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Technical Research Needs for Sustainable Buildings: Results From a Multidisciplinary NSF Workshop

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TECHNICAL RESEARCH NEEDS FOR SUSTAINABLE BUILDINGS:
Results from a Multidisciplinary NSF Workshop

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ABSTRACT

This article describes research needs for sustainable buildings as defined in a July 2009 National Science Foundation-sponsored workshop. This workshop brought together building researchers with researchers in the areas of distributed renewable energy and multifunctional materials to engage their expertise and identify overlapping research needs and opportunities. An overview of sustainable building design provided the broad context for discussion. This overview was followed by focused presentations in building control systems, advanced building envelopes, and systems and process integration. In addition, presentations on distributed renewable energy and multi-functional materials supported the participants in outlining and generating research needs that connect the topic areas. The primary outcome from this part of the workshop was the identification of key sustainable building research needs in: transformative measurements; passive strategies; regional solutions and living labs; systems integration; storage and cascades; adoption of international advances; and implementation and market transformation. These needs, along with associated technical challenges and potential impacts, are described in this paper to guide sustainable building research.

KEY WORDS

research needs, measurement, passive strategies, regional solutions, systems integration, implementation, market transformation

INTRODUCTION

Progress towards true environmental, social, and economic sustainability, in which the needs of the present are met without compromising the ability of future generations to do the same (Brundtland 1987), must include transformative advances in the building sector. Buildings in the U.S. are responsible for approximately 40% of the energy used and CO_2 generated nationally, more than the entire transportation sector (US Department of Energy 2007). Making these necessary transformative advances will require concerted efforts among and between a range of technical research communities including those with expertise in buildings, material science, physics, and the social sciences. Consequently, a need exists for a technical research agenda to outline the most pressing issues to allow these communities to work together to address them.

To address this need, the National Science Foundation (NSF) convened a July 2009 workshop to bring the necessary disciplines together to encourage collaboration among researchers in building science, distributed renewable energy and multifunctional materials. The purpose of this workshop was to identify sustainable building research needs and opportunities. This paper summarizes the presentations from this workshop, emphasizing common themes, the current status of technologies, and the most urgent breakthroughs needed to enable major advances in sustainable buildings.[1] This paper then describes the technical research needs for sustainable buildings identified through the workshop presentations and discussions. These research needs should inform and coordinate the efforts of sustainable building researchers, and help researchers from other areas, including distributed renewable energy

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and multifunctional materials, identify important technical challenges in sustainable building research that are beyond their normal areas of activity.

BACKGROUND

A number of publications have outlined sustainable building research agendas. For example, Jorge Vanegas, a leading thinker in sustainable buildings, outlines a "Roadmap and principles for built environment sustainability" (Vanegas 2003) and a leading construction researcher, Ray Levitt, makes sustainability the centerpiece of his discussion of "Construction engineering and management research for the next 50 years" (R. E. Levitt 2007). The United States Green Building Council outlines "*A National Green Building Agenda,*" which focuses on the next required steps to make transformative gains in green building (USGBC Research Committee 2008), and the National Science and Technology Council emphasizes the need to achieve net-zero energy sustainable buildings in their "*Federal Research and Development Agenda for Net-Zero Energy, High-Performance Green Buildings*" (Committee on Technology 2008).

While there are areas of overlap with these valuable research agendas for sustainable buildings, the research needs identified at the workshop and discussed in this paper emphasize technical contributions that specifically require science and engineering advances central to NSF's mission. In particular, the workshop sought to highlight research needs in which the distributed renewable energy and multifunctional materials research areas can contribute to sustainable buildings. These research areas were emphasized to increase the chance that recent and future advances in these areas are applicable to needs in sustainable building research.

METHOD—WORKSHOP LOGISTICS AND SUMMARY

Workshop participants identified technical research needs in sustainable building through the series of formal presentations and facilitated discussions outlined in Table 1. The first group of presentations covered "sustainable building infrastructure," with focused presentations on control networks, building envelopes (e.g. roof, walls, windows), and integration of building systems and processes. The second group of presentations covered "distributed renewable energy," focusing specifically on small-scale wind, organic solar, and biomass. The final group of presentations covered "multi-functional materials," focusing specifically on electroactive, energetic, and

TABLE 1. Workshop flow, topics and speakers.

