EL Program: Net-Zero Energy, High-Performance Buildings

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Strategic Goal: Sustainable and Energy-Efficient Materials and Buildings

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Summary: Buildings account for 41 % of the primary energy consumption and 74 % of the electricity consumption in the United States, while accounting for 40 % of the CO_2 emissions. To minimize the costs associated with building energy consumption, NIST will develop and deploy the measurement science to move the nation towards net-zero energy, high-performance buildings in a cost-effective manner while maintaining a healthy indoor environment. The research program will target the objective of net-zero operation by 1) reducing heating and cooling loads within the building, 2) developing measurement science for efficient heating and cooling equipment, 3) advancing the measurements of onsite energy generation technologies such as photovoltaics and micro-cogeneration, 4) evaluating the energy consumption, greenhouse gas emissions, economics, and sustainability from a whole-building perspective, and 5) aggressively promoting implementation of program results in building energy codes, standards, and practices.

DESCRIPTION

Program and Strategic Goal: Net-Zero Energy, High-Performance Buildings Program; Sustainable and Energy-Efficient Materials and Buildings Goal

Objective: To develop and deploy advances in measurement science to move the nation toward net-zero energy, high-performance buildings while maintaining a healthy indoor environment by 2016.

What is the problem? Buildings consume 41 % of the primary energy and 74 % of the electricity in the United States, while accounting for 40 % of the CO_2 emissions. Such energy consumption and emissions from the building sector pose a national challenge, and the Office of Management and Budget has thus stated as one of its multi-agency science and technology priorities for the 2014 budget to be the utilization of technical innovation to "move toward a clean energy future, address global climate change, [and] manage competing demands on environmental resources." [1] To reduce dependence on energy imports while curbing greenhouse gas emissions, the building community has embraced the idea of net-zero energy buildings, which are buildings that generate as much energy through renewable means as is consumed by the building. This vision has been documented in a Federal R&D agenda produced by the National Science and Technology Council[2] (NSTC) as well as by leading industry organizations such as the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE)[3]. Furthermore, the United Nations Intergovernmental Panel on Climate Change reports that "buildings offer the largest share of cost-effective opportunities for greenhouse gas mitigation among sectors examined,"[4] a charge taken up by the American Institute of Architects in its 2030 Challenge that calls for new buildings to be carbon neutral by 2030[5].

To achieve net-zero energy buildings, an approach is needed that implements the use of existing energy-efficient building technologies, develops new equipment and approaches to increase efficiency, and increases on-site generation of energy. NSTC reports that improved implementation of existing building technologies can reduce energy consumption by 30-50 %. The remaining 50-70 % of energy savings will result from advanced technologies and on-site energy production. Measurement science is lacking, however, in a number of areas for both improving the implementation of existing technologies and advancing new technologies, as documented in the "Measurement Science Roadmap for Net-Zero Energy Buildings."[6]

While moving towards net-zero energy buildings, it is paramount to keep in mind key constraints. In particular, the indoor air quality (IAQ) should be maintained or improved, the

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[1] White House Office of Science and Technology Policy, available at http://www.whitehouse.gov/sites/default/files/m-12-15.pdf
[2] National Science and Technology Council, "Federal Research and Development Agenda for Net-Zero Energy, High Performance Green Buildings" October 2008.
[3] American Society of Heating, Refrigerating, and Air-Conditioning Engineers, "ASHRAE Research Strategic Plan 2010-2015: Navigation for a Sustainable Future"
[4] IPCC 2007: Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.
[5] American Institute of Architects, http://www.aia.org/about/initiatives/AIAB079458
[6] Pellegrino, JL, Fanney AH, Bushby ST, Domanski PA, Healy WM, and Persily AK, "Measurement Science Roadmap for Net-Zero Energy Buildings Workshop Summary Report" NIST Technical Note 1660, March 2010.

new technologies should be cost-effective, and new approaches should be sustainable in reference to other environmental criteria.

