A National Green Building Research Agenda

November 2007

USGBC Research Committee

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Cover photo: Fossil Ridge High School – Fort Collins, Colorado – LEED Silver

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About the USGBC

The U.S. Green Building Council is the nation's leading nonprofit organization composed of corporations, builders, universities, government agencies, and other nonprofit organizations working together to promote buildings that are environmentally responsible, profitable and healthy places to live and work. From its founding in 1993 to 2007, the Council has grown to more than 12,000 member companies and organizations, a broad portfolio of LEED® programs and services, the industry's Greenbuild International Conference and Expo (www.greenbuildexpo.org), and a network of 72 local chapters, affiliates, and organizing groups. The Council's vision is a sustainable built environment within a generation. For more information, visit www.usgbc.org.

About the Research Committee

USGBC's strategic goals include research – to be a resource for existing knowledge about the built environment and a driver of relevant research. The USGBC Research Committee, created in 2006, has undertaken efforts to support these objectives.

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EXECUTIVE SUMMARY

Purpose

Green building is a dynamic, rapidly growing and evolving field, driven by a confluence of rising public concerns about global climate change, cost and availability of energy sources, and the impact of the built environment on human health and performance. Design and construction of green buildings (also known as sustainable and high-performance buildings) has increased dramatically in recent years, and this expansion has given rise to a host of technical, social, economic and design questions that the building professions are not currently configured to answer. Answering these questions requires basic research and development, which in turn requires financial support, and engagement at the institutional and individual level. At present, such levels of support fall well short of what is needed to meet the challenges of a building sector that has unsustainable impacts on people and the environment. This document is intended to identify needed research, development and deployment activities and catalyze the necessary funding for achieving a transformative leap in building performance and sustainability.

The Agenda presented by the U.S. Green Building Council (USGBC) is national in scope – naturally and implicitly touching on USGBC's concerns as well as those of other organizations. It presents research topics within a framework of program areas in order to illustrate needs and recommend priorities, thus acting as a basis of discussion among researchers, funding sources and others. The Agenda is intended to become a living document that will be revised periodically as it is informed by knowledge of related activity.

Rationale

The built environment is designed to serve human needs, but it has significant negative impacts on the natural environment and on human health and performance. Green building has developed as a holistic and practical answer to the environmental and health burdens of the built environment. Green buildings depend on the continuous improvement of building processes, technologies and performance to minimize negative environmental or health impacts, and contribute to environmental restoration and sustainable resource management. Research and the deployment of its results are means to those ends. Ultimate objectives of green buildings and this research Agenda therefore include:

- climate conditions decoupled from human activities;
- stable, sustainable energy supplies;
- clean, renewable and sufficient water resources;
- restorative use of land for the long-term sustainability of habitats;

> In the U.S., buildings are responsible for:
> - 38% of carbon dioxide emissions
> - 71% of electricity consumption
> - 39% of energy use
> - 12% of water consumption
> - 40% of non-industrial waste

- restorative use of materials and assemblies that account for life-cycle impacts; and
- enhanced human safety, health and productivity in the built environment.

To match the scale and urgency of needs, greatly increased research and deployment activity is required, along with the infrastructure to enable it. Effective research will involve a complex set of interwoven man-made and natural systems, and thus necessitate collaboration among many academic and professional disciplines representing diverse areas of expertise.

Current Research Context and Overarching Needs

The USGBC Research Committee released a report in 2007, *Green Building Research Funding: An Assessment of Current Activity in the United States,*[1] finding that investment levels are extremely low relative to the urgency and magnitude of the problems they aim to solve. In fact, research on green building constituted only about 0.2% (two-tenths of one percent) of all federally funded research from 2002 to 2004 – an average of $193 million per year. These amounts are miniscule compared not only with the environmental impact of the building industry, but also with its economic impact (at $1.1 trillion, it is more than 14% of the U.S. gross domestic product). Levels of green building research pale in comparison to amounts being invested in other sectors, and green building research funding is fundamentally fragmented and thus not conducive to creating integrated solutions.

> Research on green building practices and technologies constituted only about 0.2% (two-tenths of one percent) of all federally funded research from 2002 to 2004 – an average of $193 million per year – which is clearly not commensurate with the related environmental and economic impact. Meanwhile, the field of nanotechnology receives billions of dollars in research funding from private and public sources ($1.9 billion and $1.4 billion, respectively, in the U.S. in 2005), and may be unknowingly *creating* environmental and human health problems.

Effectively meeting these challenges and seizing the opportunities presented by green building calls not simply for incremental increases of funding levels, but for ramping up to a new, comprehensive, transformational level of support. National and regional capacity-building would include investments in expertise, research center infrastructure and technology transfer.

Research Goals and Outcomes

The Agenda's research program areas are organized in four systems-based categories, summarized below, along with key illustrative topics in each area. The Research Committee recognizes that funding and research organizations will apply both their own priorities and criteria to the Agenda. The great variety in scale and type among issues renders high-level prioritization a case of "apples and oranges;" accordingly, priorities

[1] Available on-line from the U.S. Green Building Council at http://www.usgbc.org/ShowFile.aspx?DocumentID=2465

have not been identified between programs. Priority research topics are identified as such within each program area, based on the following criteria:

- short timeframe / immediate results: relatively small or easy projects that can quickly make a substantial difference;
- significant level of expected impact;
- barrier to commercialization or market adoption ;
- sequential significance: a prerequisite for other research.

The research described within is weighted toward specific outcomes, including:

- integrated systems;
- process improvement: design, delivery and operations;
- tools for design, delivery and operations;
- building materials, components and assemblies;
- metrics, benchmarks and databases;
- policy analysis and development; and standards, codes and rating systems.

The application of these outcomes is expected to deliver the next big leap toward sustainability for the built environment and provide the groundwork for further transformation.

Delivery Process and Performance Evaluation

Building Delivery and Operation Process
This program area's goal is to transform the building process from design through operations by translating research on green building design, delivery and operations technologies and processes into high-quality data, tools and new methodologies for enhanced decision making at all project stages. Of the topics in this program area, priorities include research that will: characterize and improve understanding of barriers to using multidisciplinary, collaborative and integrated building delivery systems; and analyze the National Institute of Building Science (NIBS) National Building Integrated Modeling Standard (NBIMS) for comprehensive coverage of environmentally sustainable design, construction and operation processes and practices.

Performance Metrics and Evaluation
The goal of this program is to transform the building industry's decision-making by providing high-quality data and tools for decision making and policy development through a better understanding of the financial and economic factors of sustainable design and through translation of research findings into financial outcomes. Of the topics in this program area, priorities include research that will: develop high-quality tools and supporting data for financial decision makers; and characterize the value of sustainable attributes of buildings.

Economic and Financial Value of Sustainable Buildings
The goal of this program is to transform the building industry by delineating metrics of performance across the full spectrum of environmental goals to provide feedback for further improvements in design, construction and operations. The priority topics within this program will: identify the scope and scale of performance metrics and protocols needed; and refine/develop performance measures and metrics.

Integrated Building Systems

Building Form and Envelope
The goal of this program area is to provide high-quality, energy-efficient, healthy and productive environments through the design and operation of innovative, high-performance building envelopes. Of the research topics in this program area, priorities include developing design strategies and technologies for advanced envelope components and systems; assessing the performance of advanced envelope components and systems, both seasonally and across varied climate zones; and analyzing and optimizing a continuum of centralized and personal control options for advanced envelope systems.

Lighting and Daylighting
This program area's outcomes aim to provide indoor luminous environments using fully integrated daylighting and electric lighting solutions that optimize occupant health, comfort, performance and satisfaction while minimizing energy use and power demand. Of the research topics in this program area, the priority is the development and testing of effective light/daylight control systems.

Passive, Active and Hybrid HVAC and Controls
Results of the topics within this program will reduce energy use and improve occupant comfort, health and productivity by advancing and quantifying the performance of innovative building HVAC systems and equipment, exploring integration strategies and developing design and operation guidelines. Of the topics in this program area, priorities include research that will: develop, enhance and optimize innovative, climate-based HVAC strategies (e.g., radiant systems, evaporative cooling and naturally ventilated and mixed-mode buildings); and compare, evaluate and optimize a continuum of centralized and personal control options for advanced HVAC systems.

Materials Life Cycle Assessment
This program's goal is to develop integrated assessment methodologies and standard metrics for the selection of materials that optimize building performance and minimize environmental, ecological and human health impacts. It will support current efforts and initiate new projects that work toward the development of a transparent, rigorous, national (and internationally compatible) standard for LCA. Of the topics in this program area, priorities include research that will refine life cycle impact assessment methods for the weaker categories such as indoor air quality, land use and water use.

Water Use and Management
For the goal of reducing potable water usage in the operation of buildings and grounds, priority research topics will: develop, compile and disseminate data on building-related water by end-use; and develop and test integrated water management systems.

Buildings' Interaction with Local Environments

Ecosystems and Site Design
The goal of this program is to protect and enhance local and regional ecosystems, while reducing energy and water use and atmospheric pollution through improved design and

management of built landscapes and appropriate building siting. Research identified as priorities will develop models for assessing the life cycle financial costs and benefits of all vegetative site elements; develop or improve best management practices for on-site stormwater management, including effective utilization, treatment, infiltration and storage; and analyze, develop, and optimize landscaping strategies for brownfield restoration.

Land Use, Building Location, and Transportation
Results of this program will reduce the energy, environmental and public health impacts that result from single-use zoning, the density and location of buildings, and transportation choices for getting to and from those buildings. Of the topics in this program area, priorities include research that will: develop metrics and methodologies for reporting the transportation energy intensity of buildings; and compile data on measured transportation energy intensity of buildings in order to develop baseline performance data.

<u>Buildings' Interaction with Occupants</u>

Indoor Environmental Quality: Pollutants and Stressors
This program's goal is to develop and maintain indoor environments that benefit occupant health, comfort and performance through superior indoor air quality and optimal visual, thermal and acoustic conditions. Of the topics in this program area, priorities include research that will: fill essential gaps in knowledge of indoor chemical pollutants; and develop metrics and protocols for assessing the individual and combined effects of indoor environmental conditions.

Indoor Environmental Quality: Occupant Health and Productivity
The goal of this program is to improve scientific understanding of buildings' impacts on occupant health and performance. Of the topics in this program area, priorities include research that will: develop protocols to assess public health impacts of the built environment; and conduct assessments of impacts of IEQ on human performance, including research on mechanisms and types of tasks, in different building types.

Conclusion

The requisite substantive multidisciplinary collaboration for green building begins with communicating shared research priorities to a broad audience. A critical function of this Agenda is to promote all of these research topics as priorities for relevant funding sources, and to provide disparate research entities with direction and context within a cohesive mission. As a common basis for communication, the Research Agenda will evolve as a result of the dialogue it facilitates, and catalyze subsequent leaps toward a sustainable built environment.

INTRODUCTION

Green building is a dynamic, rapidly growing and evolving field, driven by a confluence of rising public concerns about global climate change, cost and availability of energy sources, and the impact of the built environment on human health and performance. Design and construction of green buildings has increased dramatically in recent years, and this expansion has given rise to a host of technical, social, economic and design questions that the building professions are not currently configured to answer. Answering these questions requires basic research and development, which in turn requires financial support and engagement at the institutional and individual level. At present, such levels of support fall well short of what is needed to meet the challenges of a building sector that has unsustainable impacts on people and the environment. The Agenda is intended to identify needed research, development and deployment activities and inspire the necessary funding to enable a transformative leap in building performance – one of a succession of leaps necessary on the path toward sustainability.

Rationales for Creating this Research Agenda

ECOLOGICAL and HUMAN SUSTAINABILITY

A grand and critical challenge for our society is achieving sustainability of the earth's ecosystems. There is broad agreement that human activity is changing the global climate[2] and that future consequences of this change are potentially disastrous.[3] In addition, human consumption of "ecosystem services" – resources and benefits supplied by natural ecosystems – is "weakening the natural infrastructure on which all societies depend."[4] The explosive growth of developing economies further intensifies the magnitude and urgency of the challenge.[5]

The built environment is designed to serve human needs, such as protecting people from outdoor environments. However, the built environment has significant negative impacts on the natural environment and on human health and performance. In the U.S., buildings are responsible for:

- 38% of carbon dioxide emissions;
- 71% of electricity consumption;
- 39% of energy use;
- 12% of water consumption; and
- 40% of non-industrial waste.

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[2] Allen, R., et al., "Climate Change 2007: The physical science basis: Summary for policymakers," Intergovernmental Panel on Climate Change, Working Group I, Feb. 2, 2007; http://www.ipcc.ch/SPM2feb07.pdf

[3] Adger, N., et al., "Climate Change 2007: Climate change impacts, adaptation and vulnerability," Intergovernmental Panel on Climate Change, Working Group II, Apr. 6, 2007. http://www.ipcc.ch/SPM6avr07.pdf.

[4] Millennium Ecosystem Assessment, "Living beyond our means: Natural assets and human well being." Statement from the Board, March 2005: http://www.maweb.org/documents/document.429.aspx.pdf.

[5] Friedman, T.L. *The world is flat: A brief history of the twenty-first century.* Farrar, Strauss, and Giroux, New York, 2005.

Buildings are also where most Americans spend more than 90% of their time, yet indoor environments in some buildings have been associated with human health impacts that range from asthma and respiratory tract irritation to Legionnaires' disease and cancer.[6] In addition to these health impacts, the quality of the indoor environment can also have profound effects on occupants' comfort, well-being and productivity.

Green building has developed as a holistic and practical answer to the environmental and health burdens of the conventional built environment. Based on the definition used by one federal report,[7] green building may be loosely defined as: "the practice of (1) maximizing the efficiency with which buildings and their sites use, generate and recycle energy, water, and materials, and (2) minimizing – and ultimately eliminating – buildings' impacts on human health and the environment, through better siting, design, construction, operation, maintenance, and removal—the complete building life cycle." Green buildings (similar to sustainable or high-performance buildings) depend on the continuous improvement of building processes, technologies and performance. The end goal is to minimize negative environmental or health impacts and contribute to environmental restoration and the sustainable management of our air, energy, land, water and other resources. Ultimate objectives of green buildings and this Research Agenda therefore include:

- climate conditions decoupled from human activities;
- stable, sustainable energy supplies;
- clean, renewable and sufficient water resources;
- restorative use of land for the long-term sustainability of habitats;
- restorative use of materials that accounts for life-cycle impacts; and
- enhanced human safety, health and productivity in the built environment.

Since the turn of the millennium, interest in green building in the U.S. has developed rapidly, fueled by increasing attention from many professional organizations and many notable "early adopters" in practice, industry and academia. To date, green building practice has demonstrated that changes in approaches to design, construction, technology and operation can yield significant reductions in the environmental impact of buildings while simultaneously improving the health and performance of building occupants. For example, compared with conventional U.S. practices, green buildings have demonstrated reductions in energy use by 30%, carbon emissions by 35%, water use by 50%, and construction waste by 50% or more. These are significant but are only a first step toward enabling a sustainable future for people and the planet.

When looking at the impacts of the built environment on the natural environment, it is clear that first, the best technologies currently available are not sufficient to eliminate negative impacts on the built environment, and second, given that *green* buildings only represent 2% of all buildings, technological improvements alone will not bring about needed change. This is as much the task of economists and sociologists as it is of designers and materials scientists — achieving restorative built environments that improve the natural environment, replenish resources and enhance human health and

[6] Statistics from sources cited in: U.S. Environmental Protection Agency, *Buildings and the Environment: A Statistical Summary*, December 20, 2004, http://www.epa.gov/greenbuilding/pubs/gbstats.pdf

[7] Office of the Federal Environmental Executive, *The Federal Commitment to Green Building: Experiences and Expectations*, p. 8, http://www.ofee.gov/sb/fgb_report.pdf

productivity will require *transformative changes* in technology and practice. This Research Agenda aims to articulate and promote this change.