Topic	Speaker(s)
Introduction	Larry Bank (NSF), George Lesieutre (Penn State)
Sustainable Building Infrastructure	Vivian Loftness (Carnegie Mellon University)
Controls	Gregor Henze (Colorado)
Envelope	David Sailor (Portland State)
Integration of processes and systems	David Riley (Penn State)
Discussion	Moderator: David Riley
Distributed Energy	Jane Davidson (Minnesota)
Small Wind	Ian Hiskens (Michigan)
Solar/PV	Sean Shaheen (Denver)
Biomass	Scott Turn (Hawaii/Manoa)
Discussion	Moderator : Cengiz Camci (Penn State)
Working Lunch	Three area groups confer with attendees
Multi-functional Materials	Kanti Jain (Illinois)
Electroactive	Susan Trolier-McKinstry (Penn State)
Energetic	Wilson Chiu (Connecticut)
Structural	Michael Lepech (Stanford)
Discussion	Moderator: Lesieutre
Wrap-up Discussion	Moderators

structural materials. Facilitated discussion among workshop participants took place at the end of each group of presentations, during lunch, and at the conclusion of the workshop. Presentations are summarized and synthesized in this section, while the research needs identified are outlined in the following "Results" section.

Sustainable Building Infrastructure

To guide discussion of technical research needs in sustainable buildings, a vision for buildings of the future was first presented. These buildings will be a regionally appropriate celebration of place that are energy, material, and water effective and also support the activities of the individuals and groups which occupy them. Improvements include reduced absenteeism and sick building syndrome symptoms, and improved productivity and task performance. These buildings will use passive[2] conditioning whenever possible, and when active conditioning is required, will apply "cascades" where resources such as energy and water are used more than once. These buildings will be designed for long life, and for change, with dynamic layouts and the ability to accommodate technological innovations and design for disassembly. These buildings will also contribute to the restoration of land, air, water, and energy.

Recommended design guidelines for achieving this future vision were presented and are listed in Table 2. Many of these guidelines are linked to technical research needs. For example, guideline number eight in the "Enclosure Systems" category is to "Maximize enclosure integrity and material sustainability." The possibilities for designers related to this guideline can be expanded with research in this area.

In addition to the design guidelines, the following themes were prominent in the overview presentation:

- There is a tremendous opportunity for *immediate* improvement with more widespread adoption of cost-effective, combined high-performance and passive strategies (Loftness et al. 2001). For example, lighting can be made more sustainable with high-performance strategies such as occupancy sensors and more efficient light sources (e.g. bulbs). Combining these high-performance strategies with passive conditioning such as daylighting, which can be enhanced with material innovations for transmission, reflection and diffusion, will result in improved lighting performance at drastically reduced energy consumption. Similar high-performance and passive combinations are possible to condition air. For example, more efficient mechanical conditioning units can be combined with strategies such as passive solar heating and natural and nighttime ventilation cooling. All of these strategies are dependent on material innovations for transmission, storage and emission.
- In sustainable work environments, occupants should be able to control their space configuration and conditioning. "Flexible grid–flexible density–flexible closure" systems should be developed so that each occupant can determine the level of their workspace enclosure as well as the location and density of heating, cooling, lighting, telecommunications, and furniture (Loftness, Brahme, and Mondazzi 2002). This need for occupant control is typically unmet by the current approach in building controls which have "central brain" systems with large control zones and minimal user controls. Instead, distributed sensors, actuators and controllers—including material property-based controllers offer major potential for significant energy savings and improved user comfort.
- By combining distributed, on-site, renewable energy sources with ultra-efficient design, buildings can generate more energy than they use.