Why is it hard to solve? A number of factors make the development of measurement science for net-zero energy, high-performance buildings difficult. First, the scale of buildings makes assessment in laboratory settings difficult, and the long time scales over which performance is needed necessitate long-term testing or creative ways to simulate performance over these time frames. Buildings are comprised of many different components that are seldom installed in a coordinated manner, and the overall building performance is not only dependent upon the individual performance of those components but also on the interactions between those components. Another challenge in achieving net-zero energy buildings relates to the fact that buildings are usually constructed in uncontrolled conditions, so achieving the design intent is often a challenge. Finally, building performance cannot be uniquely defined by a single metric, but rather it requires consideration and optimization of the interaction between indoor environmental quality, energy consumption, greenhouse gas emissions, sustainability, and economics.

How is it solved today, and by whom? The enabling measurement science to achieve net-zero energy, high-performance buildings does not fully exist today. The Department of Energy and its national labs, particularly the National Renewable Energy Laboratory, Lawrence Berkeley National Laboratory, Oak Ridge National Laboratory, and Pacific Northwest National Laboratory, are heavily involved in research on energy efficiency in buildings, but their focus is not solely on measurement science issues, as documented in the NSTC Federal Research and Development Agenda for Net-Zero Energy, High-Performance Buildings. Those agencies have a lead responsibility for technology development, demonstrations, and implementations, whereas NIST and DOE share the responsibilities for measurement science. Industry groups such as ASHRAE and the U.S. Green Building Council promote measurement science, but they rely on organizations such as NIST to develop that science. While research is being carried out internationally, particularly in the European Union, only NIST is devoted to developing the measurement science specifically for the U.S. building sector.

Why NIST? The program supports the measurement science needs identified by the NSTC Subcommittee on Buildings Technology Research and Development, specifically in the areas of performance metric integration, product and material life cycle assessment, and indoor environmental quality. The work carried out in this program aligns with the EL mission by promoting U.S. innovation and industrial competitiveness by anticipating and meeting the measurement science and standards needs related to clean-energy technology, a priority area identified by OMB and OSTP for FY2014. The research builds upon EL's core competency in energy-efficient and intelligent operation of buildings with healthy indoor environments. The research also supports EL's strategic goal of Sustainable and Energy-Efficient Materials and Buildings, specifically by enabling energy-efficient buildings. NIST's combination of technical expertise in building energy use, combustion, indoor air quality, building materials, and building economics creates a unique team that can address the interconnected issues that affect the evaluation of high-performance buildings.

What is the new technical idea? To help the U.S. building industry achieve net-zero energy, high-performance buildings, NIST will focus on four thrust areas. The first thrust examines whole building metrics, while the final three thrusts view the building from a component perspective.

Thrust 1: Whole Building Metrics. The first thrust will view the building as a complete system, evaluating the energy consumption, cost-effectiveness, greenhouse gas emissions, and overall sustainability of the whole building. Work in this area will build on that from the other thrust areas and will ensure that the goals of achieving energy savings while meeting the constraints of sustainability, economics, and indoor environmental quality are met.

Thrust 2: Building Envelope Load Reduction. Space conditioning, consisting of heating, cooling, and introduction of outdoor air, is the largest energy consumer in buildings. In the U.S., it accounts for 40 % of primary energy consumption in commercial buildings and 43 % in residential buildings.[7] Space conditioning is required because of heat loss or gain through the building envelope, unwanted infiltration of outside air, or buildup of contaminants within the building. The first step in reducing energy intensive space conditioning is by reducing the need for it, and NIST will work to minimize this need by evaluating the insulating capabilities of the envelope and assessing unwanted infiltration as well as controlled flows of fresh air across the envelope.

Thrust 3: Equipment Efficiency. Once building loads are reduced, the next step towards net-zero energy buildings is through the use of efficient equipment. In this program, NIST will focus on space heating and space cooling, as these end uses are the largest consumers of primary energy in buildings. NIST will improve the design and installation of vapor compression heat pump systems for energy efficient buildings and will evaluate the effectiveness of low global-warming potential alternatives to hydrofluorocarbon refrigerants. An affiliated project in NIST's Physical Measurement Laboratory will assess the quality of solid-state lighting, a technology that DOE projects can reduce lighting electricity consumption by one-fourth[8]. NIST addresses other equipment through partnerships with other agencies, specifically through DOE-sponsored work on appliances.

Thrust 4: On-Site Energy Generation. After loads are reduced and efficient equipment is installed, the remaining energy must be supplied by on-site generation to meet the goal of net-zero operation. NIST will address measurement science issues associated with photovoltaics, which are currently the predominant means of harnessing renewable energy for building use.

