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FINAL PROJECT REPORT

INDOOR ENVIRONMENTAL QUALITY RESEARCH ROADMAP 2012-2030: ENERGY-RELATED PRIORITIES

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Prepared by: Building Ecology Research Group

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PREFACE

The California Energy Commission Energy Research and Development Division supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

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- Renewable Energy Technologies
- Transportation

Indoor Environmental Quality: Research Roadmap 2012–2030: Energy-Related Priorities is the final report for the Indoor Environmental Quality: Research Roadmap 2012–2030: Energy-Related Priorities project (contract number MR-026) conducted by Building Ecology Research Group. The information from this project contributes to Energy Research and Development Division's Energy Related Environmental Research Program.

For more information about the Energy Research and Development Division, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-327-1551.

ABSTRACT

This report is an update and expansion of the 2002 report, *Energy –Related Indoor Environmental Quality Research: A Priority Agenda*. It serves two purposes: (1) to summarize lessons learned since 2002, when the first indoor environmental quality research roadmap was completed, and (2) to identify indoor environmental quality research needs specifically related to the state's policy to achieve net zero energy in new building construction and retrofitting of existing buildings during the next two decades. The report describes future scenarios and emerging trends affecting energy efficiency and indoor environmental quality, and indoor environmental quality links to energy efficiency. Consultation with experts assisted in identifying future scenarios, as well as identifying and prioritizing research needs for residential and commercial buildings. Major research needs are identified under seven topics: Sources in Low-Energy Buildings; Ventilation; Operation and Maintenance; Thermal Conditioning; Air Cleaning; Tools, Methods, and Sensors; and Cross-cutting. Several high-priority research needs were identified, including the short-term need to increase understanding of human behavior, and sources of moisture and of indoor pollutants such as particles. High-priority needs over the long-term include (1) life-cycle assessments of both indoor environmental quality and energy, and (2) increased data on exposure and health effects. To help meet these needs, research and development on indoor environmental quality and energy efficiency should be integrated with state agency and utility programs for building energy efficiency.

Keywords: indoor air quality, indoor environmental quality, research needs, research priorities, net zero energy buildings, residential, non-residential, commercial

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

Introduction

This report is an update of the 2002 report, *Energy –Related Indoor Environmental Quality Research: A Priority Agenda*. It summarizes what has been learned since the 2002 roadmap was completed, and identifies indoor environmental quality (IEQ) research needs especially related to the state's efforts to meet its goals for net zero energy buildings and retrofitting of existing buildings.

Indoor environmental quality is a major factor in the health, safety, and productivity of people. It includes aspects of indoor air aquality, thermal comfort, acoustic quality, and lighting quality. For California, the economic impacts of indoor air quality on health and productivity alone have been estimated to be at least $45 billion per year. About $11 billion of the total impact was attributed to health impacts from indoor air pollution other than environmental tobacco smoke, and about $9 billion was attributed to lost productivity in office workers and teachers.

The California Energy Commission (Energy Commission) is required to set standards for energy efficiency for new and existing buildings, and new appliances. In setting energy-efficiency standards for buildings and appliances, it must comply with the California Environmental Quality Act by considering potential impacts of such standards on human health and safety, and by mitigating any significant adverse impacts.

In 2001–2002, the Energy Commission, with a consortium of state energy agencies, funded the development of a research plan for energy-related indoor environmental quality. Subsequently, the Public Interest Energy Research (PIER) Energy-Related Environmental Research program funded several landmark studies of indoor environmental quality and related factors in California, including studies of new residential buildings, small and medium commercial buildings, and pollutant emissions from office equipment.

In recent years, the need for more-efficient buildings has grown, due to climate change legislation and policy under California's AB 32 Global Warming Solutions Act of 2006.[1]

To help meet AB 32 goals, the Energy Commission is working with the California Public Utilities Commission (CPUC), California Air Resources Board (ARB), and various stakeholders to implement the California Strategic Energy Efficiency Plan, updated in 2011. The plan has four major goals, also known as the Big Bold Energy-Efficiency Strategies. These goals include all new residential construction would be zero net energy by 2020 and all new commercial construction the same by 2030. Energy performance of Heating, Ventilation and Air-Conditioning (HVAC) will be transformed to ensure that its energy performance is optimal for California's climate; and all eligible low-income residential customers will be given the opportunity to participate in the low-income energy-efficiency program by 2020.

This update, prepared for the Energy Commission with input from experts, differs from the 2002 report in that it is: (1) focused exclusively on California's buildings, and (2) focused on

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[1] Assembly Bill 32 (Nuñez), Chapter 488, Statutes of 2006.

research necessary to support implementing the Big Bold Energy-Efficiency Strategies in a way that provides for healthy low-energy buildings. The current report also places more emphasis on residential construction.

This report discusses the methods used and the results of the research, assessment, and consultation with experts to identify and prioritize the indoor environmental quality research, development, and demonstration necessary to provide healthy low-energy buildings. These results are presented together with conclusions and recommendations to help implement the necessary research program and projects. Research project costs will depend on final project designs and available funds. Specific project cost estimates were not developed for the recommended research projects.

Future Changes to Indoor Environment

As a basis to identify research needs, this report describes possible future changes to the indoor environment that have resulted from efforts to improve building energy efficiency, and other relevant scenarios and trends. This information, along with the Energy Commission's preliminary plans for updating California's Title 24 building code, were used to help identify indoor environmental quality research needs. Many of these future changes will occur independent of state energy programs. Emerging indoor environmental quality issues, such as new materials and products, increased use of recycled materials, and emissions of semi-volatile organic compounds (SVOCs), are also likely to result in increased efforts to protect public health.

Linkages between indoor environmental quality and energy efficiency are identified in Appendix B of the report, (Table B1), Building Processes Linking IEQ, Health, and Building Energy Use. This table was revised and expanded from the 2002 report. The most important energy-related influences on indoor environmental quality are listed in Table ES-1.

Table ES-1. Most Important Energy-Related Influences on Indoor Environmental Quality

Outside air ventilation	Occupant behavior
Air-conditioning	Indoor pollutant source removal or reduction
Heating	Water condensation and leaks
Particle filtration	Space cleaning
HVAC maintenance and cleaning	Envelope insulation and tightness
Humidification	Crawl space or slab seals
Air recirculation	Windows and skylights: ventilation, lighting
Building pressure control	Gaseous air cleaning

Findings

Seven research and development (R&D) topics were identified to address indoor environmental quality and low-energy buildings:

- Sources in Low-Energy Buildings

- Ventilation
- Operation and Maintenance
- Thermal Conditioning
- Air Cleaning
- Tools, Methods, and Sensors
- Cross-cutting

The R&D topics are described in more detail in Appendix A of this report. From these topics, a total of 18 Priority Research Projects and Project Areas that address specific indoor environmental quality issues were identified, (Table ES-2). Related research activities and possible funding sources were also listed for each Priority Research Area to help reduce redundancy, increase collaboration, and facilitate co-funding. The prioritized research is organized into the seven topic areas listed above.

The most critical gaps in indoor environmental quality R&D were found to be in topics related to indoor pollution and moisture sources in buildings, human behavior, and integration of activities among and within professions and across topics. Various indoor and outdoor sources of pollutants (such as particles, aldehydes, and pesticides) and of moisture are present in buildings, and the emissions of these pollutants and moisture generally dominate indoor environmental quality relative to other factors.

Table ES-2. Project Topics and High-Priority Projects

Topics	High-Priority Projects
Sources in Low-Energy Buildings	
Moisture Risk Assessment and Mitigation	• Assess the risks of moisture-related problems in new and retrofitted low-energy buildings for factors such as new building materials, tight envelopes, super-insulation, low-energy cooling technologies, severe storms, and living/green roofs. • Develop mitigation measures for moisture problems in low-energy buildings, and assess their effectiveness.
Outdoor Air and Attached Spaces	• Develop and test approaches to controlling entry of outdoor pollutants from roadways, commercial activities, agriculture, and other sources. • Evaluate the effectiveness of airflow and pressure control strategies to control infiltration of pollutants and water vapor from adjoining spaces, outdoor air, and soil (in residences, especially garages, crawl spaces, and attics).

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Table ES2. Project Topic Areas and High-Priority Projects (continued)[2]

Topics	**High-Priority Projects**
Wood Products and Other Materials	• Assess other indoor formaldehyde and VOC sources besides regulated composite wood products, such as attic and crawlspace materials, furnishings, unregulated/exempt exterior plywood and bamboo plywood and combustion sources. • Assess acetic acid and odor emissions from engineered wood products.
Risk Assessment, Guidelines & New Chemicals	• Identify SVOCs and new chemicals in building materials and furnishings and assess their impacts on human health. • Develop guidance for rating systems and certification of low-emission materials and products.
Ventilation	
Controls	• Evaluate the potential energy savings and IEQ benefits of real-time, dynamic ventilation controls in various climate zones, weather conditions and outdoor air quality conditions. • Evaluate sensors and measurement methods for airflow and indoor air quality (IAQ) and develop improved sensors for demand control ventilation. Address current issues regarding sensor calibration, accuracy, and reliability of carbon dioxide (CO_2) sensors.
Commissioning (Cx)	• Develop and demonstrate methods to ensure reliable use and performance of ventilation systems, both residential and commercial. • Develop and demonstrate model specifications for Cx and retro-commissioning (RCx) for IEQ protection.
IEQ Performance	• Determine impacts of ventilation rates and methods as pollutant control strategies, building shell design, and occupant behavior on IAQ, human responses (comfort, health, performance), building energy use, and costs; provide related input for ventilation standards. • Assess the IEQ impacts of weatherization in multifamily buildings such as differences due to changes to ventilation systems, building shells, and occupant behavior.
High Performance	• Evaluate the candidate technologies for ventilation systems for high-performance buildings; include ventilation systems and air cleaning systems that are separate from heating and cooling systems.

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[2] See notes at end of table

Table ES2. Project Topic Areas and High-Priority Projects (continued)

Topics	High-Priority Projects
High Performance	• Develop and demonstrate IEQ-optimized ventilation, heating, and cooling systems for different building types and different climate zones in California for new and retrofit applications.
Operation And Maintenance (O&M)	
Operation and Maintenance	• Develop and demonstrate methods to ensure reliable usage and performance of ventilation systems. • Develop warning and indicator systems for IEQ maintenance needs such as outdoor air ventilation, temperature control, filter replacement and prevention of dampness and microbial problems in building envelopes and HVAC systems.
Thermal Conditioning	
Design and Operation	• Develop and demonstrate climate-optimized designs for heating, cooling, ventilating, and moisture control, for both new and retrofit applications. • Develop design guidelines for overhead fans and air movement methods to improve thermal comfort. • Develop and demonstrate design and operational strategies for energy-efficient personal comfort systems to supplement and offset central conditioning in indoor work environments. Variants of such systems are also known as "personal environmental control," "task ambient conditioning," and "personal ventilation."
Air Cleaning	
Assessment & Demonstration	• Evaluate the effectiveness and cost of particle filtration air cleaner upgrades in high-pollution areas (e.g., near roadways, rail yards, industry, agriculture), including field performance over time. • Evaluate the effectiveness and cost of active VOC air cleaners alone and in combination with particulate matter filtration. • Assess the effectiveness of passive air cleaning techniques (e.g., ceiling tile) for VOCs, ozone, nitrogen dioxide, etc. • Determine the IEQ and energy performance of ultraviolet technologies for removing microbial contaminants from the air and/or surfaces.
Technology Development	• Develop and demonstrate improvements in central air filter performance, e.g., reduced filter by-pass, routine maintenance, and higher particle removal efficiencies without increased energy use or cost.

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Table ES2. Project Topic Areas and High-Priority Projects (continued)

Topics	High-Priority Projects
Technology Development	• Investigate the mechanisms of particle removal in relation to the filter material, fiber size and shape, pattern, and other aspects of the media used.
Tools, Methods, and Sensors	
Operation and Modeling	• Develop checklists for IEQ components of Commissioning and Retro-Commissioning as possible building code measures.
Development and Demonstration	• Demonstrate the use of occupant feedback as real time sensors for thermal comfort and perceived air quality with input to building energy management systems.
Cross-Cutting	
Human Factors / Behavior	• Identify critical human IEQ impacts related to human factors and energy conservation behavior and Investigate occupant and operator habits and their effects on IEQ and energy use in various building types, including residential, schools, daycare, retirement homes, and offices. • Develop and demonstrate a strategy to employ human factors and behavior data and user feedback on IEQ at all stages of a building's life cycle.
Metrics	• Define, develop, and demonstrate IEQ metrics for Cx and Life-Cycle Impact Assessment in product selection and building rating systems especially for performance verification.
Assessment and Benchmarking	• Identify, develop, and demonstrate the metrics for tracking and comparing IEQ in buildings over time and among similar buildings. • Initially monitor IEQ and its determinants and energy use, and then periodically monitor all major building sectors, to verify and improve estimates of IEQ, health risks, and energy performance.
Program Evaluation	• Identify and assess methods and model programs for assessing progress of projects related to IEQ and its determinants. Determine data needs and database needs for evaluations. • Identify opportunities to partner with stakeholders and programs to incorporate IEQ factors in program evaluation and market evaluation, e.g., in energy-efficiency programs at state agencies and energy utilities. • Identify and periodically revise strategies for achieving healthy low-energy buildings in accordance with the 2020/2030 time frame of the Strategic Plan.

Notes:
See Appendix A for rationales and details for each Topic Area. Program Goals are as follows:

- Identify IEQ problems and opportunities.
- Develop and evaluate energy-efficient technologies for improving IEQ, health, and comfort.
- Develop and evaluate energy-efficient practices for improving IEQ, health, comfort, and productivity.
- Stimulate or assist implementation of energy-efficient technologies or practices for improving IEQ.

Summary and Conclusions

Major changes are expected in the indoor environment and its control in association with improved energy efficiency and increased public health awareness. These changes are expected in the near term and beyond, and the rate of change will be accelerated by changes in energy, climate change, and demographic factors. Progress has been made in our understanding of the relationships between energy-efficiency measures and indoor environmental quality since the 2002 report (*Energy –Related Indoor Environmental Quality Research: A Priority Agenda*), filling in some major gaps. However, many information needs remain and are growing as the pace of changing building technology accelerates.

Short-term needs include better understanding of indoor pollution sources and human behavior where currently data gaps are large. Among the most important sources are sources of moisture, indoor combustion devices, plastics, fire retardants, and products for cleaning or finishing surfaces. Research results in these areas should have large impacts on future research topic prioritization. Assessment of these data gaps is identified as a first step toward development of a more detailed research agenda in these areas. California climate-specific design, construction, and space-conditioning requirements strongly affect the presence of and potential solutions to indoor air quality problems. Moisture-related health effects have been most prominent among the areas receiving increased attention during the past ten years. Increased research on moisture sources and their control should be given high priority.

Long-term needs include integrated indoor environmental quality and energy life-cycle assessment and modeling. Modeling has advanced for focused relationships (e.g., energy and thermal conditions or lighting). However, comprehensive, integrated modeling of energy and indoor environmental quality is still more of a goal than a reality. Traditional design and construction organizational structures tend to isolate team members under the direction of the project lead so that trade-offs are made without the enriched dialogue between the many specialized team members. Life-cycle assessment tools examine materials in the early life stages from resource extraction, manufacturing, and installation, and in the demolition and ultimate disposal phases, neglecting the potentially most important building occupancy and use phase. It is in the occupancy/use phase that the indoor environmental quality impacts occur, but current life-cycle assessment applications neglect or undervalue this phase of the life cycle. Research and development methods and tools, and data acquisition, are necessary to implement integrated indoor environmental quality and energy life-cycle assessments.

Data on some aspects of indoor and personal exposure, indoor environmental quality, and health effects is scarce. There is substantial information available on particulate matter, nitrogen dioxide, carbon monoxide, and ozone but very limited data on indoor particulate matter, ultrafine particulate matter, semi-volatile organic compounds, many synthetic volatile organic compounds and mixtures of indoor air pollutants. The data on the indoor environmental quality and health effects in low-energy homes and other building types are especially scarce. These data are essential to inform regulatory decisions, professional and commercial practices, and the general public. Guidance derived from research on the implications of alternative practices can also assist building operators and occupants in making better decisions regarding energy and indoor environmental quality.

To accomplish more effective implementation of various energy and IEQ goals and objectives, an interagency task force that includes IEQ objectives can be integrated into an existing State interagency committee or activity.

Recommendations

There is a wide variety of indoor environmental quality R&D needs over the short- and long-term, and an attempt to prioritize them is provided in the report's Results section. Highest priority research areas include human behavior, indoor pollution sources, moisture control, and research topic integration. The first two areas address the most influential determinants of indoor environmental quality.

Cross-cutting priority research is suggested as a means to more effectively assist in both research and implementation of the State's goals and mandates. To help implement the report's recommended Indoor Environmental Quality Research priorities, some cross-cutting recommendations are listed below that will more effectively use the available research funding. The recommendations are also intended to improve the application of R&D results in energy-efficiency programs.

The report recommends the following actions:

- **Increase Emphasis on Human Behavior Research.**

Increase understanding of one of the most important factors affecting indoor environmental quality and energy use in the real world, i.e., the motivations and information that drive the behaviors of key players and inhibit developing effective measures to accomplish Energy Commission and other state agency goals. Research should focus on behaviors that most strongly affect indoor environmental quality.

- **Improve Understanding and Control of Pollutant Sources.**

Improve understanding of sources of indoor pollutants, their control, and the substitution of less polluting sources.

- **Develop Integrated Indoor Environmental Quality–Energy–Life-cycle Assessment Modeling.**

Support development of a comprehensive life-cycle assessment modeling approach and associated tool (or tools) necessary to focus sufficient attention on the IEQ implications of materials, products, or processes that are the subjects of life cycle assessments. Enhanced LCA tools would use available data and knowledge to assess building design and operational alternatives, materials, and systems over the full lifetime of the building .

- **Evaluate Indoor Environmental Quality Research Program Results.**

Periodic assessment of progress in addressing the most important information needs can improve the ongoing prioritization of unmet needs, and result in the expansion of on-going or planned research.

- **Update Indoor Environmental Quality Research Priorities.**

Many critical aspects of future building technology and their impacts on occupants and energy efficiency are difficult to predict. Research performed elsewhere may also inform California's efforts and the state's move toward net zero energy buildings. Therefore, the IEQ Research Priorities should be updated periodically.

- **Integrate Indoor Environmental Quality into the Energy Efficiency Plans.**

To achieve synergies and harmonize energy-efficiency R&D and action plans, consider integrating indoor environmental quality and health in all elements of the energy strategies and action plans. Focusing on only one of several objectives is an inefficient way to accomplish the full range of objectives. This approach will also help avoid unintended consequences and maximize available state funding and expertise.

CHAPTER 1: Introduction

This project's goal was to update the California Energy Commission's 2002, report, *Energy – Related Indoor Environmental Quality Research: A Priority Agenda*, focusing on California's goals for net zero energy buildings (NZEBs) and existing building retrofits. Indoor environmental quality (IEQ) is a major factor in the health, safety, and productivity of people and includes aspects of indoor air quality, thermal comfort, acoustic quality, and lighting quality. It includes aspects of indoor airquality, thermal comfort, acoustic quality, and lighting quality. For California, the economic impacts of indoor air quality on health and productivity alone have been estimated to be at least $45 billion per year.[3] About $11 billion of the total impact has been attributed to health impacts from indoor air pollution other than environmental tobacco smoke, and about $9 billion was attributed to lost productivity in office workers and teachers.

The California Energy Commission (Energy Commission) is required to set standards for energy efficiency for new and existing buildings and new appliances.[4] It must consider indoor air quality impacts in setting energy efficiency standards for buildings and appliances.[5] Further, it must comply with the California Environmental Quality Act (CEQA) by considering potential impacts of such standards on human health and safety and by mitigating any significant adverse impacts.[6]

In 2001–2002, the Energy Commission, with a consortium of state energy agencies, funded development of a research plan for energy-related IEQ.[7] This "IEQ Research Roadmap" (*Energy –Related Indoor Environmental Quality Research: A Priority Agenda)* was funded through the Energy Commission's Buildings End-Use Energy Efficiency Research area within the Public Interest Energy Research (PIER) Program.[8] Subsequently, the PIER Energy-Related Environmental Research program area funded several landmark studies of IEQ and related factors in California, including studies of new residential buildings, small and medium commercial buildings, and pollutant emissions from office equipment. PIER studies also focused on retrofits of low-income apartments, exposures from unvented combustion

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[3] California Air Resources Board (ARB), July 2005. The Report to the California Legislature: Indoor Air Pollution in California, Chapter 3. Estimates in Year 2000 dollars and population. http://www.arb.ca.gov/research/indoor/ab1173/rpt0705.pdf.

[4] AB 758, Chapter 470, Statutes of 2009.PRC Sec. 381.2 and 385.2. http://www.energy.ca.gov/ab758/.

[5] AB 4655 (Tanner; PRC 25402.8).

[6] CEQA. PRC Sec. 21000 et seq. http://ceres.ca.gov/ceqa/.

[7] Summary article is at Fisk et al., 2002, Proceedings of Indoor Air 2002, June 30 - July 5, Monterey, California. Full report is at Fisk et al., 2002, LBNL 51328, http://eetd.lbl.gov/IE/pdf/LBNL-51328.pdf.

[8] California Energy Commission, 2011a.PIER Energy-Related Environmental Research Program. http://www.energy.ca.gov/research/environmental/index.html.

appliances, and healthy zero energy buildings. In addition, the PIER Buildings End-Use Energy Efficiency program area has funded studies of building heating, ventilating, and air-conditioning (HVAC) and air leakage that are pertinent to IEQ.[9]

In recent years, the need for more-efficient buildings has grown due to a variety of drivers and also to climate change legislation and policy under California's AB 32 Global Warming Solutions Act of 2006.[10] Green buildings with increased energy efficiency were identified as a major target for reducing greenhouse gas (GHG) emissions in the AB 32 Scoping Plan.[11][12] Improved indoor air quality was one of several co-benefits expected from the plan's green building element.

To help meet AB 32 goals, the Energy Commission is working with the California Public Utilities Commission, California Air Resources Board, and various stakeholders to implement the California Strategic Energy Efficiency Plan.[13] The Strategic Plan, updated in 2011,[14] has four major goals, also known as the Big Bold Energy Efficiency Strategies:

1. All new residential construction in California will be zero net energy by 2020. The Energy Commission is currently proposing to define a net zero energy building as a building in which the societal value of energy consumed over the course of a typical year is less than or equal to the societal value of the onsite renewable energy generated.[15] The societal value of energy is the long-term projected cost of energy, including the peak demand cost (time-dependent valuation of energy), the value of associated carbon emissions, and other externalized costs.

2. All new commercial construction in California will be zero net energy by 2030;

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[9]California Energy Commission, 2011b.PIER Building End-use Efficiency Research Program. http://www.energy.ca.gov/research/buildings/index.html.

[10] Assembly Bill 32 (Nuñez), Chapter 488, Statutes of 2006

[11]ARB, 2008.Climate Change Scoping Plan. See Final version, 5/11/09, pp. 57 et seq. and Vol. 1, Appendix C, pp. C-138 et seq. http://www.arb.ca.gov/cc/scopingplan/document/scopingplandocument.htm.

[12]ARB, 2011.Green Building Strategy. http://www.arb.ca.gov/cc/greenbuildings/greenbuildings.htm.

[13]CPUC, September 2008. The California Energy Efficiency Strategic Plan. http://www.californiaenergyefficiency.com/docs/EEStrategicPlan.pdf.

[14]CPUC, 2011.The California Energy Efficiency Strategic Plan, January 2011 Update. http://www.cpuc.ca.gov/NR/rdonlyres/A54B59C2-D571-440D-9477-3363726F573A/0/CAEnergyEfficiencyStrategicPlan_Jan2011.pdf.

[15]Brook M., B. Chrisman, P. David, T. Ealey, D. Eden, K. Moore, K. Rider, P. Strait, G. D. Taylor, and J. Wu. July 2011. Draft Staff Report: Achieving Energy Savings in California Buildings (11-IEP-1F). California Energy Commission, Efficiency and Renewables Division. Publication number: CEC-400-2011-007-SD. http://www.energy.ca.gov/2011publications/CEC-400-2011-007/CEC-400-2011-007-SD.pdf.

3. Heating, Ventilation and Air-Conditioning (HVAC) will be transformed to ensure that its energy performance is optimal for California's climate; and
4. All eligible low-income residential customers will be given the opportunity to participate in the low-income energy efficiency program by 2020.

More information on the IEQ implications of California's various energy-efficiency programs for new and existing buildings is provided in Appendix E.

The following sections discuss the study methods used and the results of the research, assessment, and consultation with experts to identify and prioritize the IEQ research, development, and demonstration necessary to develop healthy low-energy buildings. These sections are followed by the results, conclusions, and recommendations to help implement the necessary research program and projects. Detailed listings of the research needs are contained in Appendix A.

CHAPTER 2: Methods

The following scope for this update of the IEQ Research Roadmap was established in consultation with the Energy Commission program manager:

- Limit research planning to the period of 2011–2030, based on the 2030 target for commercial NZEBs.
- Limit the IEQ issues to health, thermal comfort, occupant satisfaction, worker and student performance, acoustics, building energy use, and the building systems and practices affecting energy use. The quality of indoor lighting was excluded due to limited funding and the complexity necessary to characterize lighting effects on humans.
- Focus on efforts to build zero energy buildings that are now under way and are planned through 2030.
- Focus on efforts to increase the energy efficiency of existing commercial and residential buildings.
- Limit building types to residences, non-industrial commercial buildings (excluding health care buildings), and schools.
- Include the design, construction, operation, and maintenance phases of a building's life.
- Include a portfolio of different RD&D products, ranging from new information to applied products for implementation by industry or decision makers.

The 2002 report, *Energy –Related Indoor Environmental Quality Research: A Priority Agenda*, was reviewed and its table on energy-IAQ-health linkages for various building processes was revised and updated (see Appendix B). Then a draft discussion of future trends for low-energy buildings was sent to over 170 IEQ experts, building science experts, and stakeholders to identify likely scenarios and the high-priority IEQ research areas of the future. In addition, ten health scientists with extensive backgrounds in IEQ were surveyed, to help identify the major health concerns related to IEQ.

The Energy Commission held a public workshop in late July 2011 to solicit input from various stakeholders, to identify information and research needs on energy-related IEQ through 2030.[16] The workshop focused on California's research and development needs as it moves aggressively to zero net energy buildings and increased retrofitting of existing buildings, as identified in the *Integrated Energy Policy Report* proceedings and the *California Long-Term Strategic Energy Efficiency Plan*.[17][18][19] Presentations were made on preliminary assessments of

[16] http://www.energy.ca.gov/research/notices/index.html#07282011. See also: links to Presentations.

[17] http://www.energy.ca.gov/2009_energypolicy/index.html,p. 227 et seq.

major IEQ research since 2001, Energy Commission plans to achieve NZEB and building retrofit goals, future building design scenarios, IEQ research gaps, and potential IEQ research topics. Comments from the workshop were used to supplement a draft analysis of research needs and possible projects to meet those needs.

In September 2011, a two-day workshop with a panel of experts from the fields of indoor air quality, thermal comfort, and building science was assembled to help identify and prioritize the highest research needs. The panelists and their affiliations are listed in Appendix D. During extensive discussion of the research areas, the experts recommended adding several specific research topics and voted on a long list of proposed research topics. The research topics were summarized and prioritized, and then sent for review and comment to the workshop participants and about 30 other experts and selected Energy Commission staff.

Subsequently the draft final report, along with revised summaries of priority research topics, was sent for review and comment to experts and selected Energy Commission staff. The comments from these reviewers were considered in preparing the final report. More detailed information on the methods used for this report is presented in Appendix C.

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[18] Achieving Energy Savings in California Buildings, Saving Energy in Existing Buildings and Achieving a Zero-Net-Energy Future, Draft Staff Report. Pub # CEC-400-2011-007-SD. Posted July 11, 2011. http://www.energy.ca.gov/2011publications/CEC-400-2011-007/CEC-400-2011-007-SD.pdf.

[19] http://www.cpuc.ca.gov/PUC/energy/Energy+Efficiency/eesp/. See also: 2011 Update and Action Plans.

CHAPTER 3: Future Changes to the Indoor Environment

This section reviews potential or likely changes in buildings intended to meet California's energy-efficiency goals. These changes are based on a review of current Energy Commission authority, recent research, and a review of features commonly incorporated or advocated for use in "high performance buildings."[20][21][22] The future changes presented here were used to establish a basis for identifying potential indoor environmental quality impacts that might be addressed by research as buildings change to achieve net zero energy use.

Indoor environmental quality (IEQ) is very dynamic for most buildings and highly variable among buildings and regions. This is largely due to the numerous determinants of IEQ, e.g., the design, operation, and maintenance of the building; the rates of indoor and outdoor pollutant emission and removal; the local weather conditions; and the activities of building occupants and operators. Many of these determinants are related to energy use, primarily through the heating, cooling, and ventilating of buildings. Many determinants of IEQ in California's buildings are expected to change dramatically by 2030 and beyond, due to technological, economic, and demographic changes. To help identify and prioritize IEQ research needs, the potentially important changes to IEQ determinants that can be expected by 2030 are discussed below.

3.1 IEQ Linkages to Energy Efficiency

This summary of IEQ linkages is based on a detailed table of linkages presented in Appendix B. Processes that influence both IEQ and building energy performance include the following:

- ventilation[23] of conditioned and unconditioned (e.g., crawlspaces, attics) spaces
- heating
- air-conditioning
- air distribution
- air recirculation
- humidification

[20] Buildings Database, accessed 10 December 2011 at http://eere.buildinggreen.com/ and http://www.buildinggreen.com/hpb/index.cfm.

[21] High Performance Federal Buildings, accessed 10 December 2011 at http://femp.buildinggreen.com/

[22] New Buildings Institute Buildings Database, accessed 10 December 2011 at http://buildings.newbuildings.org/

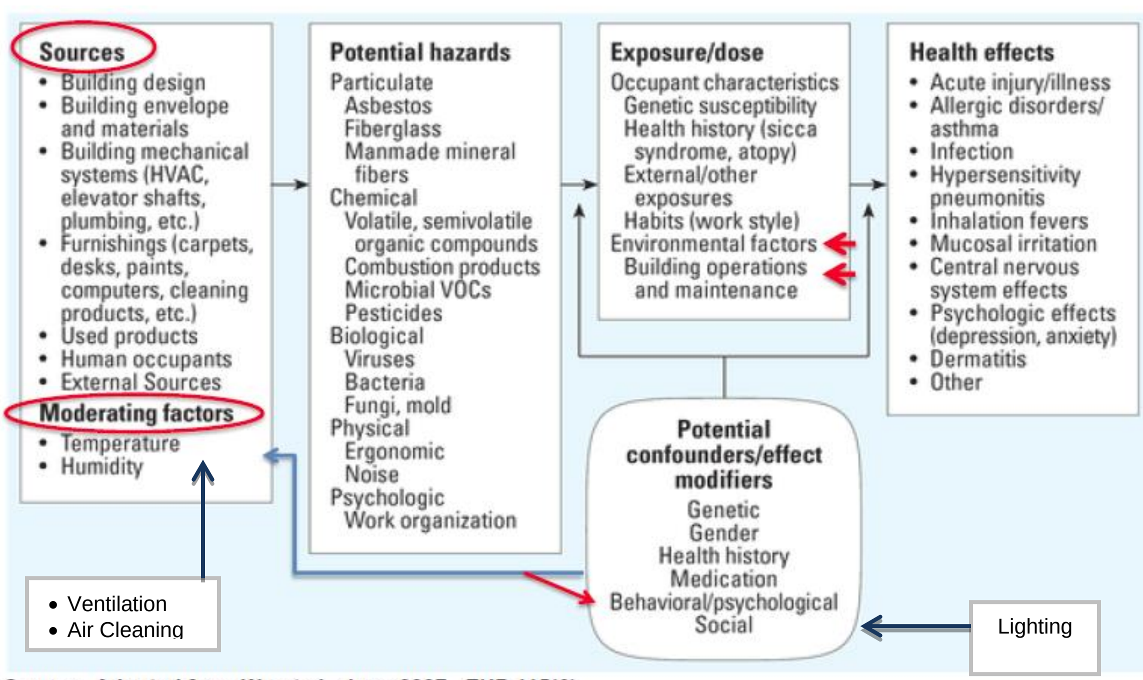
[23] In this document the term "ventilation" refers to all processes that bring outside air into buildings, i.e., mechanical ventilation, air infiltration, and natural ventilation through open doors and windows.