Controls

The second sustainable building area presentation discussed the potential contributions of enhanced control strategies with the goal of improving the sustainability, in particular energy performance, of buildings and the electrical grid. Current building control systems are composed of a large number of independent, standalone, control loops generally lacking cohesion and integration, which limits performance and reliability as buildings become more complex. The adoption of low-exergy[4] systems, such as radiant heating and cooling, and mixed-mode building design that employ both natural and mechanical ventilation are examples of the increased building complexity that requires controls

TABLE 2. ABSIC/CBPD[3] high performance guidelines.

Enclosure Systems	**Lighting**
1. Maximize individual access to the natural environment 2. Maximize day lighting for task and ambient lighting 3. Maximize natural ventilation with mixed-mode conditioning 4. Minimize enclosure heat loss/heat gain 5. Design solar heat and glare control 6. Engineer load balancing and mean radiant temperature control 7. Engineer passive and active solar heating, cooling and power 8. Maximize enclosure integrity and material sustainability	1. Provide day-light as the dominant light source without glare or overheating 2. Separate task lighting from ambient lighting (or design relocatable task-ambient systems) 3. Introduce indirect-direct lighting for spatial dynamics without shadowing 4. Maximize lighting quality with high performance luminaires 5. Provide for reconfigurability with plug-and-play fixtures 6. Design for continuous change in lighting zone size and advanced controls 7. Pursue innovative lighting systems integration
HVAC	**Siting & Massing**
1. Separate ventilation systems from thermal conditioning 2. Design for natural ventilation with mixed-mode conditioning 3. Provide task conditioning and individual control 4. Design for continuous change with plug and play HVAC & controls 5. Design architecture "unplugged" for maximum efficiency and use of passive strategies 6. Engineer load balancing and radiant temperatures 7. Separate latent and sensible load management 8. Engineer 'energy cascades' power, cooling, heating with renewables 9. Create distributed, communicating, modifiable automation systems 10. Pursue innovative HVAC system integration with enclosure systems	1. Design for density and mixed use to support full-day activities 2. Design for mixed modes of transportation and pedestrian movement 3. Maximize continuous green spaces for views, work and recreation 4. Manage all water on site, with all infrastructures to be site enhancing 5. Mass for day-light and natural ventilation in all occupied spaces 6. Mass for thermal and solar effectiveness 7. Mass for constructability, durability, change and adaptive reuse 8. Maximize amenities for physical and community health
Connectivity	
1. Engineer independent plug-and-play networks—data/voice, power, security, and environmental services—with central communication 2. Design distributed cores for accessible, modifiable vertical distribution 3. Design distributed satellite closets with plug-and-play interfaces 4. Resolve integrated, reconfigurable plenum systems – ceiling or floor 5. Ensure user accessible, modifiable grid and nodes for connectivity 6. Create wiring harnesses for data/voice, power, security, environment 7. Select terminal units that provide all services in reconfigurable boxes 8. Create distributed, communicating, modifiable automation systems	

advances. Research needs exist for improvements related to system integration; energy efficiency; peak reduction potential; and thermal energy distribution and storage strategies, which can be both passive (e.g. thermal mass of walls, floors, and ceilings) and active (e.g. ice storage, chilled water storage, eutectic salts).

Advanced control strategies will use models of individidual or combined building energy systems or even whole buildings. Such model based control is one method to pursue a performance optimum (e.g. lowest energy use, lowest energy cost, carbon emissions) while maintaining acceptable indoor environmental conditions. New construction and existing building stock would benefit from model-based control that supports continuous fault detection and diagnostics and maintain the building operation close to the design intent.

Examples of model based building control are shown in Figure 1 and include **instantaneous optimal building control** that *does not consider* storage effects. Examples of this type of control include global setpoint optimization (GSO) of a chiller, cooling tower and air-handling units (Braun et al. 1989, Brandemuehl and Bradford 1999); operation of building power plants (Van Schijndel 2002), and central chilled water plant control (Ma and Wang 2009). **Predictive optimal building control** that *does consider* these storage effects, includes building thermal mass control (Henze et al. 2005), ice and chilled water storage control (Kintner-Meyer and Emery 1995), and mixed-mode building control (Spindler 2004). While the absence of storage allows for the use of time-independent equipment models, the presence of storage requires the use of time-dependent dynamic models that account for the memory associated with the building mass and its thermal response. Research needs for model-based controls include realtime model based optimal control or offline control using response surface approach, rapid modeling and continuous model tuning, separation of energy systems from building response, and verification of effectiveness.