Why can we succeed now? Recent industry and government emphasis on building energy efficiency and CO_2 emission reductions make the goals pursued in this program extremely timely and relevant. Several factors contribute to increasing the chances for success at the current time. First, sensor technology has advanced rapidly over the last decade, particularly through the

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[7] U.S. Department of Energy, "Buildings Energy Data Book" March 2011 http://buildingsdatabook.eren.doe.gov/default.aspx

[8] U.S. Department of Energy, "Energy Savings Potential of Solid-State Lighting in General Illumination Applications" http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/backgrounder_energy-savings-forecast.pdf

incorporation of wireless communications, thereby providing new measurement capabilities to determine building performance. Computing capabilities have likewise advanced to enable better predictions of building performance. Next, several cutting edge facilities have been or are being developed at NIST that will enable researchers to better understand building performance. These facilities include the Net-Zero Energy Residential Test Facility, a new thermal insulation test apparatus, a volatile organic compound test facility, an updated National Fire Research Laboratory, a Green Concrete Performance Laboratory, and an updated integrating sphere for accelerated aging of photovoltaics. Finally, the addition of new staff who bring expertise in areas such as economics, photovoltaics, and building modeling complement the experienced staff who have led national efforts toward improving energy efficiency, indoor air quality, and cost-effectiveness of building performance.

What is the research plan? The research plan will follow the four thrusts described previously.

Thrust 1: Whole Building Metrics. Knowledge of the overall sustainability of buildings and the economics of high-performance buildings will be advanced through the evaluation of the cost-effectiveness of energy code compliance, by developing databases of the environmental performance of building technologies, and through the development of online tools for evaluating sustainability. Novel methods to measure energy consumption in residences will be explored to provide feedback to occupants, identify retrofit opportunities, and create guidelines for measurement of net-zero energy home performance. Greenhouse gas (GHG) emissions will be addressed through the development of a testbed with a well-characterized source of GHG for use in calibrating instrumentation and through computer modeling to predict the source strength of distributed sources of emissions. A key contributor of GHG emissions associated with buildings occurs during the construction phase, with concrete accounting for approximately 125 million metric tons of CO_2 equivalents in the U.S.[9] NIST will develop tools to promote incorporation of more industrial by-products in cement mixtures to reduce those GHG emissions.

Thrust 2: Building Envelope Load Reduction. NIST will aim to minimize the unwanted heat losses and gains through the building envelope by developing reference materials that allow precise evaluation of thermal insulation and by investigating the missing measurement science that impedes the use of advanced insulation. Work will also address another key energy flow across the building envelope, that being air infiltration and the introduction of ventilation air. NIST will develop the measurement science necessary to determine required ventilation rates by developing reference materials that can be used to assess emissions from building products and measurement methods to characterize the most important contributors to adverse indoor air quality. NIST will integrate the EnergyPlus building energy simulation software with the CONTAM airflow and contaminant transport software to permit analysis of impacts of energy efficiency measures on indoor air quality. Design tools will be developed that help optimize ventilation strategies such as natural and hybrid ventilation that provide outdoor air with minimal energy use.

Thrust 3: Equipment Efficiency. NIST will focus specifically on vapor compression (used for heating and cooling) equipment. In particular, research will be conducted to provide industry greater understanding of system performance as buildings become more efficient and will

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[9] US Environmental Protection Agency, "Quantifying Greenhouse Gas Emissions from Key Industrial Sectors in the United States," May 2008.

address industry challenges in modifying equipment in light of looming regulations on refrigerants. As building envelopes become more efficient, heating and cooling systems must manage smaller thermal loads, but moisture buildup and the need to mechanically ventilate buildings impose alternative demands on the systems. NIST will work with an International Energy Agency annex to develop guidelines for heat pumps and air conditioners in energy-efficient buildings. Potential regulations that limit refrigerants due to their global warming potential will force manufacturers to adopt alternative refrigerants for use in heat pumps. To optimize those systems, designers need to understand the heat transfer performance of the refrigerants in heat exchangers and the thermodynamic performance as they move through the refrigeration process. NIST will capture these key data for use by manufacturers in developing equipment meeting the environmental regulations.