A MULTIDISCIPLINARY CHALLENGE

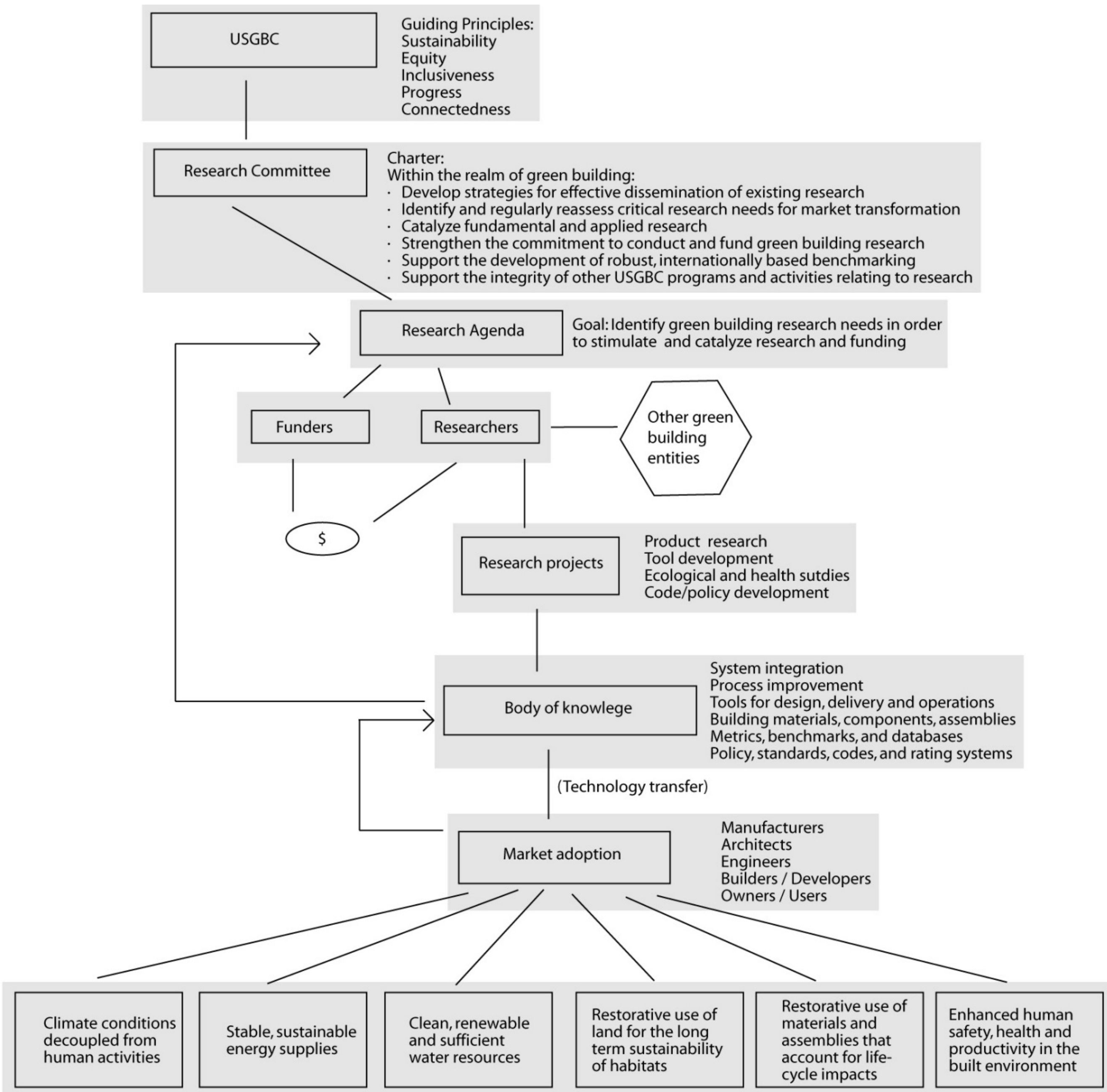
The scope of green building, and hence the scope of needed research, is vast, encompassing many professions (real estate, architecture, engineering, construction, product manufacturing, environmental and health sciences, economics, etc.), all varieties of building types, materials, climates and conditions, and a vast array of environmental concerns. Effective research will often involve treatment of a complex set of interwoven man-made and natural systems, and thus necessitate collaboration among the many academic and professional disciplines representing diverse areas of expertise.

The U.S. Green Building Council (USGBC) is uniquely positioned to be a nexus for this effort. It is a non-profit organization whose membership is composed of leaders from every sector of the building industry, which works to promote buildings that are environmentally responsible, profitable and healthy places to live and work. USGBC's primary tool for market transformation has been the LEED (Leadership in Energy and Environmental Design) Green Building Rating System, a voluntary, consensus-based national rating system. Educational and other programs are also employed to advance USGBC's goals and affect change. The USGBC Research Committee, formed in 2006, has undertaken an effort to drive market transformation by identifying critical research needs and catalyzing research activity. While continual improvement of the LEED rating systems also depends on pending research, the context and benefits of funding, conducting and applying such research are much broader. Accordingly, the Agenda speaks to the broader context.

Research in these areas has been ongoing at national labs, universities, corporations, non-profits and other organizations in the United States and abroad before this Agenda was developed. This Agenda captures the overall landscape of current research, identifies areas needing additional attention, and weaves existing and needed research into a vision for strategic engagement of funding organizations, researchers, practitioners, manufacturers, building owners and others. The aim is to catalyze a new era of expanded, effective and creatively collaborative research for green buildings. The aspiration for this Agenda is that it provide the basis for organized and constructive dialogue among green building stakeholders.

This document reflects on a monumental but essential task. Green building seeks to minimize and eventually eliminate the negative impacts of buildings on the environment and human health, and this Agenda identifies necessary research so that, with appropriate funding, institutions can produce results leading multiple professions and decision-makers to overcome barriers to progress. These barriers are technical, scientific, economic, occupational, cultural and more. While research by itself cannot surmount these barriers, it produces answers that can be used to help unlock the logjam of issues that obstruct realization of a sustainable built environment.

Figure 1: Relationships among the stakeholders and research activities.



Current Research Context and Overarching Needs

The USGBC Research Committee released a report in 2007, *Green Building Research Funding: An Assessment of Current Activity in the United States*[8]. The report found that although there is valuable and effective green building research being conducted across the country, levels of investment remain extremely low in relation to the urgency and magnitude of the problems they aim to solve. In fact, research on green building constituted only about 0.2% (two-tenths of one percent) of all federally funded research between 2002 and 2004 – an average of $193 million per year. Among the federal government agencies devoting the most to green building research are the U.S. Department of Energy (DOE) and U.S. Environmental Protection Agency (EPA); yet at both agencies, such research represents less than 4% of their research budgets. At the same time, less than one percent of the National Science Foundation's research budget goes toward green building research. In addition, despite the significant health impacts of indoor environments, the National Institutes of Health (NIH) currently funds almost no research on this issue.

Levels of green building research pale in comparison to amounts being invested in other sectors. For example, the field of nanotechnology receives billions of dollars in research funding from private and public sources ($1.9 billion and $1.4 billion, respectively, in the U.S. in 2005).[9] Yet green building research funding is an order of magnitude lower, even though such research supports national and international policy goals that include reducing greenhouse gas emissions, increasing energy security, maintaining water supplies, preserving land and protecting public health.

When last reported, industry investment in construction-related research stood at 1.2% of sales,[10] significantly less than the averages for other U.S. industries. Research-intensive industries such as communications equipment and semiconductor manufacturing each devote more than 11% of sales, the pharmaceuticals industry spends more than 8% of sales, and the software industry more than 23% of sales. In the same range as the construction industry are less research-intensive industries such as textiles, apparel and leather at 1.0%, paper and printing at 1.1%, and plastics and rubber products at 2.1%.[11] Obviously, these products are simple compared with the vast complexity of buildings.

U.S. construction industry R&D as a percentage of total R&D is only 0.2%, less than industry investments in construction research in other countries. The lowest reported percentages were from Canada, Germany and Italy at 0.3%, the highest from France at 1% and Japan at 2.1%.[12]

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[8] Available on-line from the U.S. Green Building Council at http://www.usgbc.org/ShowFile.aspx?DocumentID=2465

[9] Lux Research Inc., *The Nanotech Report, 4th Edition*, 2006, http://www.luxresearchinc.com/pdf/TNR4_TOC.pdf

[10] Department of Energy. 2006 DOE Buildings Energy Data Book. 19 February 2007. http://buildingsdatabook.eren.doe.gov

[11] National Science Foundation, Science and Engineering Indicators 2006, Chapter 4: Research and Development: Funds and Technology Linkages. 23 February 2006. http://www.nsf.gov/statistics/seind06

[12] Department of Energy. 2006 DOE Buildings Energy Data Book. 19 February 2007. http://buildingsdatabook.eren.doe.gov

These amounts are miniscule compared not only to the environmental impact of the building industry, but also to its economic impact, as U.S. building industry sectors, from design and manufacturing through construction, management and renovation, represent over $1.1 trillion, or more than 14% of the U.S. gross domestic product, and employ over 7 million people[13].

In addition to being insufficiently funded, green building research efforts are fundamentally fragmented – constituting a diverse collection of projects whose researchers and funding sources may rarely cross paths, and much of which is never brought together into any kind of coherent whole. Energy researchers may talk with other energy experts but not with water researchers, for example. This can lead to many lost opportunities to view buildings and communities as whole entities capable of overall, synergistic improvement.

Thus it is essential to develop multidisciplinary research areas and broad, collaborative funding sources for green building research. This integrated research approach will initiate the transformative paradigm shift needed to achieve sustainability of the built environment.

To effectively meet these challenges and seize the opportunities presented by green building calls not for a continuation or incremental increase of current funding levels, but a ramping up to a new, comprehensive, and transformational level of support. This *National Green Building Research Agenda* therefore illustrates the breadth of research that is critically needed to transition to a sustainable built environment, and challenges the public and private sectors to devote the resources commensurate with the scale of the environmental, economic and social opportunities we face.

While this Research Agenda outlines specific program areas requiring attention and funding, it must be read in the context of the need for a broad, sustained, multi-disciplinary, multi-funder, multi-institutional effort that builds overall national capacity in expertise in all facets of sustainable building, and thereby catalyzes national change in academia and industry. A full ramping-up of support to levels needed to meet global environmental challenges would include several phases of capacity building:

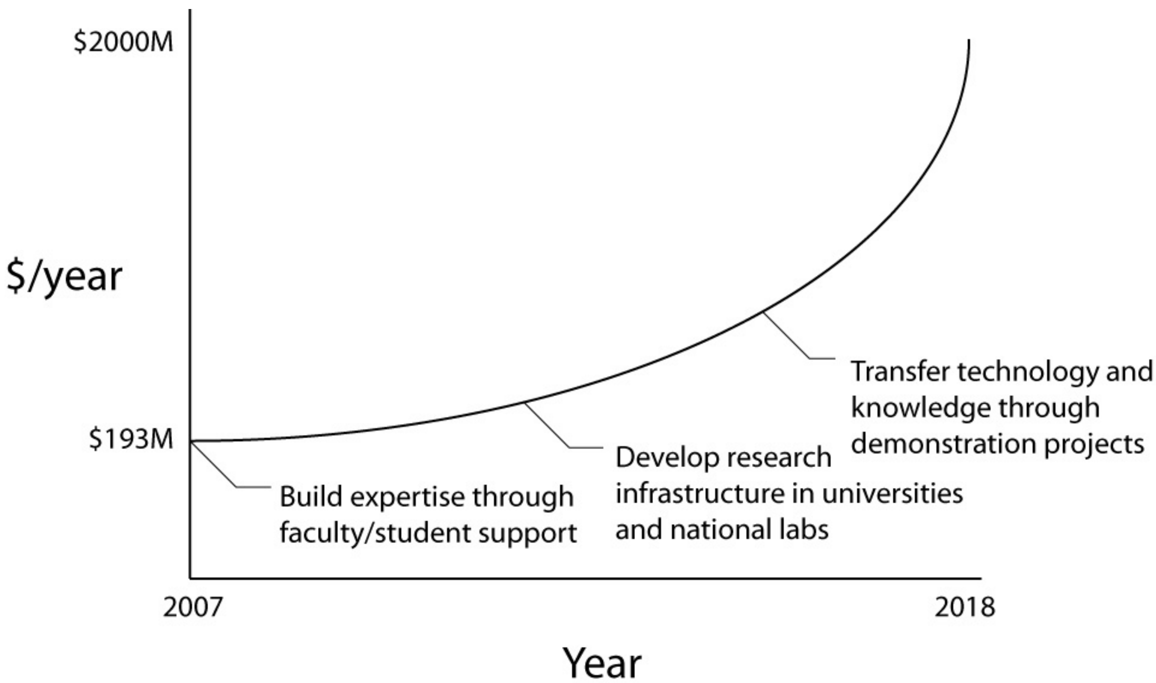
1) *Expertise:* Consistently support more faculty and students to conduct green building research and demonstrations and thereby gain necessary expertise.

2) *Research Infrastructure:* Develop regional research and educational facilities, including labs and full-scale “living labs” for hands-on experimental research, to conduct demonstration projects, and develop and test innovative materials and technologies. Grow national laboratory capacity to support research initiatives, review progress and report on results.

3) *Technology Transfer:* Fund national and regional demonstration projects (per climate zones) to catalyze green building markets, such as for renewable technologies, low-impact development and innovative passive and active building systems.

[13] U.S. Census Bureau, *2002 Economic Census: Table 2. Advance Comparative Statistics for the United States*, http://www.census.gov/econ/census02/advance/TABLE2.HTM

Figure 2: Representation of incrementally increased and sustained funding for industry-transforming research, education and implementation.



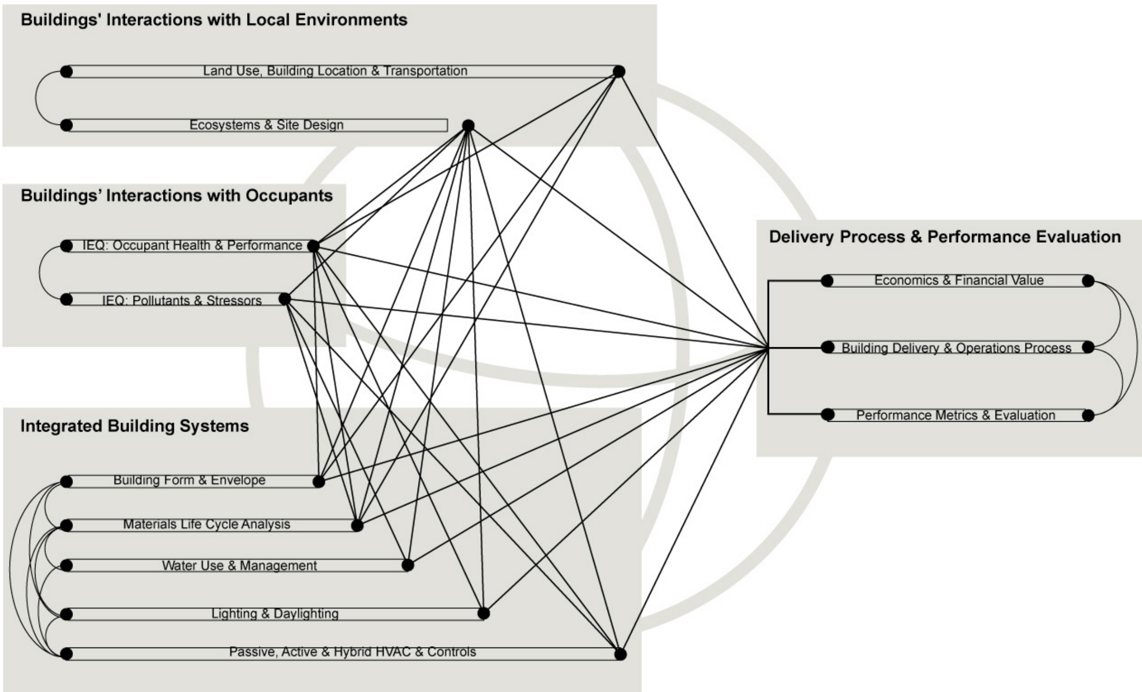
Organizational Framework

The emerging paradigm of sustainability creates tremendous opportunities to forge a healthier relationship between people and the earth's natural environment. But it complicates matters by demanding that nothing be viewed in isolation, that all issues are connected and overlapping. It is likely that new critical domains of green building research reside between traditionally stove-piped domains and disciplines. Architectural historian Antoine Picon has identified the "need to interrogate and even throw into crisis the borders, limits and lines of demarcation that we have inherited, sometimes unconsciously" and that as soon as these boundaries are "closely examined, they rapidly blur; they fall apart, giving birth to a multitude of traces for which one is tempted to invoke all sorts of images and metaphors borrowed from mathematics, from physics, and from philosophy…"[14]

This makes organization of a report like this one challenging. One could potentially organize research topics according to LEED categories: Sustainable Sites, Water Efficiency, Energy and Atmosphere, Materials and Resources, and Indoor Environmental Quality. But that could cause important research synergies to be missed – for example, a Heating, Ventilation and Air Conditioning (HVAC) system, or a daylighting strategy, should be designed both to conserve energy *and* to enhance indoor environmental quality.

[14] Picon, Antoine. "Rethinking the Boundaries: Architecture Across Space, Time and Disciplines," *Newsletter of the Society of Architectural Historians*, Vol. 49, No. 6, December 2005, p 10-11.