A tremendous opportunity in model based control is to integrate commercial building operation with utility grid operation in real time, which could minimize the inefficiencies resulting from the daily variation of electrical demand on the grid. Peak loads result in high costs for inefficient peaking plants, while drastically reduced loads at night can impair efficient operation of base load power plants. Currently, demand response is used to avoid grid stress only and is not focused on unlocking supply-side efficiency potentials. Consequently, controls research is needed for automated, online, scalable technologies that continuously integrate operations of large commercial buildings with electric grid operations. Benefits of this integration include continuous demand elasticity that will moderate market prices and volatility, more efficiently dispatched generators, better use of high efficiency building energy systems, and accelerated penetration of renewables.

An alternative to a model based approach is model-free, reinforcement learning based control that improves based on its interaction with the environment, moving towards optimal efficiency while maintaining comfort. Research needs for these learning controls include implementation of hybrid (model based and model free features) learning control, model-free adaptive control of building systems, and proof of robustness and stability.

Envelope

The building envelope includes enclosure systems such as walls, windows, and roofs. The envelope plays a key role in heat loss and gain; day lighting; and infiltration of moisture, air, and sound. A number of envelope technologies are contributing to more

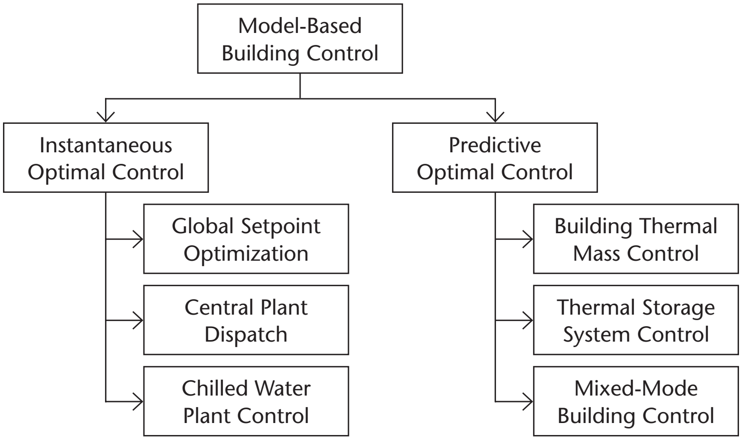

FIGURE 1. Types of model-based building control.

FIGURE 2. Example envelope technologies (from L–R: double skin façade exterior, double skin façade interior[5], cool roof, green roof[6]).

sustainable buildings, several of which are discussed here and shown in Figure 2. **Double skin facades** provide a protected cavity for shading and day lighting devices and offer energy savings as the cavity forms a thermal buffer in the winter to pre-heat air, while in the summer, the cavity vents heat from top. **Phase change materials** can smooth daily fluctuations in room temperature. These materials are solid at room temperature and when the temperature becomes warmer, the materials liquify and absorb and store heat, thus cooling the building. Conversely, when the temperature drops the material solidifies and discharges heat, warming the building. A typical embodiment of this technology is through the use of paraffin wax encapsulated in small polymer spheres. Phase change materials can be readily incorporated into wall board, concrete, and other building materials. **Cool roofs** have a high reflectance, or albedo (0.50 to 0.80) and therefore do not get as hot, which reduces the need for cooling energy and extends the life of the roof. These cooler roofs can have other benefits in the summertime such as reduction of the urban heat island effect. In the winter, however, cool roofs result in undesirable reduction of solar gain and corresponding increases in heating energy loads. Studies have concluded that the air conditioning savings of cool roofs are generally larger than the heating costs (Akbari and Konopacki, 2005). Vegetated or **Green roofs** offer similar summertime air conditioning benefits. In contrast to cool roofs, however, green roofs can also save substantial winter time heating energy (Sailor, 2008). While the cost of green roofing is typically much greater than that of conventional roofing, there is anecdotal evidence that their increased lifespan may compensate.