- dehumidification
- HVAC maintenance
- air cleaning
- space pressure control
- water leakage and condensation
- indoor pollutant source exclusion, removal, or isolation
- balanced air flows vs. depressurization/pressurization

Most of the linkages of these processes to both energy and IEQ are widely recognized. Water leakage and condensation can affect building energy performance by degrading the thermal performance of building envelopes. Condensation risks depend on the level of dehumidification by energy-using HVAC systems, the thermal characteristics of building envelopes, and the magnitude of internal and external moisture sources.

The IEQ conditions linked to building energy performance include concentrations of pollutants in air and on indoor surfaces, temperature, humidity, air movement, thermal radiation, and sound and vibration levels (not addressed in this plan). Figure 1 shows the numerous relevant factors that interact to determine IAQ. Many of these also affect energy performance. Almost all are in dynamic interaction that can change over short time periods or distances within buildings and that can vary significantly among buildings.

Figure 1: Indoor Environmental Quality and Health Effects



Source: Adapted from Wu et al., June 2007. EHP 115(6).

3.2 Energy Efficiency

Pressures to improve energy efficiency in California's buildings and reduce GHG emissions are expected to continue to 2020 and beyond. California's Strategic Energy Efficiency Plan has set an aggressive path to reduce energy use and GHG emissions for new and existing buildings by 2030, as discussed in the Introduction and in Appendix E. The plan established goals of 40 percent energy savings in all homes for all new single and multi-family homes by 2020 (zero net energy (ZNE) homes). Achieving the levels established by the plan's goals will require many times the current annual improvement rates.[24] Examples of energy-related trends that could have major impacts on IEQ, either positive or negative, are discussed below.

3.2.1 Building Shell

Building insulation levels, building air tightness, duct tightness, and window thermal performances are expected to increase in California's buildings, thereby reducing external heating loads and gains and potentially improving thermal comfort. However, thermal comfort complaints are already very common in buildings, and low-energy buildings can exacerbate overheating problems in warm climates unless sufficient cooling features are included in building designs.

The tightening of homes will increase the risk of depressurizing adjoining garages and other spaces. This will increase the need to seal the air pathways to adjoining spaces, to remove natural draft combustion appliances from these spaces (including woodstoves), and to balance exhaust ventilation from bathroom, kitchens, and clothes dryers.[25] These practices are expected to become more common and lead to lower indoor levels of VOCs and carbon monoxide (CO) from attached spaces and lower indoor levels of particulate matter (PM) and poly-aromatic hydrocarbons (PAHs) from outdoor wood smoke.

3.2.2 HVAC Design

The efficiencies of lighting systems, computer systems, and home appliances are also expected to increase, thereby reducing internal heat loads. The net effect of these changes and changes to the building shell will be that heating and cooling systems will become much smaller in size. The heating and cooling systems will also become decentralized and decoupled from ventilation systems, e.g., radiant panel, chilled beams, mini-split heat pumps, space or unit heaters. These changes could have beneficial or adverse impacts on IEQ, depending on how well the systems perform over time.

The use of outdoor air for ventilative cooling is expected to increase, according to Energy Commission plans for Title 24 updates. In addition, upcoming changes to Title 24 for

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[24]Gitt B, 2008. Greening Existing Buildings: the Next Wave. Green Technology. http://www.green-technology.org/green_technology_magazine/next_wave.htm.

[25]U.S. Department of Energy, Building Technology Program. Whole House Building Ventilation Systems, Improved Control of Air Quality. Technology Fact Sheet. http://www.ornl.gov/sci/roofs+walls/insulation/fact%20sheets/whole%20house%20ventilation%20systems.pdf .

commercial buildings will require better controls for outdoor air economizers and fault detection and diagnostic systems for HVAC systems. These changes should reduce both over- and under-ventilation by improving HVAC operation and maintenance practices. However, the increased use of outdoor air during occupied periods could also increase indoor exposures to outdoor combustion particles, pollen, mold, ozone, and ozone byproducts unless adequate air filtration and control of reactive indoor pollutants are maintained.

Demand control ventilation, where air quality sensors are used to reduce ventilation during periods of low occupancy, is expected to become more common in commercial buildings, especially in rooms with variable occupancy. The impacts on IEQ could be minimal if the controls work as designed, but sensor field performance and maintenance are currently very uncertain.

3.2.3 Existing Building Upgrades

Energy upgrades or weatherization of existing buildings is expected to continue to ramp up. It will be the major opportunity for energy-efficiency efforts in the near term, due to the recession's slowing of new construction, the increased level of federal funding for building retrofits, and the dominant share of GHG reductions from retrofits. Such efforts will generally improve thermal comfort and performance of ventilation systems. In addition, most home weatherization programs are required to meet certain limits for CO emissions from combustion appliances and for house depressurization, which will help reduce indoor pollutant levels.

Furthermore, IEQ is expected to receive more attention in existing residential buildings due to public health concerns. Asthma and allergies are expected to remain common in California's population, and the indoor environment harbors several types of asthma triggers and allergens. The Center for Disease Control's (CDC) Healthy Housing Initiative and U.S. Department of Energy's (DOE) Weatherization Plus Health program are major efforts to demonstrate and promote the control of indoor air pollutants in existing homes.[26][27]

3.2.4 Whole-House Ventilation Systems

Since 2009 the Title 24 residential standards have required mechanical ventilation systems, with air filtration in some cases. The systems became mandatory in 2011, along with air filtration for certain types of systems. When installed, these systems have not always met ventilation requirements initially or over time. Occupant complaints about thermal comfort, moisture control, odors, and noise have been reported in some low-energy homes with ventilation systems. House depressurization and air mixing issues are expected to continue, especially for exhaust-only ventilation systems or imbalanced central ventilation systems. In response to these concerns, the design, installation, commissioning, and maintenance of these systems are expected to evolve rapidly over the near term. The Energy Commission currently plans to improve the quality of building construction and the level of compliance with Title 24.

[26]http://www.cdc.gov/nceh/lead/healthyhomes.htm.

[27]http://www.waptac.org/Wx-Plus-Health.aspx.

3.2.5 Integrated Design

As discussed above, the interaction of multiple building systems affects not only energy efficiency but also IEQ. These linkages have led to the growth of "integrated building design," where all building components interactions are assessed and optimized for energy efficiency, preferably throughout the design and construction phases. Thermal comfort and noise levels are typically included as design goals, but other IEQ measures are often not included. It is expected that other IEQ measures such as low-emission building materials and moisture control will be integrated more and more into building design through improved modeling, measurement, and sensor tools.

3.3 Human Factors and Behavior

According to the Institute of Medicine, "Three classes of factors have important influences on the indoor concentration of a pollutant: the pollutant's source properties and other attributes, building characteristics, and human behavior."[28] The effects of exposures are also affected by behavior, as well as the individual's health status. Behavioral impacts play out at every stage from building conception and siting through demolition. As an example, building siting can impact the energy required for transportation to/from the building, and energy associated with water supply, runoff, and treatment. Behavioral issues are of utmost importance from design through operation. Yet knowledge of the effects of behavior on IEQ and its ultimate health impacts is almost non-existent.[29]

Decisions that occur at the time of building design set in place requirements for lighting, thermal conditioning, and other operational elements that will have long-running impacts on energy and IEQ. For example, the availability of daylight and glare can dramatically impact productivity and lighting energy requirements. Decisions about HVAC design affect the potential range of operational options to achieve comfort, air cleaning, and low-energy building operation, among other factors. The materials selected for building structures and finishes can affect pollutant exposures for years, or even the life of the building when considering potentially harmful and/or bio-accumulative semi-volatile organic compounds. Decisions made at the time of finishing or refinishing interior spaces can be equally important. While there is good evidence that energy implications are increasingly being considered at the design and construction phases, less is known about how IEQ ramifications are considered.

The knowledge basis and decision-making process is critical to improving the operation and maintenance of buildings for energy efficiency and IEQ. Critical decisions include such things as HVAC maintenance schedules, selection of filters, selection of cleaning products and

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[28] Institute of Medicine, 2011 Climate Change, the Indoor Environment, and Health. Washington, D.C.: National Research Council, p. 4.

[29]NHBC Foundation, February 2012. Today's attitudes to low and zero carbon homes (NF40). http://www.nhbcfoundation.org/Researchpublications/nf40/tabid/496/Default.aspx. Video at http://www.nhbcfoundation.org/NewsMediaCentre/NF40Film/tabid/502/Default.aspx

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cleaning schedules, thermal conditioning or ventilation set points and algorithms, and more. The operation of both commercial and residential buildings very often neglects to incorporate even the most basic principles of building science, let alone key research findings about health, productivity and opportunities for energy savings. Misguided operation leads to buildings that are over-cooled and/or over-heated, leading to energy waste and unhealthful and unproductive conditions. Selection of lowest-cost filters can miss opportunities to mitigate pollutant exposure. Selection of cleaning products that contain higher-than-necessary levels of VOCs can affect air quality. These are but a few examples. Social science research has improved our understanding of energy-related behavior but not our understanding of IEQ-related behavior. Yet there is a strong connection between energy and IEQ-related behaviors and the critical barriers to more-effective operations and to developing, demonstrating and evaluating strategies and tactics to improve operations for energy and IEQ.

Human behaviors such as appliance use, thermostat setting, and HVAC system maintenance have become important factors in reaching California's energy-efficiency goals. Behavior-related measures, such as improved marketing of efficiency programs and training of building operators, are included in the California Strategic Energy Efficiency Plan, and the resultant Action Plan and will receive increasing attention over the next two decades. Smart meters and other interactive technologies are allowing building occupants to reduce energy use and adjust comfort levels, especially during peak energy demand. Because comfort and healthy indoor air are major concerns of most building occupants, it is expected that energy-efficiency programs and manufacturers of HVAC systems and controls will focus more on promoting IEQ benefits.

3.3.1 Building Commissioning

This practice involves assessing and adjusting building operation so that it meets the design goals for energy efficiency. It has proven to be very cost effective in new commercial buildings, as well as in existing commercial buildings (where it is known as *retro-commissioning*). It is expected to continue to grow, especially with the assistance of federal funding and third-party financing. Commissioning is expected to greatly improve IEQ though improved ventilation, air cleaning, building operator training, maintenance, and even control of indoor pollutant sources where the building design addresses those issues. In addition, the training of building operators and HVAC contractors is expected to increase, with support of government energy programs, and thereby improved operation and maintenance of some HVAC systems is expected.

3.3.2 Co-Benefits or Non-Energy Benefits

Energy-efficiency programs often produce other benefits besides lower energy bills and the avoided costs of new power plants and transmission lines. These benefits are called *co-benefits, non-energy benefits,* or *externalities,* and they can be substantial. Several states and regional power authorities consider non-energy benefits in evaluating the effectiveness of energy-efficiency programs by utilities, and the CPUC allows consideration of such benefits. It is expected that non-energy benefits, including those related to IEQ and reduced liability, will become more of a factor in designing and marketing energy-efficiency programs.

Home weatherization programs can provide environmental health and safety co-benefits, such as reduced risks from:

- Combustion appliance hazards (CO and other pollutants).
- Lead-based paint hazards.
- Electrical and fire safety hazards.
- Thermal stress on individuals.
- Poor nutrition and health due to heating and cooling expenses.[30]
- Pollutant and GHG emissions from power plants and fuel extraction.

The value of such environmental co-benefits in the federal home weatherization program, (Weatherization Assistance Program)[31] excluding estimates for health impacts of indoor air quality, thermal stress, or noise, was estimated to total $869 per household (2001); a study is currently being conducted to update and expand those estimates.[32][33] Some states have also evaluated co-benefits of their low-income weatherization programs and have estimated the health and safety benefits to be substantial.[34] The topic of weatherization's co-benefits was recently the focus of an international workshop.[35]

For new energy-efficient homes, several survey studies and focus group studies have found that potential or recent homebuyers rated energy costs and resale value as their top concern, followed closely by comfort and other IEQ concerns.[36][37][38][39] Indoor environmental quality

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[30] Frank D, 2011. Heat or Eat: The Children's Healthwatch Experience. http://www.iea.org/media/workshops/2011/poverty/pres13_FRANK.pdf . Presented at IEA 2011 Workshop (Footnote 35).

[31] Weatherization Assistance Program] http://www1.eere.energy.gov/wip/wap.html

[32]Schweitzer M and Tonn B, 2002.Nonenergy Benefits From the Weatherization Assistance Program: A Summary of Findings From the Recent Literature. ORNL/CON-484. http://weatherization.ornl.gov/pdfs/ORNL_CON-484.pdf.

[33] US DOE, accessed May 2013. National Retrospective Evaluation of the Weatherization Assistance Program (WAP). http://weatherization.ornl.gov/evaluation_nr.shtml

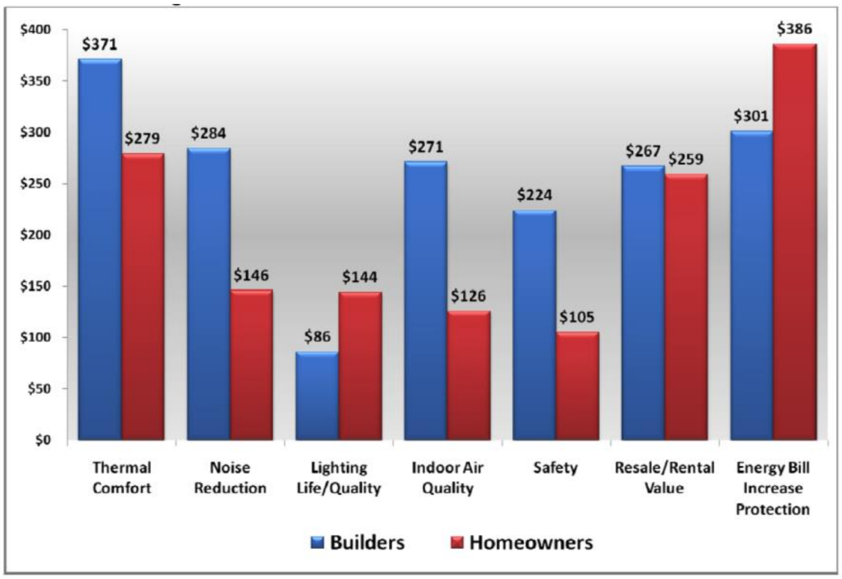
[34]Dalhoff G, 2007. An Update of the Impacts of Vermont's Weatherization Assistance Program. Prepared for Vermont State Office of Economic Opportunity Weatherization Assistance Program. http://dcf.vermont.gov/sites/dcf/files/pdf/oeo/2007ImpactofVTWeatherizationProgram.pdf.

[35] International Energy Agency, January 2011. Evaluating the co-benefits of low-income weatherisationprogrammes. http://www.iea.org/publications/freepublications/publication/low_income_energy_efficiency-1.pdf

[36]Curtis Research Associates, 2009.Home Buyers Focus Groups, Market Research Report. Report #09-201. Northwest Energy Efficiency Alliance, Portland, OR. http://neea.org/docs/reports/homebuyersfocusgroupsmarketresearchreport.pdf .

concerns of homebuyers were elevated when household members had asthma or allergies.36 In addition, a Massachusetts study of 70 ENERGY STAR homeowners and 30 builders asked how much homeowners would pay for various non-energy benefits (co-benefits).38 As shown in Figure 2, the average monetary values of the IEQ-related non-energy benefits totaled $800, when homeowners compared them to energy savings of $400 per year. The average value for thermal comfort alone was $279. However, builders gave noise reduction and IAQ significantly higher values (at 90 percent confidence intervals) than did homeowners.

Figure 2: Builder and Homeowner Valuations of Non-Energy Benefits in ENERGY STAR Homes



Source: Conant 2009.38

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[37]NAHB Research Center, Inc., February 2006. The Potential Impact of Zero Energy Homes. Prepared for National Renewable Energy Laboratory, Golden, Colorado. http://www.toolbase.org/pdf/casestudies/zehpotentialimpact.pdf.

[38]Conant D, 2009. Evaluation of the Massachusetts New Homes with ENERGY STAR® Program, 2008 Findings and Analysis, Final Report. Nexus Market Research. http://www.env.state.ma.us/dpu/docs/electric/09-64/12409nstrd2aa.pdf.

[39]RCLCO, 2008.Measuring the Market for Green Residential Development. http://www.rclco.com/pdf/Measuring_the_Market.pdf. As cited in Kaufman B, 2010. ECert Report – Emerging Trends Green Real Estate. EEBA Conference 2010. http://www.eeba.org/conference/2010/downloads/Kaufman_EEBApresentation%20Oct%2013%202010.pdf.

3.3.3 Utility Prices

Natural gas prices in California could rise from about \$3.50/million Btu (MMBTU) to \$5–\$7/MMBTU (40 percent or more) by 2030.[40] Electricity rates could also increase substantially. These price increases would further accelerate energy-efficiency measures for buildings. However, energy price increases are very uncertain because of various interrelated factors affecting supply, demand, and new technologies in the energy field.

3.3.4 Building Materials and Consumer Products

Building materials and consumer products affect many of the other linkages identified here. Some of the most important anticipated trends in building materials that affect energy and/or IEQ are listed here:

1. Increased use of lower-VOC and low- or no-formaldehyde building materials and furnishings
2. Increased use of anti-pest, anti-microbial agents
3. Increased use of plastics and resulting emissions of phthalates
4. Increased use of scented products
5. Increased use of so-called "green" cleaning products (increased indoor air chemistry in presence of ozone or NOx)
6. Introduction of probiotics (beneficial microbes) for buildings
7. Increased use of plants to clean indoor air
8. Use of "air cleaning" devices that pollute

Building materials as sources of indoor pollutants have been addressed in the past two decades or more. Major sources are composite wood products such as plywood, particle board, oriented strand board (OSB), and medium-density fiberboard (MDF). As lumber and other solid wood products become more expensive due to increased use relative to the available supply, such composite materials will be used increasingly. The California Air Resources Board has regulations governing the emissions of formaldehyde from such products, but other organic compounds are emitted also, and some of these may represent significant health hazards.[41]

Sheet products for walls and ceilings are available now, and others are being developed to adsorb formaldehyde. Other products are being developed to reduce mold formation.

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[40] California Energy Commission, 2011. 2011 Natural Gas Market Assessment: Outlook, Draft Staff Report. Pub # CEC-200-2011-012-SD. Posted September 13, 2011. http://www.energy.ca.gov/2011publications/CEC-200-2011-012/CEC-200-2011-012-SD.pdf.

[41]Hodgson, A. T. 1999.Common indoor sources of volatile organic compounds: emission rates and techniques for reducing consumer exposures. ARB Contract 95-302.

Chemicals added to new building materials for air pollutant reduction may be semi-volatile organic chemicals that themselves may be hazardous in some situations.[42]

Plasticizers such as phthalates used in resilient floors and in wall coverings also have come under scrutiny due to recent health effects studies.[43]

Products manufactured from recycled materials may be sources of pollutants that are banned or that are no longer commonly used in building materials. Increased use of recycled materials may result in sources of chemicals that were used in the original products, such as lead in paints, heavy metals, wood preservatives, and insecticides. Examples include wood painted with lead-based paints or sealed with pentachlorophenol wood preservatives, now recycled into composite wood products such as medium-density fiberboard.

3.3.5 Consumer Products

In recent years results from scientific studies have increased concern over the use of products such as flame retardants, plasticizers, and pesticides, that contain semi-volatile chemicals. Among the greatest concerns are flame retardants from bedding and furniture. In California, regulations have tended to increase the use of these products. Studies have shown higher indoor concentrations as well as human body burdens of these chemicals in California. Plasticizers used in toys, cosmetics, furnishings, and many other products are also of increased concern. Pesticides are on a continual basis of review and revision, as experience and exposures accumulate after introduction of new products or expanded use of older ones. A growing area of product development accompanied by concerns about potential health hazards is the incorporation of nanomaterials into consumer products. As attention to moisture and mold increases, efforts to control the microbial activity associated with moisture leads manufacturers to create and market products that are moisture or mold resistant. Marketing of these products introduces more consumer awareness and products as applications increase.

3.3.6 Appliances and Equipment

Appliances and equipment can be sources of pollutants. Lubricants used in motors, flame retardants used in electronics, and other chemicals can be released, particularly when the products use involves increased temperatures associated with waste heat from electricity. Cooking and water heating appliances using combustion processes are also important sources. Water use for cooking or personal hygiene can result in moisture accumulation.

3.3.7 Outdoor Air, Soil, Water, Attached/Connected Structures

Ventilation air from outdoors brings with it pollutants that may be in the outdoor air. Infiltration from outdoor air, attached structures (e.g., garages), and from soil below or around

[42] Morrison et al. 2006., Proceedings of Healthy Buildings 2006, Lisbon, Portugal.

[43]Xu,Y, Cohen Huba, E. and Little, JC, Predicting Residential Exposure to Phthalate Plasticizer Emitted from Vinyl Flooring: Sensitivity, Uncertainty, and Implications for Biomonitoring. *Environ Health Perspect* 118:253–258.

the structure can also be a source of pollutants. As buildings become tighter in the future, the amount of infiltration may change, increasing or decreasing depending on the shift in pressure differential resulting from the tightening of the envelope and changes in surface temperatures, as well as changes in indoor-outdoor temperature differences or outdoor wind direction and velocity.

3.4 Climate Change

3.4.1 Thermal Comfort Issues: More Frequent and Severe Heat Waves

Climate change has already been attributed as a causal or contributing factor in heat waves in recent years, resulting in a significant increase in deaths and hospitalizations (IOM 2011).[44][45][46] As heat waves become more frequent and intense, increased use of air-conditioning is expected. Thermal comfort often determines occupant behavior with respect to mechanical ventilation systems and air-conditioning use.[47][48]

3.4.2 Higher Outdoor Air Pollution Levels, Pollen Counts, Mold, and Bacteria

Higher temperatures are associated with increases in outdoor air pollutants, including pollen counts, mold, and bacteria.

3.4.3 Higher Pesticide Usage

An observed outcome of a warming climate is the northward migration of pests. As more and new pests are identified in localities where they have not been found historically, pesticide use is likely to increase. Increased use of pesticides indoors and outdoors will result in greater occupant exposure and likely the development and use of new products to control pests. Pesticide use and especially misuse is a recognized hazard due to the toxicity of most pesticides and their frequent use without regard to label restrictions and warnings.

Another change expected with the changing climate is more frequent and severe storms, resulting in flooding and more frequent moisture problems and resulting microbial growth including, but not limited to, mold and mildew. A common treatment of visible mold is to use pesticides, which can create new or different hazards.

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[44] Institute of Medicine, (2004) Damp Indoor Spaces and Health, Institute of Medicine, Washington, DC, National Academy Press.

[45] Spengler J.D. Climate change, indoor environments, and health. *Indoor Air*. 22(2), pages 89–95. http://onlinelibrary.wiley.com/doi/10.1111/j.1600-0668.2012.00768.x/pdf

[46] IOM (Institute of Medicine) (2011) Climate Change, the Indoor Environmental and Health, Wash DC, National Academies Press.

[47] Spengler, *op cit*.

[48] Levin, H. 2008. Indoor Climate and Climate Change, Proceedings, Indoor Air 2008, Copenhagen, Denmark. http://www.buildingecology.com/articles/indoor-climate-and-climate-change?searchterm=Indoor+Climate.

3.4.4 Severe Storms, Floods, Wildfires, Dust Storms

Expected changes in weather associated with climate change include more severe storms, floods, and dust storms. Flooding of rivers, streams, and low-lying coastal lands will result in moisture-related problems that are associated with adverse health outcomes. A more extreme climate is also associated with increased occurrence of wildfires, exposing building occupants to particles and gaseous pollutants associated with adverse health outcomes.

3.4.5 Power Outages

As air-conditioning use increases in periods of warm weather, increasing occurrence of power outages is possible. Peaking power plants will use more combustion fuels, resulting in higher levels of air pollutants associated with combustion of these fuels. A lack of electricity results in increased uses of generators with the risks associated with improperly used or inadequately ventilated generators. This can result in increased exposure to thermal stress and accompanying increases in mortality, especially in the elderly.

3.5 Socioeconomics

Several overlapping factors will shift the type, occupancy, and location of buildings in California by 2030. The IEQ implications of these shifts are discussed below.

3.5.1 Demographics

Population predictions indicate that California's population will grow from 37.3 million in 2010 to 49.2 million in 2030, a 32 percent increase.[49][50][51] The largest growth will be in the elderly age group (65 years or more)—1.6 million persons, or 38 percent, by 2020.[52] This boom in the elderly population will increase the demand for smaller, affordable housing, such as manufactured homes and multifamily homes. The smaller volume of such homes will likely increase the rate of buildup of indoor air pollutants, but it may also provide improved thermal conditions over those in a single-family home. The elderly boom will also increase the demand for extended care facilities and retirement homes, which have their own set of building characteristics and IEQ issues. Many elderly persons may continue to age in place in their existing home, which will often require alterations for improved access. Such alterations can result in increased exposures to emissions from new building materials (used in renovations) and exposures to

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[49] California Department of Finance, July 2007. *Population Projections for California and Its Counties 2000-2050,by Age, Gender and Race/Ethnicity*, Sacramento, California. http://www.dof.ca.gov/research/demographic/reports/projections/p-3/.

[50] California Energy Commission, May 2010. Transportation Energy Forecasts and Analyses For the 2009 Integrated Energy Policy Report.

[51]US Census Bureau, 2011.State and County Quick Facts, California. http://quickfacts.census.gov/qfd/states/06000.html.

[52] Levy S and Lee KO, 2011. Staff Workshop on the Economic Outlook in California, January 19, 2011, 2011 IEPR Proceeding, California Energy Commission. Center for Continuing Study of the California Economy. http://www.energy.ca.gov/2011_energypolicy/documents/#01192011.

numerous hazards, especially heavy metals and semi-volatile organic compounds (SVOCs) that tend to persist in the indoor environment and often pose significant health risks.

3.5.2 Economic Stress

The current recession and high unemployment rate has created economic stress in California, which has affected the housing market and may continue to do so for several years. The recession has increased the demand for more affordable housing, which tends to be smaller in size (see discussion above). Economic stress also impairs the ability of building owners to perform preventive or deferred maintenance and the ability of households to pay for home heating and cooling expenses.

In addition, overcrowded housing has been a major problem in California since 2000, and the rapid decline in new home construction from 2006 on has exacerbated this problem.[53] Since 2000, California has had 1.7 million overcrowded households, and two-thirds of these were renter households. There has been an increase in the number of households with multiple families, additional relatives, or young adult children living in the same home. This higher occupant density will increase the amount of human activities in a home, which tends to raises indoor air pollutant levels and the potential for overheating. It also increases the risk of contacting airborne and other infectious diseases.

3.5.3 Land Use

California Senate Bill 375[54] on transportation planning will accelerate the shift toward more infill and high-density development, which will increase the impact of outdoor pollutants from nearby roadways and commercial activities on IEQ. This impact may be mitigated somewhat by reduced-emission motor vehicles and the increased use of other transportation modes. In addition, 77 percent of young adults report wanting to live in urban centers and being willing to live in smaller spaces to accommodate their lifestyles.[53] This will create a demand for smaller housing (see discussion above), especially in urban coastal areas where job growth is located currently.

Infill pressures, along with housing affordability pressures, will increase the amount of remodeling, additions, and garage conversions. This construction activity will raise the potential for IEQ degradation due to building material emissions, inadequate ventilation, combustion appliance depressurization, and disturbances of mold, lead-based paint, and asbestos. In addition, garage conversions could increase the risk of elevating indoor levels of VOCs, SVOCs, and combustion pollutants from adjoining storage spaces or combustion appliances within or near the living space.

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[53]Department of Housing and Community Development, 2011. The State of Housing in California 2011: Supply and Affordability Problems Remain. http://www.hcd.ca.gov/hpd/HCD_PaperState_of_Housing_in_CA2011.pdf. Press release: http://www.housingca.org/site/News2?page=NewsArticle&id=5815.

[54] Sustainable Communities and Climate Protection Act of 2008 (Sustainable Communities, SB 375, Steinberg, Statutes of 2008)

3.6 Emerging Technologies and Practices

The development and market penetration of both new and improved technologies and practices will accelerate in response to demands for more-efficient buildings. Several groups have recently developed roadmaps and recommendations for developing more-efficient buildings and building systems.[55][56][57][58][59][60][61][62] However, only a few of these efforts addressed health, comfort, or other IEQ issues, and only one addressed them in a comprehensive manner.[63]

The following discussion highlights the emerging technologies and practices that can have important IEQ implications. [64]

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[55] Bonneville Power Administration (BPA), March 2011. Northwest Energy Efficiency Technology Roadmap http://www.bpa.gov/energy/n/emerging_technology/process.cfm.

[56]National Science and Technology Council, 2008.Federal Research and Development Agenda for Net-Zero Energy High Performance Green Buildings. http://www.nist.gov/el/highperformance_buildings/performance/netzero_102808.cfm.

[57] Argonne National Laboratory, February 2011. Building Efficiency: Emerging Technology Roadmap Analysis. http://www.anl.gov/renewables/research/building_emerging_tech_roadmap.html.

[58]ENVIE, 2009.Co-ordination Action on Indoor Air Quality and Health Effects. Final Report, Project no.SSPE-CT-2004-502671.Prepared for the European Commission. http://paginas.fe.up.pt/~envie/documents/finalreports/Final%20Reports%20Publishable/Publishable%20final%20activity%20report.pdf.

[59]International Energy Agency, 2011. Technology Roadmap, Energy-efficient Buildings: Heating and Cooling Equipment. http://www.iea.org/papers/2011/buildings_roadmap.pdf.

[60]Puttagunta, S. Building America Emerging Technologies Research. EEBA Conference 2010. Steven Winters Associates. http://www.eeba.org/conference/2010/program.htm.

[61]Singer BS and Tschudi WF, 2009. High Performance Healthcare Buildings: A Roadmap to Improved Energy Efficiency. LBNL- 2737E.Prepared for PIER, CIEE, and DOE. http://www.hightech.lbl.gov/documents/healthcare/lbnl-2737e.pdf.

[62]US Department of Energy (DOE), 2010.Indoor Air Quality R&D. http://www1.eere.energy.gov/buildings/indoor_air.html.

[63] ENVIE, 2009. Co-ordination Action on Indoor Air Quality and Health Effects. Final Report, Project no.SSPE-CT-2004-502671.Prepared for the European Commission. http://paginas.fe.up.pt/~envie/documents/finalreports/Final%20Reports%20Publishable/Publishable%20final%20activity%20report.pdf.

[64]Emerging technologies and practices are defined here as "those that are either: (1) not yet commercialized but are likely to be commercialized and cost-effective for a significant proportion of end-users (on a life-cycle cost basis) over the next few years; or (2) commercialized, but currently have penetrated no more than 2 percent of the appropriate market. Measures with only long-term potential, as well as measures that have already shown significant acceptance, in the market are excluded from analysis." http://www.aceee.org/topics/emerging-technologies-and-practices.