Figure 3: Interactions between research programs



The effort for this Agenda began with a workshop in September 2006 to identify greatest research needs. The USGBC Research Committee identified research topics in the most appropriate categories, while seeking and identifying overlaps. The Research Committee organized these topics into a *systems* framework: Ultimately sustainability is about how systems – natural, technological, physiological, economic, etc. – interact, and about understanding and guiding the relationships among them. Many of the most effective results from this Research Agenda will require multidisciplinary collaboration and integrated development that recognizes complex system interactions and linkages with other research areas and disciplines (see Figure 3). Therefore, the programs in the Research Agenda are organized around the following systems-based categories:

Delivery Process and Performance Evaluation
- Building Delivery and Operation Process
- Performance Metrics and Evaluation
- Economic and Financial Value

Integrated Building Systems
- Climate Adaptive Building Form and Envelope
- Lighting and Daylighting
- Passive, Active and Hybrid HVAC and Controls
- Materials Life Cycle Assessment
- Water Use and Management

Buildings' Interaction with Local Environments
- Ecosystems and Site Design
- Land use, Building Location and Transportation

Buildings' Interaction with Occupants
- IEQ: Pollutants and Stressors
- IEQ: Occupant Health and Performance

Understanding the Research Agenda's Content and Scope

The twelve categories above are programmatic areas. Each research *program* contains descriptions of desired research *topics* that were recognized by the Research Committee and/or other industry experts whose opinions were solicited. The topics are meant to be an illustrative, not exhaustive, collection of research needs. The finest level of granularity is not included: that of research *projects*. Such level of detail is beyond the scope and means of this project and is left to the researchers who are most familiar with those needs.

Organizational Hierarchy

1. Systemic Categories (Chapters)
    a. Research Programs
        i. Research Topics
            1. Research Projects

Prioritization of research has been a frequent request made of the Research Committee. The Research Committee recognizes that any organization that provides funding or conducts research will view the Agenda with their own priorities in mind, with criteria that match their desires. There is also great variety in scale and type among the issues, rendering a high-level prioritization a case of "apples and oranges." Accordingly, priorities have not been identified on the program level, but priority research topics are identified as such within each program area, based on the following criteria:

- short timeframe / immediate results: relatively small or easy projects that can quickly make a difference, perhaps substantial;
- significant level of expected impact;
- barrier to commercialization or market adoption; and
- sequential significance (a prerequisite for other research).

A green building Research Agenda requires both envisioning the possibilities for future innovations and addressing the real needs of today. As such, this Agenda looks to the future while centering on the pressing needs of those individuals and organizations striving to create a more sustainable built environment in the near term. This Agenda thus focuses on the applied research most needed by green building practitioners in the design, engineering, construction and development communities. The character of the research described is strongly weighted toward specific outcomes, including: building materials, components and assemblies; integrated systems; process improvement: design, delivery and operations; tools for design, delivery and operations; metrics, benchmarks and databases; policy analysis and development; and standards, codes and rating systems. The research is primarily focused on commercial and institutional buildings, but much of it is relevant to residential and other building types.

Programs and topics in this Agenda do not include quantitative goals because for many, especially newer areas of research, scientifically based and widely accepted goals do not yet exist. Indeed, some of the research herein described involves setting these very goals. Specific timelines to deliver the outcomes within research topics are not provided; research activity in this Agenda generally spans one to ten years. Technology transfer activities require additional time (e.g., five to eight years) although some may overlap the end of the research phase.

Research topics are presented here with the assumption that thorough literature reviews will be conducted by researchers in order to confirm or adjust the statement of general needs and to plan accordingly for their specific research projects. Additionally, effective strategies, by their nature, must take into consideration the climate zone where the technology is being applied. Building envelopes and other passive design strategies, and air handling systems, and building and landscape water use, in particular, need to be tuned to determinant climatic factors. Technology transfer is included as a topic within each program area for good reason; the transfer of knowledge and technologies into professional application too often lacks appropriate attention and planning. The process takes more time and money than the research itself and without it no real benefit will be realized. Thus, "research" as used in this Agenda sometimes can include activities spanning from applied research to market adoption.

Applying the Agenda

Achieving the transformative multidisciplinary collaboration within a working systems perspective necessary to develop a sustainable built environment begins with communicating research priorities to a broad audience. The success of this Agenda is dependent on both the depth and breadth of relevance that its contents hold for a diversity of communities (see sidebar). The variety of users reflects the variety of ways in which this document will be used; as a catalyst for funding, a source of research topics and pathways, and a record of the most pressing needs of the building community.

The highest intentions for this Agenda are that it will inspire decision makers to move these program and topic areas to the top of their funding priorities, and that it will provide researchers with a cohesive basis for planning their research and collaborating across areas of expertise. A central function of this Agenda is as a basis for discussion; one which will facilitate constructive dialogue among the stakeholders and contribute to its impact and evolution. It is the first full articulation of research needs on the part of the USGBC Research Committee, but it is well understood that such needs will change over time. The Agenda is expected to become a "living document" that grows and changes as the body of green building research evolves, facilitating transformative leaps in building performance.

Targeted audiences for this Agenda:

*Funding Sources**
- Federal and state governments (legislative and executive branches)
- Foundations
- Industry, including manufacturers and contractors
- Corporations
- Venture capitalists
- Trade associations

*Public and Private Researchers**
- Universities
- Laboratories
- Product providers
- Service providers
- Associations

* see Appendix A for specific organizations

Other potential audiences
Practitioners
- Owners and developers
- Design teams: A, E, I, LA, CM and others
- Builders
- Facility managers
- Standards developers
- Policy makers

CHAPTER 1: DELIVERY PROCESS AND PERFORMANCE EVALUATION

A clear understanding of the benefits of sustainable design and robust tools for designing, financing, procuring and implementing sustainable construction practices are critical to the success of green building. Without consistent and reliable documentation of the benefits, it is difficult for many building owners to commit to appropriate high-performance buildings. Without robust financial tools that address sustainability issues, financial institutions can not readily meet their fiduciary and statutory obligations in funding innovative and transformative technologies. Without improved procurement, construction and risk allocation methods, truly integrated design will remain elusive. In order to ensure adoption of new technologies, designs and approaches in sustainability, it is necessary to provide owners, designers and builders with the best tools to facilitate analysis of options and effective decision making.

The research proposed in this chapter considers the needs of decision makers throughout the project development process from inception to completion, and beyond to occupancy and ultimately to deconstruction or re-use. It examines the information needed to make high-quality decisions at each stage, and seeks to understand the mechanisms of decision making, how perceptions and experiences can be as powerful as plain data. It also examines the changes needed to improve the delivery process, through enhanced design tools to new contractual and risk management relationships

There are three distinct but linked programs. The first relates to building delivery and operations processes. It seeks to develop improved delivery tools, including design tools, contract forms and best practices to facilitate fully integrated and collaborative processes, the use of appropriate design and construction technology, and the allocation and management of risk throughout the project life.

The second program area is performance metrics. The program will provide consistent, reliable and verifiable information to allow for the collection, analysis and dissemination of useful data for decision makers.

The third program area addresses the economics and financial attributes of sustainable design. For those who fund buildings, there is usually a strict or implicit fiduciary duty unrelated to sustainability goals. Research in this section will connect the benefits of sustainable design with financial data such that the sustainable value can be effectively included within that duty. This program will also improve the understanding of markets, regulations and legal structures to identify how they can be used to better allocate the economic costs and benefits of green building.

Findings from all of these areas will feed into the adoption decisions for project teams and provide the necessary support for appropriate choices and high-quality decisions.

1.1 BUILDING DELIVERY AND OPERATIONS PROCESS

Program Goal: Transform design, construction and operations processes through high-quality data, tools and methodologies for enhanced decision making.

The research topics within this program area aim to:

- increase the predictability of design and construction project outcomes;
- develop design analysis and management methodologies and tools to better support the design, construction and operation of energy efficient, environmentally responsive buildings;
- provide research on the costs and benefits of new delivery systems;
- provide research on connections between design, delivery, and operations tools and systems with sustainability outcomes.

Background

Buildings have a poor track record for performing as predicted during design. Many reasons exist for energy and environmental underperformance, such as inaccurate or improperly used analysis tools; lack of integration of complex inter-connected systems; value engineering after design; poor construction practices; no building commissioning; and incomplete or improper understanding of operations and maintenance practices.

To overcome these challenges, project teams must be able to evaluate many design alternatives and confidently select effective solutions to the project's unique energy and environmental requirements. The complexity of high-performance sustainable strategies and techniques requires that all project stakeholders must be integrated.

Ideally, a full project team — owners, designers, constructors and facility managers — would be assembled at a project's outset to collaboratively generate, test, and alter the design, construction and operation of various designs through virtual simulation. However, this ideal process is currently limited by market dominance of fragmented non-collaborative project delivery systems, inadequate technological tools, and the lack of interoperability and unifying standards.

Some needs are being addressed by the creation of integrated project delivery systems based on new contractual relations between team members, all utilizing Building Information Modeling (BIM) software. BIM is a digital representation of a building's physical and functional characteristics. It provides the project team a reliable and accurate basis of knowledge on which to make decisions, from early need definition and solution conception to deconstruction or adaptive reuse. As such, BIM is useful to all project team members. BIM realizes its greatest potential when used within an integrated project delivery environment where all aspects of a building are designed, built, and operated virtually, before moving into the physical realm. The National Institute of Building Sciences (NIBS) is sponsoring the development of a National BIM Standard (NBIMS) through a volunteer committee of constituents, including designers, general contractors, researchers, software companies and others.

Key outcomes in this program area should include the development of design, analysis, and management methodologies and tools to support the design, construction and operation of energy efficient, environmentally responsive buildings. Assessment of design tools against actual building performance is discussed under the Performance Metrics and Evaluation program area.

Illustrative Research Topics

1. **PRIORITY TOPIC: Characterize and improve understanding of barriers to using multi-disciplinary, collaborative, and integrated building delivery systems**. This topic could be accomplished in a short timeframe and would yield immediate results. Fundamental to the paradigm shift toward green building is deep collaboration among involved disciplines. However, this type of effort runs counter to much conventional construction practice. This research would result in "best practice" guidelines for integrated delivery approaches in all common building delivery scenarios.

2. **PRIORITY TOPIC: Analyze the National Institute of Building Science's (NIBS) National Building Information Modeling Standard (NBIMS) for comprehensive coverage of environmentally sustainable design, construction, and operation processes and practices**. This task is identified as a priority because of its sequential and long-term significance to the practice of sustainable design, construction and operations. There is a need to identify gaps and opportunities specifically related to sustainability; these may include life-cycle assessment (LCA) for building materials and structural assemblies, energy modeling, daylighting and other indoor environmental quality issues, water use, and site impact. Technical requirements and integration standards for linking BIM files with sustainable building design, construction and operation tools must also be defined and created.

3. **Improve understanding of the connections between, and business case benefits of, various delivery systems in relation to sustainability outcomes**. To be truly effective and commonplace tools, various alternative delivery systems must be assessed for their ability to produce green buildings.

   Related topics can be found in Chapter 1.2 – Economic and Financial Value.

4. **Modify and/or develop sustainable building design, construction and operation tools which efficiently and effectively function within a BIM environment to support integrated project delivery systems**. The success of the BIM environment for sustainable building delivery will be enhanced by further development of auxiliary tools for drawing modeling, procuring, constructing, commissioning, and operating buildings. This research will develop tools that are easily integrated with BIM.

5. **Advance technology transfer**. Determine the most effective methods to parlay research results into industry practice. Widespread adoption of new technology and knowledge in the marketplace is critical for achieving sustainability goals, and thus must be planned and implemented in step with research for prompt market uptake.

1.2 ECONOMICS AND FINANCIAL VALUE

Program Goal: Provide a better understanding of the financial and economic factors of sustainable design through high-quality data, analysis and tools.

The research topics within this program area aim to:

- Identify the costs and benefits of sustainable design within a financial model;
- Develop appropriate tools to facilitate effective real estate valuation and business case decisions related to sustainable design;
- Provide research on the economic impact of policies and standards related to sustainable design.

Background

The barriers to green building are not exclusively technical. Financial, business planning, and economic factors are important considerations for owners or investors. The long- and short-term financial impact of sustainable decisions must be better understood. The market needs effective tools to support valuation and business decision making.

Institutional investment decisions can be challenging in this context. The separation between capital and operating expenses makes it difficult to fund long-term improvements in building performance. Financial institutions often require investment analyses over short time spans, which is problematic because these will tend to discount the long-term benefits of green building and can discourage investment in high-quality, long-lived materials, products, and systems that are more sustainable than cheaper options.

Market studies have shown that performance and price do not necessarily equate with what people buy; there are emotional factors, brand faithfulness, resistance to change, etc. For example, corporations and building owners have known about energy efficient investments for years, yet have significantly under-invested in them in light of the financial opportunities.

Decision making processes, business dynamics, and communication issues all need to be examined in order to better understand the market barriers.

Illustrative Research Topics

1. **PRIORITY TOPIC: Develop high-quality tools and data for financial decision makers.** This topic addresses a critical barrier to practice and could have a significant impact on market transformation. Current financial modeling often discounts the long-term value of sustainable design due to a lack of confidence in the claims related to the costs and benefits of sustainable elements. Thus it is challenging to convince real estate investors that they will be financially rewarded. There is, therefore, a critical need for reliable information on the long-term benefits of green buildings, and on the valuations of those benefits. There is also a need for methods to improve the distribution of costs and benefits such that they can be better aligned with the cost of money, as well as the financial interests of the key decision makers. In particular, there is a need to better understand and identify uncertainties related to the forecasting of financial outcomes. This research will lead to the development of reliable data on costs and benefits, and robust financial models to incorporate long-term projections and uncertainties based on other research.

2. **PRIORITY TOPIC: Characterize the financial value of sustainable attributes of buildings**. This topic addresses a critical barrier in practice, could be accomplished in a short timeframe, and could potentially have a significant impact on market transformation. It includes cost-benefit analysis, return on investment (ROI) calculations, and assessments of levelized costs of energy (LCOE), among others. In addition, better data is needed on the life expectancy of materials, products, and systems. For example, age-old traditional materials often have much longer life expectancies than modern materials, and that longevity reduces their environmental impact. Research in this area will lead to both forward-looking financial projections based on building modeling, and backward-looking analyses of existing building performance, valuations, leases, and mortgages.

   Related topics can be found in Chapter 1.3 – Performance Metrics and Evaluation.

3. **Improve understanding of labor, material and component cost and availability**. Among the most important issues of financial risk in construction is labor. Cost, quality, reliability and availability of experienced service providers, contractors, sub-contractors and commissioning agents all play a role in the success of sustainable building and operations. Sustainable materials and component systems also have similar risk factors. This issue needs to be studied and understood much better in order to plan and address costs and risks appropriately. Geographic, property type, and property size differences are some of the factors that impact labor, material, and component cost and availability. The costs and benefits of locally-produced materials need to be more clearly explained. This area of research will document the long- and short-term demands for labor and materials in sustainable design. It will also develop strategies for improving the availability and quality of green building products, including labor development (e.g., installation training for workers), and committed, ongoing growth of manufacturing.

4. **Improve understanding of legal and regulatory structures, including government regulations and incentives.** There is a need to assess and compare the effectiveness of regulatory approaches (e.g., carbon trading, carbon taxes, building codes) and incentives (e.g., tax, entitlements), including unintended

consequences of the traditional as well as progressive approaches. Government can be a key ally or, unknowingly, an obstacle. It is important to understand when and how government action can be most effective, both for specific measures, such as replacement of incandescent bulbs with compact fluorescent lights, and in gross development terms, such as tax incentives or expedited permits for green buildings. This research will develop recommendations for appropriate policy initiatives for local, state and national agencies.

5. **Improve understanding of how various actors arrive at decisions, and the information and methods needed to facilitate sustainability.** In many cases, decisions are not made through a simple cost-benefit analysis. Even where the costs and benefits can be meaningfully identified and quantified, there are many other factors that affect decision making. These include uncertainty in the forecasts, particularly for long-term life-cycle cost analyses; differing value systems between decision makers; differing approaches to positive and negative risk; and differing approaches to long- and short-term value. Research will help develop tools and methods for relating various approaches and facilitating paths forward for implementing sustainable buildings.

6. **Compile and analyze the monetary and environmental costs of the required maintenance for materials, products, and systems over their life spans.** These costs can then be compared to replacement costs if maintenance is not performed. Because much of our building stock exhibits long life spans, this data is needed to perform more realistic life-cycle costing (LCC) and life-cycle environmental evaluation of buildings. The goal of this task is to develop an accessible database of maintenance costs and life spans for key building components.

7. **Advance technology transfer**. Determine effective methods to parlay research results into professional practice. Widespread adoption of new knowledge, methods and tools in the marketplace is critical for achieving sustainability goals, and thus must be planned and implemented in step with research for prompt market uptake.