Research needs related to the building envelope include active and passive envelope and façade design features; integration of advanced materials to enhance envelope function, and building integrated photovoltaics and wind power. Current active design features can be expensive with long payback and uncertain maintenance costs. While this downside is not typically present for passive design features, their performance is more difficult to optimize. New materials and systems are needed that passively, or with simple control systems, change their properties in direct response to the needs of the building and its occupants. These energy minimizing envelope technologies along with building-integrated renewable energy technologies are both required for net zero energy buildings. A key challenge for future building envelopes is to appropriately integrate and optimize various energy efficiency strategies—for example, using rooftop photovoltaic panels in conjunction with green roofing.

Integration

Sustainable buildings require a holistic approach. Simply optimizing individual components will likely not produce the optimal overall solution. For example, technical integration issues, in which needs between systems in sustainable buildings must be balanced, are shown in Table 3. These integration issues are also present at the interfaces between buildings and the larger campus, city, or region. For instance, a “smart” grid requires integration between the building and energy production, energy storage, and demand response.

To assist with the required integration, collaboration tools such as building information modeling

TABLE 3. Example technical integration issues for sustainable buildings.

The need for . . .	Must be balanced with . . .
Design for passive conditioning	Building aesthetics
Day lighting	Energy transmission through windows
Natural ventilation for indoor air quality	Energy requirements to condition the ventilated air

(BIM); life cycle assessment; triple bottom line metrics; and geographic information systems are needed and can be developed further. Large advances are also possible through research that integrates building industry activities (e.g. planning, design, construction, and operation) and stakeholders (e.g. architects, engineers, contractors, and occupants) to encourage the more holistic approaches that are needed for more sustainable buildings.

Distributed Renewable Energy

A number of distributed renewable energy technologies can contribute to more sustainable buildings including: solar thermal, solar electric, small scale wind, geothermal, and urban biomass (from solid waste streams, biosolids, landfill gas, and biogas from waste-water treatment plants). Generally, solar and wind offer the largest total energy potential among the various distributed renewable energy resources, but the prevalence and effectiveness of these resources vary by region and by time. Consideration of these variations is essential to development of effective policies and research and development needs.

Currently, there are no technological constraints limiting more widespread implementation of solar thermal, solar electric, conventional geothermal, and biopower technologies. The **primary constraints are the lack of sustained incentive policies and cost competitiveness relative to other energy sources.** However, transformative advances in these technologies for distributed renewable energy present technological challenges that include:

- Materials to improve coating technologies, heat transfer structures, and thermal conductivity;
- Storage, specifically identifying, designing and developing new materials and composites for long-term, compact energy storage; and
- Research in thermochemical solar fuels[7] and CO_2 reuse

Distributed wind technology refers to turbine installations that are on the consumers' side of the utility meter or near the point of use. Currently, distributed wind is not typically cost effective because of the low cost of fossil energy, and wind's high capital and operation and maintenance costs. A number of research needs in distributed wind technology are related to its contribution to more sustainable buildings. First, current grid protection is typically designed only for power flow towards the load. Two-way flow, where wind energy is fed into the grid, requires more complex and expensive protection and metering. Second, there are also aesthetic issues and concerns over noise. Third, improvements in reliability are essential since turbines are exposed to the weather and not easily accessible. Finally, in turbine towers and foundations, improved materials and processes, such as self erecting installation and service are needed.

Multi-functional Materials

Sustainable building research needs related to multi-functional materials include low-cost solar hot water, made possible by a shift from metal and glass components to integrated systems manufactured with polymeric materials; building integrated solar thermal and electric systems; high density storage for space conditioning; and low-cost polymers for glazings and heat transfer structures. The status and needs in multifunctional materials were highlighted at the workshop through three example applications: window efficiency, mechanical energy harvesting, and self-healing composites.

