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

Program Manager(s): William Healy 301 975 4922, Piotr Domanski

Strategic Goal: Sustainable and Energy-Efficient Manufacturing, Materials, and Infrastructure

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

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 among its goals for the 2013 budget to "Support American Leadership in Clean Energy," "Reduce Building Energy Use," and "Invest in Regional and Community Planning Efforts for Sustainable Development." [1] To reduce dependence on energy imports while curbing greenhouse gas emissions, the building community has embraced

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[1] White House Office of Science and Technology Policy, available at http://www.whitehouse.gov/sites/default/files/microsites/ostp/fy2013omb_ee.pdf

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 new technologies should be cost-effective, and new approaches should be sustainable from a life-cycle point-of-view.

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

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[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.

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 to "Support American Leadership in Clean Energy" and "Reduce Building Energy Use" as identified by OMB and OSTP as priorities for FY2013. 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 Manufacturing, Materials, and Infrastructure, 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

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

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 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 and micro-cogeneration, which generates electricity onsite and provides heat for space or water heating.

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 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, a variable capacity chiller system, an updated National Fire Research Laboratory, and an updated integrating sphere for accelerated aging. 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. Computer simulation of prototype

[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

residences will be carried out to guide standards development by assessing the variability in model predictions. NIST will initiate such a standards effort for high-performance residential buildings through ASHRAE. 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. To improve vapor compression systems, tests will be conducted to optimize the performance of heat exchangers, and artificial intelligence-based system optimization tools will be developed. NIST will also focus on the working fluids within vapor compression systems, by evaluating the heat transfer properties and system performance of next-generation refrigerants with a low global warming potential and by investigating potential efficiency and cost improvements of chillers using modified lubricants. Even when well designed, systems will only perform as expected if they are installed correctly, so NIST will develop the measurement science to ensure that these systems are installed to achieve maximum efficiency.

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

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

in PV systems through accelerated aging tools and model development that will help assess long-term performance. In addition to PV, performance of micro-cogeneration equipment will be studied. NIST will lead a standards development effort through ASHRAE that will complete a test method to accurately capture the performance of these systems in their intended applications.

How will teamwork be ensured? The challenges in achieving net-zero energy, high-performance buildings require contributions from a wide variety of disciplines. Each of the component projects relies on a team of experts from both within and outside NIST, and regularly scheduled meetings of those teams are included in all project plans. For example, the team working on the new Net-Zero Energy Residential Test Facility meets weekly to plan instrumentation and automation efforts. To encourage collaboration among project teams, the program manager will hold quarterly meetings with project leaders 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 standards strategy to achieve the program objective. 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.

What is the impact if successful? Griffith et al.[10] estimate that energy use intensity in commercial buildings can be reduced 30 % through increased implementation of insulation, new lighting technologies, and efficient heating, ventilating, and air conditioning equipment; the measurement science developed in the areas of load reduction and equipment efficiency in this program will enable these improvements. To achieve net-zero operation, however, it is estimated that renewable energy will need to supply up to 50 % of the remaining energy requirements, and the program's efforts in on-site generation will provide the measurement science to meet this objective. The work carried out on whole building metrics will promote standards development and adoption. Currently, less than half of states have adopted the most recent energy construction codes, with eleven states having no code whatsoever. Adoption of the most recent commercial building code would result in an increase in efficiency of 40 % over standard levels present prior to 1999. NIST tools will clarify the cost-effectiveness of code adoption for code officials. In addition to the energy and emissions associated with the operational phase of buildings, it is estimated that substitution of industrial by-products for up to 35 % of portland cement can reduce the embodied energy and associated greenhouse gas emissions of concrete by one half. Finally, efforts to improve energy efficiency in buildings have often neglected indoor air quality. NIST will enable the rigorous analysis of IAQ along with energy by teaming with developers of the nation's key energy modeling software to incorporate proper air flow and contaminant modeling.

NIST has a strong history of achieving impact in the building industry. NIST thermal insulation reference materials form the basis of the measurement chain to ensure expected energy savings. Test methods developed at NIST form the basis of ratings that apply to covered appliances in buildings. Software developed by NIST is used by heating and air-conditioning equipment manufacturers to improve design of their products, while the CONTAM airflow and

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[10] Griffith, B., Long, N., Torcellini, P, Judkoff, R., Crawley, D., Ryan, J. 2007. "Assessment of the Technical Potential for Achieving Net Zero-Energy Buildings in the Commercial Sector" NREL Report No. NREL/TP-550-41957.

contaminant modeling program is widely used by designers to predict IAQ. NIST's work has resulted in ASHRAE standards that yield improved IAQ in buildings. Efforts by the Applied Economics Office have resulted in a leading environmental assessment software tool (BEES) that is used by practitioners and government agencies, and key work by NIST has been adopted into numerous ASTM building economics standards used by the construction industry.