1.3 PERFORMANCE METRICS AND EVALUATION

Program Goal: Transform the building industry by delineating metrics of performance across the full spectrum of environmental goals to provide feedback for further improvements in design, construction, and operations.

The research topics within this area aim to:

- Identify available and missing metrics for buildings and communities;
- Refine existing metrics and develop new metrics to address these gaps;
- Develop measurement and reporting protocols, benchmarks and databases;
- Evaluate actual performance of buildings and communities;
- Develop rating/labeling systems.

Background

As green building and sustainable design become more mainstream, new questions arise. How do green buildings perform over time? How do design estimates of building performance correlate with actual performance? What types of retrofits compromise or enhance performance? What is the impact on health and productivity over time? What processes are effective for transferring high-efficiency operation when tenancy or facility management changes? Do green buildings maintain higher value than non-green buildings over time? Most importantly, what are the real benefits of buildings designed to be green or sustainable? Without verifiable performance using consistent measures, the claims of progress in green buildings' energy efficiency, water use reduction, indoor environmental quality, and occupant health and productivity are not credible.

As with building delivery and operations process innovations, performance metrics and evaluation are relevant to all areas of the Research Agenda. Many performance metrics have already been developed, but some them need refinement. Other topics have not been addressed adequately. Research on improved performance metrics and evaluation has immediate applicability and benefits. One application is the continuous improvement of building rating systems. To this end, and to serve identical needs throughout the building community, both short-term and longer-term research is needed to better relate design strategies to actual performance and benefit.

Another example of immediate applicability of improved metrics is the proliferation of programs related to climate change. The 2030 Challenge, Zero Carbon, Carbon Neutral, Zero Impact, The One Liter House, and others are examples of challenges posed to the research and design community for standardizing metrics and benchmarks. The 2030 Challenge asks us to achieve carbon neutrality in buildings by 2030 by ratcheting down energy consumption in five-year increments. To achieve this comprehensive energy reduction, a more thorough dataset as well as more robust metrics are needed.

The results of these performance measures will need to be promoted in order to capture the imagination of the public and policy makers, and be weighted to address the diverse challenges facing our future. The ability to measure and communicate information about building performance is critical to our global future.

This research topic will include the development and refinement of metrics, identification of data requirements, development of data collection protocols and tools, development of databases, and design of reports and communications tools. It will also include application of these new metrics to examine key questions concerning performance and benefits of green building and sustainable design.

Related topics can be found in all chapters.

Illustrative Research Topics

1. **PRIORITY TOPIC: Identify the scope and scale of needed performance metrics and protocols.** Since this task will provide the foundation for robust and comprehensive performance measurement, it is critical that it be accomplished in the short term. There are many topics that are not addressed in current systems. Agreement is needed on the performance areas to be included and the scales for their measurement, from materials up to components, integrated systems, whole buildings, communities, watersheds, regions and finally to the national level. Various applications for performance metrics should be identified and users should be consulted to ensure a comprehensive and practical approach.

2. **PRIORITY TOPIC: Refine existing performance metrics and develop new ones.** This topic could be accomplished in a short timeframe and would yield immediate results. Identifying and cataloging existing metrics is a critical step toward ensuring that research proceeds most effectively and takes advantage of existing knowledge. Robustness, harmonization and international recognition are necessary. Since considerable work has been done in different countries on performance metrics, initial research is needed to identify, catalog, and evaluate metrics currently in use or under development and to identify gaps. Then, research is needed to refine existing metrics and to develop new metrics where none exist. Performance categories could include source and site energy, power reliability, atmospheric quality, carbon, water use efficiency, water quality, waste, indoor environmental quality, material sustainability, land/ecological footprint, ecological systems, and the emerging measures of human health, safety, mobility and security. Iteration, in an international context, is critical to reflect the diversity of building types, building age, climate conditions, and societal goals; to reflect the differences between predicted and measured performance or design and operational performance; and to reflect the critical importance of market accessible indices (and prioritization) for design and consumer selection.

3. **Develop and refine measurement tools**. These could include in-situ and portable instrumentation, ubiquitous sensing, sub-metering, occupant surveys, and more. Standards and guidelines for use of the tools will also be needed.

4. **Develop an integrated database of measurement protocols and measured performance at various project scales**. This database would be used in establishing meaningful benchmarks and targets that support environmental and human health goals. It could also be used in assessing the effectiveness and benefit of design and operational strategies and technologies. Regional and societal weighting considerations could be developed for application across the range of performance measures and building conditions (e.g., age of building, climate, building function).

5. **Refine or develop rating systems and labeling protocols**. Research on performance is critical to ongoing improvement of building rating systems such as LEED. This information will enable USGBC to refine and develop new LEED criteria to increase the program's ability to recognize superior performance and transform the market. It will also support current efforts to increase the use of performance-based methods rather than prescriptive. This research could also be used to develop or expand product certification systems in the U.S., similar to those in many other countries.

6. **Compile data and analyze design strategies as they relate to actual building performance.** Current information indicates that most buildings do not perform as well as design metrics indicate. As a result, building owners might not obtain the benefits promised. Research is needed to find the causes for the discrepancies and to determine whether performance estimates of some design strategies are reasonable. For example, building simulations during the design process must be compared to performance metrics to determine both the accuracy of predictions and the appropriateness of making predictions at a particular stage of design. This research will have four key applications – first, it will enable simulation and model developers to improve their tools; second, it will allow designers to utilize simulation tools more effectively; third, it will enable rating systems sponsors to improve their criteria; and fourth, it will enable owners and financial institutions to have confidence in the performance returns on their investments.

7. **Compile data and analyze building rating systems and sustainable design strategies as they relate to actual environmental or human health benefits.** Potential users of building rating systems want to know if the ratings reflect actual benefits for the environment or human health and, if so, the extent of those benefits. Building owners and designers want to know the impacts of their decisions on the environment and human health. This enables them to make decisions on investments in particular strategies and technologies. Policy makers also need this information to formulate regulations, standards, incentives, and other instruments.

8. **Improve understanding of interactions between humans and buildings**. How do people affect building performance? It is necessary to investigate the extent to which building occupants adapt to their surroundings. It is possible that facility operation standards do not adequately reflect the extent of comfortable adaptability to various lighting, thermal, ventilation and acoustical conditions. Further, the research should address the extent to which occupants' use of a building contributes to or detracts from its performance and how these interactions can be improved.

   Related topics can be found in Chapter 4.2 – IEQ: Occupant Health and Performance.

9. **Develop scenarios based on performance evaluations to support long-term visioning for building rating systems.** Ongoing visioning has been identified as a key component for growth and evolution of the LEED Rating System. This process should be based on rigorous scenarios to the extent possible. Scenario-building research will project potential performance levels, societal conditions and other factors into the future and enable USGBC to plan LEED's evolution to promote positive strategies.

10. **Advance technology transfer.** Widespread adoption of green building approaches, strategies, and technologies will be vastly enhanced when we can point to documented performance improvements and environmental benefits. One of the key barriers to adoption of green buildings in today's market is the question of how much benefit is obtained and at what cost.

CHAPTER 2: INTEGRATED BUILDING SYSTEMS

To achieve sustainable high-performance, buildings must support program requirements and occupant needs but must do so using a minimum of energy, water, materials and other resources. Green buildings strive for resource-efficient design and operation. To obtain improved first-order performance (e.g., 30% improvement over conventional performance) a wide variety of prescriptive envelope, lighting, HVAC and water measures can be applied. However, to achieve 50% improvement and beyond – and especially to achieve net-zero energy buildings – prescriptive, independent measures will no longer suffice. Leaps forward in building performance require design that fully integrates envelope, lighting, HVAC, and water systems, and integrates energy efficiency with renewable energy applications.

The research proposed in this chapter focuses on the advancement of building systems and components as well as the better integration of their design and operation. While the chapter is organized around separate building systems the emphasis throughout is on their integration. This integration extends to site water use and materials in later chapters. Each program area in this chapter identifies research needed for the development, enhancement and optimization of building systems and components. Corresponding tasks involve the development of benchmarking and evaluation tools that assess the performance improvement of these advancements. Finally, advancement of design and management tools is needed to support implementation by service professionals.

2.1 BUILDING FORM AND ENVELOPE

Program Goal: Provide high-quality, energy efficient, healthy and productive environments through the design and operation of innovative, high-performance building envelopes.

The research topics within this program area aim to:

- Develop design, operation, and integration strategies for dynamic, operable, high-performance envelope components and systems that manage thermal loads and facilitate daylighting;
- Quantify the performance of innovative building envelope components and systems in terms of both energy and occupant impacts;
- Develop design and operation guidelines for designers, building owners, and facility managers that address both automated and manual controls.

Background

The form and envelope of a building dramatically affect the total energy use and human experience of a building. Buildings with narrow floor plates, where most spaces are adjacent to an exterior wall, are “skin load dominated.” Their energy use patterns are dominated by heat exchange through the envelope. Ventilation and lighting can chiefly be controlled through manipulations of a dynamic and operable envelope. Building forms resulting from deep floor plates are typically “internal load dominated,” where energy use patterns more strongly reflect the activities inside the building. Heating, cooling, ventilation and lighting opportunities still exist at the building’s perimeter but these spaces represent a smaller portion of the building’s energy use. Hence the building form and envelope strongly influence the building’s mechanical system (including the size, complexity, distribution components, initial price, and operating costs) and consequently the energy use resulting from heating, cooling, and lighting. The envelope of the building (some combination of barrier, filter, or connector to the exterior environment) also strongly influences factors such as occupant comfort, quality of light, connection to the outdoors, and aesthetics.

Too often, the envelope design is driven by structural performance, economy, and exterior aesthetics. This thinking typically leads to the ubiquitous all-glass, unshaded, sealed, flush-skin curtain walls that have significant detrimental effects on energy consumption, indoor environmental quality, and occupant comfort and productivity. This type of glass curtain wall is due as much to the economies of it being a common construction practice as it is to it being an element of architectural modernism; rarely is this choice driven by energy concerns.

Large glazed areas admit daylight and permit views, but can subject the building to the risk of high cooling loads, overheating, thermal discomfort and glare. Particularly problematic are the times of peak cooling loads, which strain regional power grids. Designs, systems and operating strategies that flatten these peak loads are thus desirable in addition to reductions in total energy consumed.

The common choice of a glass curtain wall is not often driven by lighting needs either. Solar and daylight conditions vary enormously over the course of days and seasons, and occupant needs vary by task and personal preference, so in many situations facades should be designed to be dynamically responsive rather than statically optimized for a generalized condition. In contrast to the conventional sealed glass curtain wall, high-performance facades (e.g., intelligent skins, active facade systems, double-skin facades, etc.) are designed, analyzed, and operated as an integrated system that serves as a mediator and filter between the indoor and outdoor climates. They typically incorporate operational elements that provide control of solar gain, daylighting, and natural ventilation, and sometimes even smart glazing or shading systems that have optical or thermal properties that can change in response to climatic elements.

Field studies find high dissatisfaction rates in many buildings with centralized control.[15] While there is need for improvement for centralized controls to operate more effectively, there is also a need to provide occupants with some level of personal adjustment. Personal control offers great potential for optimizing both energy and comfort; this can be achieved through the control of elements of the facade or the mechanical system (the latter is covered in the HVAC Program Area).

There are numerous opportunities to better integrate envelope and mechanical conditioning strategies while simultaneously optimizing energy use and comfort. One example is mixed-mode buildings, which combine operable apertures with efficient mechanical conditioning systems. Research related to passive/active integration is covered in the HVAC Program Area.

While preliminary research has been undertaken on climate-responsive design, this design approach continues to be the exception rather than the norm. Relevant building standards and rating systems lack a regional framework because it would require better knowledge about the performance of climate-responsive building form and envelope. This challenge requires significant advances in technology, design tools, design practice and a better understanding of occupant needs and preferences.

Illustrative Research Topics

1. **PRIORITY TOPIC: Develop design strategies and technologies for advanced envelope components and systems**. This topic addresses a critical barrier in practice, could potentially have a big impact on market transformation, and has sequential significance (technologies need to be developed before they can be tested). Operable, high-performance facades offer significant potential for comfort and energy improvements in buildings, but they still remain a very small fraction of the U.S. building stock. Activities within this topic would develop technologies for new building components, assemblies, and operation configurations for dynamic facades, focusing on improving the thermal and visual performance of buildings.

2. **PRIORITY TOPIC: Determine performance of advanced envelope components and systems, both seasonally and across varied climate zones**. This topic addresses a critical barrier in practice, could potentially have a big impact, and has sequential significance (analysis has to occur before design guidelines can be developed). Once design strategies have been identified and/or developed, activities

[15] Brager, G. "Indoor Environmental Quality and Occupant Satisfaction in Naturally Ventilated Buildings," *ASHRAE Conference, Long Beach, CA, June 2006.*

in this area would develop metrics, performance assessments and benchmarks for high performance. These methods should enable one to evaluate the impacts of varying design and operation configurations of dynamic facades for thermal and daylighting functions, and for naturally-ventilated and mixed-mode buildings. Assessment is needed within various climate zones representing a range of temperature and humidity conditions.

Related topics can be found in Chapter 1.3 – Performance Metrics and Evaluation.

3. **PRIORITY TOPIC: Analyze, develop and optimize a continuum of centralized and personal control options for advanced envelope systems**. This topic represents a paradigm shift and can lead to fundamental change in building, systems and product design. Personal control offers a significant opportunity to simultaneously achieve improvements in both comfort and energy performance of buildings, but is outside the norm of conventional building practice. Such control can occur through the design of a task/ambient mechanical conditioning system (covered under the HVAC Program Area), or through operable elements of the building envelope such as operable windows, or devices for controlling solar gain or glare. There is a need to analyze the performance of such elements, develop new systems when key functionality is missing, and then optimize their design and operating strategies for both energy performance and occupant impacts. Outcomes related to this topic will include design and operation guidelines for optimized personal and centralized control of envelope components and systems.

   Related topics can be found in Chapter 2.4 – Passive, Active and Hybrid HVAC and Controls.

4. **Develop climate-based design and operation guidelines for innovative envelope strategies**. The success of technological developments will be contingent on operation of the building as designed. Because these technologies are far from standard, guidance for effective operations of these envelope systems are greatly needed. Design, specification, commissioning and operation guidelines for dynamic envelope systems should be developed for various audiences: the design team, building owner and facility manager, and the occupant when systems include user-controllable features. Activities within this topic would develop climate/regional-based design and operations tools for dynamic, innovative envelopes.

5. **Develop and determine performance of envelope and structural elements for improved thermal storage**. There is a significant need for envelope-based design strategies and technologies that will flatten the heating and (especially) cooling load profiles in a building, to minimize peak energy demands. Research is needed to develop new systems and materials with reliable, durable solutions for passive storage of energy in buildings; to evaluate performance in terms of the thermal insulation and storage characteristics of various building envelope choices; and to identify optimal systems for heating/cooling load flattening and control specific to climate.

6. **Develop and test innovative glazing technologies for daylighting and solar gain control**. Glazing selection is a critical part of building design in that it has enormous impacts on energy performance, thermal comfort, and glare control.

Research is needed to produce window/glazing/shading technologies for effective daylight distribution without glare or unwanted solar heat gain, and analyze them using optimized control strategies for a range of climates and facade orientations. Research should include evaluation of improved skylights and tubular daylighting systems.

Related topics can be found in Chapter 2.2 – Lighting and Daylighting.

7. **Design and analyze advanced shading device performance**. Exterior shading devices are one of the most effective means for blocking solar gain that contributes to cooling loads in buildings. In addition to impacts on radiative heat flow, a better understanding of conductive heat flow via thermal bridging at attachment points should be developed in order to improve overall thermal efficiency of shading devices. There is a need for performance assessment at the building scale to assess the ability to reduce cooling system sizing, and at the community scale to quantify shading impacts on urban heat island effect. Some projects within this topic could be accomplished in a short timeframe and would yield immediate results.

8. **Evaluate the effectiveness of reflective/emissive roofing, vegetated roofs, and vegetated walls on heating and cooling load reduction**. In the summer, solar gain on horizontal surfaces is three times greater than that received by south-facing vertical surfaces. Hence, a building's rooftop can contribute significantly to the building's cooling load. Research is needed on the thermal performance of advanced roof technologies, such as cool (reflective) roofs, vegetated (green) roofs, and rooftop PV or solar thermal arrays. Performance of these design strategies and technologies should be evaluated for summer vs. winter, and wet vs. dry conditions. There is a need to identify the geographic/climatic regions and seasonal weather conditions where these products truly reduce annual heating/cooling load and change the R-value and heat flow characteristics of the roofs. Activities within this topic would: 1) characterize roofing and cladding materials for their heating/cooling load reduction capabilities; 2) develop design guidelines for appropriate application of vegetated roofs; and 3) characterize emissive roofing materials' effect on local air temperatures.