Techniques for improving **window efficiency** include mechanical methods such as awnings, louvers, and blinds, which are low cost and easily available, but block light and views as well as heat. Optical methods for improving window efficiency may be passive, dynamic, or active. Passive optical methods include coatings, which are an inexpensive way to

FIGURE 3. Dynamic optical windows are clear (left image) in moderate outside temperatures and translucent (right image) in higher outside temperatures (See http://www.ravenbrick.com/).

block heat and reduce glare, but which also reduce light transmission and the availability of passive solar heat. Dynamic optical methods are those in which the transmission properties change in response to light intensity and temperature (See Figure 3). Dynamic methods are currently difficult to implement on large windows and typically make the window translucent. Active optical methods involve controlling transmission properties by electric current. These methods are currently expensive and also difficult to implement on large windows.

Materials that produce **mechanical energy** may have value in remote locations, where long-lived operation is required, but battery replacement is not an option. Current microelectromechanical energy harvesting systems operate at high frequencies, appropriate for machine tools and automotive applications. However, there is an opportunity to lower the operating frequencies of these systems to better match building vibrations.

Self-healing composites show promise in correcting the cracking due to loading that is inevitable in reinforced concrete structures. This cracking results in reduction of structural stiffness, load capacity, water tightness, and durability. Self-healing materials that reduce the need to replace concrete offer sustainability benefits including a reduced need for new cement production, which is a large contributor to global CO_2 emissions.

FINDINGS—TECHNICAL RESEARCH NEEDS

Based on the presentations and discussion at the workshop, technical research needs were outlined for sustainable buildings. These needs, summarized in Table 4, are described along with their associated technical challenges and the potential impacts that can result from addressing these needs.

Transformative Measurements

A pressing need exists to measure the **actual field performance** of various sustainable building technologies and strategies since actual performance of these buildings currently differs greatly from design predictions (Turner and Frankel 2008). Measuring actual performance is essential to inform users of the energy and environmental implications of various sustainable building technologies including passive and active solar technologies, day lighting, and green roofs.

There is an equally pressing need to improve measurement of the **true costs and benefits** of sustainable building. First-cost remains the primary decision-making driver in the building industry in part because stakeholders lack the tools to apply life-cycle costing to their projects. In addition to representing project costs and benefits over the entire life-cycle, these tools should account for economic, societal, and environmental, or "triple bottom line" costs. This more holistic view of building projects will move beyond first-cost decision making and promote more beneficial life-cycle decision making. Discussion among workshop attendees confirmed that this type of life-cycle *costing* is a necessary intermediate step prior to pursuing more detailed (and cumbersome) life-cycle *assessments*, which would estimate all of the material and energy resources and environmental emissions associated with a building.

Passive Conditioning Strategies

Passive conditioning strategies offer substantial potential benefit to sustainable buildings. While these strategies often rely on simple concepts as shown in Figure 4, significant technical challenges still exist. Material and system innovations to improve passive conditioning strategies are needed in areas such as storage, control systems, materials, and energy generation. For example, an improved understanding of the benefits and field performance of green roof systems can yield designs with optimal performance and easy maintenance. This difficulty to optimize performance is present in passive strategies from natural ventilation to mixed-mode building design

TABLE 4. Summary of workshop findings of general research needs related to buildings.