Thrust 4: On-Site Generation. NIST will promote the use of photovoltaics (PV) through experiments aimed at improving predictive models of their performance, development of techniques to better rate PV performance, and generation of the measurement science to assess the service life of polymers used in the construction of PV modules. The first effort will involve the detailed monitoring of four PV systems on the NIST campus, with the data being fed to a national database that will be used to assess model performance. The second effort will focus on decreasing the uncertainty in PV ratings by improving the critical measurement of PV spectral response, a measurement that currently leads to uncertainties of 10-30 % in the rating of new PV technologies. The third effort will provide information and standards on the lifetime of polymers in PV systems through accelerated aging tools and model development that will help assess long-term performance.

How will teamwork be ensured? The challenges in achieving net-zero energy, high-performance buildings require contributions from a wide variety of disciplines. To encourage collaboration among project teams, the program manager will hold quarterly meetings with project leaders and the Designated Goal Liaison to solicit input on the key measurement challenges needed to achieve net-zero energy high-performance buildings, to explore opportunities for synergistic interaction, and to implement an effective technology transfer strategy to achieve the program objective. The program manager will meet regularly with the program managers of the other three programs in the Strategic Goal to ensure a unified approach to achieving that goal. To coordinate activities with DOE and the national labs, program managers meet periodically with research managers from DOE's Building Technologies Program. Project leaders will identify the key researchers at other locations doing complementary work.

ACCOMPLISHMENTS and IMPACT

R&D Impact:

- **Top Journals:** Energy and Buildings (Impact Factor [IF] = 2.386); Building and Environment (IF = 2.4); Indoor Air (IF = 2.55); Solar Energy (IF = 2.475); Journal of HVAC&R Research (IF = 0.683); International Journal of Refrigeration (IF = 1.817)

- **Research Outcomes:**
  • Liu, Zhe, Reed, Cynthia H., Cox, Steven, Little, John, Persily, Andrew K. "Diffusion-controlled Reference Material for VOC Emissions Testing: Impact of Temperature and Humidity." Submitted to *Indoor Air*
  • Reed, Cynthia, Nabinger, Steven J., Emmerich, Steven J. "Predicting Gaseous Air Cleaner Performance in the Field" Submitted to *Indoor Air*
  • Lorenzetti, David M., Dols, William S., Persily, Andrew K., Sohn, Michael D. "A stiff variable time step transport solver for CONTAM." Submitted to *Building and Environment*
  • Brown, S J., Domanski, Piotr A. Dr., "Assessment of Alternative Cooling Technologies." Submitted to *Journal of Refrigeration*

- **Potential Research Impacts:** no currently approved manuscripts awaiting publication.

- **Realized Research Impacts:**
  Project: Metrics and Tools For Sustainable Buildings
  • Kneifel, Joshua. "Life-cycle carbon and cost analysis of energy efficiency measures in new commercial buildings." Energy and Buildings 42 (2010): 333-340. Times cited: 24
  • Kneifel, Joshua. "Beyond the code: Energy, carbon, and cost savings using conventional technologies." Energy and Buildings 43 (2011): 951-959. Times cited: 1

  Project: Novel Working Fluids for High-Efficiency HVAC&R Equipment
  • Kedzierski, M. A. "Viscosity and Density of Aluminum Oxide Nanolubricant." International Journal of Refrigeration 23 (2011): 3144-3151. Times cited: 0
  • Kedzierski, M. A. "Effect of Al2O3 nanolubricant on R134a pool boiling heat transfer." International Journal of Refrigeration 34 (2011): 498-508. Times cited: 8
  • Kedzierski, Mark A. "Viscosity and density of CuO nanolubricant." International Journal of Refrigeration 35 (2012): 1997-2002. Times cited: 0

  Project: Design and In-Situ Performance of Vapor Compression Systems
  • Yashar, David, Wojtusiak, Janusz, Kaufman, Kenneth, et al. "A dual-mode evolutionary algorithm for designing optimized refrigerant circuitries for finned-tube heat exchangers." HVAC&R Research 18 (2012): 834-844. Times cited: 0
  • Yashar, David, Domanski, Piotr, Cho, Hong Hyun. "An experimental and computational study of approach air distribution for a finned-tube heat exchanger." HVAC&R Research 17 (2011): 76-85. Times cited:1
  • Martinez-Ballester, Santiago, Corberan, Jose-M., Gonzalvez-Macia, Jose, Domanski, Piotr. "Impact of classical assumptions in modelling a microchannel gas cooler." International Journal of Refrigeration 34 (2011): 1898-1910. Times cited: 3