3.6.1 Building Envelope

Foam board insulation products are being used in the U.S. market to a limited extent, so far mostly for new construction or deep retrofits. Foam boards are used alone or as part of structural insulated panels (SIPs), which have foam sandwiched between composite wood or gypsum board panels). A major issue with foam board is the potential for condensation of water vapor in the wall cavity, which can lead to mold growth and structural damage unless a water or vapor barrier is included, the assembly is tightly sealed and properly drained, and insect penetration is avoided (especially in cold climates).[65] Foam boards include toxic and/or persistent, bioaccumulative fire retardants and blowing agents: hexabromocyclododecane (HBCD) and tris (1-chloro-2-propyl) phosphate (TCPP). Volatile organic compound emissions from the composite wood panels are another potential IEQ issue, especially if the product is used in interior walls. Fire safety is also an issue unless a fire safety barrier such as gypsum wallboard is included.

Polyurethane spray foam is being used to seal and insulate attics, walls, crawlspaces, and basements in new and existing buildings. In addition to moisture control and fire safety problems, spray foam poses worker health and safety risks from chemical vapors, aerosols, and dust during installation and curing. Safe re-entry times are a major concern for building occupants, especially for asthmatics, and long-term VOC off-gassing is a potential concern.[66] Off-gassing of diisocyanates, which are potent sensitizers and irritants, is an ongoing issue for these products.[67] The ASTM Subcommittee D22.05 is in the process of developing a standard test method to sample and analyze diisocyanates and other VOCs.[68]

A new type of "smart" vapor barrier is being used in residential construction, with or without foam insulation. This product allows water vapor to escape in both directions, which reduces the risk of condensation within wall cavities in all climates. This product should help reduce the incidence of moisture-related IEQ problems, especially in low-energy, airtight buildings.

3.6.2 Ventilation Systems

"Current ventilation standards are not based on maintaining the health and productivity of occupants…,"[69] but rather on satisfying at least 80 percent of building occupants based on their perceived air quality, i.e., odor and irritation response; or, they are based on meeting a specified outdoor air ventilation rate established by the ASHRAE committee responsible for Standard 62-

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[65] http://www.energysavers.gov/your_home/insulation_airsealing/index.cfm/mytopic=11620.

[66] EPA, November 29, 2011. http://epa.gov/dfe/pubs/projects/spf/exposure_potential.html#potential.

[67]http://www.cdc.gov/niosh/nas/rdrp/ch4.1b.htm.

[68]http://www.astm.org/DATABASE.CART/WORKITEMS/WK30960.htm. See also: ASTM 2011, Workshop on Spray Polyurethane Foam Insulation Emissions Testing. http://www.astm.org/SYMPOSIA/filtrexx40.cgi?+-P+MAINCOMM+D220500+-P+EVENT_ID+2034+-P+MEETING_ID+65983+/usr6/htdocs/newpilot.com/MEETINGS/sympotherinfo.frm.

[69]IOM, 2011.p 10.

2010. The rates are chosen based on professional judgment of the members of the responsible committee and there is no claim of either an empirical or a theoretical basis for the specified rates. Furthermore, ventilation standards "…do not account for the potential effects of climate change on building design and operation and on occupant behavior."[70] There are likely to be continued efforts to find the lowest ventilation rates that can protect occupant health while minimizing energy consumption. However, this type of ventilation standard has been an elusive goal for several decades, and it may not even be feasible to achieve such a science-based standard in the near term.

There will also be continued pressure due to economic forces for building operators and occupants to turn off or subvert outdoor air ventilation systems in residential and commercial buildings. There is also a small but growing trend to design buildings and ventilation systems that are resilient to the more extreme weather conditions, increased urban air pollution, and power outages that are expected as climate change accelerates.

Separate, filtered supply systems for outdoors are becoming more common in new construction. Known as Dedicated OutSSdoor Air Supply (DOAS) in commercial buildings and balanced ventilation systems in residences, these systems use more-efficient fans and ductwork compared to conventional HVAC systems. They could provide more constant ventilation, enable improved filtration of outdoor air, and create less draft on occupants. As with most types of mechanical ventilation systems, prevention of noise, drafts, depressurization, and filter clogging problems can be achieved by careful design, installation, commissioning, and maintenance.

Starting 20 years ago, displacement ventilation and underfloor air distribution systems became more common in commercial buildings.. Such systems can provide good IEQ with less energy use. Potential IEQ concerns may arise due to uneven distribution in underfloor plenums (where ductwork is not used), inadequate air mixing within the spaces, local drafts near the floor level, and maintenance problems inherent to newer technologies. There have also been concerns associated with accumulation of dirt and/or moisture in the plenums or ductwork, although these problems also apply to return air plenums above suspended ceilings and almost all types of ductwork. In theory, the underfloor systems are more easily inspected and cleaned than ceiling plenums. The practice of using boroscopes or other means for non-destructive access and inspection of concealed spaces increases the potential for reducing the problems occurring in concealed spaces of all types including plenums both above suspended ceilings and under floor as well as in ductwork.

High-efficiency heat recovery ventilators (HRVs) can provide balanced, filtered outdoor airflows to help maintain good IEQ in residences. High-efficiency HRVs are available in Europe and more recently in the United States. In addition, a United Kingdom (UK) manufacturer of HRVs for wall installation has entered the North American market for existing homes. As with other mechanical ventilation systems, the maintenance of the filters, ductwork, and airflows are essential for good performance.

[70] Op cit,

3.6.3 Heating and Cooling

Ductless mini-split heat pumps (MSHPs) are common in Europe and Japan. Their use is growing in the United States, especially in low-energy homes where heating or cooling needs cannot be met by renewable energy sources on site. These systems can be installed in various zones of the home as wall units. They are very efficient, but customer complaints about the noise, draft, controls, and aesthetics have been reported.60 A similar approach for zone heating that does not rely on new technology is to use vented gas space heaters or wood stoves, but those technologies both present potential IEQ problems due to spillage or backdrafting of combustion pollutants or, in the case of wood burning, pollution of the outdoor air nearby. Another approach is local radiant heating devices (including those utilizing parabolic reflectors), which can improve energy efficiency and comfort by enabling lower room air temperatures while providing for individual occupant thermal comfort and control.

In commercial buildings, heating and cooling technologies that are separate from the ventilation system are being used: radiant floors, radiant panels, and chilled beams.[71][72][73][74][75] These approaches should provide more localized and direct control of thermal conditions and individual occupant responsiveness. Radiant thermal control systems with DOAS are critical to the link between IEQ and energy in commercial buildings in which cost-effective ZNE is a serious goal. It is likely that thermally active building systems (TABS) (e.g., massive slabs for radiant systems), or radiant slab systems, will be needed. These slab-based systems are more likely to be used than either radiant panels or chilled beams (which is not truly a radiant system), both of which tend to be cost-prohibitive. The implementation of these technologies—together with occupant control—has significant potential for energy saving, as well as the provision of a greater level of comfort for a larger fraction of occupants.

In addition, "combined" heating and cooling systems that are integrated with hot water systems and/or ventilation systems are drawing interest in the United States, for both commercial and residential applications.[76][77] Heat pump hot water heaters (HPHW) are slowly gaining market

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[71]US DOE, 2011. Energy Savers: Radiant Heating. http://www.energysavers.gov/your_home/space_heating_cooling/index.cfm/mytopic=12590.

[72]Modera M, 2009. New Cooling Technologies and Strategies.6th Annual Southwest Regional Energy Efficiency Workshop.

[73]US DOE, 2011.New and Underutilized Technology: Active Chilled Beam Cooling with Dedicated OSA Ventilation. http://www1.eere.energy.gov/femp/technologies/eut_chilledbeam.html.

[74]California Utilities Statewide Codes and Standards Team, September 2011. Measure Information Template – Hydronic Low Temperature Radiant Cooling Systems. Codes And Standards Enhancement Initiative (CASE). See also: http://www.h-m-g.com/T24/.../radiantcooling_stakeholdermtng2.pdf.

[75] Butcher, T., 2011. "Performance of Combination Hydronic Systems." *ASHRAE Journal*, December 2011: 36-41.

[76]Greenbuilding Advisor, 2011. http://www.greenbuildingadvisor.com/community/forum/mechanicals/16419/combined-hrv-and-mini-split

share, and their relatively high Coefficient of Performance (COP) (2 to 3.5) encourages their potential rapid adoption and application in areas of relatively low electric cost as a substitute for combustion-based hot water systems. Such hot water can also be used for space heating through air or radiant distribution systems. A potential drawback of such systems is the additional complexity of installing, operating, and maintaining such systems, and the added potential for water leaks, especially in a residential setting.

3.6.4 Control Systems

Control systems for heating, ventilating, cooling, and lighting are undergoing major changes, due in large part to the development of inexpensive wireless sensors. For example:

- Dynamic controls of residential ventilation systems to adjust for the use of exhaust fans, clothes dryers, HVAC systems, window shades, and open windows are being designed and demonstrated.[78][79]
- The operation of system components can be monitored and adjusted routinely. This can also be used to periodically recommission a building.
- Occupants of commercial buildings can provide periodic feedback on thermal comfort and other IEQ factors to the building operator.
- Systems that allow personal control of airflow to each office are available. Interactive "energy dashboards" that display current system operation settings, energy usage, and energy prices to the building occupants are also available now.
- Control systems also can be programmed to learn what settings the user typically prefers under certain situations.

In general, these systems allow improved monitoring and adjustment of building energy performance. This should lead to improved IEQ, health, and task performance, assuming that the sensors and control systems operate as designed. User-friendly controls and periodic re-training of building operators appear to be necessary to meet design goals.

3.6.5 Air Cleaning

Technologies to remove gaseous air pollutants through adsorption, photo catalysis, or other methods are on the market but are not cost-effective for general application. Improved

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[77]Green Housing Coalition, 2007.Combination Water & Space Heating Systems. Build It Green, Berkeley, CA. http://www.builditgreen.org/attachments/wysiwyg/22/Combo-Systems.pdf.

[78]Hansen EK, 2010. Measuring life by real people. Active House Demonstration.http://www.activehouse.info/knowledge/measuring-life-real-people.

[79]Foldbjerg F et al., 2011. Measurements of indoor environmental quality and energy performance of 6 European zero carbon houses – a case study from the first house. *Proceedings of Indoor Air 2011* http://www.isiaq.org/news/indoor-air-2011-proceedings-now-available-on-a-flash-drive/?searchterm=Proceedings%20Indoor%20air%202011.

technologies to remove gaseous air pollutants from indoor air are being developed, including both active methods and passive methods that use modified building materials.[80]

3.6.6 Integrated and Distributed Systems

Connecting two complementary functions such as refrigeration of food or space cooling with heating of hot water for domestic or commercial uses or for space heating has already been investigated by Energy Commission-funded research. Advanced thinking at an urban scale uses central systems in dense areas to store and redistribute stored heat or coolth, and to share local energy sources. Multi-family residences above food markets represent an ideal opportunity for using waste heat from refrigeration for space heating in the floors above the market. This is essentially the application of heat pumps, run in either direction, for cooling or heating as a primary function and the other as the by-product function. The concept is not new, but under increased incentives or mandates, new applications are being explored, developed, and applied. District- or neighborhood-scale systems such as ground source heat pumps or photovoltaic systems have been installed in some U.S. and Canadian cities. These types of integrated and distributed systems may also help buffer heating, cooling, and ventilating needs during power outages and shortages, and they will also help maintain good IEQ, which will be especially beneficial for vulnerable populations such as the elderly and the hospitalized.[81]

3.7 Emerging IEQ Issues

A multitude of new building materials and products enter the market each year, and even old products are formulated or manufactured differently, often without toxicological testing, risk assessment, or any disclosure to purchasers or consumers. For example, new, previously unknown chemicals are used to replace toxic pollutants or VOCs to enable products to receive approval or listing as "low-emitting," "no-VOC," and other types of product listings considered "green" or "environmentally-preferable." Some "green" cleaning products use terpene or citrus-based compounds to replace traditional solvents that have been restricted or banned. These new, "green" solvent substitutes react with ozone to form toxic products such as formaldehyde, higher molecular weight aldehydes, acidic aerosols, and ultrafine particles.[82]

Another emerging issue is the use of recycled materials or re-use of materials that contain toxic substances such as pentachlorophenol (a wood preservative) and lead from wood paint, which are both now banned from indoor use. Other recycled materials used indoors may contain

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[80] Gall ET, 2011. Barriers and opportunities for passive removal of indoor ozone. *Atmospheric Environment* 45 (2011) 3338e3341.

[81] Currently, nearly all PV systems connected to the grid are disabled during outages. Technology to enable them to provide power to the building is available and may be more common in the future. Some off-the-grid systems power battery systems and are not affected by grid outages. Most healthcare facilities and many other buildings with critical functions have generators or other emergency power provisions.

[82]Nazaroff, W. W. et al., 2006. Indoor air chemistry: cleaning agents, ozone and toxic air contaminants. ARB Final Report. http://www.arb.ca.gov/research/single-project.php?row_id=60560.

chemicals originally used as flame retardants, plasticizers, or pesticides. At worst, there may be a concentration of undesirable chemicals through the process of repeated recycling.

Several indoor pollutants from new or existing products are considered to be "emerging pollutant issues" because they pose substantial public health concerns but have yet to be widely regulated or tested routinely in building materials and consumer products.[83] Some of these pollutants are carcinogens, endocrine disruptors, and/or known developmental and/or neurological toxins. Examples of such pollutants include SVOCs that also tend to be persistent organic pollutants (e.g., dioxins, halogenated fire retardants), organochlorine pesticides, heavy metals (e.g., mercury), and nanoparticles (e.g., laundry detergent additives).

Also emerging as a health concern are electromagnetic fields (ELF-EMF) from wiring and electrical panels and radiofrequency radiation (RFR) from wireless devices and systems inside and outside of buildings.[84] Radiofrequency radiation exposures appear to be increasing rapidly due to the growth of wireless technology for smart meters, computer networks, wireless antenna facilities, HVAC controls, and smart buildings.

Health effects and/or exposure studies are often lacking or inconclusive for these emerging pollutants. Currently only limited guidance is available on safer alternatives and precautionary approaches.84 The European Union's scientific review of the potential health effects of ELF-EMF and RFR (0 hertz [Hz] to 300 gigahertz [GHz]) is under way.[85]

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[83]Healthy Building Network and Kaiser Permanente, 2008. Toxic Chemicals in Building Materials: An Overview for Health Care Organizations. www.healthybuilding.net/healthcare/ToxicChemicalsInBuildingMaterials.pdf.

[84]European Commission, 2012.Electromagnetic Fields. http://ec.europa.eu/health/electromagnetic_fields/policy/index_en.htm

[85]http://ec.europa.eu/health/scientific_committees/emerging/docs/scenihr_q_027.pdf.

CHAPTER 4: Results

4.1 Overall Summary

Seven R&D topics regarding IEQ and low-energy buildings were identified:

- Sources
- Ventilation
- Operation and Maintenance
- Thermal Conditioning
- Air Cleaning
- Tools, Methods, and Sensors
- Cross-cutting

From these R&D topic areas, a total of 18 Priority Research Areas that address specific IEQ issues were identified, as shown in Table 1. In some cases, more detailed research project concepts are presented, based on input from the many experts who contributed to this report. The Research Topic Areas are described in more detail in Appendix A.

Table 1: Project Topics and High-Priority Projects[86]

Topics	High-Priority Projects
Sources in Low-Energy Buildings	
Moisture Risk Assessment and Mitigation	Assess the risks of moisture-related problems in low-energy buildings, new and retrofit, for factors such as new building materials, tight envelopes, super-insulation, low-energy cooling technologies, severe storms, and living/green roofs. Develop mitigation measures for moisture problems in low-energy buildings, and assess their effectiveness.
Outdoor Air and Attached Spaces	Develop and test approaches to controlling entry of outdoor pollutants from roadways, commercial activities, agriculture, and other sources Evaluate the effectiveness of airflow and pressure control strategies to control infiltration of pollutants and water vapor from adjoining spaces, outdoor air, and soil (in residences—especially garages, crawl spaces, and attics).
Wood Products and Other Materials	Assess other indoor formaldehyde and VOC sources besides regulated composite wood products, such as attic and crawlspace materials, furnishings, unregulated/exempt exterior plywood, and bamboo plywood and combustion sources. Assess acetic acid and odor emissions from engineered wood products.
Risk Assessment, Guidelines, and New Chemicals	Identify SVOCs and new chemicals in building materials and furnishings and assess their impacts on human health. Develop guidance for rating systems and certification of low-emission materials

[86] See notes at end of table

	and products.
Ventilation	
Controls	Evaluate the potential energy savings and IEQ benefits of real-time, dynamic ventilation controls in various climate zones, weather conditions, and outdoor air quality conditions. Evaluate sensors and measurement methods for airflow and IAQ, and develop improved sensors for demand control ventilation. Address current issues regarding sensor calibration, accuracy, and reliability of carbon dioxide (CO_2) sensors.
Commissioning (Cx)	Develop and demonstrate methods to ensure reliable usage and performance of ventilation systems, both residential and commercial. Develop and demonstrate model specifications for Cx and retro-commissioning (RCx) for IEQ protection.
IEQ Performance	Determine the impacts of ventilation rates and methods as pollutant control strategies, building shell design, and occupant behavior on IAQ, human responses (comfort, health, and performance), building energy use, and costs. Provide related input for ventilation standards. Assess the IEQ impacts of weatherization in multifamily buildings, e.g., differences due to changes to ventilation systems, building shells, and occupant behavior.
High Performance	Evaluate the candidate technologies for ventilation systems for high-performance buildings; include ventilation systems and air cleaning systems that are separate from heating and cooling systems. Develop and demonstrate IEQ-optimized ventilation, heating, and cooling systems for different building types and different climate zones in California, for both new and retrofit applications.
Operation And Maintenance (O&M)	
Operation and Maintenance	Develop and demonstrate methods to ensure reliable usage and performance of ventilation systems. Develop warning and indicator systems for IEQ maintenance needs, such as outdoor air ventilation, temperature control, filter replacement, and prevention of dampness and microbial problems in building envelopes and HVAC systems.
Thermal Conditioning	
Design and Operation	Develop and demonstrate climate-optimized designs for heating, cooling, ventilating, and moisture control, for both new and retrofit applications. Develop design guidelines for overhead fans and air movement methods to improve thermal comfort. Develop and demonstrate design and operational strategies for energy-efficient personal comfort systems to supplement and offset central conditioning in indoor work environments. Variants of such systems are also known as “personal environmental control,” “task ambient conditioning,” and “personal ventilation”.
Air Cleaning	
Assessment and Demonstration	Evaluate the effectiveness and cost of particle filtration air cleaner upgrades in high-pollution areas (e.g., near roadways, railyards, industry, agriculture), including field performance over time. Evaluate the effectiveness and cost of active VOC air cleaners alone and in combination with PM filtration. Assess the effectiveness of passive air cleaning techniques (e.g., ceiling tile) for VOCs, ozone, nitrogen dioxide (NO_2), etc. Determine the IEQ and energy performance of ultraviolet (UV) technologies for removing microbial contaminants from the air and/or surfaces.
Technology Development	Develop and demonstrate improvements in central air filter performance, e.g., reduced filter by-pass, routine maintenance, and higher particle removal

	efficiencies without increased energy use or cost. Investigate the mechanisms of particle removal in relation to filter material, fiber size and shape, pattern, and other aspects of the media used.
Tools, Methods, and Sensors	
Operation and Modeling	Develop checklists for IEQ components of Commissioning and Retro-Commissioning as possible building code measures.
Development and Demonstration	Demonstrate the use of occupant feedback as real time sensors for thermal comfort and perceived air quality with input to building energy managements systems.
Cross-Cutting	
Metrics	Define, develop, and demonstrate IEQ metrics for Cx and Life Cycle Impact Assessment in product selection and building rating systems especially for performance verification.
Human Factors / Behavior	Identify critical human IEQ impacts related to human factors and energy conservation behavior; and Investigate occupant and operator habits and their effects on IEQ and energy use in various building types including residential, schools, daycare, retirement homes, and offices. Develop and demonstrate a strategy to employ human factors and behavior data and user feedback on IEQ at all stages of a building's life cycle.
Assessment and Benchmarking	Identify, develop, and demonstrate the metrics for tracking and comparing IEQ in buildings over time and among similar buildings. Initially monitor IEQ and its determinants and energy use initially, and then periodically monitor all major building sectors, to verify and improve estimates of IEQ, health risks, and energy performance.
Program Evaluation	Identify and assess methods and model programs for assessing progress of projects related to IEQ and its determinants. Determine data needs and database needs for evaluations. Identify opportunities to partner with stakeholders and programs to incorporate IEQ factors in program evaluation and market evaluation, e.g., in energy-efficiency programs at state agencies and energy utilities. Identify and periodically revise strategies for achieving healthy low-energy buildings in accordance with the 2020/2030 time frame of the Strategic Plan.

Notes:

See Appendix A for rationales and details for each Topic and Priority Research Area.

Program Goals are as follows:

- Identifying IEQ problems and opportunities.
- Develop and evaluate energy-efficient technologies for improving IEQ, health, and comfort
- Develop and evaluate energy-efficient practices for improving IEQ, health, comfort, and productivity
- Stimulating or assisting implementation of energy-efficient technologies or practices for improving IEQ.

4.2 Summary of Priority Research

The following summary of the issues provides an overview of the major outcome of the effort presented in this report.

Major data gaps exist for IEQ and IEQ-energy use relationships in several existing building types, including those with the majority of the occupants (e.g., small office, small retail, and multi-family low- and high-rise apartments) and building types typically occupied by vulnerable populations such as the elderly, the infirm, and the very young.

There are clearly very few data for low-energy or net zero energy buildings of any occupancy type. This points to an immediate and ongoing need to monitor new buildings that have very low energy-use profiles, to determine the IEQ impacts of the key measures implemented to reduce energy use.

Human behavior in regard to building energy use is partially characterized for some building types, but there are almost no data available for the impacts of human behavior on indoor air quality. There is also a lack of data on the factors that influence human behavior that affects IEQ and the impacts of poor IEQ on occupants. It is clear, however, that personal behavior determines the dominant indoor pollutant exposures.[87][88]

There is a significant need for an improved understanding of the decision drivers for building IEQ, as well as long-term building/system performance that affects both energy use and IEQ. Among the major determinants of indoor air quality and pollutant exposures indoors are the sources of indoor pollutants. These sources include the building fabric (structure, finishes, equipment), furnishings, consumer products, and occupant activities. While progress has been made in characterizing many building materials that are sources of indoor pollutants, the cleaning, maintenance, and refinishing of materials has not received sufficient attention. These post-construction period activities can be important sources of strong pollutant emissions and occupant exposures.

With few exceptions, furnishings are not selected by the building design or development team. Therefore, they have not received sufficient attention in terms of characterizing their emissions and providing guidance to purchasers, whether at the household or organizational and institutional levels. Similarly, consumer products and even building surface maintenance products are not well characterized in terms of their emissions of pollutants into indoor air or their impact on moisture accumulation and microbial growth. The difficulties in determining what furnishings, finishes, and consumer products will be indoor pollutant sources remains one of the major challenges to the provision of good indoor air quality.

In recent years a consensus has emerged in the scientific community that moisture is an important factor in occupant health, especially for sensitive populations such as asthmatic and allergic individuals. While much attention has focused on mold in buildings with moisture problems, current attention has turned toward moisture as a contributing or adjuvant factor in many adverse health outcomes. The advent of gene-based analysis has begun to dramatically expanded knowledge of the microbial ecology of the indoor environment.[89] Addressing moisture in buildings is a complex problem involving occupants' behavior, building plumbing and space conditioning systems, building ventilation characteristics, and the building envelope and its openings.

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[87]Rodes, C, Kamnes, R., and Wiener, R. 1991. The Significance and Characteristics of the Assessment Measurements for Indoor Contaminants. *Indoor Air* 1 (2) 2.123-145:

[88] Wallace, L.A., 1987. The Total Exposure Assessment Methodology (TEAM) Study , Summary and Analysis: Volume I , Washington, DC, US Environmental Protection, Agency (report No. EPA/600/6-87/002A).

[89] Microbiology of the Indoor Environment http://www.microbe.net

4.3 High-Priority R&D Projects

Table 1 presented the high-priority research issues based on input from experts and the workshop panel. For each topic area selected, high-priority projects are identified based on anticipated trends in IEQ, Strategic Plan needs, and input from the workshop panel. Topic areas apply to both residential and commercial buildings unless specified otherwise. Additional R&D projects that are included in eighteen Priority Research descriptions (Appendix A) may become high priorities in the future as new issues and opportunities arise. The high-priority projects presented in Table 1 are discussed below.

Sources in Low-Energy Buildings

In the Sources topic area, the source types of most concern are those where the scope of the problem is not well understood yet: moisture in low-energy buildings, formaldehyde sources other than composite wood, new chemicals emitted from building materials or consumer products, especially SVOCs; and air entering a building, especially residences, from outdoor air or attached spaces. Although control of pollutants and water vapor from outdoor air and adjoining spaces is better understood, both risk assessment and mitigation research for these sources have a high priority. Guidance on controlling these pollutant sources also is a high priority because it helps implement effective mitigation measures through standards, guidelines, and various rating and certifying low-emission products and practices.

Ventilation

Four research areas are addressed in the Ventilation topic area. The high priorities in the Commissioning (Cx) topic address the need to obtain reliable usage and performance of the ventilation system and to develop model Cx specifications for HVAC systems—especially for residential buildings, where required outdoor air ventilation is a major change in practice. The Controls topic priorities include the need to save energy and improve IEQ by using real-time adjustments for indoor and outdoor conditions (weather and air quality) and the use of natural ventilation. Another Controls priority is to improve the control and measurement of ventilation airflows and IEQ, especially for CO_2 sensors used for demand control ventilation and to investigate new control technologies.

Also in the Ventilation topic are two research areas related to IEQ. One focuses primarily on understanding the IEQ performance associated with different technologies and applications of ventilation. Far too little is known about the aspects of ventilation that contribute to indoor air pollution and adverse occupant health and comfort effects. The other focuses on the technologies most strongly favored by those designing high-performance buildings. These buildings give us the best idea of what the move toward low-energy buildings might bring with it in terms of IEQ.

Operations and Maintenance

In the Operation and Maintenance (O&M) topic area, two high-priority topics are identified. The first involves the development and demonstration of methods to ensure reliable usage and performance of ventilation systems. The need for this is inferred from the data on ventilation system performance that shows strong deviation of performance from design and/or codes and standards. The second topic is developing warning and indicator systems for IEQ maintenance needs such as outdoor air ventilation, temperature control, filter replacement, and prevention of dampness and microbial problems in building envelopes and HVAC systems.

Thermal Conditioning

In the Thermal Conditioning topic area, the one high-priority topic identified is Design and Operation. There are two research proposals considered high priority. They include development and demonstration of climate-optimized designs for heating, cooling, ventilating, and moisture control, for both new and retrofit applications; and development of design guidelines for overhead fans and air movement methods to improve thermal comfort. Because ventilation systems affect thermal conditions, the Thermal Conditioning topic is closely linked to the Ventilation topics. In addition, the Thermal Conditioning topic is close linked to the Human Behavior topic. Human behavior can affect thermal conditions, but humans can also adapt somewhat to a wider range of thermal conditions.

Air Cleaning

There are needs in the Air Cleaning topic area to improve the use of existing technologies and to develop new technologies, especially in the cleaning of gases from the air. Expert input for this report diverged in terms of the experts' confidence in the adequacy of existing knowledge regarding the mechanisms of particle removal by media filters. The project areas identified as high priority include the assessment and demonstration of gas phase technologies, development of improvements in the use of central system filtration technologies to avoid known problems and of new gas phase technologies, operation and modeling tools for analysis of filter performance, and development and demonstration of occupant feedback as input not only for air quality related to filter performance but also of system thermal conditioning. Field testing will be needed to confirm the IEQ and cost performance of these new technologies.

Cross-Cutting

While there are links among most of the research topics, many of the research proposals did not fit well into the traditional categories of building research and performance factors. A series of cross-cutting issues were identified, including: Metrics, Human Factors/Behavior, Assessment and Benchmarking, and Program Evaluation. All of these topics are considered of high priority. More important, the linkage of various aspects of building energy and indoor environmental quality as a unifying theme comes through more clearly in these topic areas.

CHAPTER 5: Discussion

The research project proposals presented in this report are based on our recognition and understanding of the IEQ impacts of energy-efficiency-driven changes expected in the future as well as on current energy-related IEQ issues. While current Energy Commission-funded research is addressing some closely related issues, this roadmap focuses more strongly on the future and a changing building inventory strongly influenced by the State's commitments to energy efficiency and control of greenhouse gas emissions. It is assumed that without more explicit attention to the IEQ implications of energy-efficiency measures, IEQ problems can and likely will occur.

It is expected that future building design and construction, driven by both government policies and market pressures, will result in buildings that differ significantly from most of those existing today in terms of energy efficiency. Given the current scope of IEQ problems and the major changes expected in buildings in the near future and beyond, IEQ problems can be expected to grow, unless more explicit attention is paid to their avoidance.

Eighteen Priority Research issues have been organized in seven topics that reflect the major categories of topics addressed by researchers and professionals dealing with IEQ. In general, the past research projects have been focused primarily on the Sources and Ventilation categories, although attention to Operation and Maintenance and Commissioning has increased in recent years. Research issues are listed and prioritized, but more detailed research proposals and budgets were beyond the scope of this project, and they would depend on available funding and changing R&D needs. Identification of the topics and the preparation of the research issues in this roadmap are based on the need for an integrated approach to the every phase of the building process; this includes regulation, planning, development, design, construction, occupancy, maintenance and operation, and renovation (including energy-efficiency retrofits).

This project identified three key drivers for maintaining IEQ that need more R&D attention: Sources, Human Behavior, and Integration. These topics are discussed below.

5.1 Sources

There is wide agreement that the control of sources is top priority for efforts to avoid future IAQ problems and address many existing problems. The strength and duration of emissions have the most impact on IAQ and are most susceptible to effective control. Controlling sources has the simultaneous benefit of limiting the risk of exposure and limiting the energy costs of controlling exposure through ventilation. Source control is more reliable than ventilation in protecting against exposure. A recent review of IAQ issues in low-energy homes using mechanical heat recovery ventilation recommends that pollutant source control be given more emphasis in building regulations and other mechanisms.[90]

While there still remain many challenges in source control, much progress has been made. The restrictions on tobacco smoking in workplaces and public buildings exemplify a source control measure and are arguably the most effective single action ever taken to improve IAQ in non-residential buildings. Efforts are under way now in many locales to address smoking in multi-family residential buildings. Two other major sources of indoor pollutants have been reduced by the California Air Resources Board regulations: limits on formaldehyde emissions from composite wood regulations (now also mandated at the federal level), and limits on ozone emissions from portable air cleaners.

Source control of indoor and outdoor pollutants continues to deserve attention. Single-family residences remain locations of uncontrolled tobacco smoking. The control of indoor pollutant emissions from building materials and appliances is still largely voluntary in California, the United States, and other countries. However, there is a growing trend toward mandatory emission requirements for sources of indoor VOCs. For example, France now requires VOC emission testing and labeling of building materials and plans to consider regulation of emissions from other indoor products such as air fresheners and cleaning agents. [91][92] Germany requires flooring products and adhesives to be tested and labeled for VOC emissions.[93] Switzerland taxes building materials based on their VOC emissions.[94] Research issues regarding combustion pollutants, VOCs, and other chemical emissions have been included in this roadmap under the Sources topic area.

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[90] Zero Carbon Trust and NHBC, January 2012. Mechanical Ventilation with Heat Recovery in New Homes, Interim Report. Ventilation and Indoor Air Quality Task Group. http://www.nhbcfoundation.org/NewsMediaCentre/VIAQtaskgroupinterimreport/tabid/501/Default.aspx .

[91] French Republic, May 13, 2011. French notification on the labeling of building and decoration material. Ministry of Ecology, Energy, Sustainable Development and Sea.http://www.developpement-durable.gouv.fr/Chapitre-I-Mode-d-emploi-de-l.html (French). Summary and links in English at: French Regulations on VOC emissions from construction products, www.eurofins.com/product-testing-services/topics/compliance-with-law/european-national-legislation/french-regulation-on-voc-emissions.aspx.