Objective	Technical challenges
Transformative measurements • Measure field performance and true costs for all energy sources (e.g. efficiency, passive, solar) • Equip stakeholders to look beyond 1st costs to **life cycle costing** with **triple bottom line** (economic, societal and environmental costs	• First cost remains the primary decision-making driver • LCA for systems is currently too ambitious as it requires an international life cycle inventory • Quantification of societal and environmental costs
Passive strategies • Pursue material and system innovations for conservation • Improve passive strategies for conditioning (storage, control systems, materials, energy generation)	• Must optimize performance across climatic regions, seasons, and time of day variations
Regional solutions (living labs) • Establish solutions that account for region-specific factors	• Tendency to strive for a single national model
Systems integration • Optimize larger systems (e.g. whole building, campuses, cities, utility grid) • Optimize systems over time/ occupancy • Establish national goals for integrated service—break single point of responsibility	• Silo'ed education & training • Fragmented industry • No feedback loops for design
Storage, "energy cascades" • Using buildings as energy storage, developing innovative storage materials solutions • Cascading 'waste' energies through all system demands with mixed use planning and load balancing	• Regulations, codes
Adoption of international advances • Encourage international partnerships in and across research and industry. • Develop a pipeline to get research and technology advances from other countries to U.S. markets	• Incentives ($) for international partners • Policy measures needed
Implementation, market transformation • Implement future advances more rapidly • Implement best practices that are already technically and economically feasible	• Lack of incentives, even disincentives for individual actors

FIGURE 4. Example passive conditioning strategies (from L–R: light shelves that block glare and reflect light deep into interior spaces[8], wind towers[9] that enable natural ventilation, and a green wall[10] that improves air quality).

to daylighting. An improved understanding of these passive strategies is essential to achieve the energy reduction necessary for net-zero energy buildings.

Regional Solutions and Living Labs

The need for regional solutions was emphasized in both the sustainable building and distributed renewable energy presentations. In both areas, optimal solutions are highly dependent on regional characteristics such as climate and material and workforce availability. For example, solar panels on a cool roof may be appropriate for a building in Phoenix, while wind turbines on a green roof are appropriate for a building in Chicago. Sustainable building research must consider these regional differences and provide guidelines that recognize regional differences in any national model or standards for sustainable buildings. To facilitate this regional focus, building research laboratories should be established in various regions, hosted by universities, to seek regionally appropriate advances and provide the essential training to produce a new generation of Ph.D. graduates who can lead future research for more sustainable buildings

Systems Integration

Systems integration is a needed focus for sustainable building research to avoid optimizing single components at the expense of larger systems. Systems integration is a key technical challenge with multiple scales and dimensions. For example, there is a need to understand and optimize the interrelationships of various systems (e.g. envelope, thermal conditioning, water, and lighting) within a building. There is also a need for research to optimize the interrelationships between buildings and larger scale systems (e.g. electric grid, campuses, and cities). For the individual building and on the larger scale, innovative control systems are needed to address the interfaces between subsystems.

Systems integration research is also needed on another dimension, between the various stakeholders (e.g. architects, engineers, contractors, owners, and occupants) and phases (e.g. finance, design, construction, use, abandonment) that comprise the fragmented U.S. building industry. Integration among these stakeholders and phases is essential to enable multi-disciplinary expertise and accomplishment. Research into contracting structures, leadership, and vertical integration of teams is needed to encourage this integration. In parallel, this issue must be addressed in education, by breaking through the siloed education and training that is the dominant paradigm in engineering and architecture.

Storage and "Cascades"

Trends towards more distributed energy sources means buildings will play an increasingly important role in providing storage and "cascades" for more efficient use of resources including energy and water. Cascades are the use of "wastes" from one process to generate inputs for another. An example of a water cascade is reuse of sink and bathwater to flush toilets and irrigate landscaping, which reduces potable water consumption. An energy cascade example is an on-site steam turbine used to generate electrical energy, with the waste heat from this generation process used to heat and cool the building through absorption and subsequent waste heat used to heat water for the building. To improve storage capabilities, research is needed into innovative materials solutions, such as the phase-change materials discussed previously. Research that identifies and enables these types of cascades in buildings has vast potential to enhance resource efficiency in the U.S.