  Project: Performance Measurements of Photovoltaics and Distributed Generation Systems
  • Boyd, Matthew. "Analytical model for solar irradiance near a planar vertical diffuse reflector - Formulation, validation, and simulations." Solar Energy 91 (2013): 79-92. Times cited: 0

Project: Ventilation and Indoor Air Quality in High-Performance Buildings

• Ng, Lisa C., Musser, Amy, Persily, Andrew K., et al. "Multizone airflow models for calculating infiltration rates in commercial reference buildings." Energy and Buildings 58 (2013): 11-18. Times cited: 0

• Emmerich, Steven J., Polidoro, Brian, Axley, James W. "Impact of adaptive thermal comfort on climatic suitability of natural ventilation in office buildings." Energy and Buildings (43): 2101-2107. Times cited: 5.

• Emmerich, Steven J., Heinzerling, David, Choi, Jung-il, et al. "Multizone modeling of strategies to reduce the spread of airborne infectious agents in healthcare facilities." Building and Environment 60 (2013): 105-115. Times cited: 0

• Sundell, J., Levin, H., Nazaroff, W. W., et al . " Ventilation rates and health: multidisciplinary review of the scientific literature." Indoor Air 21 (2011): 191-204. Times Cited: 16

• Ng, Lisa C., Musser, Amy, Persily, Andrew, et al. "Indoor air quality analyses of commercial reference buildings." Building and Environment 58 (2012): 179-187. Times cited: 2

• Persily, Andrew K., Emmerich, Steven. "Indoor air quality in sustainable, energy efficient buildings." HVAC&R Research 18 (2012): 4-20. Times cited: 0

• Wang, Liangzhu (Leon), Dols, W. Stuart, Emmerich, Steven. "Simultaneous solutions of coupled thermal airflow problem for natural ventilation in buildings." HVAC&R Research 18 (2012): 264-274. Times cited: 1.

• Wang, Liangzhu (Leon), Dols, W. Stuart, Chen, Qingyan. "Using CFD Capabilities of CONTAM 3.0 for Simulating Airflow and Contaminant Transport in and around Buildings." HVAC&R Research 16 (2010): 749-763. Times cited: 1

Project: Contaminant Control in High-Performance Buildings

• Wei, Wenjuan, Greer, Sylvester, Howard-Reed, Cynthia, et al. "VOC emissions from a LIFE reference: Small chamber tests and factorial studies." Building and Environment 57 (2012): 282-289. Times cited: 0

• Reed, Cynthia H., Liu, Zhe, Benning, Jennifer, et al. "Developing a Diffusive Reference Material for VOC Emissions Testing: Pilot Interlaboratory Study." Building and Environment 46 (2011): 1504-1511. Times cited: 5

Project: Development of Testbed for Wireless Sensor Network Use in Buildings

• Jang, W. S., Healy, W. M. "Wireless sensor network performance metrics for building applications." Energy and Buildings 42 (2010): 862-868. Times cited: 8

Impact of Standards and Tools:

- **Technology Transfer Outcomes:**
    - Net-Zero Energy Residential Test Facility completed for use by industry in assessing technologies for achieving net-zero energy status. (*Measuring Performance of Net-Zero Energy Homes*, FY13)

- EVAP-COND/ISHED software made publicly available to allow air conditioner and heat pump manufacturers to optimize the design of heat exchangers (*Design and In-Situ Performance of Vapor Compression Systems*, FY13)
  Available at http://www.nist.gov/el/building_environment/evapcond_software.cfm
- Reference VOC source developed which is to serve as a NIST Standard Reference Material (*Contaminant Control in High-Performance Buildings*, FY12)