[92]French Republic. 2010. Indoor air quality in the grenelle laws and the second national health and environmental action plan. Ministry of Ecology, Energy, Sustainable Development and Sea. As cited in Zero Carbon Trust and NHBC, 2012.

[93]Eurofins, 2012.Eurofins Product Testing - German AgBB / DIBt. http://www.eurofins.com/product-testing-services/topics/compliance-with-law/european-national-legislation/german-agbb--dibt.aspx.

[94] Swiss Federal Office for the Environment (FOEN), Department of the Environment, Transport, Energy and Communications, 1997. Ordinance of 12 November 1997 on the Incentive Tax on Volatile Organic Compounds (OVOC). http://www.admin.ch/ch/e/rs/c814_018.html.

Strong emphasis appears in this report on control of sources of moisture in occupied spaces, ventilation systems, and various parts of a structure, including residential crawl spaces and attics. While water itself is not considered a pollutant, avoiding moisture problems in buildings is now recognized as a high-priority measure for protecting occupants from the adverse health effects associated with excess moisture.[95] In addition, water vapor emitted from new lumber and other construction materials in new, tight homes may require additional drying time before occupancy.[96] Moisture research issues have been included in this report, not only in the Sources topic but also in topics related to Ventilation, a major defense against build-up of water vapor and condensation.

5.2 Human Behavior

Because human activities and decisions heavily influence every IEQ determinant at every stage of building's life cycle, human behavior is arguably the most important IEQ topic. Human actions can undo or counter any attempt to provide good IEQ, whether it is an HVAC installer putting a damper or valve in backwards, a building manager blocking an air intake or failing to replace air filters, or an occupant turning off a ventilation system or bringing a major pollutant source into a building. Consequently, without understanding the "who," "what," and "why" of human actions and decisions at each life cycle stage of a building, many efforts to provide good IEQ will be diluted or even thwarted.

There is also a need to understand human behavior among different socioeconomic and cultural groups, in order to find effective solutions for IEQ problems. Achieving energy-efficiency and IEQ goals for market acceptance of healthy, efficient buildings depends on the approval of opinion leaders in communities and social groups, as demonstrated by successful marketing programs using the Community-Based Social Marketing (CBSM) approach.[97][98] The success of CBSM hinges on understanding the needs, preferences, and motivations of the various decision makers and users of the buildings and technologies. Prioritizing and addressing human behavior issues will improve the success of R&D efforts in affecting practice in the real world. It will also help identify the communication methods and strategies (e.g., labels, outreach, curriculum, peer influence, opinion leaders, word of mouth) that work best for each segment of

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[95]California Department of Public Health, 2011, Statement on Dampness and Mold. http://www.cal-iaq.org/phocadownload/statement_on_building_dampness_mold_and%20health2011.pdf

[96]Zero Carbon Trust and NHBC, January 2012. Mechanical Ventilation With Heat Recovery In New Homes, Interim Report. Ventilation and Indoor Air Quality Task Group. http://www.nhbcfoundation.org/NewsMediaCentre/VIAQtaskgroupinterimreport/tabid/501/Default.aspx

[97]Schultz P. W., Nolan J. M., Cialdini R. B., Goldstein N. J., Griskevicius Vladas (2007). The Constructive, Destructive, and Reconstructive Power of Social Norms. Psychological Science, 18(5), 429-434.Abstract at http://www.cbsm.com.

[98]McKenzie-Mohr D, 2000. Promoting Sustainable Behavior: An Introduction to Community-Based Social Marketing Journal of Social Issues, Vol. 56, No. 3, 2000, pp. 543–554

the target market. However, human behavior remains one of the least researched and understood areas of energy efficiency as it relates to human health and safety, including IEQ.[99]

Another important aspect of human behavior is the value individuals and institutions place on healthy, comfortable, and efficient buildings. Building owners can consider the added value of a buying such a building, but financial institutions must consider the market value of such buildings when they issue loans to builders and homeowners. In fact, two studies from the Pacific Northwest show that green, healthy homes sell at a higher price and sooner than other homes, even in the currently depressed market.[100][101] In addition, a study of low-energy homes in four European Union (EU) nations found that, based on energy savings alone, the energy-efficiency investments were cost-effective. The extra capital costs compared to standard design were 2.85–10 percent but that the discounted payback period was 4–19 years.[102] The life cycle costs and payback periods were lowest in the warmer climates (Spain and Italy), which are similar to much of California's climate.

Because some aspects or elements of healthy, comfortable, and efficient buildings currently cost more initially, financing often becomes a limiting factor in starting such a building project, and in consumer acceptance. In addition, when funding energy-efficiency programs, energy utilities consider the value of energy-efficiency savings but rarely the value of healthy, comfortable buildings. However, consumers appear to rate indoor air quality and non-toxic building materials as one of the most important factors in a new home purchase, following energy-

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[99]Skumatz L, 2009. Lessons Learned and Next Steps in Energy Efficiency Measurement and Attribution: Energy Savings, Net to Gross, Non-Energy Benefits, and Persistence of Energy Efficiency Behavior. Prepared for CIEE, Berkeley, CA. http://www.uc-ciee.org/downloads/EEM_A.pdf.

"Although these measures were designed to help improve IAQ in new homes compared with homes built to minimum code, they alone cannot prevent all IAQ problems. Occupant behavior is also important. (source: EPA IAQ Specifications for IAQPlus houses - http://epa.gov/indoorairplus/construction_specifications.html#low-emission).

[100]Earth Advantage, 2011.Certified Homes Outperform Non-Certified Homes for Fourth Year. http://www.earthadvantage.org/resources/library/research/certified-homes-outperform-non-certified-homes-for-fourth-year/.

[101]RCLCO, 2008.Measuring the Market for Green Residential Development.http://www.rclco.com/pdf/Measuring_the_Market.pdf. As cited in Kaufman B, 2010. ECert Report – Emerging Trends Green Real Estate. EEBA Conference 2010. http://www.eeba.org/conference/2010/downloads/Kaufman_EEBApresentation Oct 13 2010.pdf , pp. 23-25

[102] Ford B et al., 2007. The Passivhaus Standard In European Warm Climates: Design Guidelines For Comfortable Low Energy Homes. Part 1.A review of comfortable low-energy homes. Passive-On Project, Intelligent Energy Europe. http://www.passive-on.org/CD/1.%20Technical%20Guidelines/Part%201/Part%201%20-%20English.pdf.

related factors.[103] There is a large need to firm up estimates of health, comfort, and perhaps reduced liability co-benefits for "green" buildings, so that these benefits can be used to market green, healthy buildings, to raise the expectations of the buyers and users, and to support investment by financial institutions and utilities.

5.3 Integration

Indoor air quality is a relatively new societal concern. Unlike thermal comfort, noise, and illumination, all of which have many decades and even centuries of research history, IAQ research only began in earnest in the United States and Europe in the 1970s. Unlike many other human health hazards, it is largely unregulated, in spite of the fact that most people spend the vast majority of their time indoors and many serious health hazards are well documented. The few relevant regulations that exist are focused either on ventilation rates in buildings or on specific sources of indoor air pollutants such as environmental tobacco smoke, composite wood products, and combustion devices.

Many aspects of indoor environmental quality and the technologies that control or otherwise affect it are interactive and often closely connected.[104] Within the thermal comfort domain alone, there are five environmental factors and two human factors that determine human responses to thermal conditions.[105] Ventilation requirements strongly depend on pollution sources and on human occupancy.[106][107] Outdoor air filtration and air cleaning requirements depend on the outdoor air quality, ventilation flow rates, and the requirements associated with the uses of the indoor environment. System installation, operation, and maintenance—or changes in occupancy patterns or occupant behaviors—can alter a building's energy and indoor environmental performance. Figure 3 depicts the intersections of many of the major determinants of indoor environmental quality.

The strong interrelationships among many of the research topics presented in this report emerge from the various factors that interact to produce indoor air quality and associated

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[103]ASHRAE 2010, Standard 55-2010. Thermal environmental conditions for human occupancy. Atlanta: American Society for Heating, Refrigeration, and Air-conditioning, Inc. accessed 10 December 2011 at http://www.techstreet.com/standards/ashrae/55_2010?product_id=1741646

[104]ASHRAE 2011.*Guideline 10, Interactions Affecting the Achievement of Acceptable Indoor Environments*. Atlanta: American Society for Heating, Refrigeration, and Air-conditioning, Inc. accessed 10 December 2011 at http://www.techstreet.com/cgi-bin/detail?product_id=1771697.

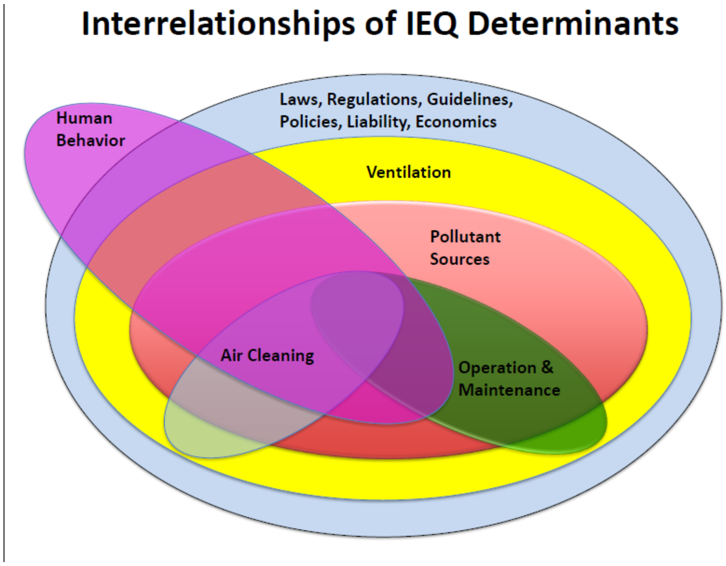
[105]ASHRAE 2010, Standard 55-2010. Thermal environmental conditions for human occupancy. Atlanta: American Society for Heating, Refrigeration, and Air-conditioning, Inc. accessed 10 December 2011 at http://www.techstreet.com/standards/ashrae/55_2010?product_id=1741646

[106]ASHRAE, 2010, Standard 62.1-2010, Ventilation for Acceptable Indoor Air Quality. accessed 10 December 2011 at http://www.techstreet.com/standards/ashrae/62_1_2010?product_id=1720986

[107]ASHRAE, 2010, Standard 62.2, Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings. accessed 10 December 2011 at http://www.techstreet.com/standards/ashrae/62_2_2010?product_id=1703549

thermal, lighting, noise, and other energy-relevant characteristics of the indoor environment While individual research projects necessarily have limited scope due to practical considerations of available resources, time, and purpose, an attempt has been made in this report to maintain clarity about the interconnectedness of the various research topics and specific proposals.

Figure 3: Interrelationships of IEQ Determinants



Source: T. J. Phillips

As is the case in the building energy-efficiency field, the strong interrelationships of IEQ determinants also require an integrated approach. One way this report addresses the interconnectedness of various topics is by including research topic areas and research project proposals under the Cross-Cutting topic. There are four cross-cutting topic areas: Metrics, Human Factors / Behavior, Assessment and Benchmarking, and Program Evaluation. The integration issue is also addressed under the High-Performance Buildings topic area, under Ventilation. That topic area stresses optimization of IEQ and energy efficiency through integrated design.

5.4 Cross-Cutting Research Areas

Integration is also addressed in the research proposals included in the Cross-Cutting topic area where each topic generally is connected to more than one of the other topic areas. Following is a brief summary of the research project proposals under the Cross-Cutting topic area:

- The Metrics research project proposals are considered important to provide the basis for progress in many of the other research areas. Some of the metrics needed are applicable to a wide variety of research needs and address basic problems and barriers that impair more rapid or complete pursuit of the topics.
- The Assessment and Benchmarking research project proposals are intended to build on and extend the work started under the Indoor Environmental Quality and Heating,

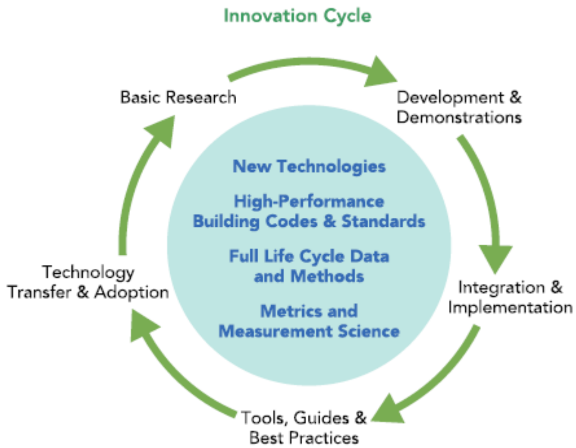
Ventilating, and Air Conditioning Survey of Small and Medium Commercial Buildings, exploring more small- and medium-sized buildings in the building types already studied and in others not yet included. There is a paucity of information available on the energy and IEQ performance of small- and medium-sized commercial buildings, in spite of the fact that there is more square footage in them than in large commercial buildings. There are also more occupants in small and medium commercial buildings than in the larger buildings studied in most studies completed to date.

- The research proposals in the Human Factors / Behavior topic area are needed because of the importance attributed to this topic area by most experts. There is a nearly complete lack of information on the factors that motivate and inform people's decisions that affect the indoor air quality in the buildings where their decisions determine the energy and IEQ characteristics.
- The Program Evaluation priority research project proposals are recommended to develop an ongoing process for obtaining an overview of the needs and the degree to which the Energy Commission's and others' research fulfill the identified needs. Most of the research projects can be divided into three major phases:

  1. Assessment of the state of knowledge about and characteristics of IEQ in relation to energy-efficiency-measure implementation
  2. Technology development to improve energy and/or IEQ that have strong connections and impacts
  3. Demonstration projects that enable the testing and evaluation of new technologies or new applications of existing technologies

  These phases of research, development, and demonstration should be integrated and evaluated at each stage. They should also include a process for feedback from users at every stage to guide further research, as shown in the example in Figure 4.

Figure 4: Program Evaluation and RD&D as a Continuous Improvement Process: User Feedback Is Needed at Every Stage



Source: Modified from NSTC 2008.[108]

5.5 Other R&D Implementation Needs

There is an urgent need to integrate IEQ research with the California Long Term Energy Efficiency Strategic Plan[109]. The Strategic Plan and its resultant Action Plans[110] outline efforts to develop technology, conduct marketing and outreach, and accelerate energy-efficiency performance and verification. These efforts would provide an excellent platform for IEQ research and demonstration projects that address many of the same issues, especially human behavior and performance of technologies and buildings. Integrating IEQ and energy-efficiency R&D could provide synergistic benefits.

Some research topics have great merit but will take concerted effort, major funding, and a long time period to develop. Most research topic areas need better metrics and tools. The two main examples of such research topics are Metrics and Tools and Health-based Ventilation Standards. Performance-based programs for energy efficiency and IEQ need clear targets (metrics) and acceptable methods (tools) to assess and verify performance. However, health-based ventilation standards and product emission standards will take a long time to develop. They are also difficult and expensive topic areas to study, and good indoor exposure measurements are usually lacking. To make progress in this area will require collaborative health-IEQ studies, such as the International Child Cancer Cohort Collaborative.

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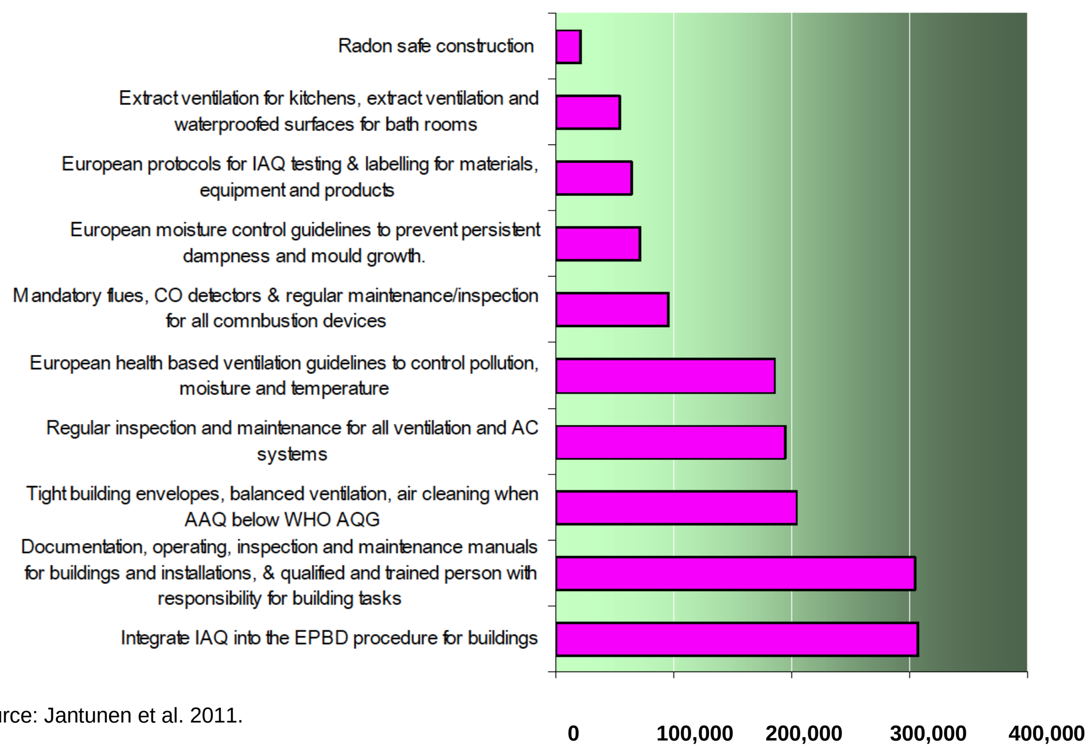
[108]National Science and Technology Council, 2008.Federal Research and Development Agenda for Net-Zero Energy High Performance Green Buildings. http://www.nist.gov/el/highperformance_buildings/performance/netzero_102808.cfm.

[109] http://www.cpuc.ca.gov/NR/rdonlyres/D4321448-208C-48F9-9F62-1BBB14A8D717/0/EEStrategicPlan.pdf

[110] http://www.cpuc.ca.gov/NR/rdonlyres/041CB347-6AA8-4EE7-AE3C-324B4A3F0A98/0/ZNE_Action_Plan_June_2011_Update.pdf

This study's time and budget constraints limited the scope of consultation with subject matter experts and did not allow a formal risk assessment. However, several other programs are addressing some of the same research topics identified here. Some of these programs are addressing health risks of indoor pollutants, suggesting many opportunities for collaboration and leveraging (see footnotes in Research Topics and Research Project Priorities, Appendix A). An important example is the work taking place in the EU, where extensive monitoring and health risk assessment has been conducted over the last ten years.[111] Analyses of the impacts of IEQ on mortality and disease in Europe indicate that individual measures to improve IEQ can greatly reduce the Burden of Disease (as measured in Disability Adjusted Life Years, DALY). Also, this analysis indicates that the greatest improvements can come from improving the operation and maintenance of buildings and integrating IEQ into the EU's Energy Performance of Building Directive (EPBD) for building energy efficiency and climate change and renewable energy programs for buildings. This is illustrated in Figure 5 and explained in Table 2 below.

Figure 5: Potential DALY/Year Benefits at the Tenth Year of Implementation of 10 IAQ Policies in EU-26



Source: Jantunen et al. 2011.

Notes: For DALY/year*million, divide by 484 (million inhabitants) i.e. 400,000 DALY/year corresponds to ca. 2000 DALY/year*million).
AAQ: ambient air quality. AQG: air quality guidelines. DALY: disability adjusted life years. EPBD: EU Energy Performance of Buildings Directive.

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111 Jantunen et al., 2011.Promoting actions for healthy indoor air (IAIAQ).Directorate General for Health and Consumers, European Commission.
http://www.ec.europa.eu/health/healthy_environments/docs/env_iaiaq.pdf

Table 2: Temporal Increase of the Annual Public Health Benefits of the Alternative IAIAQ Policy Scenarios in EU-27 as the Implementation of the Different Policies Slowly Saturate the Building Stock

Existing or proposed EU-regulation and respective IAIAQ Scenario	Start year	Annual health benefit in DALY/million in year 2 000	2 005	2 010	2 015	2 020	∞
CPD (89/106/EEC Construction Products), Scenario 1	2 000	0	35	70	100	120	400
GPSD (2001/95/EC General Product Safety), Scenario 1	2 002		2	5	6	7	9
EPBD (2002/91/EC Energy Performance of Buildings), Scenario 1	2 003		60	190	300	400	800
REACH (EC/1907/2006 Chemicals), Scenario 1	2 007			5	10	13	17
REACH implementation with focus on IAQ, Scenario 2	2 011				10	15	30
CPD+GPSD+ Integration of IAQ impacts of indoor combustion equipment into CPD&GPSD, Scenario 2	2 011				100	180	600
European harmionised protocols for IAQ lbling of building & indoor materials & products, Scenario 4	2 011				60	120	300
Ban on unflued combustion, CO detectors, regular maintenance&inspectiuon, Scenario 5	2 011				100	180	300
EPBD + Integration of IAQ into EPDB recast Scenario 6	2 011				160	350	1 200
Integration of IAQ into EU Climt Act & Renwbl Enrg Pckg & Recast of Energy lbl. Scenario 7	2 011				300	600	2 000

Source: Jantunen et al. 2011.

Notes: IAIAQ is used to indicate "Promoting Actions for Indoor Air Quality." EU-27 refers to the 27 Member States of the European Union

DALY: disability adjusted life years. EPBD: EU Energy Performance of Buildings Directive.[112]

There is a general problem of relative underfunding of indoor environment research including, but not limited to, its relationship to energy efficiency (see text in the Policies section of Appendix E). There is a strong need for more coordination and collaboration with energy-efficiency tech development efforts (in California and elsewhere) and Strategic Plan implementation activities. This lack of adequate funding underscores the need for database coordination, common metrics, and other measures to take greater advantage of available research.

5.6 Limitations and a Few Caveats

There are many uncharacterized risks of indoor pollution, especially the infinitely diverse mixtures of pollutants found in indoor air. Progress made in implementation of the Clean Air Act and the South Coast Air Quality Management District's architectural coatings and other rules has significantly reduced the occurrence of many VOCs in indoor air.[113][114][115] Some green

[112]Jantunen et al., 2011.Promoting actions for healthy indoor air (IAIAQ).Directorate General for Health and Consumers, European Commission. http://www.ec.europa.eu/health/healthy_environments/docs/env_iaiaq.pdf

[113]Hodgson, A.T.; Levin, H.. 2003. Classification of measured indoor volatile organic compounds based on noncancer health and comfort considerations. LBNL-53308. www.lbl.gov.

building programs are already providing incentives to manufacturers to remove some toxics from their product lines, resulting in a reduction in emissions from many products.

This report does not include input from experts regarding specific research project funding levels. Initially the questions posed to experts in the context of project costs limited amounts to about $500,000 for projects to be done in the near- and mid-term periods. Obviously, funding of R&D projects will be very project specific and will largely depend on available funding, the perceived value of the project outcomes, the scope of the project, and the time frame.

[114]Hodgson, A.T.; Levin, H. 2003. Volatile organic compounds in indoor air: A review of concentrations measured in North America since 1990. LBNL-51715. www.lbl.gov.

[115]Levin, H, and AT Hodgson, 2006."VOC Concentrations of Interest in North American Offices and Homes. Healthy Buildings 2006, Lisbon, Portugal, June 4-8, 2006. http://www.buildingecology.com/articles/voc-concentrations-of-interest-in-north-american-offices-and-homes/

CHAPTER 6: Summary and Conclusions

6.1 Short-Term Needs

Human Behavior and Sources are the two biggest data gaps identified in this report. Results of research in these areas should have large impacts on future research topic prioritization. This is true because each plays a key role in the determination of IAQ. It is also true due to the relative paucity of research results to inform actions intended to ameliorate the potential for adverse effects from energy-efficiency measure implementation. Research and development is needed now, in the short-term, to fill these gaps and help guide energy-efficiency programs. It is also necessary to help inform and guide builders and building owners of the benefits of healthy, comfortable, and efficient buildings, i.e., to build the market. A white paper addressing each of these gaps would help researchers assess current information and target critical research needs. Human behavior is a relatively new field of inquiry in terms of IEQ, and it has the added complexity of large variations among population groups, of differing personality types, and of behavior affecting IEQ and vice versa.

Regarding indoor pollutant and sources, various groups have attempted to assess and prioritize sources and pollutants in terms of population health hazards at the national and multi-national level.[116,117,118] However, different types of health effect time frames, populations, and databases have been used in such assessments, and those assessments may not apply directly to California conditions.

Climate-specific design, construction, and space-conditioning requirements strongly affect the presence of and potential solutions to indoor air quality problems. California building locations are dominated by inland climates where, at least in buildings constructed in the past five or six decades, air-conditioning is common. Meanwhile, air-conditioning is less common in pre-World War II buildings and in coastal and mountain climate zones, which are less and more extreme, respectively. Benchmarking of additional building types, further problem identification, and IEQ problem solutions must be carefully targeted by climate zone, construction, and building operational characteristics. The SMCB study reported that several different types of small- and medium-sized commercial buildings are characterized by special problems that may not be as common in their large building counterparts. Further investigation of these problems is

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[116]Jantunen et al., 2011.Promoting actions for healthy indoor air (IAIAQ).Directorate General for Health and Consumers, European Commission. http://www.ec.europa.eu/health/healthy_environments/docs/env_iaiaq.pdf

[117]Logue et al., 2011.Hazard Assessment of Chemical Air Contaminants Measured in Residences. *Indoor Air*. 2011;21(2):92-109. http://onlinelibrary.wiley.com/doi/10.1111/j.1600-0668.2010.00683.x/pdf

[118]Bartzis J, 2010. The BUMA Project: Prioritization of building materials as indoor pollution sources (2006-2009). University of West Macedonia, Greece. Presented at Belgian Presidency, December 203, 2010.BUMA project information at http://www.uowm.gr/bumaproject/.

warranted due to the large fraction of the population working, shopping, or visiting these buildings daily.[119]

Some energy-efficiency programs also give rise to other immediate needs and concerns, e.g., health-based metrics, residential ventilation, thermal comfort in low-energy buildings, natural ventilation mixed-mode ventilation, and commercial building demand controlled ventilation (DCV). These needs should be integrated into the Strategic Plan where feasible.

6.2 Long-Term Needs

6.2.1 Integrated IEQ-Energy-LCA Modeling

For almost three decades, progressive design professionals (architects, engineers and energy specialists) have repeatedly advocated and even claimed adoption of an integrated design process.[120][121] Yet integration is still more of a goal and mantra than a reality. The natural division of labor among design professionals and the many specialized consultants involved in most complex projects present an important obstacle to integrated design. Yet the best designs tend to reflect thinking that links the various building systems and the functions that they provide; or, at least, consider their design as a group. Assessing trade-offs among various approaches to design is essential, especially when "pushing the envelope" on energy efficiency or general building performance.

Modeling software for integrated design of high performance buildings, such as the Building Information Model, is now being used in many cases, and initiatives are underway to develop a national standard for such models.[122] Adapting these models to design for good indoor air quality can be the subject of case studies and explorations of the processes that resulted in the solutions chosen by the design team or implemented by contractors or operators.

Life Cycle Assessment (LCA) methods for building materials do not currently include the use phase—the most important phase for energy and IEQ. Where the IEQ element of an LCA analysis is present, it is usually based on total volatile organic compound (TVOC) content or, in some rare instances, emissions. Ultimately, there is a need to integrate results based on models of emissions decay over time and on estimates of emissions from replacement, cleaning, resurfacing, etc. In green building LCAs, for example, materials (e.g., window glass, concrete, an insulated wall assembly) are treated the same regardless of whether they are on the north,

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[119] Bennett, Wu, and Trout, 2011; Indoor Environmental Quality and Heating, Ventilating, and Air Conditioning Survey of Small and Medium Size Commercial Buildings: Field Study. CEC-500-2011-043

[120] Rush, Richard D., (ed.) 1986. *The Building Systems Integrated Handbook*, Washington, DC: American Institute of Architects., 445 pages.

[121]ASHRAE 2009.*Indoor Air Quality Guide: Best Practices for Design, Construction, and Commissioning, Part 1*,Atlanta: American Society of Heating, Refrigerating, and Air-conditioning, Inc., 4-7. http://www.ashrae.org/FreeIAQGuidance.

[122] National Institute of Building Sciences, accessed 2012. Whole Building Design Guide: Building Information Modeling. http://www.wbdg.org/bim/bim.php.

east, west, or south facade. In fact, the daytime and nighttime energy performance and illumination, as well as the aesthetic impacts, are strongly dependent on their location, especially their compass orientation. The impact on indoor air quality depends strongly on their VOC emission rates which will be affected by their adjacent temperatures and the effect of solar radiation on their thermal profiles. Ventilation rates differ among different parts of the building and, thus, affect the impact of emissions on the air quality in any space. There is an inescapable need to connect IEQ (thermal, IAQ, illumination) and energy over the life cycle of a building, while recognizing that the range of impacts can be strongly affected by occupant or operator behavior.

6.2.2 Exposure and Health Effects Data

One of the major limitations in the IEQ field is the lack of human exposure and health effects data for indoor pollution.[123] Many research studies examine building ventilation or indoor or personal exposures to pollutants, but very few studies combine those data with measurements of symptoms, physiological responses, hospitalization, or other health end points. Many studies address sensitive populations such as the young and asthmatics, but the chemically sensitive population has received very little study, although preliminary studies indicate major differences in their physiological responses to indoor pollutants.

Another major need is better understanding of the health effects of pollutant mixtures that are usually found in indoor environments, rather than studies of one pollutant at a time. Effects of mixtures may be additive, synergistic, prophylactic, or even entirely independent. [124][125] For example, a preliminary assessment of VOC levels in U.S. homes suggests that synergistic effects among the numerous lipophilic and hydrophilic compounds should be considered.[126] Improving our health effects data is expensive and a lengthy process, but it will be needed to address some of the emerging IEQ issues and to reduce the uncertainty in setting healthful ventilation standards, air cleaning standards, and product emission standards.

There is a need to establish an interagency task force to integrate IEQ and building energy efficiency plans among several governmental organizations including the Energy Commission, the CPUC, Department of General Services, Office of the State Architect, State Buildings Standards Commission, Department of Housing and Community Development, and local

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[123]US Surgeon General, 2005.Workshop on Healthy Indoor Environment. http://www.surgeongeneral.gov/topics/indoorenv/collabefforts.htm.

[124]Kortenkamp et al. 2007. State of the Art Report on Mixture Toxicity: Final Report. (070307/2007/485103/ETU/D.1), Commissioned by the European Commission Director General for Environment. http://ec.europa.eu/environment/chemicals/pdf/report_Mixture%20toxicity.pdf

[125]ASHRAE 2011. Guideline 10-2011. Atlanta: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc. ASHRAE. http://www.techstreet.com/products/1771697

[126] Jackson MC et al., 2011. Comparison of metrics for characterizing the quality of indoor air. *Proceedings of Indoor Air 2011*, Austin, Texas. http://www.isiaq.org/publications. Paper 115.

governments. This task force will ideally be integrated with energy efficiency and building technology research planning efforts. It can promote integrated building design that addresses IEQ performance (at least ventilation and thermal comfort performance goals). It should develop a strategic plan to target critical short- and long-term IEQ needs.

CHAPTER 7: Recommendations

In addition to the seven research topic areas and priority research descriptions summarized in the Results section and the more detailed, specific research project discussions in Appendix A, the following recommendations are presented.

- **Integrate IEQ into the Strategic Energy Efficiency Plan and its Action Plans. Indoor Environmental Quality should be integrated by considering IEQ and health at every step.**

Indoor Environmental Quality issues such as thermal comfort, odor, and noise are among the leading concerns that building occupants and homeowners have about their building, but they currently have little or no assurance that the building will meet their expectations for good IEQ. Over the next 20 years and beyond, the implementation of the Strategic Plan will affect building design, operation, and technology development, all of which can adversely affect IEQ. However, these activities also offer the opportunity to improve IEQ and reduce liability for builders, owners, and operators. The co-benefits (non-energy benefits) from improved IEQ, such as improved human health, safety, and performance and reduced liability can be quite substantial.