Adoption of International Advances

All of these research needs will benefit from improved international partnerships within and across research and industry. These partnerships will allow the U.S. to adapt and use worldwide technical best practices for sustainable building. Specific policy measures and incentives for international partners will help facilitate this collaboration, but even without these measures, partners will benefit through an improved ability to get their research and technology advances to U.S. markets. These partnerships will also help the U.S. learn from policy measures that have advanced sustainable building in other countries. For example, energy prices, commitment to alternative energy, and research budgets are all policy-related factors that influence the adoption of sustainable buildings, simply consider the enormous impact that adoption incentive tariffs had on turning cloudy Germany into a solar powerhouse. Partnerships with other countries will help us understand which of these factors may be most effective in the U.S. In addition to helping the U.S. adopt worldwide best practices, these international partnerships also encourage the collaboration that is essential to address the global issues, such as climate change, that sustainability aims to address.

Implementation and Market Transformation

Implementation and market transformation is often viewed as separate from technical research advances. However, workshop participants emphasized the pressing **need for rigorous research** to improve understanding of implementation for sustainable building strategies. Workshop participants identified countless examples of strategies and technologies for more sustainable buildings that are currently technically and economically feasible, but that are not penetrating the market. Various barriers could be preventing the implementation of more sustainable strategies. One such barrier is the lack of incentive, and often disincentive, for individual actors to pursue sustainable solutions. For example, a design firm that makes an extra effort to reduce the costs of a sustainable building for their client may actually reduce their own fees if they are tied to the total project cost. Research which improves understanding of how to address these types of implementation barriers will speed adoption of current strategies and future advances for more sustainable buildings.

CONCLUSIONS

The proceedings and technical research recommendations from a multidisciplinary workshop on sustainable buildings are described in this paper, which is expected to help guide the research community by identifying urgent breakthroughs needed to enable major advances in sustainable buildings. When considering these recommendations, readers should consider that the workshop was held for NSF's directorate of engineering. As a result, most workshop participants had an engineering background, which is reflected in the technical nature of the research needs identified. Readers should also bear in mind that, while workshop presenters were selected as experts in their respective areas, time allocated for discussion did not allow complete consensus among workshop participants on the research needs identified. However, all major research needs were presented to attendees at the conclusion of the workshop with no disagreements voiced.

This workshop sought to facilitate collaboration between building researchers and their counterparts in the areas of distributed renewable energy and multifunctional materials. While this multidisciplinary approach challenged workshop organizers and attendees who were often unfamiliar with the nuances of each others' fields, the approach also highlighted research needs that might have otherwise been overlooked. For example, distributed renewable energy and building technologies both depend on climate and therefore require regional solutions, which is reflected in the recommendation for regional learning labs. Just as collaboration is a key, but often lacking, element to success in the building industry, it is also essential to addressing sustainable building research needs. To address the technical research needs for sustainable buildings that are outlined in this paper, the research community must continue to emphasize and refine their abilities in multidisciplinary collaboration.

NOTES

1. Workshop presentations are available at http://www.cfs.psu.edu/nsf09.aspx.
2. Passive conditioning integrates natural systems to help regulate characteristics of the built environment, such as temperature, humidity, and lighting. Day lighting and natural ventilation are examples of passive conditioning strategies.
3. Advanced Building Systems Integration Consortium (ABSIC) is a university-industry-government partnership to improve commercial buildings. The Center for Building Performance and Diagnostics (CBPD) in the School of Architecture at Carnegie Mellon works with ABSIC to undertake research projects, and was an NSF Industry–University Cooperative Research Center for ten years.
4. Low-exergy systems use low valued energy that can be delivered by more sustainable energy sources (e.g., ground source, heat pumps, solar collectors).
5. Façade images by Terri Meyer Boake (http://www.architecture.uwaterloo.ca/faculty_projects/terri/)
6. Image by Simon Garbut (http://en.wikipedia.org/wiki/File:Green_Roof_at_Vend%C3%A9e_Historial,_les_Lucs.jpg)
7. This involves the concentration of solar energy to provide high temperature heat for chemical reactors, heat exchangers and separators.
8. Image from: http://commons.wikimedia.org/wiki/File:LightingshelvesUSDOE.jpg.
9. Image from: http://commons.wikimedia.org/wiki/File:6-wind_tower.jpg.
10. Image from: http://commons.wikimedia.org/wiki/File:Miscellaneous_facades_in_Madrid_-_Green_wall.JPG.

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