9. **Further develop design strategies and technologies for building-integrated photovoltaics and solar thermal systems**. The first step in creating high-performance buildings is to reduce the need for mechanical heating and cooling and electric lighting. Beyond that, buildings should use renewable sources of energy where possible to supply needed energy. A great deal of research is still needed to develop design strategies and technologies to integrate and optimize renewable energy and mechanical systems on an on-site basis. This would include evaluating and comparing climate-based shading impacts on PV systems.

10. **Optimize envelope materials in relation to basic building form**. Conventional building design and construction practice has led to the ubiquity of glass curtain walls, even in climates where their use generates high heating and cooling loads. Research is needed to better correlate envelope material and assembly selection with overall building form. This research could generate building design guidelines related to building form and envelope.

11. **Advance technology transfer.** Once these components, systems, and guidelines are developed, each must be brought from the researcher to the market in order to have the desired impact on the built environment.

2.2 LIGHTING AND DAYLIGHTING

Program Goal: Provide indoor luminous environments using fully integrated daylighting and electric lighting solutions that optimize occupant health, comfort, performance and satisfaction while minimizing energy use and power demand.

The research topics within this program area aim to:

- Maximize effective utilization of daylight as a primary light source to address energy and power criteria;
- Identify and quantify the impact of design and operational variables on occupant needs;
- Provide robust and flexible design solutions (i.e., fixture, source, controls) that accommodate dynamic variability intrinsic to climate and building site;
- Maximize the efficiency of each lighting and daylighting system component within the framework of optimizing the overall effectiveness of the complete design solution;
- Provide flexibility to meet changing occupant tasks and preferences, and building operating requirements;
- Minimize life cycle impacts of materials and products utilized to accomplish the performance objectives above.

Background

Creating lighting solutions that enhance sustainable building design involves a series of complex tradeoffs and optimization tasks. Lighting design solutions impact occupant performance, comfort, health and satisfaction. They are also key determinants of annual building energy use, load shape, peak cooling load and peak electric demand. A successful solution must address the tradeoffs between each of these performance issues over a wide range of independent (e.g., building type, climate) and dynamic (e.g., change in task, time of day) variables. These solutions are expressed initially in terms of design criteria and constraints, and eventually in terms of hardware, software, operating practice, etc. For example, the optimal lighting design requirements for a vertical, laptop screen-based visual task will be very different from those for a horizontal paper visual task, and will vary further between users. Finally, lighting and daylighting systems must be optimized in the broader context of overall building design, by recognizing their interdependence with envelope design and HVAC design.

While much is known about each of these issues there are important gaps in our knowledge. These gaps span the full set of individual issues noted above and are particularly critical at points of design coordination or system integration such as how to admit enough daylight without creating glare. The gaps can also be expressed in terms of (1) the missing information, tools or technologies that prevent a performance goal from being met by anyone; (2) the difference between plans and design intent and the actual construction and operation of the planned concept; and (3) the lack of acceptance of design solutions that have been proven by leading practitioners but not yet adopted into the mainstream. The good news is that current technologies, tools and design knowledge can partially address our goals.

Design of electric light delivery systems is an art and a science. Improvements to lighting efficiency must not overlook the fact that while there are measurable outcomes and performance parameters that can be quantified, compared, adjusted and optimized, there are also other strong subjective design parameters such as appearance, sparkle, color, and so on. Research in electric light sources, fixtures, and systems of control must respect the dual goals of objective and subjective improvements.

The effectiveness of daylight delivery systems in buildings is shaped by several primary factors. The combination of building form, geometry, orientation and latitude set fundamental constraints on the availability of daylight. The size and placement of apertures, coupled with the details of glazing and shading properties determines the admittance of useful light from both direct sunlight and diffuse daylight. Daylight delivery systems maximize useful light admitted in cloudy conditions but then control or minimize the light on bright sunny days. Control can be achieved partly by architectural design and partly by materials and device selection. The optimization of daylighting techniques for saving energy is often intertwined with the physiological, emotional and aesthetic aspects of window and skylight design. This is both an opportunity and a challenge in that the non-energy benefits can be used to help sell the energy-related functions. Innovative design solutions should (1) provide for deeper horizontal daylight penetration; (2) allow diffuse, glare-free sunlight into a room as a viable light source; and (3) create an effective glare-free view out a window while providing adequate daylight admittance.

Lighting, and to a lesser extent daylighting, are mature businesses in that many of the components and systems needed by designers exist today, but there is continued pressure to improve their price/performance ratios. Each of these topics has been the subject of past or current R&D at some level, but they all require a sustained effort in order to achieve the desired performance goals. Several key project areas require critical attention and are discussed below.

Illustrative Research Topics

This section describes research topics that deserve additional support and action in the near term. The focus is on program areas where additional research funding could make a noticeable difference in the technology and systems solutions available to designers and operators of both new and existing buildings. Several promising research areas in which significant research investments are already being made by both public and private sources (e.g., LEDs and OLEDs) have been omitted in favor of topics that have not been adequately addressed in funded R&D programs. For example, increasing electric source efficiency to more closely approach the theoretical limits for source efficacy (> 200 lumens/watt) would provide large potential savings. These savings might be achieved by additional improvements in gas discharge lamps or by further development of solid state light sources, both LED and OLED.

1. **PRIORITY TOPIC: Develop and test effective daylight/electric light control systems**. This research will result in a significant impact on energy use, demand response and occupant satisfaction. Some topics could be accomplished in a short timeframe and would yield immediate results. Regardless of the efficiency of a light source, one that remains “on” in an unoccupied or daylit space is wasting energy. Control systems consist of occupancy sensors, actuators (e.g., dimmable ballast), and the physical network and communications protocols that tie all the elements

together. There can be many functional drivers for a single control system: tuning light levels for occupant preference or task needs, daylight dimming, load shedding and demand response, and lumen maintenance. The controls infrastructure can be based on a separate wiring network, power line carrier signals over the power network, or wireless systems, each with its own strengths and weaknesses.

Effective systems integration is needed between daylighting and electric lighting components, including manual and automated control systems. Controls can be on/off, step switching, or dimming. Photosensor type, placement, and response are all issues in successful system design and operations. Efficient and flexible independent control of direct and indirect ambient sources and effective integration of task lighting are important elements of this research topic. The sensitivity of these decisions to room design details and glazing/shading choices is also important to understand. Highly sophisticated controls may cost more and may be difficult to commission. Research is needed to reduce or eliminate the cost and performance risk involved with calibration and commissioning. Additional research is needed to determine the time-dependent value of control operation (the correlation of savings to periods of peak electric demand, and the opportunity to aggressively control electric loads as part of a demand response program).

2. **Quantify impacts of daylight, lighting quality and emerging electric light technologies on occupant health and performance.** Conduct research through controlled field studies, experimentation, and intervention studies to study the mechanisms whereby daylight and lighting quality impact occupant health and performance. Daylight exposure and health outcomes should be studied in a variety of building types to identify the range of light levels and exposure times within which positive health impacts are likely. Individual differences that mediate response to daylight exposure should be identified(such as age, health status, susceptibility to seasonal affective disorder). This research would enable the development of architectural design guidelines for differential daylight strategies which maximize human health, comfort and performance.

   Related topics can be found in Chapter 4.2 – IEQ: Occupant Health and Performance.

3. **Improve understanding of occupant behaviors that impact the effectiveness of energy efficient lighting strategies.** It is often observed that people continue to use task lights when ambient light levels are within recommended ranges, while in other circumstances people will work in spaces lit below nominal levels. Past occupant studies of lighting controls should be expanded to guide the development of systems that result in more reliable and larger energy savings. A clearer understanding of occupant response to dynamic luminous environments is essential as occupants will otherwise disable controls and sensors. Controlled field testing should be used to develop design guidelines and improve predictive models of occupant response to lighting controls in spaces with variable lighting levels. This would allow the development of operations guidelines better suited to occupant needs and wants.

4. **Develop integrated exterior facade systems to enhance daylight quantity and quality through facade and top-lighting systems.** Simulation and field experiments should be conducted for a variety of building types to assess the daylight opportunity as it is affected by fenestration design; building orientation;

environmental factors that block daylight, especially vegetation and nearby buildings; and photovoltaics or other renewable energy systems. The performance of both static and dynamic systems should be investigated as daily and seasonal control is essential. This work will be useful to manufacturers of new technology and will allow for improved guidelines for daylight design relative to massing and exterior facade factors.

Related topics can be found in Chapter 2.1 – Building Form and Envelope.

5. **Develop and analyze methods to enhance lighting quality in building interiors.** Develop and test interior design solutions that enhance lighting quality in interior spaces using side-lighting and top-lighting strategies. Develop appropriate metrics for engineering performance and occupant acceptance. Interior solutions that should be evaluated include optical properties of room and furniture surfaces (e.g., hue, reflectivity, and specularity), furniture layouts, partition heights and opacity, ceiling height and form, the presence of atria, and the use of clerestories and skylights. This will allow for improved guidelines for architectural spaces that provide comfortable, energy-efficient task-oriented lighting that makes maximum use of available daylight.

   Related topics can be found in Chapter 4.2 – IEQ: Occupant Health and Performance.

6. **Quantify the life cycle economics of lighting decisions**. Evaluate the overall life cycle economics of lighting systems in buildings, including daylighting solutions. The life cycle assessment will include: the first cost of installed systems; operating energy costs; comparative occupant health and performance costs and benefits; indirect financial costs or benefits associated with ownership of the space and potential owner benefits of high-performance spaces. Overall environmental impacts will include those associated with cradle-to-cradle impacts of the technologies and systems of interest for electric lighting and daylighting.

   Related topics can be found in Chapter 2.3 – Materials Life Cycle Assessment.

7. **Improve electric light source efficacy**. There is a need for light sources that are highly efficient (200 l/w), dimmable, long-life, non-toxic, scalable in lumen output, affordable, and which provide good color rendition. Both point and large-area light sources must be considered.

8. **Improve electric light fixtures**. Fixtures are the practical interface between most building electric light sources and the interior luminous environment. They manipulate the light emerging from sources and “shape” its distribution (and sometimes color) to meet designer and user needs. Ideally fixtures are designed around the optical, geometric and thermal characteristics of lighting sources, and good fixture design further enhances the effectiveness of an efficient source. Mismatches between sources and fixtures can negatively impact energy and comfort. A critical function for many fixtures is not only shaping where the luminous flux from the lamp will go but also where it will not go. There is a wide range of quality in the design, construction, and practical application of fixtures, all of which impact energy efficiency as well as comfort.

9. **Advance technology transfer.** As with other research program areas, bringing new technologies and systems from the lab into practice is a vital component of successful research.

2.3 MATERIALS LIFE CYCLE ASSESSMENT (LCA)

Program Goal: Develop integrated assessment methodologies and standard metrics for the selection of materials that optimize building performance and minimize environmental, ecological and human health impacts. Support current efforts and initiate new projects that work toward the development of a transparent, rigorous, national standard for LCA in the built environment.

The research topics within this program area aim to:

- Develop an effective and rigorous integrated system for life cycle assessment of building products;
- Provide appropriate tools to professionals to specify materials and assemblies in a way that accurately accounts for the impacts of extraction/acquisition, manufacture, transportation, use, disassembly, and disposal/recycling of the material;
- Provide support for the U.S. Life Cycle Inventory (LCI) Database;
- Integrate LCA efforts and tool development into green building rating systems, such as LEED.

Background

The science of environmental and human health impact assessment of materials is at a historical juncture. Environmental advocacy groups and, for the most part, the building industry, have collectively come to the conclusion that knowing only a portion of a product's impact is not enough. If the full details are known, then scientific and value-based judgments can be made and defended based on information and analysis that is broadly accepted as credible. The development of LCA methodology, databases and software has been impressive. But to be given the chance to deliver on its promise, additional materials data are needed – especially in the areas of land and water use and human health impacts. The depository of that data – the U.S. Life Cycle Inventory (LCI) Database[16] – must be made robust and capable of supporting future LCA methods and practical application.

However, the costs of the current "top-down" approach to gathering and reporting generic and product-specific LCA data are high, even for fundamental building materials. Gathering and reporting LCA data is expensive, which explains why only the federal government and the largest companies have been involved in doing so to date. Both product-specific and generic LCA information is needed. Adding the capability for input of voluntary "bottom-up" data from companies, and for input in a single "top-down" database will foster a rapid growth of LCA data and provide a lower-cost and self-sustaining strategy for information sharing. Such a voluntary system could be verified by third-party review.

Needs related to LCA include: data on the market shares for different types of assembly in different types of construction and in different geographic areas; and increased industry and government support of the long-term maintenance and growth of the U.S.

[16] The U.S. Life-Cycle Inventory database was created by the National Renewable Energy Laboratory and the Athena Institute. It is publicly available at http://nrel.gov/lci.

LCI database. A robust database will allow LCA software tools to reliably, consistently, and comprehensively inform purchasing decisions. Data development includes improvement of the U.S. LCI Database and additional infrastructure to facilitate ongoing data contribution by manufacturers and others.

Widespread adoption of an LCA-informed procurement process will spur companies to improve the life cycle impacts of their products in order to stay competitive in the marketplace, and contribute information about improved performance to the database. It will facilitate the continuous product improvement necessary to reduce negative environmental and health impacts. While this research is focused on building materials and assemblies, the program's success will provide great leverage for promoting LCA in other manufacturing sectors. The research should also provide a framework to record the financial implications associated with chemical emissions and the health of occupants and the environment.

Illustrative Research Topics

Topics one through five could be accomplished in a short timeframe and would yield immediate results.

1. **PRIORITY TOPIC: Refine life cycle impact assessment methods.** Much LCA research is dependent upon the completion of this research topic. Of the dozen or so impact areas assessed by building material LCAs, indoor air quality, land use, and water use are most in need of further research. New initiatives to address these research needs should be created in partnership with international teams that are beginning to address some of the same issues. The partnership can also help to ensure that results of the international efforts support needs of users in the U.S. to the maximum possible extent.
    a. *Indoor Air Quality.* Chemical emissions from installation and use of building materials have a major impact on human health, but little is known of the specific impacts of individual chemicals, or combinations of chemicals and the mechanisms by which these effects occur. Of particular concern are the many organic chemicals used in a wide range of building applications, and emerging products employing nanomaterials and responsive substances such as chromogenic materials. A comprehensive list of materials used in building products should be developed and fundamental research undertaken on both the level of emissions of hazardous chemicals and the impact of those chemicals on biological organisms.
    b. *Land Use and Water Use.* The two highest-priority impacts for refinement, according to developers of the peer-reviewed U.S. EPA impact assessment methodology TRACI (Tool for the Reduction and Assessment of Chemical and other Impacts), are land use and water use. These methods need to address issues such as the extent of land disruption, time required for land restoration, and quality of water, soil, and habitat resources.

Related topics can be found in Chapter 4.2 – IEQ: Occupant Health and Performance; Chapter 2.5 – Water Use and Management; and Chapter 3.1 – Ecosystems and Site Design.

2. **Research and develop a standardized, robust and reliable data resource for LCA-based material and product specification**. Research and activities should support the further development of the U.S. LCI Database. The database should be expanded from both the bottom up and the top down. Both database expansions should facilitate the emergence and effective operation of third-party validation/verification systems, so that the LCA information is reliable and transparent.

   a. *Bottom up:* For the bottom up expansion, a system by which companies can voluntarily create and report product-specific LCA data without releasing proprietary information should be developed. The system should be designed to provide a business-to-business mechanism and incentives for developing and reporting LCA information of increasing accuracy and scope.

   b. *Top down:* The Input-Output LCA database, based on national statistics compiled by the U.S. Bureau of Economic Analysis and adapted by LCA experts to quantify life-cycle environmental impacts, should be expanded to distinguish more specific industries and commodities. These databases have a reasonable level of breadth, but require more specificity to inform building assembly, and ultimately material decisions

3. **Develop and expand existing LCA software tools to support building project teams and enhance diffusion of knowledge throughout the industry.** This would entail development of a universal software platform that would facilitate comparative evaluation of processes and products. Efforts should be made to ensure compatibility of new and existing building LCA software tools with existing international databases, and ensure their transparency, future growth, public availability and data input capability.

   Related topics can be found in Chapter 1.1 – Building Delivery and Operations Process.

4. **Develop an internet-based "Life Cycle Computation and Publishing System.**" This system would enable third parties to define the functional unit, durability, usage phase parameters, end-of-life fate, product or assembly manufacture, energy flows, and processing stages in the database compilation, and to have the resulting model results published transparently on the Internet.

   Related topics can be found in Chapter 1.1 – Building Delivery and Operations Process.