What is the standards strategy? To achieve the objective of the program, NIST will participate in standards activities related to the design of new buildings, the retrofit of existing buildings, and the performance of building components and systems.

The sector of the building industry that is involved in efforts to move towards net-zero energy, high-performance buildings is represented by ASHRAE, an organization that includes builders, equipment manufacturers, building operators, building designers, academics, researchers, and government officials. Other key organizations include ASTM International and the International Code Council (ICC). NIST's key role is in providing critical technical contributions to clarify the most sustainable approaches toward increasing energy efficiency. Of note, NIST facilities are used as part of the development of standard methods of test to rate energy efficiency of equipment and emissions to validate that the standard accomplishes its intended result. Additionally, the program provides software tools to accelerate standard development and adoption by building code officials.

For new commercial buildings and major retrofits of commercial buildings, NIST will provide technical support to the committee developing ASHRAE Standard 90.1 (version 2013), which is the standard most adopted in the U.S. for minimum efficiency. To look beyond the minimum efficiency standard toward net-zero energy high-performance buildings, however, NIST will target its activities toward the more ambitious ASHRAE Standard 189.1, which aims for a 30 % improvement in energy efficiency over Standard 90.1 while considering other high-performance criteria such as indoor air quality and sustainability. NIST will serve in a leadership role on this committee to help align the research from the program to address critical technical questions that arise in the standards process. A new version of this standard is expected in 2013. In a parallel effort, a NIST staff member now serves in a leadership position on the ICC's committee developing the International Green Construction Code to ensure that the program activities are represented in that venue.

For the design of new residential buildings, NIST will work with ASHRAE and other key stakeholders to initiate an effort to develop a standard for the design of high-performance, green residential buildings. For residential retrofits, the program will commission a study to map the standards landscape and identify gaps that could be addressed by NIST. Additionally, NIST will conduct round-robins of energy audits to demonstrate differences among various standard protocols.

While contributions to whole building standards are important, it should be noted that these standards rely on methods of test and other measurement standards of building components and systems. NIST facilities and personnel serve a unique role in contributing to these efforts, particularly in developing standard methods of test to assess performance. By engaging with industry stakeholders, NIST staff will identify opportunities to offer measurement services or develop reference materials that will help those stakeholders determine conformance to standards.

How will knowledge transfer be achieved? 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 and product emissions will be transferred in the form of standard reference materials and measurement services. Additional measurement services may emerge from work on photovoltaics and 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.

MAJOR ACCOMPLISHMENTS

Outcomes:

- Completed design and construction of Net-Zero Energy Residential Test Facility
- In conjunction with NIST Office of Facilities and Property Management, completed design and instrumentation of four campus photovoltaic systems totaling 700 kW of capacity
- Held workshop and completed roadmap entitled "Measurement Science Roadmap for Net-Zero Energy Buildings: Workshop Summary Report"[vi]. Available at http://www.energetics.com/news/Documents/NetZeroEnergyBuildings.pdf
- Online version of the Building for Environmental and Economic Sustainability software for selecting cost-effective, environmentally-preferable building products. Available at http://www.nist.gov/el/economics/BEESSoftware.cfm
- Published online Climate Suitability Tool to help building designers identify opportunities for using natural or hybrid ventilation to reduce energy consumption in buildings. Available at http://www.bfrl.nist.gov/IAQanalysis/software/CSTdesc.htm
- Published online software, LoopDA, for building designers to size openings for natural ventilation. Available at http://www.bfrl.nist.gov/IAQanalysis/software/LOOPDAdesc.htm
- Developed online software tool, EVAP-COND/ISHED, that simulates and optimizes the performance of finned-tube heat exchangers. Available at http://www.nist.gov/el/building_environment/evapcond_software.cfm
- Completed development of new standard reference material (SRM 1450d) for the thermal properties of insulation.
- Developed candidate reference material for testing the VOC emissions of materials
- Constructed new test facilities, including: product emissions testing chamber, photovoltaic spectral response laboratory, mini-breadboard heat pump, chiller evaluation rig
- Contributed leadership in developing and revising ASHRAE Standards 62.1 and 62.2, ventilation standards for commercial and residential buildings, respectively.
- Led the development of standards through ASTM Committee E06.81 for evaluating the economics of energy measures in buildings
- Worked with leading architects and engineers to develop R&D plan for sustainability tool as documented in report: "Industry Needs Workshop: Metrics and Tools for

Sustainable Buildings: Summary Report" Available at
http://www.nist.gov/manuscript-publication-search.cfm?pub_id=907857

Recognition of EL:

- Xiaohong Gu received the Best Technical Poster Award at the 2012 NREL Photovoltaic Reliability Workshop.
- William Healy, Tania Ullah, and John Roller received a 2011 ASHRAE Technical Paper Award.
- 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 of buildings materials.
- A team of EL researchers received the 2009 DOC Silver Medal for their efforts to develop test methods to rate the energy efficiency of appliances.