- **Potential Technology Transfer Impacts:**
  - ASHRAE Standard 189.1: Standard for the Design of High-Performance, Green Buildings Except Low-Rise Residential Buildings chaired by NIST staff *(Ventilation and Indoor Air Quality in Low-Energy Buildings* project, FY13)
  - Climate Suitability Tool developed to identify opportunities for building designers to use natural or hybrid ventilation to reduce energy consumption in buildings (*Ventilation and Indoor Air Quality in Low-Energy Buildings* project, FY12)
    Available at at http://www.bfrl.nist.gov/IAQanalysis/software/CSTdesc.htm
  - LoopDA software developed to provide building designers a tool to size openings for natural ventilation. (*Ventilation and Indoor Air Quality in Low-Energy Buildings* project, FY12)
    Available at http://www.bfrl.nist.gov/IAQanalysis/software/LOOPDAdesc.htm

- **Realized Technology Transfer Impacts:**
  - CONTAM multizone airflow and contaminant transport analysis software used by building designers to assess ventilation effectiveness and indoor air quality. (Latest version part of *Ventilation and Indoor Air Quality in Low-Energy Buildings* project, FY13)
    Available at http://www.bfrl.nist.gov/IAQanalysis/CONTAM/index.htm
  - CYCLE_D software and Standard Reference Database 49 used by designers of vapor compression cycles with alternative refrigerants (Latest version part of *Novel Working Fluids for High-Efficiency HVAC&R Equipment* project, FY12)
    Available at http://www.nist.gov/srd/nist49.cfm
  - NIST-issued Standard Reference Materials for Thermal Insulation mandated by law to be used by insulation industry to meet Federal Trade Commission labeling rules (*Measurement Techniques for Advanced Insulation*, latest SRM issued FY11)
  - The BEES (Building for Environmental and Economic Sustainability) software provides building designers a powerful technique for selecting cost-effective, environmentally-preferable building products. (Latest version part of *Metrics and Tools for Sustainable Buildings* project, FY10)
    Available at http://www.bfrl.nist.gov/IAQanalysis/CONTAM/index.htm
  - ASHRAE Standard 62.2, ventilation standard for residential buildings which was chaired by NIST staff, forms the basis for ventilation requirements in model codes (*Ventilation and Indoor Air Quality in Low-Energy Buildings*, FY10)

Other: As the first line in promulgating the knowledge achieved, staff will write technical articles in leading journals and present findings at relevant conferences. Software will be developed and made publicly available to practitioners, most notably in the areas of economics and sustainability, vapor compression systems, and indoor airflow. Standard practices and guidelines will provide tools for the concrete industry to increase the use of industrial by-products in the manufacture of cement. Measurement knowledge gained in the areas of thermal insulation, product emissions, and photovoltaics will be transferred in the form of standard reference materials and measurement services. Additional measurement services may emerge from work on greenhouse gas emissions. NIST staff will provide critical technical contributions to standards development, particularly through ASHRAE and ASTM International, and will provide tools to improve standards or accelerate their adoption. When appropriate, researchers will seek patents on technologies that may find more widespread use through such protection and will pursue CRADAs with companies to help advance knowledge and standards development in particular industry sectors.

Recognition of EL:

- The team that was responsible for design and monitoring of the Net-Zero Energy Residential Test Facility was awarded the Department of Commerce Energy and Environmental Stewardship Award in the "Lean, Clean, and Green" category. (2013)
- Brian Dougherty was part of a NIST team that was awarded the Department of Commerce Energy and Environmental Stewardship Award in the "Renewable Energy" category for his design contributions to the NIST Photovoltaic Arrays. (2013)
- Piotr Domanski received the Wilbur T. Pentzer Achievement and Leadership Award from the U.S. National Committee of the International Institute of Refrigeration. (2012)
- Xiaohong Gu received the Best Technical Poster Award at the 2012 NREL Photovoltaic Reliability Workshop.
- Steven Emmerich received the 2012 ASHRAE Environmental Health Award for his efforts in indoor air quality.
- Robert Zarr was awarded the 2011 Thermal Conductivity Award by the International Thermal Conductivity Conference.
- Brian Dougherty was part of a NIST team that was awarded the 2011 Federal Energy Award for installation of photovoltaics on the NIST campus.
- Barbara Lippiatt received the 2010 GreenGov Presidential Award for her work on the BEES software tool that measures the environmental performance on building materials.