Integrating IEQ into the plan is an efficient way to achieve healthy, efficient buildings and avoid piecemeal approaches. Further, the plan's marketing, outreach, training, and program evaluation efforts offer an excellent platform to also address IEQ issues in a cost-effective manner. The benefits of this integration of IEQ and energy efficiency would accumulate over time and eventually become very sizable.

- **Human Behavior Research**

Emphasis should be placed on establishing a human behavior research component for research project prioritization and regulatory initiatives. The success of adoption and proper use of improved or new technology and regulatory initiatives strongly depends on human factors, especially where a major shift in building and technology design is occurring. There should be consideration of human behavior factors in all IEQ-oriented research related to development, demonstration, and regulation of energy-efficiency technology.

- **Integrated IEQ-Energy-LCA modeling**

Past building-related life cycle assessments (LCAs) have generally focused on inventories of resources consumed and pollution emitted in the original production and the end-of-life disposal of buildings materials, while neglecting their contribution to energy use and IEQ aspects in the building use phase. Since, generally, buildings have long service lives, the vast majority of their total life cycle energy use and environmental impacts are during the use phase. It is challenging to conduct LCAs of materials without knowing how a material will be used in a building, but the specific use of the material as part of the whole building has a profound effect on its energy and environmental impacts. Thus, research to improve the resources (databases, applications, and analytical tools) available to LCA practitioners is an important need to gain a more comprehensive understanding of buildings' performance with respect to energy and indoor environmental quality.

- **IEQ Research Program Results Evaluation**

Staff should evaluate the research program's results periodically as part of the larger framework of Energy Commission research, especially the research targeted at achievement of zero net energy goals. Measures with potential to impact IEQ should be identified and their consequences addressed.

- **Update IEQ Research Roadmap**

The *Indoor Environmental Quality Research Roadmap 2012–2030: Energy-Related Priorities* should be updated periodically (to evaluate progress, assumptions, and emerging issues) in the context of evolving building technology and knowledge, based on IEQ research both by the Energy Commission and by the broader research community. This could be done with input from the task force recommended above, together with stakeholder input.

GLOSSARY

AAQ	ambient air quality
AQG	air quality guidelines
ARB	California Air Resources Board
ASTM	American Society for Testing and Materials
CASE	Codes And Standards Enhancement
CBSM	Community Based Social Marketing
CDC	Center for Disease Control
CEC	California Energy Commission
CEQA	California Environmental Quality Act
CO	carbon monoxide
CO_2	carbon dioxide
COP	Coefficient of Performance
CPD	Construction Products Directive
CPUC	California Public Utilities Commission
Cx	Commissioning
DALY	Disability Adjusted Life Years
DCV	demand controlled ventilation
DOAS	Dedicated Outdoor Air Supply
DOE	U.S. Department of Energy
ELF-EMF	electromagnetic fields
EPBD	Energy Performance of Building Directive
EU	European Union
GHG	greenhouse gas
GHz	gigahertz
GPSD	General Product Safety Directive
HBCD	hexabromocyclododecane

HPHW	Heat pump hot water heaters
HRV	heat recovery ventilators
HVAC	heating, ventilating, and air-conditioning
IAQ	indoor air quality
IEQ	Indoor Environmental Quality
IEPR	Integrated Energy Policy Report
LBNL	Lawrence Berkeley National Laboratory
LCA	Life Cycle Assessment
MDF	medium-density fiberboard
MSHP	mini-split heat pumps
NO_2	nitrogen dioxide
NOx	nitrogen oxides
NZEB	net zero energy building
O&M	Operation and Maintenance
OSB	oriented strand board
PAH	poly-aromatic hydrocarbons
PIER	Public Interest Energy Research
PM	particulate matter
PV	photovoltaic
RCx	retro-commissioning
RD&D	research, development, and demonstration
REACH	Registration, Evaluation, Authorisation and Restriction of Chemical substances
RFR	radiofrequency radiation
SIP	structural insulated panel
SMCB	small and medium commercial buildings
SVOC	semi-volatile organic compound
TABS	thermally active building systems

TCPP	tris (1-chloro-2-propyl) phosphate
TDV	time-dependent valuation
TEAM	Total Exposure Assessment Methodology
TVOC	total volatile organic compound
U.S. DOE	U.S. Department of Energy
VOC	volatile organic compound
ZNE	zero net energy

APPENDIX A: Research Topics and Research Project Priorities

Table A1. Project Topic Areas[127]

Sources in Low-Energy Buildings
Moisture Risk Assessment and Mitigation
Outdoor Air and Attached Spaces
Wood Products and Other Materials
Risk Assessment, Guidelines and New Chemicals
Ventilation
Controls
Commissioning (Cx)
IEQ Performance
High Performance
Operation And Maintenance (O&M)
Thermal Conditioning:
Design and Operation
Air Cleaning
Assessment and Demonstration
Technology Development
Tools, Methods, Sensors
Operation and Modeling
Development and Demonstration
Cross-Cutting
Metrics
Human Factors / Behavior
Assessment and Benchmarking
Program Evaluation

Notes:

In Appendix A, "Topics" is the broadest category. There are seven topics. Within the topics there may be one or more "areas" of research (as listed in Table A1).

The specific research "project" descriptions are referred to as "projects." Since some Topics have several "areas" and some have only one, the use of the term "area" is introduced. It could also be called "subtopic" or "topic area." We have tried to be consistent in the use of these terms.

See Project Descriptions in Appendix A for rationales and details for each Topic Area.

[127] See notes at end of table

Program Goals are as follows:

- Identifying IEQ problems and opportunities.
- Develop and evaluate energy-efficient technologies for improving IEQ, health and comfort
- Develop and evaluate energy-efficient practices for improving IEQ, health, comfort and productivity
- Stimulating or assisting implementation of energy-efficient technologies or practices for improving IEQ.

TOPIC: SOURCES IN LOW-ENERGY BUILDINGS

PRIORITY RESEARCH: MOISTURE RISK ASSESSMENT AND MITIGATION

Specific Regulatory or Policy-Related Needs

It has become increasingly clear that the presence of moisture is associated with health risk. Addressing moisture sources is a high-priority topic area.

The California Department of Public Health has released a statement regarding "Dampness and Mold," warning of the potential health risk associated with "…water damage, dampness, visible mold, or mold odor…." [128] This reflects the growing evidence and awareness that moisture is an important indicator of potential building health hazards.

The Division of Occupational Safety and Health (Cal /OSHA) moisture regulation requires mitigation of moisture risk by removing sources of moisture and moist materials. This applies only to buildings where workers are present. "When exterior water intrusion, leakage from interior water sources, or other uncontrolled accumulation of water occurs, the intrusion, leakage or accumulation shall be corrected because of the potential for these conditions to cause the growth of mold."[129]

Clear definitions and effective means for preventing, remediating, and assessing dampness and mold are lacking. Regulations and guidelines will not be effective without improvement in definitions and procedures associated with moisture in buildings and associated risks. Some energy efficiency measures increase the risk of dampness and excess moisture in buildings.

Residential environments need more specific measures to prevent the presence of excess moisture. In residential retrofits, among other measures, this suggests the need to investigate whether replacing single-pane glazing systems, especially in the cooler climate regions of the state, will reduce the risks of indoor dampness. It also suggests the need to require exhaust systems that operate automatically during moisture-generating activities such as cooking, laundry, cleaning, and bathing activities.

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[128]California Department of Public Health, 2011. Statement on Building Dampness, Mold, and Health, September 2011. http://www.cal-iaq.org/phocadownload/statement_on_building_dampness_mold_and%20health2011.pdf.

[129] California Department of Industrial Safety, 2002. Title 8, Subchapter 7. General Industry Safety Orders, Group 2. Safe Practices and Personal Protection, Article 9. Sanitation Section 3362, Subsection g. http://www.dir.ca.gov/title8/3362.html.

Objectives and General Approach

The purpose of this research is to find the key factors in the implementation of building energy efficiency measures that contribute to moisture problems and the associated risks. The approach is to identify the risk factors and means to implement their potential mitigation.

Some of the important questions to be answered include the following:

- Are moisture issues in low E-energy buildings different from regular E-energy buildings?
- What are the characteristic moisture sources, pathways, and reservoirs?
- What are the specific risks and effective mitigation strategies?
- Are there sufficient guidelines available to enable designers and builders who build more tightly to build more carefully?

There is a need to develop and demonstrate methods of controlling moisture, e.g.:

a. Address the major risks identified above.

b. Evaluate approaches to providing effective spot ventilation of high high-moisture areas in low E-energy homes with whole whole-house mechanical ventilation.

c. Demonstrate design and quality control methods for preventing leaks in building shells.

d. Explore methods to prevent buildup of water and microbes in HVAC systems (ducts, filters, cooling coils, condensate pans), in both conventional cooling systems and energy energy-efficient evaporative cooling systems.

e. Evaluate leak detector approaches for plumbing systems.

f. Explore moisture-buffering strategies, i.e., the use of materials and ventilation strategies to reduce moisture levels on surfaces and in air.

g. Explore UV radiation of wetted surface – (biofilms[130] on air air-conditioning coils.)

h. Explore methods to prevent moisture buildup in crawlspaces in various building types, including portable classrooms and residences.

There is a need for more accurate and practical means to characterize moisture in buildings. The available tools are limited and may be too expensive for the market.

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[130] A biofilm is any group of microorganisms in which cells stick to each other on a surface. These adherent cells are frequently embedded within a self-produced matrix of extracellular polymeric substance (EPS). Biofilm EPS, which is also referred to as slime (although not everything described as slime is a biofilm), is a polymeric conglomeration generally composed of extracellular DNA, proteins, and polysaccharides. Biofilms may form on living or non-living surfaces and can be prevalent in natural, industrial and hospital settings…. The microbial cells growing in a biofilm are physiologically distinct from planktonic cells of the same organism, which, by contrast, are single-cells that may float or swim in a liquid medium." (source: Wikipedia.org. http://en.wikipedia.org/wiki/Biofilm)

Research is needed that identifies the factors in HVAC systems that are most strongly associated with the increased symptoms found in air-conditioned buildings. Once these factors are identified, means to eliminate or mitigate them should be explored.

Among the technologies to be investigated should be the application of UV radiation of wetted surfaces of cooling coils in AC systems. There is preliminary evidence of the efficacy of UV radiation in reducing the illness rates in offices. However, this study was done in Montreal, Canada, with a climate quite different from California's climates. There is a need to investigate the efficacy of this approach in California buildings and to study the organisms that might be involved. If the study can show efficacy in California's climates, it will be important to identify the organisms that may be contributing to the symptom prevalence and illness-related absenteeism. Both traditional culture-based and the emerging non-culture culture-based methods of microbial identification may be used.

Investigate the impacts of low low-energy cooling technologies on the risks of microbial exposure and health risks: e.g., open windows vs. a/c.AC, chilled beams; radiant cooled floors or ceilings, individual cooling systems; personal or user-controlled chilled panels, personal fans.

Examine the effects of installation, maintenance, operation, and design. Examine maintenance impacts on moisture and microbial contamination of AC systems.

Commercial and residential field studies: e.g., examine the IEQ performance of central and through-the-wall AC systems.

Why the Research Area Is Considered a Priority

Health and Safety Issues

There is increasing scientific evidence that dampness and resulting microbial growth in buildings is associated with increases in adverse occupant health effects such as allergic and respiratory disease.[131] [132] [133] [134] [135]There is strong scientific evidence that moisture is associated with increased risks of adverse health effects.

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[131]Mendell, M., Mirer, A., Cheung, K, Tong, M., and Douwes, J., 2011, Respiratory and Allergic Health Effects of Dampness, Mold, and Dampness-Related Agents: A Review of the Epidemiologic Evidence *Environmental Health Perspectives*. 119:748–756. http://www.ncbi.nlm.nih.gov/pmc/articles/PMC3114807/pdf/ehp-119-748.pdf

[132] Bornehag et al. Indoor Air 2004; 14: 243–257.

[133] Institute of Medicine 2004, Damp Indoor Spaces; http://www.iom.edu/Reports/2004/Damp-Indoor-Spaces-and-Health.aspx.

[134] WHO, Guidelines for IAQ – Dampness and Mould, 2009; http://www.euro.who.int/document/e92645.pdf.

[135] Mendell et al, 2011. *Environ Health Perspect* 119:748–756,)

Air-conditioning systems have been implicated in increased incidence of building related symptoms, also known as Sick Building Syndrome (SBS). As the climate warms, there will be a continuation of the historical increase in the adoption of air-conditioning (AC) in residences and other building types. Older residences that lack air-conditioning are more likely to install AC systems. A high fraction of new residences will also be constructed with AC systems.

There is a need to improve understanding of the major contributors to Indoor Environmental Quality (IEQ) problems and to develop guidelines for retrofit as well as new residential and non-residential AC systems that will not increase symptoms and illness of building occupants. Air-conditioning functions by removing moisture from ventilation air.

Higher incidences of Sick Building Syndrome (SBS, also known as Building Related Symptoms, BRS) have been found associated with the presence of air-conditioning in buildings. Many of the hypothesized causes of the problems are associated with air-conditioners' process of moisture removal as well as with humidification in air-conditioning systems.[136] [137] [138] [139]

Moisture is widely associated with microbial growth.[140] After 3 weeks of ultraviolet germicidal irradiation (UVGI) of cooling coils in a Canadian office building, researchers found lower microbial and endotoxin concentrations on the irradiated coil surfaces. Furthermore, there was a significant reduction in the overall rate of reported work-related symptoms and in the incidence of occupant mucosal and general symptoms. [141]

Energy efficiency may increase dampness problems by reducing outdoor air ventilation, reducing drying in walls, and sealing attics and crawl spaces. However, well designed and constructed energy-efficient buildings may have superior envelopes less prone to dampness

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[136] Mendell et al, 2008. Risk factors in heating, ventilating, and air-conditioning systems for occupant symptoms in US office buildings: the US EPA BASE study. *Indoor Air* 18 (4): 301–316.

[137] Sieber, W.K., Stayner, L.T., Malkin, R., Peterson, M.R., Mendell, M.J., Wallingford, K.M., Crandall, M.S., Wilcox, T.G. and Reed, L. (1996) The National Institute for Occupational Safety and Health indoor environmental evaluation experience. Part Three: Associations between environmental factors and selfreported health conditions. *Appl. Occup. Environ. Hyg.*, 11, 1387–1392.

[138] Seppänen, O., Fisk, W.J. and Mendell, M.J. (1999) Association of ventilation rates and CO2 concentrations with health and other responses in commercial and institutional buildings. *Indoor Air*, 9, 226–252.

[139] Seppänen, O. and Fisk, W.J. (2002) Association of ventilation system type with SBS symptoms in office workers. *Indoor Air*, 12, 98–112.

[140] Mendell, M., Mirer, A., Cheung, K, Tong, M., and Douwes, J., 2011, Respiratory and Allergic Health Effects of Dampness, Mold, and Dampness-Related Agents: A Review of the Epidemiologic Evidence *Environmental Health Perspectives*. 119:748–756.

[141] Menzies, Popa, Hanley, Rand, and Milton, 2003. Effect of ultraviolet germicidal lights installed in office ventilation systems on workers' health and wellbeing: double-blind multiple crossover trial. *The Lancet* 362: 1785-91.

problems. Thus, there is a need to improve understanding of energy-efficient envelope designs that do not contribute to moisture problems.

There is also increased concern about emissions (including but not limited to moisture) from indoor combustion sources, especially gas stoves. Gas stoves contribute both moisture and pollutants and are arguably one of the biggest single indoor pollutant sources. Electric stoves produce significant amounts of moisture and can also produce odors, and particles in homes. Prior work for the Energy Commission has examined both gas stove emissions and the effectiveness of exhaust hoods, but some additional work is needed.

Effects of climate change, including increased severity and frequency of storms, will result in more moisture problems. Indoor moisture problems from wind-driven rain and flooding may increase due to changes in severe storm patterns. Research has shown that post-flood levels of microbes can be an order of magnitude higher than pre-flood or simultaneous outdoor concentrations. Post-remediation, microbe levels return to reflect outdoor levels only after 60 days post-flood.[142][143] Culture-based microbial identification methods are limited compared to the newer, gene-based methods. [144] These culture-independent methods are enabling research into the microbial ecology of the indoor environment promising a potentially significant acceleration in understanding of the association between microbiology of the indoor environment and health.[145][146][147]

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[142]Miia Pitkäranta, Teija Meklin, Anne Hyvärinen, Aino Nevalainen, Lars Paulin, Petri Auvinen, Ulla Lignell and Helena Rintala, 2011. Molecular profiling of fungal communities in moisture damaged buildings before and after remediation - a comparison of culture-dependent and culture-independent methods. BMC Microbiology 2011, 11:235. http://www.biomedcentral.com/content/pdf/1471-2180-11-235.pdf

[143]Cho, SookJa, Ju-Hyeong Park, Kathleen Kreiss and Jean M. Cox-Ganser, 2010. Levels of microbial: agents in floor dust during remediation of a water-damaged office building. *Indoor Air*. 21:417-426. http://onlinelibrary.wiley.com/doi/10.1111/j.1600-0668.2011.00722.x/pdf.

[144]Mika Frankel, Michael Timm, Erik Wind Hansen and Anne Mette Madsen, 2012. Comparison of Sampling methods for assessment of indoor microbial exposure. *Indoor Air*, 22(5): 405–414. http://onlinelibrary.wiley.com/doi/10.1111/j.1600-0668.2012.00770.x/pdf

[145]Levin, H. 2011. Building Ecology: Linking Microbial Ecology with Indoor Environment and Building Science. In *Proceedings of Indoor Air 2011*, 12th International Conference on Indoor Air Quality and Climate, Austin, TX, June 5-12, 2011. http://www.isiaq.org/news/indoor-air-2011-proceedings-now-available-on-a-flash-drive/?searchterm=Proceedings%20Indoor%20air%202011

[146]http://www.microbe.net/

[147] Humphries, C., 2012. Indoor Ecosystems. *Science* 335: 648-650. http://www.sciencemag.org/content/335/6069/648.full.pdf?sid=6c439e7a-ad6c-48c8-ab82-3ae68877ff51

In a warming climate, there will be an increased demand for and use of cooling. Air-conditioning is energy intensive and is clearly established as a risk factor for health symptoms; especially respiratory symptoms.[148] There is a need to understand what design, maintenance, and operation issues related to air-conditioning systems contribute to these risks.

Low-energy cooling technologies are needed to address the need for reduced energy use while also reducing risks of excess dampness and moisture. Evaporative cooling, a popular cooling technology in drier regions of the State, has impacts on indoor ozone and moisture that may have health consequences.

Guideline Needs

Moisture and mold are not well understood, in terms of how to reduce the risks they pose to public health. Education of both those who create or manage buildings, as well as those who occupy buildings, is necessary. This involves understanding and recognizing moisture problems and motivating action to control or remove the source. The focus must be on the operational phase as much as on the design and construction phases.

Guidelines are needed for low-energy cooling; for design, maintenance, and operation of air-conditioning systems to minimize health risks and risks of microbial exposure.

Abundant law suits and publicity associated with mold problems in buildings has left a large gap in public understanding of the health risks of mold in buildings and human mold exposure. The science is still evolving. Meanwhile guidelines are needed based on what is known.

Project Area: Sources – Moisture (High-priority indicated by asterisk)

Identify the most common building-related risk factors for moisture problems, evaluate corrective measures, and produce associated guidelines. Change building standards as needed

Assess the risks from, and the mitigation measures for, moisture problems in low-energy buildings, both new and retrofit (assuming, among other factors, increased severity and frequency of storms), e.g.:

a. Risks of moisture emissions from new building materials
b. Risks of water condensation on interior surfaces and building cavities
c. Risks of water leakage from severe storms and wind-driven rain
d. Risks of water leakage from green/living roofs
e. Risks of building tightening, super-insulation, and low-energy cooling technologies, such as evaporative cooling and radiant floor cooling, that can affect indoor humidity, condensation, and levels of house dust mite allergens.

[148] Seppänen, O. Fisk, WJ, and Mendell, MJ. 1999. Association of Ventilation Rates and CO_2 Concentrations with Health and Other Responses in Commercial and Institutional Buildings. *Indoor Air* 9: 226–252.

Evaluate the effects of air-conditioning system design, operation, and maintenance on moisture and microbial contamination in HVAC systems.

Develop or verify low-energy cooling technologies that pose low microbial exposure and health risks.

Develop and demonstrate methods of controlling moisture, e.g.:

a. Address the major risks identified above.

b. Evaluate approaches to providing effective spot ventilation of high-moisture areas in low-energy homes with whole-house mechanical ventilation.

c. Demonstrate design and quality control methods for preventing leaks in building shells.[149]

d. Explore methods to prevent buildup of water and microbes in HVAC systems (ducts, filters, condensate pans), in both conventional cooling systems and energy-efficient evaporative cooling systems.

e. Evaluate leak detector approaches for plumbing systems.

f. Explore moisture-buffering strategies, i.e., the use of materials and ventilation strategies to reduce moisture levels on surfaces and in air.

g. Explore UV radiation of wetted surface (biofilms) which, commonly grow on air-conditioning coils.)

h. Explore methods to prevent moisture buildup in crawlspaces in various building types, including portable classrooms and residences.

There is a need for more-effective means of characterizing moisture, visible or hidden, in indoor environments.[150] [151] This should include development of better instruments and guidelines for their use, as well as the improvement of already-demonstrated semi-quantitative subjective evaluations, and appropriate combinations of the instrumented and subjective assessment tools.

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[149]Persily, A., 1993. Envelope Design Guidelines for Federal Office Buildings: Thermal Integrity and Airtightness NISTIR 4821. Gaithersburg: National Institute for Standards and Technology.

[150] Harriman, Spatial and Temporal Variations of Moisture in Buildings: Factors Which Influence Microbial Growth Rates and the Ecology of the Indoor Environment. *Proceedings of Indoor Air 2011* Paper a1587.

[151] ASHRAE, 2013 Position Document, Limiting Indoor Mold Growth and Managing Moisture in Building Systems. https://www.ashrae.org/about-ashrae/position-documents.

Develop more-effective means of characterizing moisture-related microorganisms that are harmful to occupants' health, and that may be visible or hidden, and within the building structure or the building contents, in indoor environments.[152]

Assess the efficacy of exhaust fans coupled to kitchen stove operation to limit build-up of moisture from cooking processes.

Investigate occurrence of dampness and microbial growth in (various types of) HVAC.

How the Research Results Could Be Used

In new construction, as higher insulation and tighter envelope requirements are considered for adoption into Title 24, it will be important to identify the measures necessary to avoid increasing moisture levels indoors.

As retrofit requirements are considered for adoption, identify the energy and IEQ co-benefits of requiring double-glazing in older structures with single-pane glazing elements.

The research can inform guidelines and standards for ventilation system design, construction, and operation. Some of the critical factors can be considered for inclusion in Title 24 regulations.

Retrofit requirements for residences may use evidence from research in this topic area to reduce potential health risks associated with room-scale (window box or split systems) or whole-house (central) air-conditioning systems.

Expected Research Products

> *Inform regulation, inform technology, inform public information/marketing efforts, inform training program, subsidies (tax incentives or partial funding), inform further research priority definition.*

Related R&D Application Categories

Thermal comfort

Ventilation.

Source implications of conditioning and venting of crawl spaces and attics (moving ducts into these spaces) (durability issues – closed attic hides roof leaks)

Temporal (Real time?) ventilation rate control that accounts for both energy costs and indoor air quality (addresses other factors that are not addressed by constant mode control)

Need to understand the best ventilation systems for future high-performance buildings that don't recirculate heated or cooled air. Couple ventilation and filtration.

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152 ASHRAE, 2013 Position Document, Limiting Indoor Mold Growth and Managing Moisture in Building Systems. https://www.ashrae.org/about-ashrae/position-documents.

Co-funding or Leverage Opportunities

ASHRAE, ARTI, DOE, EPA, and HVAC and A/C system manufacturers are all among the candidates for co-funding or leveraging of research in this topic group area.

The ARB should consider this a high-priority indoor source (it is discussed in ARB's 2005 Report to the Legislature).

TOPIC AREA: SOURCES IN LOW-ENERGY BUILDINGS

PRIORITY RESEARCH: OUTDOOR AIR AND ATTACHED SPACES

Specific Regulatory or Policy-related Needs

As houses are tightened to reduce air leakage and infiltration airflows, ventilation rates will be lower. Thus, any pollutants that enter the house from the garage, through leakage, or through open doors will be removed by ventilation more slowly, and the pollutant concentrations will be higher.

Description: Objectives and General Approach

The overall objective is to identify effective means to reduce the potential for entry into living spaces of pollutants from outdoors or from ancillary structures (including from materials stored in garages).

Behavior plays an important role. Operation of mechanical systems, opening and closing of windows and doors, and the types of materials brought into and stored in garages, basements, or attics are important as potential sources of pollutants. Keeping doors between garages and living areas closed is necessary but not always done. An enhanced understanding of occupant behavior can lead to more effective informational campaigns as well as inform regulations.

Why the Research Area Is Considered a Priority

Health and Safety Issues. Air enters buildings from outside through many pathways, some intentional, some not; some with higher or more harmful pollutant loads than others. Outdoor air and air from attached ancillary structures or portions of structures such as garages, crawl spaces, basements, and attics, can be quite hazardous. Buildings located next to busy roadways or industrial and agricultural sites are susceptible to intrusion of pollutants of substantial concern (e.g., ultrafine particulate matter [PM]; diesel; volatile organic compounds [VOCs] from roadways; and dust, pesticides, and pollen from agricultural sites, among others).

A substantial amount of air from attached garages can enter the home's indoor air. This air often contains air contaminants from sources such as vehicle fuel exhaust fumes, gasoline-powered lawn equipment, solvents, oils, paints, and pesticides. A Public Interest Energy Research (PIER) study of 125 new single-family homes found that home-to-garage pressure testing guidelines were exceeded in 65 percent of the homes.[153] In a three-home pilot study, tracer gas measurements indicated that between 4 percent and 11 percent of emissions from the attached garage sources entered the home. Other studies have measured or calculated that VOCs from an attached garage contribute significantly to VOC levels in homes.[154] [155]

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153 Offermann 2009. Ventilation and indoor air quality in new homes. Final report. Prepared for ARB and California Energy Commission/PIER. http://www.arb.ca.gov/research/single-project.php?row_id=64697.

154 Batterman S, Jia C, Hatzivasilis G., 2007. Migration of volatile organic compounds from attached garages to residences: a major exposure source.Environ Res. 2007 Jun;104(2):224-40. http://www.ncbi.nlm.nih.gov/pubmed/17350611

In addition, home depressurization can bring other pollutants into a building through other pathways. In the new single family homes study mentioned above, 60 percent of the homes with attached garages had living spaces above the garage, and some homes had HVAC equipment located in the garage. Stack effect airflows have the potential to drive air from the lower space to the space above it through any available leakage pathways. Depressurization can also pull in toxics such as radon, termiticides and VOCs from soil. Therefore, it is important to reduce the potential for flow of pollutants from sources in the garage to the spaces above, as well as horizontally adjacent to, the garage.[156]

Substantial concern exists among health experts regarding building occupant exposure to polluted air from nearby motor vehicle roadways. Fine particles and gases from combustion processes are among the greatest health hazards in indoor air. Location distant from such sources is the most effective solution, but absent the ability to change a building's location, other measures may be important, including pressure control and filtration.

There may be diverse treatment of walls and doorways or ceilings/floors between garages and living spaces that can reduce the infiltration of air from garages and crawl spaces into living spaces.

The Energy Commission may want to consider adopting requirements for verification of a pressure limit across the separation between attached garages and adjacent living areas that will protect against air flow from garages to living spaces. It may also wish to consider other measures to protect against airflow from the garage to the occupied portions of the dwelling. Related research would include development and validation of methods for measurement that can be easily and inexpensively implemented by typical construction companies.

Locational requirements for schools and day care centers, as well as nursing homes and other health care facilities, could be considered for regulatory action.

<u>Guideline Needs</u>. Homeowners and consumers need education on the hazards associated with products they may use in or store in garages. They also need information on means to investigate and control airflow from their garages or other attached structures, as well as from outdoor air to occupied portions of their homes.

Non-residential buildings generally are more likely to have HVAC systems circulating air from outdoors and to be under positive rather than negative pressure. These systems can and should be used to filter outdoor air in locations where the air is most polluted.

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[155] Graham LA, Noseworthy L, Fugler D, O'Leary K, Karman D, Grande C., 2004. Contribution of vehicle emissions from an attached garage to residential indoor air pollution levels. *J Air Waste Manag Assoc*. 2004 May;54(5):563-84.

[156]Offermann 2009.*Op cit,* p. 55.

High-Priority Research Projects

Develop and test approaches to controlling entry of outdoor pollutants (e.g., filtration, window and air intake locations, pressure control, landscaping,).

Evaluate the effectiveness of airflow and pressure-control strategies to control infiltration of moisture and pollutants from adjoining spaces, such as garages, crawl spaces, and attics.

Lower-Priority Projects

Investigate air flow from a variety of building designs (including but not limited to homes with attached garages) to determine the characteristic air flows and the factors that govern those flows.

Investigate potential for various residential ventilation system designs and operational patterns to control infiltration of garage (or crawl space, basement, and attic) air into living areas. Of special note is outdoor-to-indoor transport of ozone. This is of concern especially in residences that depend on open windows for cooling during high temperatures, which tend to coincide with elevated ozone. Investigate what might be done to reduce this transport.[157]

Develop and test information/education campaigns to encourage and assist home owners and occupants in maintaining doors separating homes and attached garages in a closed position, and avoiding storage of pollutant sources in attached garages.

Related Project Areas and Topics

Ventilation

Air Cleaning

O&M

Tools: Metrics

Cross-Cutting: Behavior, Assessment

Related Research

The ARB/University of California, Davis (UCD) study "Benefits of High Efficiency Filtration to Children with Asthma," (Bennett) is examining the effectiveness of both central and portable high-efficiency filtration systems in reducing pollutant exposures and asthma symptoms in children with asthma. Expect completion in 2016.

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[157]Chun Chen, Bin Zhao, Charles J. Weschler, 2012. Assessing the Influence of Indoor Exposure to "Outdoor Ozone" on the Relationship between Ozone and Short-term Mortality in U.S. Communities. *Environmental Health Perspectives*. 120:235-240. http://www.ncbi.nlm.nih.gov/pmc/articles/PMC3279450/pdf/ehp.1103970.pdf.

TOPIC AREA: SOURCES IN LOW-ENERGY BUILDINGS

PRIORITY RESEARCH: WOOD PRODUCTS AND OTHER MATERIALS

Specific regulatory or policy-related needs

Formaldehyde and other VOC emissions from currently marketed and labeled products and phenol formaldehyde resin exterior grade plywood are assumed to be low-emitting. Verification of this claim is warranted because new sources of these products have entered the market, and testing has shown that labeled or certified products do not always conform to the requirements for labeling or certification.[158][159]

Guidelines for major VOC emissions from composite wood products are needed. To date, only formaldehyde is regulated, but emissions' testing shows substantial emissions of many other VOCs, some at rather high levels compared to other VOC sources.

Description: Objectives and General Approach

Why the Research Area Is Considered a Priority

Health and safety issues. Formaldehyde is arguably the best-understood indoor air pollutant from a health perspective and is often found at concentrations believed to cause irritation or acute health effects. It is a listed Proposition 65 substance and is also listed as a carcinogen by the World Health Organization's International Agency for Research on Cancer(IARC) and the U.S.'s National Toxicology Program (NTP). Other VOCs emitted by composite wood products are strong odorants and some are irritants; among them is acetic acid.