5. **Develop transparent public data on selected envelope and structure assembly types within a comprehensive set of assembly groups relevant to U.S. construction**. Provide information that, when combined with LCI data on the inputs to construction, installation, use, and end-of-life processing, provides complete and comparable LCI results per functional unit for a set of representative assembly types within each group (e.g., algorithms that translate user input parameters into material

quantities). For example, given the input of a specific construction project, LCI data could be processed to provide side-by-side comparisons of the environmental effects of various different window technologies. Develop an internet-based tool for authoring assembly definitions, to grow a transparent resource on building assemblies. Create data on the market shares for different types of assemblies in different types of construction, including geographic differentiation.

Related topics can be found in Chapter 1.1 – Building Delivery and Operations Process.

6. **Develop LCA-informed products.** Research is needed in order to develop products that account for environmental impacts at all stages of their life cycles. Standardized product designs for deconstruction and reuse should be developed to reduce manufacture and extraction impacts and to reduce the extent of construction demolition materials entering the waste stream. Research should also develop a means to specify and select materials based on ease of cleaning and maintenance. Such a means would allow for reductions in indoor pollution, as well as water and chemical use.

   Related topics can be found in Chapter 1.1 – Building Delivery and Operations Process.

7. **Advance technology transfer.** Determine the most effective methods to parlay research results into industry practice. Widespread adoption of new technology and knowledge in the marketplace is critical for achieving sustainability goals, and thus must be planned and implemented in step with research for prompt market uptake. Establish long-term industry and government commitment for the maintenance and growth of the U.S. LCI database.

2.4 PASSIVE, ACTIVE AND HYBRID HVAC AND CONTROLS

Program Goal: Reduce energy use and improve occupant comfort, health, and productivity by advancing and quantifying the performance of innovative building HVAC systems and equipment, exploring integration strategies, and developing design and operation guidelines.

The research topics within this program area aim to:

- Quantify the performance of innovative building HVAC components and systems in terms of both energy and occupant impacts;
- Develop and test climate-based design, operation, and integration strategies for dynamic high-performance HVAC components and systems that satisfy thermal loads using passive and active systems concepts;
- Develop design and operation guidelines for designers, building owners, and facility managers that address both automated and manual controls.

Background

HVAC systems, be they mechanical, passive, or some hybrid thereof are significant consumers of energy in buildings. U.S. Department of Energy statistics from 2005 indicate that about 33% of energy used in commercial buildings is for space heating, space cooling, and ventilation. In addition, the HVAC system in a building is a primary determinant of the quality of the indoor air, and hence a strong influence on occupant comfort and satisfaction. This program area organizes research to reduce HVAC energy use and improve occupant health and productivity.

Research is needed to improve primary HVAC systems and secondary distribution systems, including thermal storage, energy recovery, fan and duct systems, controls, demand controlled ventilation, desiccant and evaporative systems, and alternative refrigerants. HVAC systems and components include passive, active, and hybrid strategies. The most energy efficient approach is to utilize passive strategies as much as possible before active (mechanical) systems are applied.

Passive strategies take advantage of climate resources such as sun and wind to condition buildings while consuming little or no energy from the conventional, often non-renewable, sources of electricity. Much can be done with passive cooling through evaporative and/or radiant cooling, especially in one-story buildings. Passive heating using direct or indirect gain can supplement the heating needs of buildings even if they have high internal loads.

The adaptive model of thermal comfort asserts that people can adapt to a larger range of conditions than assumed and articulated in current codes and standards. This notion goes hand-in-hand with passive thermal conditioning because it allows building temperature and humidity levels to vary through a wider comfort band, allowing interior conditions to more closely follow outdoor changes throughout the day. Building designs can take advantage of this wider and more flexible comfort band and further employ passive cooling and heating systems.

Natural ventilation through operable windows potentially provides many benefits in terms of energy reduction and improved comfort, health and productivity, but cannot provide sufficient cooling and dehumidification in all climates at all times of the year. Given modern expectations, engineers are uneasy about the limited predictability and control over indoor thermal conditions in a naturally ventilated building. (The complex set of factors creating these expectations, and hence this unease, is worthy of further study in itself.) Mixed-mode or hybrid buildings, which combine operable windows with efficient mechanical conditioning systems, can offer lower energy use if designed and operated properly. Documented performance is essential to generate design and operation guidelines to optimize both energy efficiency and comfort.

There is a need to better integrate passive and mechanical conditioning strategies, to simultaneously optimize energy use and comfort. This challenge must be supported by advances in technology, design tools, design practice, and a better understanding of occupant needs and preferences.

As discussed above in the Building Form and Envelope program area, field studies find high occupant dissatisfaction rates in some buildings with centralized HVAC control. While there is a need for improvement for centralized controls to operate more simply and effectively, there is also a need to provide occupants with some level of personal adjustment. Personal control through task-ambient conditioning systems offers the potential for optimizing both energy and comfort; this can be achieved through control of an operable facade, or through the mechanical system. There is a need for documenting performance and cost implications of these systems to guide design decisions.

Distributed control can create additional challenges. There is a need to understand the performance and control implications within a whole building in view of the imbalances of air and energy distributions that might result from the use of personal environmental control devices in open and semi-open spaces.

Whole-building, integrated systems that will extend coverage to equipment and control system efficiencies also deserve research.[17]

Illustrative Research Topics

1. **PRIORITY TOPIC: Develop, enhance and optimize innovative, climate-based HVAC strategies** (e.g., radiant systems, evaporative cooling, naturally ventilated and mixed-mode buildings, etc.). This topic has high potential for impact, and will enable subsequent research into innovative HVAC systems. The success of technological developments will be contingent on operation of the building as designed.

   The energy and comfort performance of systems and equipment must be improved, with the understanding that system requirements vary depending upon regional climates. Research into energy consumption of fan and duct distribution systems is needed. Enhancement of the seasonal performance of design and operation configurations should address the issue of adaptation to the dynamic temperature

[17] Research should be coordinated with ASHRAE, in line with their Research Strategic Plan 2005-2010, http://www.ashrae.org/doclib/200641713376_347.pdf

and humidity of indoor environments. In order to reduce the cost of innovative, climate-based HVAC systems, development and enhancement of components and improvement of system performance is needed.

2. **PRIORITY TOPIC: Compare, evaluate, and optimize a continuum of centralized and personal control options for advanced HVAC systems**. This topic has high potential for impact, and will enable subsequent research into innovative HVAC systems. It will achieve the next evolution in thermal comfort, while saving energy through personal controls.

   Research will include the sensing and control functions of a distributed, occupant-regulated (but centrally optimized) passive, active and hybrid HVAC systems that account for indoor and outdoor environmental dynamics (weather, occupancy, utility pricing, etc). An important objective of this research is to incorporate learning based on occupant behavior and preferences, within the intelligent control strategy. Development of advanced adaptive and intelligent controls will aid this objective. Simple, user-friendly control interfaces are needed.

3. **Test and develop innovative thermal energy and air distribution systems that enable distributed environmental control** (e.g., task ambient conditioning, under-floor air distribution). Task ambient conditioning and under-floor air distribution are in limited use; additional development, analysis and testing (lab and field) are needed to characterize performance and increase the applicability and credibility of such systems. Existing technologies for distributed control of HVAC need further development. Alternative thermal distribution systems (refrigerant or water rather than air) should also be explored. Aspects of this topic could be accomplished in a short timeframe and would yield immediate results.

4. **Develop techniques and tools to evaluate, characterize and benchmark overall performance of advanced HVAC strategies**. Techniques and tools are needed to evaluate, compare, characterize, benchmark, and optimize overall performance in terms of ambient and microclimate IEQ, and occupant comfort, health and productivity. This will enable the characterization of non-energy performance characteristics of advanced HVAC strategies. Aspects of this topic could be accomplished in a short timeframe and would yield immediate results.

5. **Produce improved design tools for passive and hybrid components and systems.** Because passive, active, and hybrid technologies are far from standard, manuals for effective design and operation of these HVAC systems are greatly needed. In addition, there is a need for design and operations guidelines for innovative, climate-based HVAC systems.

6. **Demonstrate performance of low energy cooling and dehumidification**. Research is needed into passive, non-vapor compression systems such as evaporative, dessicant, and thermoelectric cooling as well as passive strategies. Particular emphasis should be placed on alternative means (other than condensation) of dehumidification. This research will allow further performance characterization of non-vapor compression cooling systems, as well as of passive cooling strategies.

7. **Improve understanding of delivered efficiency rather than component efficiency for HVAC equipment**. Better performance maps of equipment are needed so we can better model and analyze systems. Data is currently available on performance of individual components, but this information needs to be placed into a context of whole building energy use. Such research could look at data from low-energy buildings in order to understand part-load operational effects and actual run-time of systems. This research would lead to better guidelines for right-sizing systems for buildings.

8. **Advance technology transfer.** Determine the most effective methods to parlay research results into industry practice. Widespread adoption of new technology and knowledge in the marketplace is critical for achieving sustainability goals, and thus must be planned and implemented in step with research for prompt market uptake.

2.5 WATER USE AND MANAGEMENT

Program Goal: Reduce potable water usage in the operation of buildings and grounds.

The research topics within this program area aim to:
- Create metrics for evaluating building-related water use;
- Compile baseline data on water consumption in and around buildings;
- Develop strategies and tactics for minimizing water use;
- Ensure water quality and availability;
- Disseminate information and incorporate technologies into practices.

Background

Water resources are being stretched increasingly thin – not only in drought-prone parts of the country, but also in temperate, less challenged regions, through the depletion of aquifers and surface waters. In some areas of the U.S., groundwater is being depleted faster than it is being replenished, and groundwater pollution and salt-water intrusion are rendering some aquifers unusable. Most activities using water also produce wastewater that must be transported and treated (consuming energy in the process). In some areas, wastewater treatment capacity is severely restricted, increasing the incentive to reduce potable water use.

In addition, unsustainable practices are further stressed by extreme weather patterns. These may worsen in coming years; altered patterns of precipitation are among the predicted effects of global climate change. According to some climate models, these changes will create significant water shortages in some parts of the world while increasing precipitation and risk of flooding in other areas. With potentially less water available from precipitation and snowmelt, these regions will have to place a higher burden on aquifers that are already heavily taxed, transport water from other regions, or use less water.

The redesign of fixtures, equipment, and systems to use less water than current practices has the potential to dramatically reduce potable water needs of buildings, thus helping to alleviate the effects of droughts and aquifer depletion. Similar or even greater water savings can be achieved outdoors through low water use landscaping strategies, more efficient irrigation equipment, more advanced irrigation controls, and innovative strategies for using graywater or collected rainwater.

This program area includes measures to gain a greater understanding of how water is used in and around buildings. It also includes the development of fixtures, appliances, systems and equipment that reduce potable water use in and around buildings. The equipment and systems of interest here include everything within or outside a building that currently requires water for operation, including plumbing fixtures, mechanical equipment, fire protection systems, appliances, irrigation equipment, and equipment that requires process water. It also includes systems that promote the use of alternative on-site sources of water and reclaimed municipal wastewater in lieu of potable water. Stormwater infiltration management, discussed in the Ecosystems and Site Design sub-chapter, is important for surface water quality, groundwater recharge, habitat protection, and public health and safety; it is a component and point of discussion in land use regulations.

Non-proprietary research into water-efficient products, technologies, and practices has been conducted by the water utility industry over the past 15 years. This research has led to better testing of plumbing fixtures, improvements in existing products, and the the industry's development of new products and technologies. Within some water efficiency topic areas, industry has been relatively successful in developing water-efficient technologies, especially in the commercial sectors of food service, medical systems, and laundry and cleaning equipment. There have also been significant developments in residential plumbing fixtures and appliances. However, this is not true in all areas, and many of those that have been developed are not yet suitable for widespread use due to a wide range of factors, including code issues, cost, performance, and variations in building/use type. The cooperative relationship between the water utility industry and those firms developing the cutting-edge water-efficient technologies and products must be maintained and encouraged to grow.

Illustrative Research Topics

1. **PRIORITY TOPIC: Develop, compile, and disseminate data on building-related water by end-use**. This research addresses a critical barrier in practice and could potentially have a large impact on market transformation. It is essential to systematically compile and disseminate the knowledge that currently exists and to ensure that there is a common framework for the collection of data and knowledge in the future.

   The water consumption within buildings should be collected by building type, occupancy, location, and size. This would be analogous to the Energy Information Administration's Commercial Buildings Energy Consumption Survey. Data on water consumption within buildings also needs to be collected by type of fixture, fitting, and appliance. Much, but not all, of this data already exists in many separate pieces, each of which must be further validated and brought together. Work should involve further testing and verification of existing water-efficient technologies for efficacy, performance, and human health concerns. Much testing and verification has already been completed involving performance, water use reduction, economics, and other factors. Supplementary work is required to fill in the gaps that remain. The value of reducing potable water usage needs to be articulated in terms of economic, ecological and social value. Among the research outcomes of this topic area will be: published metrics, databases, and methodologies, including appropriate normalization and benchmarks to report accurately and usefully the water usage within buildings; published data to verify water-performance of specific technologies and products; and technology transfer materials to educate end users.

2. **PRIORITY TOPIC: Develop and test integrated water management systems**. This topic challenges us to take a fresh look at how water is used throughout the built environment. Taking a systems approach to water management could result in significant water savings.

   Water management solutions will be critical in the future as water supplies become more stressed and population growth places greater demand on limited supplies.

Define, develop and test new systems that integrate on-site water sources and consumption with conventional potable water sources. To minimize the import of water and maximize the recovery and reuse of water on the site, well-integrated systems should include, for example, stormwater retention/collection, condensate recovery, the development of innovative irrigation and irrigation control technologies, and alternative and onsite wastewater and sewage treatment systems. Even more advanced systems could incorporate new technologies for treating waste products—transforming solid waste into useful material. Among the research outcomes will be a systematic review of water availability, functionality and usage within the built environment**.**

3. **Quantify relationships between water savings, energy savings, and air quality**. Develop interactive information on how water conservation and the installation of water-efficient products and technologies also impacts energy use and air quality. This will allow for the documentation of the synergistic effect that water usage has on energy use and air quality.

4. **Develop and test technologies required for using onsite sources of water**. Identify water management systems that could incorporate all types of on-site sources of non-potable water including rainwater, stormwater, graywater, cooling tower water, and filter backwash water. Determine appropriate non-potable applications and incorporate their use into the water management system. The system could, for example, include storage and filtration of stormwater and other collected water. This research effort could include development of new technologies and products.

5. **Develop and test low-cost, practical graywater technologies**. There is a need to examine and field test new graywater collection and treatment systems, and new technologies for cost-effective, low-maintenance systems that facilitate the use of non-potable water for building functions that currently rely on, but do not require potable water. Strategies should be developed to integrate new technologies into the marketplace. Specific research into the area of existing health codes and water quality is necessary in order to overcome the impediments to widespread application of the newest graywater treatment and re-use technologies now appearing on the North American marketplace.

6. **Develop and test low- and no-water technologies**. There is a need for further development of existing technologies for cost-effective, low-maintenance plumbing fixtures, equipment, and appliances that meet current minimum performance standards while using little or no water for all building types, including residential, commercial, industrial, and institutional. Among the areas currently requiring further testing and development are long-term performance and maintenance requirements of waterless urinals, and net zero-water-use wastewater systems. These developments may address issues including increased performance under specific conditions, easier or less expensive maintenance, reduced space requirements, and code requirements. Strategies should be developed to integrate new technologies into the marketplace.

7. **Develop HVAC systems that are more water efficient**. Develop and test systems for reusing HVAC condensate/blowdown. Develop realistic methods for treating condensate on site to remove dissolved solids so that this water can be recycled

indefinitely, minus evaporative losses. Develop a method to show the impact of energy conservation methods on cooling tower water use.

Related topics can be found in Chapter 2.4 – Passive, Active and Hybrid HVAC and Controls.

8. **Advance technology transfer and model code development**. Regional building codes, zoning ordinances, and standards often affect the ability to use certain water-conserving technologies and systems. Changing codes, standards, and laws necessitates a deeper level of understanding of these systems and clear demonstration of efficacy and safety. This program area will determine the most effective methods to parlay research results into code changes and accepted best practices. Widespread adoption of new technology and knowledge in the marketplace is critical for achieving the desired sustainability outcomes, and thus must be planned and implemented in step with research for prompt market uptake. A significant effort may be required to educate the public and policy makers on the local, state and federal levels.

CHAPTER 3: BUILDINGS' INTERACTIONS WITH LOCAL ENVIRONMENTS

Buildings do not exist in isolation – they interact with the site on which they are built. They may concentrate stormwater runoff or serve to capture and infiltrate that stormwater. Their development may damage ecosystems or contribute to ecological restoration. By virtue of location and various characteristics of local and regional land use, buildings may be responsible for significant transportation energy consumption and environmental impacts.

