining load with efficient systems: if passive design could not fulfill all requirements, the team considered highly energy-efficient (but now smaller) active systems.
6. Include feedback in the design (a 10×E principle): The team provided controls and monitoring to

[10] Conventional "value engineering" examines the cost of each energy-efficiency measure in isolation, often rejecting certain measures due to perceived high capital costs, which often increases lifecycle cost. In contrast, whole-system engineering analyzes the costs and benefits of an integrated package of efficiency measures, often leading to lower capital and operating costs.

[11] For example, the computer room would normally have been cooled by a traditional compressor-based air conditioner that might also have backed up the night-sky system. Instead, the designers cooled the computer room with a cheap airside economizer, saving both energy and capital cost.

	Base Case	10×E Design Case
Capital cost	Typical capital cost for this building type and location	Modest capital cost premium ($372/ft^2., $4,000/m^2 in 2003 US$)
Operational energy consumption	Energy consumption complies with Title 24, the California building energy code	27% total energy reduction compared to a building of similar area, type, occupancy and plug/proceess loads built to Title-24 code.[12] Verified energy use intensity was 141 kBtu/ft^2-y (445 kWh/m^2-y)
Embodied emissions materials	No effort made to reduce	Emissions were reduced by 31% from 302 tons (274 of emissions metric tons) to 209, primarily via high-volume-fly-ash concrete (50% replacement of cement) and salvaged materials
Water usage	No effort made to reduce water consumption	Non-irrigated landscaping, low-flow faucets, and dual-flush toilets reduce water usage by 33%
Stormwater management	Stormwater that falls on site is channeled into centralized infrastructure	43% of precipitation is managed onsite, reducing the load on and need for added capacity in the central stormwater sytem

help staff prevent problems, ensure correct diagnosis, and permit monitoring to improve operation and the team's future design work, and to educate occupants and visitors.

In addition to taking those design steps, the team demonstrated the following 10×E principles:

1. Seek systemic causes and ultimate purposes: Rather than designing for the building's cooling and heating load as most would normally do, the team asked what thermal comfort the occupants would require—and whether or not they could eliminate the building's cooling and heating load.
2. Use measured data and explicit analysis, not assumptions and rules: The team used careful analysis to understand loads rather than assuming far worse conditions.
3. Wring multiple benefits from single expenditures: during the collaborative design process: The team was able to design many aspects of the building to serve multiple purposes.
4. Meet minimized peak demand; optimize over integrated demand: The team designed the building to minimize peak demand and adapt to a variable load in a variety of ways, often passively and through controls.

The design team delivered a building to the Global Ecology department with **almost half (56 percent) the operating costs** of a comparable existing building.[12] Remarkably, the team accomplished this at only a **modest capital cost premium**. The table above summarizes the measured results.

[12] See Appendix B for details.

[13] Typically 5–10 fold

Appendix A
Factor Ten Engineering

Factor Ten Engineering is an ambitious initiative undertaken by Rocky Mountain Institute to strengthen design and engineering pedagogy and practice. Though a tenfold gain in resource productivity is achievable, it is not for the faint-hearted. It requires bold and gutsy designers willing to question familiar practice and work closely with people from other disciplines.

From the radically efficient design RMI regularly creates and teaches, we have become convinced that *radical*[13] efficiency by design (a) works, (b) can be adopted by designers new to it, (c) can be formally taught, (d) can yield extraordinary value, often including big savings that cost less than small savings and important synergies with renewable and distributed supply, and (e) should spread rapidly if we and others develop the right examples (proofs), principles, and tools (notably design software), and properly inform design customers/users and improve reward systems.

In light of this need, 10×E is an RMI initiative focused on transforming the teaching and practice of engineering and design, in order to spread *radical* and *cost-competitive* energy and resource efficiency. Based on many collaborations with practicing engineers and designers, we believe that the following actions must happen to enable this transformation:

At the academic level:

- Provide case studies and design principles that explain how to do integrative design and illustrating its major benefits
- Recruit professors and universities to teach the cases and principles
- Encourage students to learn them

At the industry level:

- Convince project decision-makers that greater attention to energy and resource use is indispensable
- Provide hands-on experiences to show concretely what is different and why it is better
- Provide case studies and design principles that explain how to do integrative design and illustrating its major benefits
- Create the tools and reward systems that will enable implementation

Find out more about Factor Ten Engineering, whole-system thinking, and 10×E principles at rmi.org/rmi/10xE. Explore RMI's experience redesigning buildings, transportation and energy systems at rmi.org.

Appendix B
Energy Performance Details

The stated 72 percent electricity savings over a code-compliant building includes credit for an early design descision to move lab freezers to a nearby, unconditioned warehouse. The energy model accounted for this move by reducing the cooling load and floor space. In addition, the savings are for HVAC and lighting electricity use only—not electricity for process loads and miscellaneous equipment, nor natural gas for space heating.

When the design case building energy model is compared to a baseline building that is the same size and has no lab freezers, and process loads, miscellaneous equipment, and space heating are included in the boundary of analysis, the whole-building energy savings are 27 percent, as shown in *Figure 3*. According to 2009 verified energy use, the GEC is one of the most energy efficient labs in the U.S., as shown in *Figure 4*.

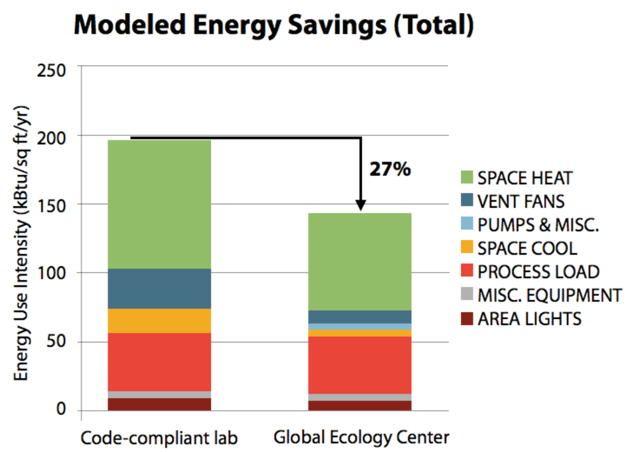


Figure 3: Modeled savings in total energy use (electricity and natural gas) compared to similar-sized 2001 Title-24 code-compliant building.

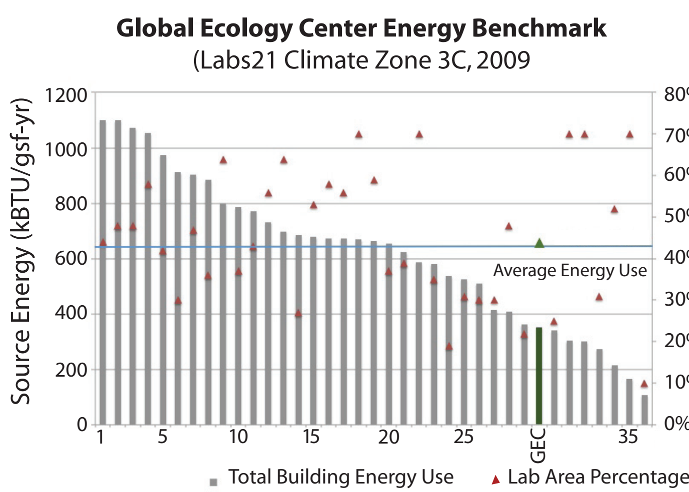


Figure 4: Results from Labs21 Benchmarking Tool. The GEC uses 44% less source energy than the average existing laboratory and is one of the most energy-efficient in the U.S.