While the ARB regulations have strongly affected available composite wood products, exterior grade plywood is exempt. There have been no recent studies of emissions since the ARB formaldehyde report of 1997.[160]

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[158]Alevantis, L,. R. Miller, H. Levin, and J. Waldman. 2006. Long Term Building Air Measurements for VOCs & Aldehydes at a California Five-Building Sustainable Office Complex, Volumes 1 and 2.. California Department of Health Services. Final Report, submitted to the US Environmental Protection Agency through the Public Health Institute. available at: http://www.cal-iaq.org/phocadownload/east_end_vocs_206_vol_1.pdf and http://www.cal-iaq.org/phocadownload/east_end_vocs_2006_vol_2.pdf

[159]Alevantis, L.E., H. Levin, R. Miller, J.M. Waldman, and D. Mudarri, 2006. Lessons Learned from Product Testing, Source Evaluation, and Air Sampling from a Five-Building Sustainable Office Complex. Healthy Buildings 2006, Lisbon, Portugal, June 4-8, 2006. http://www.buildingecology.com/articles/lessons-learned-from-product-testing-source-evaluation-and-air-sampling-from-a-five-building-sustainable-office-complex/

[160] Kelly, TJ, 1997, Determination of formaldehyde and toluene diisocyanate emissions from indoor residential sources. ARB Contract Number: 93-315. http://www.arb.ca.gov/research/single-project.php?row_id=55595.

Composite wood products (hardwood plywood, particleboard, low- and medium-density fiberboard) are regulated by ARB to limit the emissions of formaldehyde, but *coincident* emissions of other substances are not regulated at the present time. There are many unregulated building materials and products that emit formaldehyde. Survey results from relatively new California homes found formaldehyde levels that *frequently* exceeded current guidelines. While some of this formaldehyde will be addressed in future construction by ARB's regulation, it is clear that there are many other sources of formaldehyde in homes.

Because of their extensive use in residential and many non-residential buildings, wood products are of potential concern. Chemicals other than formaldehyde (e.g., higher molecular weight aldehydes, terpenes, aromatic hydrocarbons) are also emitted, often in strong enough rates to result in elevated concentrations in indoor air. While some of these emissions are relatively short-lived, others may persist for months or even years after initial construction. Among the pollutants of concern are irritants and odorous substances that have been the subjects of concern in problem buildings. These include formaldehyde and acetaldehyde, as well as the by-products of ozone reactions with some of the other chemical emissions.

Guideline needs

The ARB began focusing attention on formaldehyde emissions by developing guidelines for action at certain specified concentrations. Emissions are part of the equation for calculating concentrations based on ventilation rates and amount of source present. The plywood industry has used concentration metrics for characterizing emissions, but these metrics can mislead users into believing the concentrations reported from emissions tests will be found in residences. Since emission tests are done at ventilation rates usually higher than those required for residences and commonly found in studies of residential ventilation, concentrations can easily exceed expected values. This was found in the California new residential study.[161] Guidelines to help designers, specifiers, and consumers interpret emissions data or labeling would provide simple tables to indicate the interrelationships between emission rates, ventilation, and concentrations. Consumers also need to be aware of the other important sources of formaldehyde.

High-Priority Topic

Assess other indoor formaldehyde sources besides regulated composite wood products, such as coatings and finishes, attic and crawlspace insulation materials, and unregulated/exempt exterior plywood and bamboo plywood.

Low-Priority Topic

Investigate the emissions of acetic acid from composite wood, and the impact of including more composite wood in the conditioned space.

[161] Offerman, 2010. [op cit.]

Investigate emissions from oriented strand board (OSB) with gypsum board over it. There have been reports of odor issues that impact people's perceptions. There is a concern that such odors may lead to the use of air fresheners to cover up the odors. Air fresheners are generally discouraged due to the adverse health associations of their common contents.

Related R&D Project Areas and Topics

Sources – Risk Assessment of New Chemicals

Cross-cutting: Integrated design

Co-funding or Leverage Opportunities

U.S. Environmental Protection Agency (U.S. EPA) regulations on formaldehyde emissions from composite wood, mandated by Congressional legislation and under development. The first part is expected in 2013.

As more-stringent ARB regulations go into effect, it will become important to determine the degree to which they are implemented and the impact on the marketplace.

Related Work

U.S. Environmental Protection Agency regulations on formaldehyde emissions from composite wood, mandated by Congressional legislation and under development in late 2011.

Levin, H. 2011. National Programs to Assess IEQ Effects of Building Materials and Products, prepared for the U.S. Environmental Protection Agency [162]

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[162] http://www.epa.gov/iaq/pdfs/hal_levin_paper.pdf

TOPIC: SOURCES IN LOW-ENERGY BUILDINGS

PRIORITY RESEARCH: RISK ASSESSMENT, GUIDELINES AND NEW CHEMICALS

Specific Regulatory and Policy-related Needs

To justify the use of relatively low ventilation rates in energy-efficient buildings and net zero energy buildings (NZEBs), it will be necessary to have regulatory and policy tools that can effectively control building- and occupant-related sources of exposures to hazardous chemicals in these structures.

Description: Objectives and General Approach

One objective is to increase the basis for establishing health-based target concentration values for chemicals emitted from common indoor pollutant sources and commonly found in indoor air. This requires substantial expansion of the number of chemicals for which authoritative guidance is available regarding concentrations that can result in exposures with the potential to cause adverse health effects. Another objective is to develop guidelines that will be useful in a variety of current and future design tools and standards, emissions testing and certification programs, and other sources of information based on maximum acceptable indoor concentrations.

The identification of chemicals of concern (COC), their prioritization with respect to human health risks, and the establishment of exposure guidelines will primarily be accomplished via an extensive critical review of the related scientific literature. Information on chemical exposures in indoor environments will be obtained by review of indoor and personal exposure studies such as National Health and Nutrition Examination Study (NHANES)[163] , Relationships of Indoor, Outdoor, and Personal Air (RIOPA) [164], and Total Exposure Assessment Methodology (TEAM) [165], and by review of biomonitoring studies. For some chemicals with minimal exposure data, it may be necessary to obtain additional measurements through a limited field investigation. To the fullest extent possible, the study will coordinate its activities related to the identification and prioritization of COC with the California Department of Toxic Substances Control (DTSC's) program on Safer Consumer Products and with the California Office of Environmental Health Hazard Assessment (OEHHA's) program to develop Reference Exposure Levels for chemical pollutants.

Why the Research Area Is Considered a Priority

Health and safety issues. There is abundant evidence, as well as consensus among health scientists, that indoor pollutant exposures are responsible for important adverse health effects. However, there is not strong agreement on which indoor pollutants are the most important

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163 http://www.cdc.gov/nchs/nhanes.htm

164 http://www.ncbi.nlm.nih.gov/pubmed/16454009

165 http://nepis.epa.gov/Adobe/PDF/2000UC5T.PDF

health hazards. In California, reliance on OEHHA Chronic and Acute Reference Exposure Levels and the Safe Drinking Water Act (Prop 65) provides guidance for a limited number of pollutants, but there are many common indoor air pollutants that are not covered by these important sources of guidance. Other (non-chemical) hazards are not covered by these programs.

New chemicals and products are frequently introduced into commerce, often without any toxicological review, and often without any disclosure to purchasers/consumers. In addition, new chemicals are used to replace toxic pollutants or VOCs in order to achieve approval as "low-emitting" or "no-VOC," and other types of products considered "green" or "environmentally preferable." However, some "green" cleaning products use terpenoids (often citrus- or pine oil-based compounds) that react with ozone to form toxic products such as formaldehyde, higher-molecular-weight aldehydes, acidic aerosols, and secondary organic aerosols, including ultrafine particles.[166]

Several indoor pollutants are considered to be "emerging pollutant issues," i.e., they pose substantial public health concerns but have yet to be widely regulated or tested routinely in building materials and consumer products. Some of these pollutants are suspected endocrine disruptors and/or known developmental and/or neurological toxins. Examples of such pollutants include semi-volatile organic compounds (SVOCs) that also tend to be persistent organic pollutants (e.g., dioxins, brominated fire retardants), organochlorine pesticides, heavy metals (e.g., mercury), and nanoparticles. Also emerging as an exposure of concern are electromagnetic fields (EMF). Health effects and/or exposure studies are often lacking or inconclusive for these types of pollutants, but guidance is needed regarding safer alternatives.

An increased emphasis on the inclusion of recycled materials or re-use of materials also creates the potential for an increased exposure to toxics and irritants. An obvious example is the recycling of wood treated with preservatives such as pentachlorophenol that are now restricted from use indoors, or wood painted with lead-based paints. Other recycled materials may contain chemicals originally used as flame retardants, plasticizers, or pesticides. Rubber-based products commonly used in recycling may lead to indoor emissions of aromatic hydrocarbons. At worst, there may be a concentration of undesirable chemicals through the process of repeated recycling.

A multitude of new building materials and products enter the market each year, and even old products are reformulated or manufactured differently. But for a large number of indoor pollutants we have little or no toxicity information, standards, or guideline values. This results in a gap in the ability of designers, building investigators, standards-writers, researchers, and many others to evaluate building designs and building performance or to provide guidance for those engaged in these activities. A toxicological review of the most common indoor air pollutants and those believed to be most hazardous could assist in the advancement of many aspects of various efforts to create healthy net zero energy buildings. Special attention is

[166]Nazaroff WW et al., 2006. Indoor air chemistry: cleaning agents, ozone and toxic air contaminants. ARB Final Report. http://www.arb.ca.gov/research/single-project.php?row_id=60560.

warranted for products used in schools due to the greater potential impact on the young, and products used in homes due to the greater fraction of time spent there, especially by the infants, children, the elderly, and the infirm.

When implementing energy-efficiency strategies for buildings, it also will be necessary to have regulatory and policy tools to control and reduce the risks associated with hazardous SVOCs and metals that occur via exposure pathways other than inhalation; since ventilation generally is not an effective removal mechanism for these pollutant classes, the tools must be oriented toward source control to prevent their introduction into structures.

Regulatory and policy tools are needed to ensure that new or emerging interior products (e.g., new types of thermal insulation), consumer products used indoors, and new ventilation systems and strategies do not result in unacceptable exposures to chemicals of concern (COC). "Green" building strategies typically provide incentives for the use of products with recycled material contents. A report of a State of California study of emissions testing of green versus traditional materials indicated that green materials performed no better than traditional materials in terms of VOC emissions.[167]

Materials are sometimes listed as "green" based on emissions tests or manufacturers' claims or declarations. Section 01350, created for use in the Capitol Area East End Complex during the late 1990s and beginning of the 2000s, has been updated by the California Department of Public Health.[168] But it needs further development in many areas, including addition of specific test procedures for wet-applied products and criteria for many pollutants that are not currently covered by OEHHA Chronic recommended exposure limits (RELs) or not sufficiently addressed by OEHHA Acute RELs.

Regulatory and policy tools are needed to ensure that potential risks of occupant exposures to COC are evaluated for interior products with recycled material contents and that products with unacceptable risks are not promoted for use in construction. Policies to control chemical exposure risks likely will have a product-centric focus; however, these policies should simultaneously encourage the use of a whole-building approach for managing chemical risks in new construction and renovation and in weatherization programs.

There is a need to identify the most important indoor pollutants and common "new chemicals" that pose health concerns, and to conduct health risk assessments. This has begun with a

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[167]Alevantis, L., 2003. Building Material Emissions Study. Final Report. California Integrated Waste Management Board, Publication #433-03-015 (Accessed 12 November 2011 at. http://www.cal-iaq.org/phocadownload/building_materials_emissions_study_2003.pdf and at) http://www.calrecycle.ca.gov/publications/Detail.aspx?PublicationID=1027

[168]CDPH Standard Practice for Testing of VOCs from Various Sources Using Small-scale Environmental Chambers (2004). (Accessed November 13, 2011, at http://www.cal-iaq.org/vocs/voc-publications.

screening-level review to identify high-volume production and high-use chemicals with potential toxicity.[169]

Guideline Needs. Various groups have published guidelines on RELs and control actions for a short list of indoor air pollutants.[170][171][172][173] Some groups have also implemented the Precautionary Principle by listing toxic pollutants and products whose use should be avoided or minimized, such as polyvinyl chloride products and brominated fire retardants.[174]

There remains a need for health-based guidelines for new chemicals that are found in or emitted from some of the "green" building materials and recycled materials. Consumer information is needed to assist the public in understanding the potential for health hazards in building materials, consumer products, some common green products such as terpenoids containing cleaning products or paints containing linseed oil, and other potential sources of indoor air pollutants.

There is a need for guidelines on acceptable levels of indoor air pollutants and material loading rates that are not harmful under normal use in buildings. There is a need for health risk assessments of the most common indoor air pollutants for which there are no available, relevant guidelines or reference exposure levels.

Green building programs encourage bringing waste streams into indoor environment. There is a need to review the toxicity of pollutant risks before recommending the use of such materials.

There is a need to develop guidance based on assessments of acute and chronic health hazards of common indoor pollutants (including irritants and multiple pollutant exposures). Develop

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[169]See ToxCast and ExpoCast by US EPA's National Exposure Research Laboratory. http://www.epa.gov/comptox/.

[170]ARB, accessed 2011. Indoor Air Quality Guidelines. http://www.arb.ca.gov/research/indoor/guidelines.htm.

[171] CMHC, last updated 2010. Exposure Guidelines for Residential Indoor Air Quality (1987 and link to update). http://www.hc-sc.gc.ca/ewh-semt/pubs/air/exposure-exposition/index-eng.php.

[172] WHO, 2010. Indoor Air Quality Guidelines: Selected Pollutants. http://www.euro.who.int/en/what-we-publish/information-for-the-media/sections/latest-press-releases/first-who-indoor-air-quality-guidelines-on-indoor-chemicals-now-released.

[173] WHO, 2009.WHO Guidelines for Indoor Air Quality: Dampness and Mould. http://www.euro.who.int/__data/assets/pdf_file/0017/43325/E92645.pdf.

[174] Davidge M, Ravitz A, Ritchie K, Grossman P, Guenther R, Lent T, Malin N, Brukman E, 2011. The Red List and Beyond: Engaging to Find Healthy Materials & Transform the Industry. Living Future 2011. http://cascadiagbc.org/living-future/11/program/thur-pm-presentations/02%20M%20The%20Red%20List%20and%20Beyond.zip

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health effects summaries and control guidelines for the known hazards, for incorporation into best practice guidelines and green building programs.

High-Priority Research Projects

Assess new chemicals in products about which little or nothing is known, and for which no guidance exists when selecting products that may contain the new chemicals. This is particularly relevant for use in material certification or screening for use in building rating systems, or for use in building certification programs.

Additional Research Projects

Identify SVOCs in building materials and furnishings, and assess their impacts on human health.

Identify and assess the most commonly used and potentially significant chemical sources in cleaning products. (Schools are cleaned every day with new products, e.g., glycol ethers.)

Conduct research to find limits for chemicals that do not have ceiling recommended exposure limits (CRELs)

Evaluate emissions and health hazards from nanomaterials in consumer products that can enter the indoor environment.

Assess the potential exposures and health effects of electromagnetic fields (EMF) from electrical wiring in buildings and from wireless devices in or near buildings, such as wireless networks, smart meters, and cell towers. Assess potential exposure reduction methods.

Assess chemicals commonly found in or emitted from building products and materials. Include toxicologists qualified to conduct toxicology reviews and health hazard assessments, and chemists experienced in product formulation. Identify chemicals of concern (COC) of sufficient priority to warrant recommendations that official health hazards assessments be conducted by OEHHA. Identify substantive data gaps requiring additional resources for investigation. Incorporate and make substantive use of indoor air quality models, chemical pathway and exposure models, and quantitative structure-activity relationship (QSAR) models. Create best practices documents for dissemination to the public, building design professionals, building maintenance organizations, and product manufacturers. The best practices can also provide input for educational programs targeting the public and individuals responsible for maintenance of schools and other building types.

Demonstrate the source control strategies with the highest potential to mitigate serious chemical exposure risks and the highest potential for practical implementation by a combination of laboratory studies and field-oriented studies.

Co-funding or Leverage Opportunities

European Commission (EC) projects such as those listed below.

U.S. EPA, National Institute of Environmental Health Sciences (NIEHS), National Institutes of Health (NIH), DOE, and Health Canada may also be funding projects on this topic.

Related Work

ARB 2005, indoor air priorities in AB 1173 Report to the Legislature.[175]

ARB/UCD Indoor PM in vitro toxicity assessment.[176]

Lawrence Berkeley National Laboratory (LBNL) risk assessment of indoor pollutants; Logue, et al, 2011. [177]

HEIMTSA (Health and Environment Integrated Methodology and Toolbox for Scenario Assessment)/European Commission integrated approach using health impact assessment, cost benefit analysis, and policy scenario development.[178]

INTERA/EC 2011. Integrated Exposure for Risk Assessment in Indoor Air: A review of existing indoor air pollutant exposure data and models.[179]

Sarigiannis, D. A. et al., 2011. Review of indoor carbonyl and VOC exposures and health risks in Europe.[180]

Sarigiannis, D. A., 2010. Review of multiple exposure assessment methods, biomarkers, and exposure indices.[181]

SEAWIND/EU – Sound Exposure and Risk Assessment of Wireless Network Devices.[182]

Various presentations at Indoor Air 2011, Austin, Texas.

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175 http://www.arb.ca.gov/research/indoor/ab1173/ab1173.htm.

176 Matsumura F, et al. ,2010. Assessment of Health Impacts of Particulate Matter from Indoor Air Sources Phase I: Development of In Vitro Methodology. ARB Final Report. http://www.arb.ca.gov/research/single-project.php?row_id=64742.

177 Logue, et al., 2011. Hazard Assessment of Chemical Air Contaminants Measured in Residences. Indoor Air 21, no. 2 (2011): 92-109. LBNL Report 3650E. http://homes.lbl.gov/sites/all/files/hazard-assessment-lbnl3650e.pdf.

178 http://www.heimtsa.eu/TheProject/tabid/170/Default.aspx. See also: various reports at Deliverables link.

179 http://www.intera-home.eu/. (See Links page also).

180 Environment International (2011) 37: 743-765.

181http://www.heimtsa.eu/LinkClick.aspx?fileticket=eLxJY%2b5Erek%3d&tabid=2937&mid=6403&forcedownload=true.

182 http://seawind-fp7.eu/project-overview/.

U.S. EPA National Exposure Research Laboratory (NERL) ToxCast and ExpoCast programs http://www.epa.gov/nerl/.

European Commission's REACH program [http://ec.europa.eu/environment/chemicals/reach/reach_intro.htm]

World Health Organization (WHO) Indoor pollutant guideline development process (http://www.euro.who.int/en/what-we-do/health-topics/environment-and-health/Housing-and-health/publications/2010/who-guidelines-for-indoor-air-quality-selected-pollutants)

TOPIC AREA: VENTILATION
PRIORITY RESEARCH: CONTROLS

Specific Regulatory or Policy-Related Needs

In residential buildings, Title 24 now requires mechanical ventilation systems in new homes. Net zero energy buildings will require tighter and tighter building shells. To ensure adequate ventilation, measurement of ventilation airflow rates will be needed in building commissioning. Reliable control systems that provide useful real-time information to occupants will be needed. User-friendly control systems will also need to be developed and evaluated to address the needs of various types of users, especially in the residential sector. There is also a need for rigorous evaluation of control systems to demonstrate proper performance and reliability. Zoned HVAC systems are also becoming more popular in new homes, but they do not always provide good thermal comfort or energy efficiency.[183]

In commercial buildings, Title 24 is poised to require fault detection and diagnostics systems (FDD), which should include dynamic monitoring of ventilation airflows. Demand control ventilation and increased natural ventilation are also being proposed for wider usage in future Title 24 updates. The reliability of the hardware is often a problem, and gear-driven interconnections and other reliability measures have been proposed for the 2013 Title 24 update to improve control system reliability of nonresidential economizers.[184] Cal OSHA regulations also require annual HVAC inspection and verification of ventilation outdoor airflow rates. In residential buildings, Title 24 currently requires acceptance testing to verify that CO_2 sensors are working properly and that the fans and dampers modulate properly. All of these measures depend on accurate and reliable measurement and tracking of ventilation airflow rates.

Historically, explicit requirements to limit CO_2 concentrations in various versions of ASHRAE Standard 62 prior to 1999 and implied limits in ASHRAE Standard 62.1-1999 and subsequent editions of that standard have been based on a single assumed CO_2 generation rate per person, regardless of sex, age, actual activity or metabolic rate, body surface area, or diet. These factors are all relevant and most are important to the actual CO2 generation from any single individual. To the extent that any group of occupants differs in any of these factors from the ASHRAE "default" assumption of a typical, sedentary office worker, there may and often are significant deviations from the assumed generation rate, and use of the actual rates will produce different estimates of ventilation per person and different assessments of the quality of indoor air as indicated by the adequacy of ventilation for a given set of occupants. EPA's Exposure Factors

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[183] Proctor, John, Rick Chitwood, Bruce A. Wilcox, 2011. Efficiency Characteristics and Opportunities of New California Homes. California Energy Commission. Publication number: CEC-500-2012-062.

[184] PECI, April 28, 2011. HVAC Controls & Economizing. Nonresidential HVAC Stakeholder Meeting #3. California Statewide Utility Codes and Standards Program. http://www.h-m-g.com/T24/NonresHVAC/2011_04_08_presentations/Stakeholder%20Meeting%203%20NR-7%20-%20PECI.pdf.

Handbook 2011[185] provides detailed inhalation rates and body surface area data for both sexes of various ages, for various activity levels, and for various body types (normal and obese). Since building codes have historically referenced the ASHRAE ventilation standards and even current Title 24 regulations are based, to some extent, on ASHRAE's residential and non-residential ventilation rate requirements, it is important to reassess all requirements based on or related to ventilation rates that rely on or specify CO_2 concentration limits.

Description: Objectives and General Approach

The overall objective is to improve the field performance of HVAC control systems by addressing user-friendliness of the technologies and the accuracy and reliability of the systems. Building occupant and building manager surveys and literature reviews are needed to determine user issues with control systems. A combination of modeling, laboratory, and field studies will be used to evaluate, improve, and demonstrate ventilation control systems for residential and commercial buildings. Both existing buildings and new low-energy buildings will be evaluated. To help optimize IEQ and energy use under variable conditions, dynamic control systems will be modeled for various weather conditions, ventilation strategies, and ventilation reductions for outdoor air pollution episodes. Methods for meeting the ASHRAE 62.2 ventilation standards will be evaluated.

Why the Research Area Is Considered a Priority

Health and Safety Issues. Commercial and residential buildings are often under- or over-ventilated, which can lead to IEQ problems or wasted energy, respectively. Accurate and reliable control of ventilation systems is critical in achieving the intended ventilation rates in both existing and new buildings. It will be especially important in low-energy and NZEB buildings, where margins of error for ventilation-related problems are smaller. In addition, future buildings will need control systems that can easily and quickly adapt to power outages, heat waves, smog alerts, wildfires, dust storms, and other episodic problems.

In commercial buildings, air balance companies adjust damper settings at the time of construction to obtain desired minimum ventilation rates; however, most buildings have no systems for continuously or periodically monitoring and controlling ventilation rates. The only common real-time control systems are based on carbon dioxide (CO_2) sensors, which are often inaccurate. In residential buildings, ventilation is largely uncontrolled. In new or retrofitted homes with mechanical ventilation, dampers, fan speeds, and timers may be installed at the time of home construction to control mechanical ventilation rates. Control systems are used to set the operation times and allow manual overrides and boost functions. However, users of

[185] U.S. Environmental Protection Agency, 2011. Exposure factors Handbook, 2011. http://cfpub.epa.gov/ncea/risk/recordisplay.cfm?deid=236252 (especially Chapters 6 and 7)

control systems for various types residential ventilation systems in low-energy homes have reported various problems in understanding the controls and using them properly.[186][187][188][189]

Ventilation is typically controlled through damper settings, fan settings, and/or thermostats (indirectly), but these approaches do not control ventilation rates accurately and consistently. Demand control ventilation systems using CO_2 sensors are becoming more common, but these sensors have often been found to be inaccurate and unreliable.[190][191] Also, values used to assess ventilation based on CO_2 measurements are virtually all based on a single average CO_2 emission rate (also referred to as a generation rate) that is assumed to be typical of an sedentary adult office worker. There are significant differences in CO_2 generation rates within and between the sexes, within and between different age groups, and among different activity levels.[192] These differences are almost universally ignored in applications of CO2 measurements to assess and to control ventilation.

Ventilation systems and controls also require commissioning, operator training, and routine maintenance, but these practices as a whole are relatively rare,[193] especially in residential buildings. In addition, the types of users of control systems are very diverse. Consequently, user instruction, user-friendly control systems, and feedback on system status are also essential to maintaining good ventilation.

Guideline Needs. Various types of ventilation control systems are already on the market. Laboratory and field data are needed to verify performance of approved systems and to identify which approaches perform the best and to develop improved control systems.

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[186]Zero Carbon Trust and NHBC Foundation, January 2012. Mechanical Ventilation With Heat Recovery In New Homes, Interim Report. Ventilation And Indoor Air Quality Task Group. www.nhbcfoundation.org/NewsMediaCentre/VIAQtaskgroupinterimreport/tabid/501/Default.aspx

[187]Good Homes Alliance, 2012. Ventilation and good indoor air quality in low-energy homes: Finding proven good practice. http://www.goodhomes.org.uk/news/170.

[188] NHBC Foundation, March 2012. The impact of occupant behaviour and use of controls on domestic energy use. NF38. http://www.nhbcfoundation.org/Researchpublications/NF38/tabid/504/Default.aspx.

[189] NHBC Foundation, February 2012. Today's attitudes to low and zero carbon homes (NF40). http://www.nhbcfoundation.org/Researchpublications/nf40/tabid/496/Default.aspx. Video at http://www.nhbcfoundation.org/NewsMediaCentre/NF40Film/tabid/502/Default.aspx.

[190]Fisk et al. 2010.CO_2 Monitoring for Demand Controlled Ventilation in Commercial Buildings. LBNL-3279E.

[191]Shrestha et al. 2009. Product Report, product testing report, wall mounted carbon dioxide (CO2) transmitters, June 2009 National Building Controls Information Center, Iowa State University. (See also, Shrestha, 2010. *ASHRAE Transactions*, 4 papers.)

[192] U.S. Environmental Protection Agency, 2011. Exposure factors Handbook, 2011. http://cfpub.epa.gov/ncea/risk/recordisplay.cfm?deid=236252 (especially Chapters 6 and 7).

[193] Fisk et al, 2010, *Op Cit.*

High-Priority Research Projects

Evaluate the potential energy savings of real-time, dynamic IEQ-based controls in various climate zones, weather conditions, and outdoor air conditions, especially for schools.

Evaluate sensors and measurement methods for airflow and indoor air quality (IAQ), and develop improved sensors for demand control ventilation. Address current issues regarding sensor calibration, accuracy, and reliability of CO_2 sensors.

Develop detailed, occupancy-specific guidelines for using CO_2 values to assess ventilation and evaluate IAQ. These guidelines should be developed to assist design professionals, code officials, and others to determine occupant characteristics critical to interpretation of CO_2 concentration values.

Lower-Priority Research Projects

Conduct home occupant surveys to user issues with control systems and to recommend best practices.

Evaluate controls in residential ventilation systems.

Investigate calibration and field verification methods to help improve commissioning, life cycle performance, and standards compliance.

Evaluate minimum ventilation controls for naturally ventilated buildings.

Conduct demonstration projects using improved sensors and control systems.

Verify that controls provide design ventilation rates under a range of operational scenarios.

Trends that make this a priority research topic include increases in building shell and duct tightness, use of demand control ventilation, energy prices, class sizes in schools, ESCO retrofits, and mechanical ventilation in homes.

Related R&D Areas and Topics

Ventilation: Commissioning.

Operation and Maintenance.

Tools, Sensors, etc.

Cross-cutting: Behavior

Demonstrate methods to improve the performance and reliability of venting systems for cooking appliances and high-moisture areas, such as low-noise fans, automatic controls, and high-removal-efficiency range hoods.

Passive survivability: heat waves, power outages, and wildfires.

Impact of control system and activity/authority/responsibility/access.

Develop and evaluate user-friendly ventilation technology and controls.

Related Work

Mechanical ventilation and IEQ performance in new Dutch homes.[194]

Active House demonstration, automated natural ventilation.[195]

Thermostat placement in R2000 homes: Canada Mortgage and Housing Corporation (CMHC) gas fireplace study.[196]

Shelter In Place research: LBNL and University of Texas, Austin (J. Siegel).

LBNL Residential Integrated Ventilation Energy Controller.[197]

The CPUC is focusing part of its Energy Efficiency Strategy Action Plan on improved performance of rooftop package HVAC systems in California's climate. These types of systems are prone to exhibit poor ventilation and filtration performance.

DOE, National Institute of Standards and Technology (NIST), U.S. Department of Housing and Urban Development (HUD), CMHC, National Research Council (NRC) Canada, and energy groups in the Pacific Northwest and other U.S. regions may be interested in co-funding projects on improved control systems for ventilation.

In Europe, some projects in PassNet and other programs are demonstrating the use of CO_2 sensors for residential ventilation control.

UK studies of heat recovery ventilator (HRV) performance and user issues. Four ongoing field studies are mentioned.[198][199]

UK studies of occupant satisfaction in low-energy homes.[200][201]

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[194] Van Dijken F, Balvers JR, Boerstra AC. The quality of mechanical ventilation systems in newly built Dutch dwellings. Indoor Air 2011 proceedings.

[195] Hansen EK, 2010. Measuring life by real people. Active House Demonstration. http://www.activehouse.info/knowledge/measuring-life-real-people.

[196] CHC Housing Research Highlight, Technical Series 11-100. http://trk.cp20.com/Tracking/t.c?Obfu-NKDp-X2ZNQ4.

[197] http://www.lbl.gov/tt/techs/lbnl2715.html.

[198]Zero Carbon Trust and NHBC Foundation, January 2012. Mechanical Ventilation With Heat Recovery In New Homes, Interim Report. Ventilation And Indoor Air Quality Task Group. www.nhbcfoundation.org/NewsMediaCentre/VIAQtaskgroupinterimreport/tabid/501/Default.aspx.

[199]Good Homes Alliance, 2012. Ventilation and good indoor air quality in low-energy homes: Finding proven good practice. http://www.goodhomes.org.uk/news/170.

[200] NHBC Foundation, March 2012. The impact of occupant behaviour and use of controls on domestic energy use. NF38. http://www.nhbcfoundation.org/Researchpublications/NF38/tabid/504/Default.aspx.

TOPIC AREA: VENTILATION
PRIORITY RESEARCH: COMMISSIONING

Specific Regulatory or Policy-related Needs

Current Title 24 regulations require commissioning (Cx) measures for new and existing commercial buildings and HVAC quality installation (verification testing) for system performance. California's Strategic Energy Efficiency Plan includes improved quality installation and maintenance and development of new climate-appropriate HVAC technologies. CalGreen Building Standards currently require limited Cx in commercial buildings and full Cx in the voluntary standards. Commissioning measures would also help meet the Cal/OSHA regulations for annual inspection and testing of HVAC systems in commercial buildings, which is rarely done in California.

Commissioning of residential ventilation systems, both whole-house and local ventilation, is also needed to achieve the desired IEQ and energy performance in new homes. Critical research needs include projects to (1) examine the IEQ benefits of Cx, and (2) evaluate Cx methods in residential buildings.

Description: Objectives and General Approach

The overall objective is to assess the IEQ impacts of Cx and to improve the performance of residential HVAC systems through Cx. Existing case studies and existing literature will be evaluated for IEQ impacts of Cx. Procedures for Cx of residential HVAC will be developed and evaluated. New and existing buildings, including low-energy buildings, will undergo commissioning; IEQ, ventilation, occupant survey, and energy data will be collected before and after Cx. Lessons learned and best practices will be published, and demonstration buildings will be used for professional training and public education.