The research topics proposed in this chapter seek to gain a greater understanding of how buildings interact with their local and regional environments. Greater understanding of how to mitigate stormwater runoff and remove pollutants from it, development of more effective strategies to remove pollutants from stormwater and prevent the urban heat island effect, and new approaches to prevent bird collisions and restore brownfields or damaged ecosystems are among the site-related research priorities being advanced here. Relating to transportation, there is a need to quantify the predicted transportation energy use that can be attributed to buildings—which could form a more objective mechanism for awarding location-specific credits in LEED or other green building rating systems.

The research programs outlined in this chapter ("Ecosystems and Site Design" and "Building Location and Transportation Intensity of Buildings") collectively broaden the Agenda of green building, addressing the all-important issues of how buildings interact with the sites and regions in which they are located.

3.1 ECOSYSTEMS AND SITE DESIGN

Program Goal: Protect and enhance local and regional ecosystems while reducing energy and water use and atmospheric pollution through improved design and management of built landscapes and appropriate building siting.

The research topics within this program area aim to:

- Analyze, develop and test site design and building strategies that protect, restore, and support diverse, healthy, and locally appropriate ecosystems, inclusive of water, land, soils, and air;
- Analyze, develop and test building and site design strategies that improve building energy performance and reduce pollution and the urban heat island effect;
- Develop new technologies and policies to restore the ecological health of brownfield sites and accelerate brownfield redevelopment;
- Improve the management of stormwater on building sites, engender several generations of water use onsite, and more effectively remove pollutants from stormwater;
- Disseminate information and incorporate technologies into practice.

Background

Land development and the management of landscapes around buildings have significant impacts on local and regional ecosystem health, building-specific and regional energy use, local aquifers and surface waters, land and soil restoration, air quality, and human health and well being. Every construction project has immediate and direct impacts on the site ecosystems, which to date have been predominantly negative. While the development community and environmentalists have historically been at odds regarding land development, it is becoming increasingly clear that environmentally responsible development can actually improve, rather than harm, local ecosystem health through protection of natural areas and restoration of damaged ecosystems. The treatment and management of building sites can also positively affect building occupants and visitors through opportunities for healthful recreation.

Environmentally responsible building recognizes that an important component of design, construction, and operation involves outdoor spaces and the interactions between buildings and the ecosystems in which they are located. This includes ecological impacts that may extend from a building beyond the landscape (such as light pollution, bird collisions, effluent flows or air pollution), land and soil impacts, atmospheric impacts, and the water flows on a building and site, including stormwater.

Cumulatively, the manner in which building sites are developed has the potential to shape the public and ecological health of a region. While this Research Agenda addresses regional scale issues to only a limited extent, it explicitly acknowledges that design, construction and operation decisions made at the building site scale can have a profound impact on the surrounding region.

Current ecosystem and site design research efforts include ecological restoration practices, development of metrics to measure ecosystem health, strategies for reducing chemical use on landscapes (e.g., pesticides, fertilizers), environmentally responsible stormwater management, green roofs, landscape and site practices to reduce building and regional energy use, greater understanding of the impacts of and measures to reduce light pollution, the prevention of bird collisions with buildings, and brownfield remediation. While additional research is needed to address these issues on a larger regional scale, it is outside of this Research Agenda's scope.

Related topics can be found in Chapter 2.5 – Water Use and Management.

Illustrative Research Topics

1. **PRIORITY TOPIC: Develop models for assessing the life cycle costs and benefits of all landscape elements**. Much subsequent research will be dependent on the outcomes of this research. Locally appropriate vegetation on building sites offers a wide range of benefits, including a reduction in building cooling loads, reduction of urban heat island effect; the contribution of nutrients to the local ecosystem or municipal compost system; aesthetic benefits that lead to increased property values; increased wildlife habitat, and food production. Some studies have been completed at the municipal level that quantify the financial costs and benefits of street trees, but more work is necessary to enable informed decisions about the economic and environmental impacts of trees and other landscape elements including vegetated infiltration swales and rainwater gardens, porous pavements, green roofs, and other landscaping features—which are often value-engineered out of a project without consideration of their long-term benefits. In addition, a mechanism to understand the tradeoffs between water and energy benefits is needed. The outcomes of this research will be the creation of metrics and benchmarks to assess costs, benefits, and tradeoffs of green landscape elements; regional databases that can inform policy development, and the creation of design tools.

   Related topics can be found in Chapter 2.1 – Building Form and Envelope.

2. **PRIORITY TOPIC: Develop or improve best management practices for on-site stormwater management, including effective utilization, treatment, infiltration and storage.** This research is a priority because of the potential impact of its research outcomes and because of the dependence of future research on its outcomes.

   A common goal of green building projects is not to increase stormwater runoff from a site, or to reduce stormwater runoff. Future goals will be to eliminate all stormwater runoff and to maximize the use of storm and rainwater to reduce the need for piped water supplies. Achieving these goals demands innovations in both practices and technologies, and research into long-term performance, environmental benefits, maintenance requirements, and cost-effectiveness of these systems. Practices needing further research include systems to remove pollutants from surface runoff, development of infiltration basins and raingardens, porous pavement systems, daylit streams, constructed wetlands, and green roofs. There is a need for significant additional research in these areas, especially pollutant removal systems and the design of infiltration and storage capability of landscapes, as well as the integrated systems that will support effective use of on-site water. Through field studies of existing systems, these benefits can be quantified in each U.S. climate. For example, porous pavement systems allow increased stormwater infiltration, thus helping to reduce downstream flooding, limit surface water pollution, recharge aquifers, and—in certain urban areas—reduce the frequency of combined sewage overflow problems. As a fairly new material, however, there is still a great deal that is not known. Outcomes of this research would be new technologies and systems integration strategies, as well as design guidelines for landscape elements.

Related topics can be found in Chapter 2.1 – Building Form and Envelope.

3. **PRIORITY TOPIC: Analyze, develop, and optimize landscaping strategies for brownfield restoration.** This is a time-critical research topic first because land pressures are increasing (and will likely continue to increase), and second because brownfield sites have the potential to contaminate soil and water beyond return.

   Research outcomes have the potential to make a significant impact in land use and development patterns in many parts of the country while protecting water and other ecological resources. A significant percentage of available building sites, especially in urban areas, are contaminated by hazardous chemicals, and termed brownfields. Development of brownfields is costly, both because of the actual costs of remediation, and due to liability, often dissuading developers from building on brownfields. This puts pressure on previously undeveloped (greenfield) sites. Research is needed to analyze, develop, and optimize landscaping methods for streamlined, cost-effective brownfield remediation—including such strategies as bioremediation and phytoremediation. This research would lead to the development of landscaping technologies and remediation process improvements; as well as policy analysis and development to facilitate an increase in brownfield remediation.

4. **Characterize the impact of landscape design and site/building integration on human comfort, health and productivity.** Specific aspects of site design can have significant impacts on people. These include issues such as: the use of vegetation to mitigate automobile pollution and noise; landscaping and site design to promote seasonal shading; landscaping and site design to promote natural ventilation; landscaping to facilitate daylighting of interior spaces; and a landscape-inspired connection with nature that supports mental and emotional health (biophilia). Research is necessary to better characterize these impacts and to quantify specific ways in which site and building design can further promote human health and well being.

   Related topics can be found in Chapter 4.2 – IEQ: Occupant Health and Performance.

5. **Characterize the direct impact of buildings and impervious surfaces on urban heat island and atmospheric pollution effects.** Beyond the immediate benefits of cooling load reductions for buildings, more widespread use of landscaping in site design has the potential to significantly reduce regional temperatures, which drive cooling loads for entire communities. Heat absorptive materials commonly used on building roofs combined with increasingly hard surfaced sites for parking and roadways, have been significantly increasing the surrounding ambient temperature through the heat island effect. Research is necessary to directly quantify the impact of integrated building and site design strategies and materials on both the site microclimate and the greater urban climate. Research must be climate specific, and

should incorporate the atmospheric benefits (from both the landscape materials and reduced energy supply requirements) of how environmentally responsible site design can extend to entire communities. This will allow the development of architectural design guidelines, site design guidelines, standards, and codes that reduce building energy use and address the ecosystem imbalance caused by the urban heat island effect.

6. **Analyze, develop and optimize landscape design strategies to promote ecological and habitat restoration at the site scale.** Ecological restoration is an important goal for building sites, particularly previously developed or disturbed sites. With climate change will come the migration of plant communities, and some experts suggest that the climate will change too rapidly for natural migrations to keep up — necessitating human intervention. Ecological restoration involves removal of invasive species, elimination or downsizing of high-maintenance turf areas, and establishment of diverse communities of native vegetation. In addition, ecological restoration must be designed to ensure appropriate habitats for native species of animals, plants, fungi, and bacteria. In some parts of the country, a quantitative method has been developed to determine the ecological health of a piece of land — using a process called "Floristic Quality Assessment." Outcomes of this research would be a comprehensive understanding of the costs, benefits, and ongoing maintenance requirements of ecological restoration, and the development and expansion of Floristic Quality Assessment protocols (to reflect all flora and fauna) for all major U.S. climate regions.

7. **Evaluate the efficacy and water quality benefits of porous pavement systems**. Assess the long-term benefits of reduced runoff and storm sewer discharges on vegetation, human health and the environment. Groundwater recharge through porous pavement may also save energy by preventing large regional water transfers. Perform a life-cycle evaluation of permeable pavement systems to determine lifetime effectiveness, costs and related issues.

3.2 LAND USE, BUILDING LOCATION, AND TRANSPORTATION

Program Goals: Reduce the energy, environmental, and public health impacts that result from single use zoning, the density and location of buildings, and transportation choices for getting to and from those buildings.

The research topics that follow aim to:

- Demonstrate the significance of location- and transportation-related energy consumption of buildings (the "transportation energy intensity" of buildings).
- Establish robust, yet practical, metrics for reporting the predicted transportation-related energy consumption of individual buildings. This would be based on their location and the transportation options available to building occupants.
- Develop a simple scientifically valid method by which the transportation energy intensity of buildings can be assessed through a performance-based approach.

Background

Buildings consume energy directly for heating, cooling, lighting, ventilation, and process energy, and they are partially responsible for the transportation energy use of the people getting to and from them. To date, relatively little attention has been paid to the transportation component of a building's overall energy footprint, even though this transportation energy use can be very significant, especially relative to greenhouse gas emissions.

A recent investigation[18] suggests that, averaged nationally, a new office building built to the ASHRAE 90.1-2004 energy code will consume nearly 2.4 times as much energy per square foot for workers commuting to and from the building than the building itself consumes for operation. Should these findings be supported by more thorough peer-reviewed research, there may be reason to give more weight to location- and transportation-related measures in the planning, siting, and design of green buildings—and in the priorities represented in green building rating systems.

A wide range of factors influence the transportation energy intensity of buildings. These include land-use density, diversity of building uses and services in the area, availability of public transit and other alternatives to private automobile transportation; distance to public transit, availability and convenience of parking, walkability of the area, suitability for bicycle commuting, and incentives offered to building occupants for using lower-impact transportation alternatives.

In addition to the energy consumption resulting from the transportation energy intensity of buildings, the location of buildings and the transportation options available to building occupants also affect human productivity (especially time wasted in traffic), human health, commuter and pedestrian safety, infrastructure costs, stormwater runoff, ecosystem health, and biodiversity. These non-energy impacts associated with building location and transportation options are important and should also be investigated once the first two critical tasks have been addressed.

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[18] *Environmental Building News* (Volume 16, No. 9, September 2007).

Illustrative Research Topics

1. **PRIORITY TOPIC: Develop metrics and methodologies for reporting the "transportation energy intensity" of buildings.** This research could be accomplished in a short timeframe and yield immediate policy and behavioral results. Much subsequent research will be dependent on robust databases and consistent metrics. Metrics, databases, benchmarks, and methodologies are needed to report accurately and usefully the transportation energy intensity of buildings, based on a wide range of factors, including location, type of building, modes of transportation available, land-use density, diversity of building types and services, parking availability and cost, walkability, and company incentives to avoid using a private automobile. A supporting body of research and data can be found in The National Personal Transportation Surveys and the National Household Transportation Survey published by the U.S. Department of Transportation. Many state and municipal transportation agencies have more specific transportation data and models. Methods for defining transportation impacts for a building on a per-square-foot or per-capita basis is a sizeable challenge that will involve the following components:

    a. Understand and identify metrics for measuring factors that affect the transportation energy intensity of buildings, such as development density, diversity of building types and services, socioeconomic diversity in the vicinity, street connectivity, access to key services, access to public transit and other non-automobile transportation options, walkability, safety, parking management, bicycle accessibility and infrastructure, and non-automobile commuting incentives offered by employers.

    b. Develop a weighting scale for a full range of factors so that a single number could represent the predicted transportation energy intensity of a specific building.

    c. Develop methodologies for easily and efficiently calculating and reporting the factors on a building-specific basis.

    The outcome of this research would be a scientifically valid yet simple method by which the transportation energy intensity of buildings could be incorporated into LEED or other green building rating systems through a performance-based approach.

    Related topics can be found in Chapter 1.3 – Performance Metrics and Evaluation.

2. **PRIORITY TOPIC: Compile data on measured transportation energy intensity of buildings—to develop baseline performance data.** Development of baseline data enables further research on building-related transportation energy. The transportation energy consumption for specific buildings and community settings should be collected to establish baseline data that can help to verify or improve the accuracy of metrics defined in the previous research topic. Research outcomes will seek to correlate building location, land-use patterns, and company operation to transportation energy and compare it with baseline levels. This data should be collected for a range of existing commercial building types and in different areas of the U.S. to gain an understanding of how the transportation energy intensity of buildings varies by building type and geographic region. The outcome of this

research would be a database that includes transportation energy intensity information for buildings by building type, geographic region, and land-use setting to establish baseline information that can be used to verify and refine transportation energy intensity models.

3. **Compile data on non-energy transportation impacts of buildings and land-use patterns**. Identify and establish metrics for other environmental and resource impacts tied to transportation choices in a range of existing commercial building/land use settings in the U.S. Collect data by building type, geographic region, and land-use setting to establish baseline information that can be used to verify and refine non-energy transportation impacts, especially CO_2 and other greenhouse gasses. Similar to the baseline data on energy use, there is a need to establish baseline levels of non-energy transportation impacts by building type and land use setting.

4. **Compile data on the health impacts associated with different transportation choices.** Human health impacts, including obesity, anger and depression, allergies and asthma, associated with various transportation choices and building/land-use settings in the U.S. should be identified and compiled into an ongoing database. EPA/OEHHA CURES weightings might be a good start for existing research. The challenge for the data is further refinement of the causal linkages between exposure, concentration, and epidemiology. It will also be important to maintain and adapt these linkages as the composition of urban smog and smog precursors change with an evolving transportation fuel infrastructure.

5. **Investigate opportunities for reduction of transportation impacts**. There is a need to identify the barriers, opportunities and improvements possible in energy, environmental and human impacts of transportation choices given innovations in building/land-use settings and/or transportation alternatives. Opportunities should be sought to strengthen multi-use zoning and support for mixed modes of transportation.

6. **Complete policy development, land planning models and zoning models, and advance technology transfer.** The need for shared solutions supported by policy, technology and finance is critical for the building, planning and development communities. Ensure communication strategies customized to organizations, practitioners, and policy makers, such as economic indicators and model zoning codes.

CHAPTER 4: BUILDINGS' INTERACTIONS WITH OCCUPANTS

Buildings are habitats for people. Just as with natural systems, the quality of the habitat strongly influences the health and well being of its residents. Quality is an emergent property of the interaction between many factors in both natural and built habitats. For the built environment, quality derives from all of the processes, expertise, technologies, and values that are brought together in design, construction, operation and maintenance of a building. The materials, facade, siting, location, and land use features are all components of the building as experienced by its occupants.

The research proposed in this chapter considers the reciprocal influences of people and buildings. We know from existing research and theory that the features and attributes of buildings – from thermal and air quality conditions to acoustics – can support or inhibit human behavior often in unexpected ways. We also know that people are not passive actors in the building system. Their perceptions and experiences can influence how the building functions.

The two programs described in this chapter ("Indoor Environmental Quality: Measuring Pollutants and Stressors" and "Indoor Environmental Quality: Occupant Health and Performance") are intricately linked, but separated for clarity. The first section focuses on generating knowledge about environmental conditions, while the second section focuses on how IEQ affects the building occupants. We expect that IEQ research will be undertaken by interdisciplinary teams with expertise in environmental systems, human health, and work performance.

Findings from the IEQ research will be fed forward into new building design, construction, maintenance and operations, creating a "virtuous circle" that connects all of the systems addressed in this Agenda.