Why the Research Area Is Considered a Priority

Health and Safety Issues. HVAC systems often do not provide the intended levels of airflows, thermal comfort, and pressure balance, let alone the intended levels of energy efficiency.[202] This is largely due to improper installation and maintenance of HVAC systems, lack of compliance inspections, and lack of building permits. Commissioning of new and existing commercial buildings has proven to be very cost effective regarding energy, while also improving IEQ in commercial buildings. Commissioning of residential HVAC systems is rare in the United States, but it is required in some European countries. Commissioning provides some assurance for building owners and occupants that the building will perform adequately as designed.

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[201] NHBC Foundation, February 2012. Today's attitudes to low and zero carbon homes (NF40). http://www.nhbcfoundation.org/Researchpublications/nf40/tabid/496/Default.aspx. Video at http://www.nhbcfoundation.org/NewsMediaCentre/NF40Film/tabid/502/Default.aspx.

[202] http://cx.lbl.gov/cost-benefit.html.

Guideline Needs. Guidelines and green building programs need science-based recommendations for commission HVAC systems. Such recommendations are important for voluntary efforts such as buildings for sensitive populations, buildings using advanced design and new technologies, and third-party energy retrofitters (ESCOs).

High-Priority Research Projects

Develop and demonstrate methods to ensure reliable usage and performance of ventilation systems, both residential and commercial.

Develop and demonstrate model specifications for Cx and retro-commissioning (RCx) for IEQ protection.

Lower-Priority Projects

Assess and track the long-term performance of ventilation systems in new and retrofit applications.

Assess the IEQ performance of Monitor-Based Commissioning in new and existing buildings.

Assess the energy-IEQ trade-offs among pre-occupancy flushing times.

Related R&D Areas and Topics

Tools category.

Ventilation category.

Develop Best Practice Guidelines for IEQ in Installation, Cx, Weatherization (Wx), and O&M.

Develop and demonstrate methods to ensure reliable usage and performance of ventilation systems.

Related Work

California Commissioning Collaborative: 5 PIER Projects; presentations at meetings.[203][204]

PIER/DOE/LBNL: Healthy Zero Energy Buildings (HZEB, commercial), Healthy Home (multifamily), and RESAVE (residential) projects.[205]

CMHC EQuilibrium Sustainable Housing Demonstration Initiative.[206]

NRC Canada: Field Study on Indoor Air Quality, Ventilation and Health.[207]

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[203] http://www.cacx.org/PIER/.

[204] http://www.cacx.org/meetings/index.html.

[205] http://hzeb.lbl.gov/; http://apartmentenergy-ieqretrofits.lbl.gov/projects; http://resave.lbl.gov/

[206] http://www.cmhc-schl.gc.ca/en/inpr/su/eqho/.

[207] http://archive.nrc-cnrc.gc.ca/eng/projects/irc/air-initiative/fieldstudy.html.

Northwest Energy Efficiency Alliance: Planned study on performance of mechanical ventilation in homes. Contact: Charlie Stephens.

Swedish Pilot Study: Square QA System.[208]

HUD Healthy House

DOE Builder Challenge

EPA ENERGY STAR Version 3

Building Performance Institute

Air Conditioning Contractors of America (ACCA)/Residential Energy Services Network (RESNET) standards, ACCA QI Standard

National Institute for Occupational Safety and Health (NIOSH), National Center for Healthy Housing, Collaborative for High Performance Schools (CHPS).

Various low-energy and zero energy building projects in California, the United States, and abroad.

UK studies of HRV performance and user issues. Four ongoing field studies are mentioned.[209][210]

UK studies of occupant satisfaction in low-energy homes.[211][212]

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[208] Mjornell and Kovacs. SQUARE QA System in Swedish Pilot Project. http://www.iee-square.eu/InformationPublications/Presentations.asp.

[209] Zero Carbon Trust and NHBC Foundation, January 2012. Mechanical Ventilation With Heat Recovery In New Homes, Interim Report. Ventilation And Indoor Air Quality Task Group. http://www.nhbcfoundation.org/NewsMediaCentre/VIAQtaskgroupinterimreport/tabid/501/Default.aspx

[210] Good Homes Alliance, 2012. Ventilation and good indoor air quality in low-energy homes: Finding proven good practice. http://www.goodhomes.org.uk/news/170.

[211] NHBC Foundation, March 2012. The impact of occupant behaviour and use of controls on domestic energy use. NF38. http://www.nhbcfoundation.org/Researchpublications/NF38/tabid/504/Default.aspx.

[212] NHBC Foundation, February 2012. Today's attitudes to low and zero carbon homes (NF40). http://www.nhbcfoundation.org/Researchpublications/nf40/tabid/496/Default.aspx. Video at http://www.nhbcfoundation.org/NewsMediaCentre/NF40Film/tabid/502/Default.aspx.

TOPIC AREA: VENTILATION

PRIORITY RESEARCH: IEQ PERFORMANCE

Specific Regulatory or Policy-Related Needs

Field studies have confirmed that new and existing homes, classrooms, and commercial buildings in California often do not meet the ventilation requirements of Title 24, and that many commercial buildings are over-ventilated relative to Title 24 requirements. Maintenance problems such as closed or broken outdoor air dampers are a common problem in commercial buildings, and dirty or leaky air filters are common in both commercial and residential buildings. Compliance with Title 24 ventilation standards is a widespread problem, especially in remodels and retrofits where building permits are frequently not requested.

Title 24 has recently required that new homes have mechanical ventilation systems and that the systems undergo limited acceptance testing, which are major changes for the building industry and home occupants. However, data are lacking on how the various types of installed systems perform, how users interact with the control systems, and how the systems are maintained. Outside of California, some occupants of new homes with mechanical ventilation systems have reported complaints of drafts, odors, and noise from the mechanical ventilation system, and overheating in the summer has also been reported.

In addition, residential and commercial retrofit efforts have expanded recently, and the Energy Commission plans to begin developing retrofit and Cx standards under AB 758 (see Appendix E). Building retrofits will offer opportunities to improve ventilation systems and save energy, but it also raises issues about how much a building should be tightened, when and how mechanical ventilation systems should be should be upgraded, whether Cx will address all modes of operation (full and partial), and how pressure drops from air filters will affect ventilation and thermal comfort.

Description: Objectives and General Approach

The overall objective is to assess the impact of ventilation on IEQ, health, and human performance in new and retrofit buildings. Ventilation system performance in existing and new residential and commercial buildings will be simulated and verified in the field. For existing buildings, the effectiveness of mitigation measures to reduce air leakage and depressurization and to improve airflows, air mixing, air cleaning, thermal comfort, and health symptoms will be assessed. First costs and life-cycle costs will also be estimated.

Why the Research Area Is Considered a Priority

Health and Safety Issues**.** Low ventilation rates have been associated with sick building syndrome (SBS) symptoms in commercial buildings, increased respiratory illness, reduced satisfaction with air quality, increased absence in schools and offices, and reduced office and school work performance.[213] Ventilation is needed to control exposures to indoor-generated

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[213] http://www.iaqscience.lbl.gov/vent-summary.html; http://www.iaqscience.lbl.gov/performance-summary.html.

pollutants that pose acute and chronic health risks, including pollutants from indoor sources of moisture, building material emissions, and other indoor pollutants. However, ventilation can also introduce outdoor air pollutants such as combustion pollutants, ozone, pollen, and mold.[214]

Guideline Needs. Guidelines and green building programs need science-based recommendations for designing, commissioning, and operating new and retrofit buildings to meet IEQ goals. Such recommendations are important for voluntary efforts such as buildings for sensitive populations, buildings using advanced design and new technologies, and third-party energy retrofitters (ESCOs). In addition, building standards allow much flexibility in how ventilation systems are designed, so guidelines for achieving IEQ for different system types are also needed.

High-Priority Research Projects

Determine how ventilation rates and methods in new buildings affect IEQ conditions, occupant health and performance, building energy consumption, and costs; provide related input for ventilation standards.

Assess the IEQ impacts of retrofits in single-family, multifamily, and commercial buildings, e.g., changes in ventilation systems, building shells, nearby pollutant sources, and occupant behavior.

Lower-Priority Research Projects

Assess the effects on IEQ, air exchange rate, and energy use produced by depressurization of attached garages and building shells by exhaust fans, whole-house exhaust fans, clothes driers, duct leakage, etc. (See Source-Outdoor Air and Attached Spaces topic).

Assess the noise impacts of ventilation systems.

Assess IEQ and energy trade-offs among pre-occupancy flushing times.

Assess the IEQ and energy benefits of ceiling fans and ventilation systems powered by DC current from photovoltaic and renewable power sources.

Description: Objectives and General Approach

Ventilation system performance in existing and new residential and commercial buildings will be simulated and verified in the field. For existing buildings, the effectiveness of mitigation measures to reduce air leakage and depressurization and to improve airflows, air mixing, air cleaning, thermal comfort, and health symptoms will be assessed. First costs and life-cycle costs will also be estimated.

Related R&D Areas and Topics

All other topic areas, but especially Ventilation-Cx, O&M, and Air Cleaning.

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214 http://www.iaqscience.lbl.gov/vent-disadvantages.html.

TOPIC: VENTILATION

PRIORITY RESEARCH: HIGH-PERFORMANCE DESIGN

Specific Regulatory or Policy-related Needs

Efficient delivery of clean outdoor air, good thermal comfort, and low noise are essential to public and market acceptance of low-energy buildings, but this requires whole-building design to optimize IEQ and energy performance. Current Title 24 residential standards allow various types of ventilation systems, which can vary widely in IEQ performance. Future Title 24 residential standards are expected to require tighter building shells, which will exacerbate problems such as overheating, poor air mixing, clogged air filters, noise complaints, and excessive building depressurization. The Energy Commission plans to require thermal mass and external shading to address overheating issues (see Appendix E, California policies). However, IEQ data on high-performance buildings in California is lacking.

Future Title 24 standards are expected to require increased use of economizers and night cooling, which both greatly increase the amount of outdoor airflows and the need for air cleaning.

Critical needs include projects to address known problems in low-energy buildings that will be exacerbated by tightening of building shells and ductwork, including mixing, noise, odors, thermal comfort, and infiltration from attached spaces.

Description: Objectives and General Approach

The overall objective is to identify and demonstrate the best approaches to achieving IEQ goals in low-energy buildings in California. Modeling and field testing will evaluate IEQ- and energy-optimized building designs for low-energy buildings. Existing case studies and exemplary buildings will be evaluated. Demonstration projects will be conducted to collect field data, with assistance from partners where possible. First- and life-cycle costs will also be estimated. Lessons learned and best practices will be published, and demonstration buildings will be used for professional training and public education.

Why the Research Area Is Considered a Priority

Health and Safety Issues**.** "High performance buildings" is a descriptor that generally applies to buildings with low energy end use intensity (EUI) profiles, although there are no standardized requirements or widely-accepted definitions. Low-energy buildings are designed and constructed to use between 80 percent and 90 percent less energy than the average energy use of comparable buildings built in the past decade. Such buildings are likely to apply many of the best current technologies, as well as new features related to ventilation. Since ventilation is currently believed to be associated with a significant fraction of total building-related energy use, there will be a strong push to minimize it, as well as to make it more efficient.

Current knowledge of low-energy or high performance buildings' indoor environmental quality is extremely limited. Some low-energy building designs are reported to have problems in overheating, odors, clogged filters, and noise. Natural ventilation and hybrid ventilation (or natural-mechanical mixed mode) approaches offer substantial energy efficiencies, but also increase the need for filtering outdoor air. The use of radiant heating and cooling technologies is increasing, but application of these technologies in large buildings is not well established in the United States. Control of indoor thermal conditions will be less frequently associated with ventilation systems and more frequently through radiant heating and cooling systems.

Overheating is predicted to be much more common as the climate warms, especially in warmer climates.[215][216] As climate warms, there will also be more outdoor air pollution from photochemical reactions (ozone), dust storms, and wildfires, as well as from higher levels of pollen. There may also be more pesticide use due to increases in insect-borne diseases. Thus, there will be even greater challenges to achieving energy efficiency, and high performance will require substantial improvements over current systems.

Guideline Needs. Guidelines and green building programs need science-based recommendations for optimizing IEQ and energy in new and existing buildings. Such recommendations are important for voluntary efforts such as buildings for sensitive populations, buildings using advanced design and new technologies, and third-party energy retrofitters (ESCOs). Designers of buildings for vulnerable populations will need to address outdoor air pollution and power outage episodes by designing ventilation and air cleaning systems that can anticipate or adapt in real-time to such episodes.

High-Priority Research Projects

Understand the best ventilation systems for high-performance buildings; include ventilation systems and air cleaning systems that are separate from heating and cooling systems.

Develop and demonstrate IEQ-optimized ventilation, heating, and cooling systems for different building types and different climate zones in California, for both new and retrofit applications.

Lower-Priority Projects

Assess the noise impacts of different low-energy ventilation and air distribution systems.

Assess the IEQ performance of low-energy cooling and heating systems, including economizers for residential ventilation/nighttime cooling.

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[215]Coley DA, Kershaw TJ, 2008. Modeling the Impact of Climate Change in Schools: the Issue of Overheating, *Climate Change Impacts and Adaption Conference: Dangerous Rates of Change*, University of Exeter, 22nd - 24th Sep 2008.
http://www.exeter.ac.uk/research/excellence/keythemes/climate/conference/documents/schools.pdf

[216]IEAA, 2007.The Passivhaus Standard in European Warm Climates:

Design Guidelines for Comfortable Low Energy Homes, Part 1. A review of comfortable low-energy homes. http://www.iee-library.eu/images/all_ieelibrary_docs/designguidelines_en.pdf.

Assess the effectiveness of mitigation strategies such as thermal mass and movable exterior shading in maintaining thermal comfort; assess the energy savings and costs as well.

Related Work

The Intelligent Energy for Europe Passive-On project: Passive House design in warm climates in Europe.[217][218]

CMHC Equilibrium Sustainable Housing Demonstration Initiative.[219]

NRC Canada: Field Study on Indoor Air Quality, Ventilation and Health.[220]

ARB has funded a $1.3 million study with LBNL to do this. They will examine combinations of mechanical ventilation and filtration systems for homes to identify technologies that are low energy and protective of the indoor air.

Active House project.[221]

PIER/DOE/LBNL: Healthy Zero Energy Buildings (HZEB, commercial), Healthy Home (multifamily), and RESAVE (residential) projects.[222]

NIST NZEB, High Performance Building Project.[223]

ASHRAE 1565-TRP (rebid), "Development of the ASHRAE Design Guide for Dedicated Outdoor-Air Systems." [224]

DOE/Oak Ridge National Laboratory (ORNL) Weatherization Assistance Program IAQ Study.[225]

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217 http://www.passive-on.org/en/cd.php, see Browse CD link for guidelines, results, etc.

218 Schneider J, 2009. Passive Houses in South West Europe.http://www.passivhaustagung.de/Passive_House_E/PH_MedClim.html.

219 http://www.cmhc-schl.gc.ca/en/inpr/su/eqho/.

220 http://www.nrc-cnrc.gc.ca/eng/projects/irc/air-initiative/fieldstudy.html.

221 ActiveHouse.info, Knowledge and Sharing http://activehouse.info/knowledge

222 PIER/DOE/LBNL: Healthy Zero Energy Buildings (HZEB, commercial), Healthy Home (multifamily), and RESAVE (residential) projects http://hzeb.lbl.gov/; http://apartmentenergy-ieqretrofits.lbl.gov/projects; http://resave.lbl.gov/

223 NIST NZEB, High Performance Building Project http://www.nist.gov/el/building_environment/heattrans/netzero.cfm.

224 http://www.ashrae.org/File%20Library/docLib/Research/Fall2011RFPs/1565-TRP.pdf.

225 http://weatherization.ornl.gov/evaluation_nr.shtml; http://2011.acinational.org/sites/default/files/session/81122/aci11eval6roseerin.pdf.

LBNL/PIER projects: Healthy Zero Energy Buildings (HZEB, commercial), Healthy Home (multifamily), and RESAVE (residential) projects.[226]

CMHC EQuilibrium Sustainable Housing Demonstration Initiative.[227]

Health studies with IEQ components:

- NRC Canada: Field Study on Indoor Air Quality, Ventilation and Health.[228]
- NIH et al., Childhood Cancer Cohort Consortium: various prospective studies of environmental and biological determinants of common diseases, including the NIH National Children's Health Study.[229]
- Canadian Healthy Infant Longitudinal Development (CHILD) Study.[230]

R&D work on ventilation and IEQ has been funded by DOE, HUD, U.S. EPA, NIH, NIOSH, the National Center for Healthy Housing, and CHPS.

Various low-energy and zero energy building projects in California, the United States, and abroad have addressed ventilation and IEQ issues.

ASHRAE TC 9.5, TC 6.3, and the Standard 62.1 and 62.2 committees recommend research funding on ventilation issues.

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[226] http://hzeb.lbl.gov/; http://apartmentenergy-ieqretrofits.lbl.gov/projects; http://resave.lbl.gov/

[227] http://www.cmhc-schl.gc.ca/en/inpr/su/eqho/.

[228] http://archive.nrc-cnrc.gc.ca/eng/projects/irc/air-initiative/fieldstudy.html.

[229] https://communities.nci.nih.gov/i4c/default.aspx.

[230] http://www.canadianchildstudy.ca/overview.html - gpm1_1.

TOPIC: OPERATION AND MAINTENANCE

PRIORITY RESEARCH: OPERATION AND MAINTENANCE

Specific Regulatory or Policy-Related Needs

Adequate maintenance of HVAC systems is frequently lacking in small and medium commercial buildings, classrooms, and residences in California.[231][232][233] Thermal comfort is a common complaint in all major types of buildings in California. Water leaks and condensation in buildings are also very common. Current and future Title 24 standards and new building technologies programs are expected to increase maintenance needs for HVAC systems, although requirements for fault detection and diagnostic systems are expected to improve HVAC maintenance, at least in commercial buildings.

Description: Objectives and General Approach

The overall objective is to help improve operation and maintenance (O&M) of buildings and their systems that affect IEQ. Operation and maintenance problems and potential solutions need to be assessed in a white paper to target the major problems and potential causes. Surveys and focus groups on HVAC O&M practices, IEQ management, attitudes, and incentives conducted with owners and/or facility managers of large office buildings, schools, and residences (all major types) are needed. Field studies are needed on the O&M, performance, and commissioning of HVAC systems to identify the causes of poor O&M and to test likely solutions.

Why the Research Area Is Considered a Priority

Health and Safety Issues. Buildings can last for 50 to 100 years and provide good IEQ if they receive proper maintenance throughout their lifetime. However, proper O&M can often be lacking, especially in residential, small commercial, and school buildings. Lack of adequate O&M can adversely impact IEQ by causing various problems such as closed air dampers, blocked vents, dirty air filters, excessive moisture, pest infestations, and hazardous carbon monoxide levels. In addition, the scheduling of local or building ventilation by building operators or occupants can have a significant effect on IEQ, depending on when indoor source emissions occur.

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[231] Bennett et al., 2011.Ventilation and indoor air quality (IAQ) in small and medium commercial buildings (SMCB) Phase II Field Study. ARB and California Energy Commission/PIER Final Report. http://www.arb.ca.gov/research/single-project.php?row_id=64797.

[232]http://www.arb.ca.gov/research/indoor/pcs/pcs.htm.

[233]Offermann 2009.Ventilation and indoor air quality in new homes. Final report. Prepared for ARB and California Energy Commission/PIER. http://www.arb.ca.gov/research/single-project.php?row_id=64697.

The CPUC's current Zero Net Energy Action Plan for commercial buildings includes efforts to increase training for building operators. The increased use of natural ventilation, different ventilation strategies and controls, and adjustable shading will increase the need for training of building operators and occupants.[234] Operation and maintenance issues for residential HVAC and shading will also need to be addressed.

Critical needs in this topic area include: (1) determining O&M improvements needed for residential buildings and schools, especially ventilation systems; and (2) guidelines and demonstrations on how to improve O&M for good IEQ in schools, residences, and small and medium commercial buildings.

Guideline Needs. Voluntary green building programs, Property Assessed Clean Energy (PACE) programs, and ESCOs are also concerned about the long-term performance of buildings and often address IEQ in their marketing and training programs. Advanced builders often employ new technologies that have non-standard maintenance requirements. These users need to address O&M needs in order to avoid major IEQ and credibility problems, achieve energy-efficiency goals, and minimize liability.

High-Priority Research Projects

Develop and demonstrate methods to ensure reliable usage and performance of ventilation systems.

Develop warning and indicator systems for IEQ maintenance needs such as outdoor air ventilation, temperature control, filter replacement, and prevention of dampness and microbial problems in building envelopes and HVAC systems.

Lower-Priority Projects

Best Practice Guidelines for O&M.

Durability of highly insulating building envelope systems, especially controlling moisture from exterior, occupants, and plumbing.

Design goals vs. real-world performance.

Persistence of operator and owner training.

User-friendly controls.

Sensor based control methods.

Flexible low rates and operation schedules.

Good maintenance access for filters and ductwork.

Labeling for proper filter type.

Costs and benefits of maintenance contracts.

Related R&D Areas and Topics

Moisture Risk Assessment and Mitigation

Ventilation

- Guidance for mixed-mode buildings where people also operate windows
- Guidance on how to meet thermal comfort criteria and how to consider adaptive comfort.
- Evaluate the effectiveness of various methods of dust removal from surfaces and furnishings, and of reducing dust penetration and track-in, as a means of reducing SVOC and allergen exposures.
- Demonstrate methods to improve the performance and reliability of venting systems for cooking appliances and high-moisture areas, such as low-noise fans, automatic controls, and high-removal-efficiency range hoods.
- Filtration: selection, installation, replacement, maintenance.

Cross Cutting: Behavior.

- Evaluate the effectiveness of various methods of dust removal from surfaces and furnishings, and of reducing dust penetration and track-in, as a means of reducing SVOC and allergen exposures.
- Passive survivability: heat waves, power outages, and wildfires.

Related Work

ARB/LBNL (Singer and Walker) Study on "Reducing In-Home Exposure to Air Pollution"; study of the effectiveness of various types and combinations of residential mechanical ventilation systems and high-efficiency filtration systems. Expect completion in 2015.

Washington State University WSU: O&M Rating System for Commercial Buildings.[235]

DOE/LBNL: Healthy Zero Energy Buildings (HZEB, commercial), Healthy Home (multifamily), and RESAVE (residential) projects.[236]

Northwest Energy Efficiency Alliance: planned study on performance of mechanical ventilation in homes. Contact: Charlie Stephens.

Swedish Pilot Study of Multifamily Passive House Retrofits: Square QA System.[237][238]

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[235] http://www.energy.wsu.edu/Documents/Commercial_Bldg_O&M_Rating_System_Prill.pdf.

[236] http://hzeb.lbl.gov/; http://apartmentenergy-ieqretrofits.lbl.gov/projects; http://resave.lbl.gov/.

Active House Demonstration project.

The CPUC plans to market energy-efficiency programs and train building operators. IEQ modules could be added cost-effectively to surveys, marketing efforts, and training programs.

EPA, DOE, ASHRAE, NIOSH, HUD, CMHC, NRC Canada, and energy groups in the Pacific Northwest and other U.S. regions may be interested in co-funding projects on O&M in low-energy buildings.

CHPS has a best practices manual on building O&M that may be updated.[239] LEED certifies existing buildings for O&M practices.[240]

Green building programs and energy utilities often fund energy-efficiency training programs for building and facility managers. These programs address HVAC systems and often also address IEQ.

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[237] Mjornell and Kovacs. SQUARE QA: System in Swedish Pilot Project. http://www.iee-square.eu/InformationPublications/Reports/SQUARE_Pilot_project_Sweden_EN.pdf.

[238] Mjornell et al., 2010.Monitoring of indoor environment and energy use in the

renovated buildings at Brogården in Alingsås. Presented at PassivHusNorden.

[239] CHPS, 2006. http://chps.net/dev/Drupal/node/39.

[240] http://www.usgbc.org/DisplayPage.aspx?CMSPageID=2513.

TOPIC: THERMAL CONDITIONING

PRIORITY RESEARCH: DEVELOPMENT AND DEMONSTRATION

Specific Regulatory or Policy-related Needs

Title 24 incorporates ASHRAE Standard 55 for thermal comfort as a design goal. However, thermal conditions are not usually verified in the building inspection process, and only dry bulb temperature (and not wet bulb temperature) is used to control HVAC systems. In the near future, the Title 24 and AB 758 programs for new and retrofit buildings are expected to increase air sealing and insulation, which together can drastically increase the incidence of overheating.

Increasing reliance on natural ventilation and hybrid ventilation may also lead to thermal condition problems, even in California's milder climate zones.248 Thermal conditions in new homes have been modeled for proposed revisions to Title 24; preliminary estimates indicate that single-family homes in several climate zones would not meet ASHRAE 55 criteria for a substantial portion of the year.[241]

To avoid widespread complaints by builders and building owners and to avoid loss of credibility, building energy programs that radically change building design and operation will need to carefully evaluate impacts on thermal conditions. Current building technology usually controls thermal conditions by heating or cooling air or by altering airflow velocity, especially for cooling. Other technologies separate the heating and or cooling functions from the ventilation function. New high-performance buildings are increasingly using this approach to improve both energy efficiency and thermal comfort. Traditional heating methods that use radiators, and newer technologies such as radiant-heated floors, chilled beams, and radiant panels, have been used in some newer, low-energy buildings. In addition, the use of natural ventilation, especially for cooling, is expected to increase. This will allow occupants to save energy by adapting to a wider range of thermal conditions by changing their behavior, e.g., altering their clothing choices and the operation of building components such as fans, windows, and skylights.

Critical needs include: (1) pilot and demonstration programs to verify that buildings are performing adequately in terms of thermal conditions, especially in schools and homes; and (2) guidelines and demonstrations on how to optimize air movement, natural ventilation, and energy efficiency while maintaining thermal comfort.

Description: Objectives and General Approach

The overall objective is to assess the likely strategies for maintaining thermal comfort in low-energy buildings and to verify their field performance. Thermal condition guidelines for

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[241] Pande A, 2011.Compressorless Comfort Homes. Residential HVAC Baseline. Presentation at Residential Stakeholder Meeting California, Statewide Utility Codes and Standards Program, May 13, Davis, CA. http://www.h-m-.com/T24/Res_Topics/2011.05.13MeetingDocuments/Compressorless_Homes_HVAC_Baseline_Pande_051311.pdf.

designing and operating new and retrofit buildings will be developed for California's climate-zones, for the near future and for building life cycles. The guidelines will provide design and verification tools for optimizing and integrating building features to minimize cooling loads, e.g., glazing, thermal mass, enhanced stack effects, night purge ventilation, movable exterior shading, overhead fans, and radiant heating and cooling (chilled beam, radiant panels, etc.). Modeling predictions of thermal conditions will be compared to field results in pilot and demonstration projects, including K-12 classrooms and other high-occupancy buildings. Data on thermal comfort, occupant perception, and energy usage will be obtained and analyzed. Solutions for thermal condition problems in existing buildings will also be developed. Approaches to encouraging adaptive behavior will also be developed and demonstrated. Demonstration buildings and other case studies will be monitored initially and over the next five years to assess thermal comfort and to implement improved strategies.

Why the Research Topic Is Considered a Priority

Health and Safety Issues. Thermal condition problems, both overheating and overcooling, are some of the most common type of IEQ complaints by occupants in various types of buildings in California.[242][243][244][245] Thermal conditions can adversely affect perceived air quality, increase responses to airborne irritants, reduce worker and student performance, and, in extreme cases, lead to premature death in sensitive populations. Thermal condition problems, mainly overheating, have also been reported and/or predicted in low-energy homes in California and other regions, and in schools and office buildings using natural ventilation in California.[246] Climate change is expected to increase the frequency and severity of thermal condition problems in California; especially in climate zones where air-conditioned buildings are not common.[247][248]

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[242]CBE, 2007.Occupant Satisfaction with IEQ in Green and LEED-Certified Buildings. http://www.cbe.berkeley.edu/research/briefs-LEED.htm.

[243]Price et al., 2007. Study of Ventilation Practices, and Household Characteristics in New California Homes. Final Report, ARB Contract 03-326. http://www.arb.ca.gov/research/single-project.php?row_id=60915.

[244]Offermann 2009.Ventilation and indoor air quality in new homes. Final report. Prepared for ARB and California Energy Commission/PIER. http://www.arb.ca.gov/research/single-project.php?row_id=64697.

[245]ARB and CDPH, 2004.Final Report to the Legislature: Environmental Health Conditions in California's Portable Classrooms. http://www.arb.ca.gov/research/indoor/pcs/pcs.htm.

[246]San Francisco federal office building: http://www.beyondchron.org/articles/San_Francisco_s_Green_Building_Nightmare_5428.html.

[247]Coley DA, Kershaw TJ, 2008. Modeling the Impact of Climate Change in Schools: the Issue of Overheating, *Climate Change Impacts and Adaption Conference: Dangerous Rates of Change*, University of Exeter, 22nd - 24th Sep 2008. http://www.exeter.ac.uk/research/excellence/keythemes/climate/conference/documents/schools.pdf.

Guideline Needs. Guidelines, best practices, voluntary green building programs, PACE programs, and ESCOs are often more aggressive in tightening and insulating buildings. Thermal comfort goals are included in Title 24 but also need to be included in green building rating and labeling programs. These programs also need to carefully address thermal conditions.

High-Priority Research Projects

Develop and demonstrate climate-optimized designs for heating, cooling, and moisture control to meet thermal comfort goals, for existing, new, and retrofit buildings, including mixed-mode designs. Assess the costs and benefits (energy and non-energy).

Develop design guidelines for overhead fans and air movement methods to improve thermal comfort.

Develop and demonstrate design and operational strategies for energy-efficient personal comfort systems to supplement and offset central conditioning in indoor work environments. Variants of such systems are also known as "personal environmental control," "task ambient conditioning," and "personal ventilation."

Lower-Priority Projects

- Investigate the potential for radiant systems combined with DOAS to reduce energy use while improving IAQ and thermal comfort.
- Develop and demonstrate the prevention of overheating in low-energy, super-insulated homes and super-tight commercial buildings.
- Demonstrate methods to improve air movement, such as ceiling fans.
- Develop and demonstrate systems to encourage adaptive behavior by occupants.

Related R&D Topics and Projects

Ventilation, Operation and Maintenance, Tools, and Cross-Cutting - Behavior Projects.

Develop and test tools/models to predict indoor environmental quality to be built into the energy models for building simulation and/or operation.

Compare various IEQ impacts of energy conservation and efficiency measures encouraged in California green-building home programs (e.g., Cal Green, Build It Green, ENERGY STAR, Passive House, ALA Health House).

Assess passive survivability of buildings in response to heat waves, power outages, and wildfires.

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[248] English P, 2010. Public Health Vulnerabilities to Climate Change and Mapping of Risk. CDPH presentation. http://www.cdph.ca.gov/programs/cclho/Documents/English05132010.pdf.

Investigate barriers to the development and deployment of demand control ventilation sensors that are reliable upon initial deployment and over time. Develop and test improved sensors.

Develop and demonstrate intuitive, real-time controls that give feedback, primarily classrooms with teacher access to the controls.

Related Work

Breathe Easy Study: intervention study of asthmatics in energy-efficient, multifamily homes in Seattle.[249]

CMHC Equilibrium Sustainable Housing Demonstration Initiative.[250]

NRC Canada: Field Study on Indoor Air Quality, Ventilation and Health[251]

The IEAA Passive-On project: Passive House design in warm climates in Europe.[252][253]

Northwest Energy Efficiency Alliance: Planned study on performance of mechanical ventilation in homes. Contact: Charlie Stephens.

HUD: Greening of Bellingham Housing Authority Buildings. Project to monitor energy and survey occupant satisfaction before and after a retrofit of a large multifamily building.[254]

HUD and University of Minnesota: Energy and IEQ monitoring of weatherized public housing and senior housing.[255]

PIER/DOE/LBNL: Healthy Zero Energy Buildings (HZEB, commercial), Healthy Home (multifamily), and RESAVE (residential) projects. In progress. [256]

NIST NZEB, High-Performance Building Project. In progress.[257]

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[249]Takaro et al., 2011. The Breathe-Easy Home: The Impact of Asthma-Friendly Home Construction on Clinical Outcomes and Trigger Exposure. *Am J Public Health* 101:55–62.