4.1 Indoor Environmental Quality (IEQ): Pollutants and Stressors

Program Goal: Develop and maintain indoor environments that benefit occupant health, comfort and performance through superior indoor air quality; good visual, thermal and acoustic conditions; and connection to the outdoor environment.

The research topics within this program aim to:

- Clarify the chemistry, biology and mechanics of indoor environmental quality (IEQ) to inform improvement strategies;
- Develop metrics and tools to quantify indoor conditions and simplify the processes of understanding, assessing and improving IEQ;
- Develop design/engineering strategies appropriate to climate, building type and conditions, to create and maintain indoor environments that support human health, comfort, and performance.

Background

People spend up to 90% of their time indoors, increasing their chances of exposure to pollutants and other indoor environmental stressors including noise, glare and uncomfortable temperatures. As discussed in the Health and Performance Impacts of Buildings program area, there is growing evidence of many potentially harmful effects of poor IEQ on building occupants.

Making the link between potential sources of pollution or discomfort and actual health and performance effects is a very challenging task, involving the interaction of a complex array of variables. First, indoor pollutants may arise from many sources, indoor or outdoor, and may have chemical, biological, gaseous and/or particulate elements. Second, these pollutants interact with a range of indoor conditions including varying levels of temperature, humidity, ventilation and occupant behavior. Third, levels of occupant exposure to indoor pollutants or stressors will vary based on circumstances, and actual physical reactions will vary not only by pollutant and its level but also by characteristics of the occupant.

In addition to the complicated issues of indoor air quality (IAQ), the broader topic of indoor environmental quality (IEQ) also includes such factors as acoustics, thermal comfort, electric lighting, daylighting, and access to views of the outdoors – affecting a full range of human sensory conditions. Unfortunately, these topics frequently are studied – and designed – in isolation, with experts in each field making recommendations independent of other indoor environmental conditions. For instance, natural ventilation design may improve air exchange rates and thermal comfort, but could reduce overall IEQ if external noise, pollutants or excess humidity enter the building.

There remain many large gaps in our knowledge of IEQ. For indoor air quality, these gaps include understanding baseline indoor pollutant levels, pollutant sources, the number and nature of pollutants, pollutant pathways and exposure scenarios, impacts on health and productivity, emissions testing and certification protocols (for products, materials, and buildings), and effective strategies to improve indoor air quality through product manufacturing, building design, construction, operation and maintenance, and occupant behavior. For daylighting, knowledge gaps include how to effectively integrate natural and electric lighting to support occupant needs, and support visual comfort and health, while also reducing consumption of non-renewable energy sources (Note: The Lighting and Daylighting program area addresses these issues in more detail).

Indoor acoustics have largely been ignored in sustainability research, even though acoustic conditions are known from field studies to be a significant negative factor in occupant satisfaction and performance. In addition to lowered partitions and open windows (mentioned above), acoustic conditions are influenced by materials selection, building site, use of demountable walls rather than hard walls, and quiet HVAC systems.

Beyond progress in these specialty disciplines, a greater need is for multidisciplinary research on the combined impact of indoor environments on all the senses of their occupants. This challenge requires significant advances in basic IEQ science, evaluation metrics and protocols, design strategies, and building operations.

Related topics can be found in Chapter 2.4 – Passive, Active and Hybrid HVAC and Controls, topic 4; and Chapter 4.2 – IEQ: Occupant Health and Performance.

Illustrative Research Topics

1. **PRIORITY TOPIC: Fill essential gaps in knowledge of indoor chemical pollutants.** Research on this topic is a prerequisite for other research. There is also too little known about indoor chemical pollutants to provide sufficient guidance to produce effective IEQ metrics or adequately inform product testing, certification or formulation standards.

   There is a great deal that is not yet known about indoor chemical pollutants, including knowledge that is needed to help identify the most serious hazards and develop strategies to avoid and/or mitigate them. First, more work is needed to characterize indoor chemical pollutants and their typical levels. Such research could include indoor air testing, product emissions testing and analyses of product formulations. Second, more research is needed to establish priority rankings of the highest risk chemicals and mixtures, so that additional study and action may be directed to the top priority risks. Third, it is essential to improve understanding of the indoor 'interactive' fate of chemicals and mixtures, e.g., how different substances react with each other indoors, and under what circumstances they are absorbed by various surfaces.

2. **PRIORITIY TOPIC: Develop metrics and protocols for assessing the individual and combined effects of indoor environmental conditions**. Standard research methods for assessing combined effects are needed for future research. Sound metrics and protocols are also critical to help move the marketplace toward a more standardized and effective focus on IEQ. There is admittedly a "chicken and egg" problem here in that many scientific gaps (e.g., of indoor biology, chemistry and dynamics) need to be filled in order to develop good metrics, yet since we will never have perfect knowledge, we still need to develop metrics based on the best available information.

IEQ is arguably the most difficult major environmental impact of buildings to measure at this time. First, there is a need for databases of typical baseline conditions (adjusted for climate, building type and condition) against which IEQ problems and improvements can be evaluated. Second, standard assessment approaches for evaluating IEQ in common building types are needed to facilitate comparison of the impacts of sustainable and non-sustainable design strategies on IEQ in new and renovated buildings. Third, the results of these assessments need to be translated into simple building IEQ indices (summarizing indoor environmental conditions in a simple numerical format) to facilitate measurement, understanding and communication of IEQ levels.

3. **Develop more effective standards and protocols for product emissions testing.** The green building marketplace has demonstrated its interest in labeling and certification schemes that indicate which products have the lowest chemical emissions. While several such programs have developed, there are significant gaps in the science underlying them, and a general lack of consistency in approaches. Better information on relative ranking of chemical hazards (see topic 2 above) is needed, as are more consistent laboratory emissions testing protocols.

   Related topics can be found in Chapter 2.3 – Materials Life Cycle Assessment, topic 1a.

4. **Investigate mold and other biological pollutants.** Research has demonstrated that indoor biological contaminants can negatively impact human health, but knowledge of the relationships among building conditions, occupant exposures and health impacts remains limited. Characteristics and health impacts associated with mold allergens and mycotoxins need to be identified. Standardized and quantitative methods to assess mold exposure should be developed and implemented, including studies to establish biomarkers (or surrogate biomarkers) of exposure to mold in humans. Research is also needed to identify physical conditions that are conducive to mold and other asthma triggers, and the effectiveness of exposure reduction methods. Design, operation, maintenance, and behavioral strategies to reduce exposures to biological pollutants are all needed. Research should also investigate relationships of biological pollutant exposure levels to sensitization and allergic reactions, and assess the effects of early-life exposures on the development of the immune system.

5. **Improve understanding of indoor particulates.** While there has been significant research on outdoor particulate pollution, there has been much less study of particulates indoors. The major indoor particulate sources for different indoor environments need to be identified. The relative contribution of indoor and outdoor sources to indoor particulate matter should be better characterized. Research should also investigate the chemical composition and size distribution of indoor particulate matter, and indoor particulate matter re-suspension issues and impacts on exposure. The health impacts and risks of indoor particulate matter deserve to be studied, and particulate matter mitigation strategies assessed. Finally, effective design and engineering strategies to minimize particulate pollutant levels need to be developed.

6. **Develop risk assessment techniques and precautionary principles to improve building design and operations for human health and performance.** Advance the use of risk assessment techniques to support design, engineering, and management decision making. The ability of specific HVAC configurations to deliver thermal comfort, air quality, and acoustic quality over time, for example, or of specific facade assemblies to eliminate thermal bridging, vapor migration and degradation, should be tested in the field, and built into risk factors for the building community.

4.2 Indoor Environmental Quality (IEQ): Occupant Health and Performance

Program Goal: Improve scientific understanding of buildings' impacts on occupant health and performance.

The research topics within this program area aim to:

- Develop methods and protocols to assess health and performance outcomes;
- Identify mechanisms and pathways of impact (physiological, behavioral, and psychological) related to how building design, maintenance, and operation affect health and performance.

Background

People spend increasing amounts of time indoors in conditions that differ dramatically from those in which human physiology, cognition and behavior evolved. We are exposed to chemicals; materials; heating, cooling, and ventilation systems; noise; and lighting conditions that have many unknown impacts on human health and performance. Evidence of the negative impacts that poor indoor environmental quality can have on building occupants continues to mount. Known health impacts of indoor pollutants range from lung cancer caused by exposure to radon and secondhand smoke, to carbon monoxide poisoning, to allergies and asthma triggered by mold and numerous other biological pollutants.

Whereas the "Indoor Environmental Quality: Measuring Pollutants and Stressors" program area covers issues of the physical conditions of buildings and how they produce pollutants and other sources of discomfort and performance loss, this program area focuses specifically on the effects of indoor environmental factors on human beings, as measured by health outcomes, satisfaction and performance. These programs are separated here only because health research is a distinct subject that receives significant funding and attention, yet within which attention paid to indoor environmental impacts so far has been inadequate.

Many have claimed that green building strategies produce higher levels of indoor environmental quality and should, thus, be more supportive of health and productivity than standard buildings. Yet, support for the "green building hypothesis" remains elusive. Existing studies have been difficult to replicate in some cases, and, in others, research methods have come under attack. There is a clear need for improved metrics and protocols that can identify and measure links between building features and human outcomes. There is also a need to recognize the rigor required for this research, the need for large subject bases, controlled interventions, and longitudinal studies. In all respects, defining the link between more sustainable, healthier built environments and human health and performance outcomes is dependent on rigorous studies with multi-disciplinary teams that include professionals engaged in the built environment.

In addition to better understanding the links between building features and maintenance and human outcomes, we also need to better understand the links between health and performance. For instance, what kinds of illnesses and symptoms interfere with which types of tasks? Are performance losses more likely to occur with complex cognitive tasks than with simple tasks? What are the underlying mechanisms? Does building-related illness affect concentration, logical thinking, or memory – the building blocks of productivity, especially in a knowledge-based economy? An important factor is occupant behavior, e.g., we can't neglect the role that people themselves play in transmitting illnesses. Can the building environment counteract the behavioral spread of viruses or bacteria, e.g., through the common practice of coming to work with a cold or flu (sometimes referred to as "presenteeism" in the workplace literature)? Or should "telecommuting" become more ubiquitous, encouraging people to work from home in such circumstances?

Alleviating building-related discomforts and illnesses is a key goal of this research program, but we also need to determine whether and how indoor environments may actually promote health and performance. Recent research on daylight and contact with nature in healthcare settings, as well as research on the integration of physical activity into building and community, through stairway design and bicycle paths for example, shows the positive potential of thoughtfully-designed buildings. However, the research has been limited and needs to be expanded to other settings, such as workplaces and schools.

Related topics can be found in Chapter 1.2 – Economics and Financial Value; Chapter 2.2 – Lighting and Daylighting; Chapter 2.4 – Passive, Active and Hybrid HVAC and Controls; Chapter 2.3 – Materials Life Cycle Assessment; and Chapter 4.1 – IEQ: Pollutants and Stressors.

Illustrative Research Topics

1. **PRIORITY TOPIC: Conduct public health impact assessments.** Research on this topic is a prerequisite to other research on health impacts.

   While poor IEQ has been associated with significant health effects, there are no protocols to establish the proportion of diseases that may be attributed to indoor environmental factors. Research is needed to establish the attributable risks of selected health endpoints to measurable IEQ parameters. This will require gathering data from studies linking characteristics of buildings and systems to health outcomes in diverse building types, including offices, factories, health care settings, schools, and housing. From this data, and other information from existing studies, estimates will need to be developed of statistical associations including relative risks, odds ratios and dose-response relationships.

   In addition to indoor air quality, research should include other physical and environmental factors of buildings that may have health consequences (e.g., daylighting, temperatures, and views). The dose-effect relationships are critical first steps in developing design and building operations strategies to reduce negative outcomes and enhance positive outcomes. Statistical associations developed between IEQ parameters and health impacts can then be used to estimate proportions of diseases attributable to IEQ, and track this information better in the future. In the short term, methods for quick, initial assessments of user comfort, IEQ satisfaction, and perceived health and performance should be developed. The development of robust initial assessment methods would serve as a way to identify conditions that warrant the full application of the health and performance protocols.

2. **PRIORITY TOPIC: Conduct assessments of IEQ impacts on human performance in various building types, including research on biological mechanisms and types of tasks.** Research on this topic is a prerequisite for other performance-related research.

   While studies have already indicated that such factors as ventilation and thermal comfort can impact human performance, many uncertainties remain. There are as yet no generally accepted methodological approaches to studying performance, which can range from repetitive factory work to student learning activities. Lack of standard approaches makes different studies difficult to compare. Performance in offices, factories, healthcare, schools and homes will vary significantly, and must span individual and organizational indices, ranging from speed and accuracy to retention rates to creativity. Research is needed both to clarify the biological mechanisms that impact performance, and apply that information to developing the required metrics. This includes evaluating methods and defining research protocols for measuring human performance impacts from IEQ, developing dose-effect relationships for key indoor contaminants on human performance measures; quantifying relationships between health symptoms and human performance; conducting controlled studies to determine key IEQ parameters that affect human performance, and conducting research to examine the potential for improving performance and productivity in various indoor settings (e.g., offices, schools, etc.) through actions designed to improve IEQ.

   We have identified research topics #1 and #2 as critical first steps in the IEQ research program areas. Without the protocols for assessing health and performance outcomes, the other illustrative topics cannot be carried out successfully. These are not easy first steps. They will involve a multidisciplinary approach to developing and testing protocols before they can be widely applied. At present, each discipline necessary to this task (e.g., from acoustics to toxicology) comes with different conceptual frameworks, different problems to solve, and different research methods. The disciplinary boundaries need to dissolve in order to find a common ground with a set of refined tools that can be implemented in field settings individually or together.

3. **Conduct assessments of the impacts of building and community design on physical activity and health.** In addition to IEQ, the public health community is increasingly focusing on other health impacts of building and community design – e.g., the ways in which such designs discourage exercise through lack of walkability. Research is needed to establish links between design features and such health risks as obesity.

4. **Develop indices and tools to assess the economic impacts of building-related health and performance impacts.** Human health and performance outcomes have individual, organizational and societal cost/benefits, all of which can be translated into economic terms. This information is needed to determine and demonstrate the economic value of various building strategies. This will ultimately contribute to the development of 'triple bottom line accounting' that reflects profit, people and planet.

   Related topics can be found in Chapter 1.2 – Economics and Financial Value.

APPENDIX A: POTENTIAL FUNDING SOURCES[19] AND RESEARCH COLLABORATORS

Potential Funding Organizations

- Air-Conditioning and Refrigeration Institute (ARI)
- American Society of Heating Refrigeration and Air Conditioning Engineers
- California Department of Education
- California Department of General Services
- California Department of Health Services
- California Energy Commission
- California Urban Water Conservation Council
- Environmental Working Group, Society of Environmental Toxicology & Chemistry
- Illuminating Engineering Society of North America
- International Facility Management Association
- National Institute for Occupational Safety and Health
- National Institute of Environmental Health Sciences
- National Institute of Health
- National Institute of Standards and Technology
- National Science Foundation
- New York State Energy Research and Development Authority
- Society of Human Resource Management
- Transportation Research Board
- U.S. Department of Agriculture
- U.S. Department of Energy
- U.S. Department of Housing and Urban Development
- U.S. Department of Interior
- U.S. Department of Transportation
- U.S. DHHS Centers for Disease Control
- U.S. Environmental Protection Agency
- U.S. General Services Administration
- U.S. Geological Survey, Biology Division

Potential Supporters

- Alliance for Water Efficiency
- American Cancer Society
- American Hospital Association
- American Institute of Architects
- American Lung Association
- American Water Works Association
- Athena Institute
- Collaborative for High Performing Schools
- Lawrence Berkeley National Laboratory
- National Fenestration Rating Council

[19] Funding depends on availability of funds, organizational mission, etc.

- National Institute of Building Sciences
- Pacific Northwest National Laboratory
- National Renewable Energy Laboratory
- Oak Ridge National Laboratory
- Society of Building Science Educators
- Urban Land Institute

General Types of Organizations for Potential Partnering

- Architecture, engineering, construction, and facility management industry associations
- Building product manufacturers
- Certification bodies for products, professionals, etc.
- Energy utilities
- Industry associations for materials and products
- Private foundations
- Relevant software development company trade associations
- State Departments of Transportation
- State General Services Administrations
- State research agencies (e.g., state energy offices)
- Water utilities

APPENDIX B: 2006 RESEARCH AGENDA WORKSHOP

The September 2006 workshop initiated organizational and content development for the Agenda.

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- Scott Muldavin, Executive Director, Green Building Finance Consortium
- Dan Nall, Senior Vice President of Flack + Kurtz, Inc.
- Greg Norris, President, Sylvatica
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