[250]http://www.cmhc-schl.gc.ca/en/inpr/su/eqho/.

[251]http://archive.nrc-cnrc.gc.ca/eng/projects/irc/air-initiative/fieldstudy.html.

[252]http://www.passive-on.org/en/cd.php, see Browse CD link for guidelines, results, etc.

[253]Schneider J, 2009. Passive Houses in South West Europe. http://www.passivhaustagung.de/Passive_House_E/PH_MedClim.html.

[254]Washington State University, 2012. http://whatcom.wsu.edu/carbonmasters/documents/BHA_Project.pdf.

[255]University of Minnesota, Sustainable Housing Initiative. http://www.mnshi.umn.edu/projects/projects.html, see Viking Terrace and GREAT studies.

[256] http://hzeb.lbl.gov/; http://apartmentenergy-ieqretrofits.lbl.gov/projects; http://resave.lbl.gov/

NHBC: Several building projects to study HRV performance, IEQ, and occupant behavior. In progress.[258]

Swedish Pilot Study of building commissioning of low-energy homes: Square QA System.[259]

Zero Carbon Trust: Apartment block retrofit and post-occupancy survey.

http://www.zerocarbonhub.org/building.aspx?news=23.

ARB research on indoor fans for cooling.[260]

Research Groups:

- NIST is developing improved models for IEQ in buildings that allow better assessments of new building designs and technologies.
- European groups such as the British Research Establishment and Passive House International are doing work in this area.
- U.S. EPA, DOE, HUD, CMHC, NRC Canada, and energy groups in the Pacific Northwest and other U.S. regions may be interested in co-funding projects on overheating problems in low-energy buildings.

ASTM Standards:

- E631 Terminology of Building Constructions
- E1334 Practice for Rating the Serviceability of a Building or Building-Related Facility
- E1480 Terminology of Facility Management (Building-Related)
- E1679 Practice for Setting the Requirements for the Serviceability of a Building or Building-Related Facility

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[257] http://www.nist.gov/el/building_environment/heattrans/netzero.cfm.

[258] Zero Carbon Hub, January 2012. Mechanical Ventilation with Heat Recovery in New Homes, Interim Report. Ventilation and Indoor Air Quality Task Group. http://www.zerocarbonhub.org/news_details.aspx?article=28.

[259] Mjornell and Kovacs. SQUARE QA System in Swedish Pilot Project. http://www.iee-square.eu/InformationPublications/Presentations.asp.

[260] Arens E, 2012. Air movement as an energy-efficient means toward occupant comfort (in progress). http://www.arb.ca.gov/research/single-project.php?row_id=65025.

TOPIC: AIR CLEANING

PRIORITY RESEARCH: ASSESSMENT AND DEMONSTRATION

Specific Regulatory or Policy-related Needs

Current Title 24, CalGreen, and Cal OSHA regulations require some air filtration for ventilation systems. Research has shown high levels of particulate matter along busy roadways, with high diesel truck traffic resulting in elevated levels of particulate matter in buildings close to those roads. In addition, outdoor air pollution can be brought into buildings and is a concern in high-pollution areas. Retrofit and commissioning programs for existing buildings have opportunities to improve air filter installations and removal efficiency. The state programs that develop these regulations, along with local governments and school districts that implement the regulations, need science-based recommendations on optimum filter efficiencies that consider future trends in outdoor air quality and energy and maintenance costs.

Critical needs include R&D to (1) demonstrate filter upgrades that improve IEQ in existing buildings for the growing weatherization, PACE, and ESCO programs, and (2) determine the optimum approaches for air cleaning, especially for vulnerable populations in homes, schools, and retirement/extended care homes in high pollution areas.

Description: Objectives and General Approach

The overall objective of this research area is to identify energy-efficient, highly effective ways to reduce infiltration of pollutants and to reduce pollutants being recirculated within buildings. This work includes: (1) modeling of IAQ, energy, and cost impacts to assess the effects of air cleaner installation quality, removal efficiency, and building and duct leakage in residential and commercial buildings, (2) field studies to identify IEQ and air cleaner performance and user behavior in new and existing buildings, before and after commissioning, changes in filter efficiency and type, and other interventions, and (3) demonstration studies of recommended air cleaner approaches over multiple years.

Why the Research Area Is Considered a Priority

Health and safety issues. Air cleaners in HVAC systems help reduce the level of indoor air pollutants from outdoor and recirculated air, primarily for particulate matter pollution.[261] However, air filters in commercial and residential buildings often have very low removal efficiency for particulate matter due to low efficiency ratings, air leakage or bypass, and poor maintenance. In addition, air filtration will become more important in the future because outdoor air pollution in California is expected to worsen due to more dense land development, population growth, and possibly climate change impacts.

Guideline Needs. Voluntary guidelines and green building programs also need science-based recommendations for air cleaners, both for air cleaners in HVAC systems and for stand-alone

[261] http://eetd.lbl.gov/ie/viaq/v_filtration_1.html.

air cleaners. These voluntary programs address the needs of sensitive populations, such as asthmatics, and of builder using advanced design and new technologies.

High-Priority R&D Project Areas

Evaluate the effectiveness and cost of upgrading air cleaners in high pollution areas (near roadways, rail yards, industry, agriculture, etc.), including field performance of particle filtration over time.

Evaluate the effectiveness and cost of active VOC air cleaners alone and in combination with PM filtration.

Assess the noise impact of various air cleaning technologies for both particles and VOCs when evaluating effectiveness.

Assess the effectiveness of passive air cleaning techniques for VOCs, ozone, NO_2, etc. (e.g., ceiling tile).

Determine the IEQ and energy performance of UV technologies for removing microbial contaminants from air and/or surfaces.

Lower-Priority Research Projects

- Evaluate the long-term energy and air quality performance of high efficiency filters and portable air cleaners.
- Assess the removal of ultrafine PM and the reduction in personal exposures, symptoms, and health effects by portable air cleaners and HVAC air cleaners/filters.
- Determine the best combination of mechanical ventilation and filtration for most common applications.
- Examine user behavior impacts on the IAQ and energy performance of air cleaning and filtration technologies.
- Assess the benefits and risks of tighter envelopes for reducing penetration of outdoor air pollutants (super-tight homes of the future).
- Test the effectiveness of air filtration technologies used in schools.
- Evaluate the effectiveness of exhaust filtration for gas stoves.

Related R&D Areas, Topics and Projects

All Areas, but especially Ventilation and Operation and Maintenance.

- Develop and demonstrate methods to ensure reliable usage and performance of ventilation systems.

- Develop Best Practice Guidelines for IEQ in Installation, Commissioning (Cx), Weatherization (Wx), and O&M.
- Develop and demonstrate methods to ensure reliable usage and performance of ventilation systems

Related Work

ARB/UCD (Bennett) Study "Benefits of High Efficiency Filtration to Children with Asthma," to examine effectiveness of both central and portable high-efficiency filtration systems in reducing pollutant exposures and asthma symptoms in children with asthma. Expect completion in 2016.

ARB/LBNL (Singer and Walker) Study on "Reducing In-Home Exposure to Air Pollution." Study of the effectiveness of various types and combinations of residential mechanical ventilation systems and high-efficiency filtration systems. Expect completion in 2015.

ARB is funding a $3.35 million study that will examine the effectiveness of high-efficiency filtration in reducing particles and ozone in 200 homes of children with asthma in Fresno and Riverside.

CEC/DOE/LBNL: Healthy Zero Energy Buildings (HZEB, commercial), Healthy Home (multifamily), and RESAVE (residential) projects.[262]

CMHC HRV air filter study.[263]

Northwest Energy Efficiency Alliance: Planned study on performance of mechanical ventilation in homes. Contact: Charlie Stephens.

CMHC Equilibrium Sustainable Housing Demonstration Initiative.[264]

NRC Canada: Field Study on Indoor Air Quality, Ventilation and Health.[265]

Intelligent Energy Europe: Square QA System for Retrofitting Multifamily Homes.[266]

Test methods and filter effectiveness research: Jeff Siegel, University of Texas, Austin.[267]

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[262] http://hzeb.lbl.gov/; http://apartmentenergy-ieqretrofits.lbl.gov/projects; http://resave.lbl.gov/

[263] CMHC 2006.Identifying and Removing Pollutants from Heat Recovery Ventilators. Research Highlight, Technical Series 06-103. http://publications.gc.ca/collections/Collection/NH18-22-106-103E.pdf?.

[264] http://www.cmhc-schl.gc.ca/en/inpr/su/eqho/.

[265] http://archive.nrc-cnrc.gc.ca/eng/projects/irc/air-initiative/fieldstudy.html

[266] http://iee-square.eu/InformationPublications/Reports/SQUARE_Energy_Improvement_Measures_Indoor_Environment_EN.pdf.

[267] http://www.caee.utexas.edu/igert/projects.cfm.

SCAQMD Pilot Study of High Performance Air Filtration for Classrooms.[268]

Other R&D programs:

- U.S. EPA, DOE, HUD, NIOSH, National Center for Healthy Housing, CHPS.
- Various low-energy and zero energy building projects in California, U.S., and abroad. Energy and/or IEQ projects by California State and local government, universities, and utilities in new and existing buildings.
- ASHRAE and HVAC manufacturers.

[268] www.aqmd.gov/rfp/attachments/2010/AQMDPilotStudyFinalReport.pdf.

TOPIC: AIR CLEANING

PRIORITY RESEARCH: TECHNOLOGY DEVELOPMENT

Specific Regulatory or Policy-related Needs

Current regulations in California require a certain level of filter particle removal efficiency (Minimum Efficiency Reporting Value [MERV] rating) but do not require ventilation systems to have air-cleaning capacity for episodic events or VOCs. Cal/OSHA has developed guidance for commercial building operators for wildfire events that allows temporary reductions in outdoor air ventilation rates while still providing exhaust ventilation for bathrooms and other areas that require negative air pressure. Retrofit and commissioning programs for existing buildings have opportunities to improve air filter installations and filter efficiency, and to address future needs related to climate change. State and local agencies and school districts that address the needs of sensitive populations need science-based recommendations on best practices and technologies that can improve air cleaner performance.

Critical needs include (1) development of air cleaner technologies with increased particle and VOC removal efficiency, lower cost, and lower energy use, and (2) improved practices for installing, operating, and maintaining air cleaners.

Description: Objectives and General Approach

The overall objective is to accelerate improvements in the technology and the practices of air cleaning in order to improve field performance of filters and air cleaners. White papers on potential improvements to central air and VOC filter performance should be produced. Improved installation and O&M practices can be developed. Lab and field studies of new technologies to reduce air cleaner energy use and to remove VOCs must be conducted. Demonstration studies with multi-year follow-up to examine measure persistence should be conducted. Lessons learned and best practices can be published, and demonstration buildings can be used for professional training and public education.

Why the Research Area Is Considered a Priority

Health and Safety Issues. Air filters in HVAC systems and stand-alone air cleaners are used to control air pollutants from common outdoor sources such as combustion pollution, wood smoke, and seasonal pollen and mold. Future climate change is expected to increase episodes of outdoor air pollution from smog, wildfires, and dust storms. Improved filter performance for particulate matter (PM) and ozone removal is needed to address these challenges. Measures to address practices that lead to improper filter selection, installation (air bypass), and lack of maintenance are also needed to achieve IEQ design goals.

In addition, the increasing use of building materials, cleaning products, and other consumer products that emit volatile organic compounds (VOCs) has created a demand for air cleaners that can remove VOCs from indoor air. Volatile organic compounds and their reaction by-products are associated with increased irritation symptoms and complaints in commercial buildings, and some VOC and SVOC compounds also have chronic health effects such as cancer. Some technologies can remove VOCs, but they need to be evaluated for effectiveness, reliability, and production of ozone or other toxic by-products. Some of the most effective technologies are expensive and/or create a significant pressure drop.

Guideline Needs. Voluntary guidelines and green building programs also need science-based recommendations for air cleaner best practices and technologies. Some voluntary programs address the needs of sensitive populations, such as asthmatics, and of builders using advanced design and new technologies.

High-Priority R&D Projects

Demonstrate improvements in central air filter performance, e.g., reduced filter by-pass, routine maintenance, and higher particle removal efficiencies without increased energy use or cost.

Develop VOC air-cleaning technologies that are effective, do not produce toxic or irritating by-product emissions, reduce energy use, and are cost effective. Focus on VOCS that are emitted from indoor sources, have concentrations affected by building ventilation rates, and affect perceived air quality and/or health.

Lower-Priority Projects

- Develop and demonstrate practical technologies for reducing ozone from air passing through HVAC systems or from indoor air.
- Develop air-cleaning technologies that do not degrade the quality air that passes through the filter over its lifetime.
- Assess and demonstrate approaches for sensing the loading of filters and improving filter maintenance practices.
- Develop practical and effective gas phase air-cleaning systems for formaldehyde.
- Improve understanding of the mechanisms of particle removal in relation to filter material, fiber size and shape, pattern, and other aspects of the media used.
- Evaluate the efficacy of new materials now marketed as capable of removing VOCs from indoor air.

Related R&D Topics and Projects

All categories, but especially Air Cleaning – Assessment and Demonstration, and Ventilation.

Develop Best Practice Guidelines for IEQ in Installation, Commissioning (Cx), Weatherization (Wx), and O&M.

Demonstrate methods to improve the performance and reliability of venting systems for cooking appliances and high-moisture areas, such as low-noise fans, automatic controls, and high-removal-efficiency range hoods (grease hoods may be an issue for HRV systems).

Related Work

ARB: Ozone from In-Duct Air Cleaners.[269]

LBNL: Photocatalytic Air Cleaner Development.[270][271]

PIER/DOE/LBNL: Healthy Zero Energy Buildings (HZEB, commercial), Healthy Home (multifamily), and RESAVE (residential) projects.[272][273]

ARB/LBNL: (Destaillats) "Evaluation of Pollutant Emissions from Portable Air Cleaners" http://www.arb.ca.gov/research/single-project.php?row_id=65032 . Expect completion in 2013.

NRC Canada, Institute for Research in Construction: Air cleaner test method.[274]

CMHC Equilibrium Sustainable Housing Demonstration Initiative.[275]

NRC Canada: Field Study on Indoor Air Quality, Ventilation and Health.[276]

Integrative Graduate Education and Research Traineeship (IGERT) Program, University of Texas, Austin: Jeff Siegel.[277]

Portable HEPA and outdoor air cleaner.[278]

Other R&D Programs

- EPA, DOE, HUD, NIOSH, National Center for Healthy Housing.
- Syracuse University air cleaning R&D projects.[279]

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269 ARB/Morrison et al., in progress. http://www.arb.ca.gov/research/single-project.php?row_id=64860.

270 http://eetdnews.lbl.gov/nl29/eetd-nl29-4-pco.html.

271 Berdahl, P., and H. Akbari, 2008.Evaluation of Titanium Dioxide as a Photocatalyst for Removing Air Pollutants. California Energy Commission, PIER Energy-Related Environmental Research Program. CEC-500-2007-112.

272 http://eetdnews.lbl.gov/nl29/eetd-nl29-4-pco.html.

273 http://hzeb.lbl.gov/; http://apartmentenergy-ieqretrofits.lbl.gov/projects; http://resave.lbl.gov/

274 http://www.nrc-cnrc.gc.ca/ci-ic/v16n3.

275 http://www.cmhc-schl.gc.ca/en/inpr/su/eqho/.

276 http://archive.nrc-cnrc.gc.ca/eng/projects/irc/air-initiative/fieldstudy.html.

277 http://www.caee.utexas.edu/igert/projects.cfm.

278 http://www.hepairx.com/Research-Studies.

279 http://www.syracusecoe.org/coe/sub1.html?skuvar=130; http://www.syracusecoe.org/coe/sub1.html?skuvar=32.

- ASHRAE and HVAC manufacturers.
- Various low-energy and zero energy building projects in California, U.S., and abroad.
- Energy and/or IEQ projects by California State and local government, universities, and utilities in new and existing buildings.
- CHPS and local school districts.
- American Lung Association.

TOPIC : TOOLS, METHODS, SENSORS.

PRIORITY RESEARCH: OPERATIONS AND MODELING

Specific Regulatory or Policy-related Needs. Modeling and simulation are essential for demonstrating compliance with energy regulations. These regulations should be supplemented with requirements for modeling of indoor environmental quality, with an emphasis on indoor air quality and thermal conditions.

Why the Research Area Is Considered a Priority

Health and Safety Issues. Design methods are an essential part of energy analysis. There are many tools available to model energy use in relation to some or most of the following: facade elements, roofs, insulation values, ventilation rates, or thermal conditions. However, there are no tools that integrate all of these and include indoor air quality. Such tools require assumptions about indoor pollutant sources and their strengths, outdoor air quality, climate, etc. To include energy and the full range of indoor environmental conditions in a single model would provide a significant benefit to designers. Such tools would be most useful if they allow simulations using a wide range of values for various input parameters.

Guideline Needs. Researchers can use sophisticated tools to model a range of designs and provide guidance in the form of tables or rules of thumb to enable designers to start with some preliminary knowledge of the energy and IEQ

COMFEN, an LBNL model that simulates energy use, thermal comfort, and lighting quality, goes part of the way but stops at the envelope.[280] It could be amplified or augmented to enable modeling and simulation of indoor air quality, thermal conditions, and projected climate changes CONTAM, a NIST model for contaminant transport within buildings, also enables researchers to do sophisticated modeling.[281]

High-Priority Project

Develop checklists for IAQ component of commissioning and retro-commissioning (could be added into the green building code)

Lower-Priority Research Projects

Develop tools, models, etc. to predict indoor environmental quality to be built into the energy models for building simulation and/or operation.

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[280] http://windows.lbl.gov/software/comfen/comfen.html. Includes tutorial/demonstration.

[281] NIST, CONTAM [http://www.bfrl.nist.gov/IAQanalysis/CONTAM/]

Integrate flue simulation models into CONTAM.[282]

How do you operate ventilation in mixed mode buildings where people also operate windows to address thermal comfort criteria? The issues are all linked together. Need guidance for design and O&M communities on the best strategies.

Develop guidelines for manufacturers to use in developing Environmental Product Declarations (EPDs) for products used in and within buildings. Guidelines are needed to ensure EPDs provide relevant, verified and comparable information about environmental impacts of these products.

Best practices, green-building standards, and guidelines. Need effective commissioning procedures for new structures.

Description: Objectives and General Approach

Review existing tools to determine the best candidates for inclusion in a set of integrated design tools. There are abundant tools for energy modeling and for lighting design, but existing tools do not enable the integration of energy, thermal comfort, and indoor air quality in a comprehensive simulation tool. Computer-assisted design and other software already in common use can be integrated with energy, thermal comfort, lighting, and IAQ modeling tools to provide integrated software useful for researchers. Research using such tools can result in the production of guidelines for designers, building operators, and even policy-makers.

Related R&D Project Areas and Topics

Tool-Development and Demonstration

Ventilation

Thermal Conditioning

O&M

Air Cleaning

Sources

Human Factors Metrics

Co-funding or Leverage Opportunities

NIST, DOE/LBNL, HVAC manufacturers.

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[282]*Op Cit.*

PIER/DOE/LBNL: Healthy Zero Energy Buildings (HZEB, commercial) and RESAVE (residential) projects.[283]

NIST NZEB, High Performance Building Project.[284]

The IEAA Passive-On project: Passive House design in warm climates in Europe.[285][286]

CMHC Equilibrium Sustainable Housing Demonstration Initiative.[287]

NRC Canada: Field Study on Indoor Air Quality, Ventilation and Health.[288]

Active House project.[289]

Related Work

Various EU projects that involve IEQ or exposure, or health risk modeling.[290]

NIST Metrics and Tools for Sustainable Buildings Program.[291]

NIST CONTAM validation in manufactured homes – Persily et. al

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[283] http://hzeb.lbl.gov/; http://apartmentenergy-ieqretrofits.lbl.gov/projects; http://resave.lbl.gov/

[284] http://www.nist.gov/el/building_environment/heattrans/netzero.cfm.

[285] http://www.passive-on.org/en/cd.php, see Browse CD link for guidelines, results, etc.

[286] Schneider J, 2009. Passive Houses in South West Europe.http://www.passivhaustagung.de/Passive_House_E/PH_MedClim.html.

[287] http://www.cmhc-schl.gc.ca/en/inpr/su/eqho/.

[288] http://archive.nrc-cnrc.gc.ca/eng/projects/irc/air-initiative/fieldstudy.html.

[289] http://activehouse.info/knowledge.

[290] Kephalopoulos K et al., 2011. EC Actions on Indoor Air Quality. http://www.inive.org/members_area/medias/pdf/Inive/EnVIE/Kephalopoulos.pdf.

[291] http://www.nist.gov/el/economics/metrics_for_sustainable_bldg.cfm

TOPIC: TOOLS, METHODS, SENSORS

PRIORITY RESEARCH: TOOLS: DEVELOPMENT AND DEMONSTRATION

Why the Research Area Is Considered a Priority

Health and safety issues. Inaccurate or inadequate measurements currently are common in building technologies that control the operation of a building (e.g., unreliable CO_2 sensors for demand controlled ventilation, now increasingly common in densely occupied spaces). Building investigators addressing complaints or inadequacies in buildings are often limited by the instruments available to them or the means to properly utilize available tools. Both cost and technology development limits of these types result in poorly performing buildings that neither meet energy or other regulations and that often have poor indoor air quality.

Specific Regulatory and Policy-related Needs. Regulations mandating specific IEQ performance or IEQ-relevant building performance should be supported with tools for verification of the required or targeted performance levels. ASHRAE has developed IEQ and energy performance measurement and verification guidance documents, but the indoor air quality portions of the available guidance are the least well-developed and practical for field application.[292] Furthermore, they provide the lowest level of assurance that IAQ is healthy for building occupants.

Guideline Needs. This project area has a number of different research Projects that can lead to tools that should be applied in the design and operation of both residential and non-residential buildings to achieve improved indoor air quality or can be applied in research to advance the procurement of new and necessary knowledge.

High-Priority Research Projects

Occupants as sensors in real time as sensors for thermal comfort and perceived air quality with input to building energy managements systems.

Indicator lights, dashboards; fault detection, warnings/alarms/alert, attention required.

IAQ “Tricorder,” i.e., a handheld device for measuring multiple key parameters, performing data analysis and diagnostics, and recording data.

Standard static pressure ports in duct work to simplify measurement, critical in HVAC system commissioning for both residential and non-residential buildings.

Improved algorithms in variable-air-volume systems.

Stealth (automatic, remote) versus learning-opportunity-type (display, dashboard, interactive, etc.) control systems

[292] ASHRAE, 2010, Performance Measurement Protocols For Commercial Buildings. http://www.techstreet.com/products/1703581

Monitor and sensor technology

There are numerous technologies that either do not currently exist or require improvement in performance or reduced cost in order to be useful for research or building applications. This project area identifies a number of these technologies (e.g., an inexpensive, multi-pollutant, portable, accurate, real-time monitor, stable, reliable CO_2 sensors, sensors for other chemicals of concern) some of which are currently beyond practical achievability but represent such an important idea that if it were to be developed, it would make a very great difference.

This project area includes a number of different research topics that can enable advances in both research and practice.

Related R&D Project Areas and Topics

Tools: Design and Operation

Ventilation

Thermal Conditioning

O&M

Air Cleaning

Sources

Behavior

Metrics

Co-funding or Leverage Opportunities

- NIST, DOE/LBNL, Argonne National Laboratory, HVAC manufacturers.
- PIER/DOE/LBNL: Healthy Zero Energy Buildings (HZEB, commercial) and RESAVE (residential) projects.[293]
- NIST NZEB, High-Performance Building Project.[294]
- The IEAA Passive-On project: Passive House design in warm climates in Europe.[295][296]

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[293]http://hzeb.lbl.gov/; http://apartmentenergy-ieqretrofits.lbl.gov/projects; http://resave.lbl.gov/

[294] http://www.nist.gov/high-performance-buildings_pp.cfm

[295] http://www.passive-on.org/en/cd.php, see Browse CD link for guidelines, results, etc.

[296] Schneider J, 2009. Passive Houses in South West Europe.http://www.passivhaustagung.de/Passive_House_E/PH_MedClim.html.

- CMHC Equilibrium Sustainable Housing Demonstration Initiative.[297]
- NRC Canada: Field Study on Indoor Air Quality, Ventilation and Health.[298]
- Active House project.[299]
- ASHRAE 1565-TRP (rebid), "Development of the ASHRAE Design Guide for Dedicated Outdoor-Air Systems." [300]

Related Work

Various EU projects that involve IEQ or exposure, or health risk modeling.[301]

NIST Metrics and Tools for Sustainable Buildings Program.[302]

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[297] http://www.cmhc-schl.gc.ca/en/inpr/su/eqho/.

[298] http://archive.nrc-cnrc.gc.ca/eng/projects/irc/air-initiative/fieldstudy.html. SUNDAY NIGHT

[299] http://activehouse.info/knowledge.

[300] http://www.ashrae.org/File%20Library/docLib/Research/Fall2011RFPs/1565-TRP.pdf.

[301] Kephalopoulos K et al., 2011. EC Actions on Indoor Air Quality. http://www.inive.org/members_area/medias/pdf/.../Kephalopoulos.pdf.

[302] http://www.nist.gov/el/highperformance_buildings/performance/metrics_for_sustainable_bldg.cfm.

TOPIC: LIFE CYCLE /CROSS-CUTTING ISSUES

PRIORITY RESEARCH: METRICS

Specific Regulatory or Policy-related Needs.

Life cycle / Cross-cutting is a topic created to embrace a wide range of research needs covered in other Topics and Research Project descriptions but which lack sufficient focus on the full life cycle of a building or where there are tools and metrics that could serve a variety of the specific Research Projects.

Why the Research Area Is Considered a Priority

Health and safety issues. Indoor environmental quality metrics based on appropriate methods of measuring or assessing indoor air quality, thermal comfort conditions, ventilation, and noise are needed to evaluate buildings and building technologies. Common IEQ metrics would allow IEQ to be compared among different time periods and among different buildings.

Metrics that address IEQ over a product's life cycle are also needed to address long-term health and safety concerns. The process of aging and use will change the IAQ-relevant performance of a product. Emissions testing is focused on products when they are newly manufactured, but full life-cycle characterization is not currently done. Additional focused attention is needed for the evaluation of materials with respect to their cleaning potential and requirements, maintenance, use, refinishing, and other periodic functions over the length of the service life of a material or product. Software tools compatible with computer-assisted design (CAD) can be developed to allow modeling of the materials as used in specific building designs. Such tools have been developed and used in Europe.[303] Building information database development provides a platform for integration of building components into such analyses.

Material emissions are often taken as an indicator of the IAQ implications of a material. However, over the full life cycle, chemicals used for care and maintenance of the product may be of greater significance for IAQ.

Ventilation can significantly alter exposures to pollutants from indoor sources. Ventilation generally changes over time, but characterization of ventilation at a single time does not necessarily provide necessary information for determining average or peak pollutant exposures. Natural ventilation in buildings with multiple spaces is difficult to characterize. Measurements of air changes per hour or per occupant are imprecise and subject to short-term variations as a result of openings in the building envelope or wind direction and velocity.

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[303] Both the Dutch software program, EcoQuantum (developed for life-cycle assessment of materials used in houses by the environmental institute, IVAM, at the University of Amsterdam) and LEGOE software (developed in Germany for use with CAD software) were developed for design professionals and in use in the late 1990s. EcoQuantum included a component specifically addressing indoor air-quality impacts of materials as used in a building design.

Considering the full life cycle of a material has multiple health and safety considerations. For example, many energy-efficient lighting technologies are associated with the toxic chemicals required in their production or final product. When these devices fail or are broken, toxics may be released. A good historical example is the PCBs used in transformers for fluorescent lights.

Metrics will primarily serve the needs of researchers and policy-makers. It is unlikely that building professionals will use metrics and life cycle impact assessments (LCIAs) unless they are very simple. As more useful and robust metrics become available, the results of their use can be the basis for policy considerations, standards, guidelines, and demonstration projects.

Identify any specific regulatory or policy-related needs.

Regulatory changes are not indicated at this time. As data becomes available on low-energy buildings, this potential need should be reexamined.

Guideline needs. Sources of pollutants cannot be assessed adequately simply by measuring emissions from new products. Guidelines are need for life-cycle assessment of IAQ performance. One key concern is with the lack of basic information about health risk, emissions, microbial contamination resistance, durability, and other factors that would be needed to develop metrics, the calculation methods will need to be complex. It is unlikely that building professionals will use metrics and LCIAs unless they are very simple. Metrics will primarily serve the needs of researchers and policy-makers.

High Priority Projects

Define, develop, and demonstrate IEQ metrics for Commissioning.

Define, develop, and demonstrate IEQ metrics for Life-Cycle Impact Assessment in product selection and building rating systems, especially for performance verification.

Lower-Priority Research Projects

Perform analyses and develop tools that enable consideration of benefits and costs decision making about building design, retrofit, and operation. Analyze data from case studies and surveys.

Description: Objectives and General Approach

New metrics need to be developed, starting with an overview or white paper to frame a research agenda and build on previous research on IEQ metrics, especially health-based metrics.

Life-cycle assessments generally fail to consider IAQ performance of a material in the use phase. This major shortcoming will be addressed by software tools that model and analyze materials as used in a building design or completed building. Materials must be evaluated as used in the actual building in order to model their full life-cycle IAQ and energy implications. Software tools compatible with computer-assisted design (CAD) must be developed that allow modeling of the materials as used in specific building designs. Building information modeling (BIM) provides a platform for integration of building components into such analyses.

A full life-cycle analysis of the IAQ performance of building components and equipment will be conducted. Energy-related technologies will be evaluated as used in specific building designs for time periods spanning their full lives, including not only energy implications but also IAQ.

Related Work

IEA Workshop on Co-Benefits of Weatherization[304]

[304] http://www.iea.org/papers/2011/low_income_energy_efficiency.pdf

TOPIC: CROSS-CUTTING

PRIORITY RESEARCH: HUMAN FACTORS / BEHAVIOR

Specific Regulatory or Policy-related Needs

While many behaviors that influence energy use and IEQ (such as building operation, incentives for behavioral changes) are already addressed in policy (e.g., through pricing of energy, restriction on the sale of strong formaldehyde emitting composite wood products), behavior is largely unaddressed by policy and regulation. Nevertheless, it is clear that behavior can undermine or overwhelm even the "smartest" and most efficient technologies including specific devices, designs, and systems. It is clear from examination of the available research and the potential IEQ impacts of potential energy efficiency measures available for Energy Commission consideration, that a substantial effort devoted to research on all the potential means of influencing behavior can do far more than technology alone to achieve energy efficiency goals while also protecting occupant health. Therefore, this topic, although nearly last in this report, should be considered together with and in addition to all other possible research identified heretofore.

Why the Research Area Is Considered a Priority

Health and safety issues – perception that low-energy buildings will have IEQ problems that need to be addressed. The decisions and actions of building owners, operators, and users greatly impact both energy efficiency and indoor environmental quality. These impacts will continue and may become even more important as buildings become more sophisticated and expectations about building performance rise. Despite the centrality of behavior to building performance, the study of these relationships remains outside the scope of many research programs. An improved understanding of the myriad ways that people interact with building systems is critical for California to achieve low-energy use buildings that protect health and productivity. It is therefore critical for PIER to fund research in this area.

There is a strong connection between behavior and integrated design as an important decision point and this connection could be a focus of behavioral research. Research should extend to the critical role that building operators should have in this process, yet operators rarely participate on integrated design teams. It would be useful for research to identify critical decision points (i.e., design, construction, handoff, early occupancy, stabilized occupancy, commissioning, minor renovation, major renovation, decommissioning) and then try to map which stakeholders are involved at each point, and what decisions are being made that have the greatest energy/IEQ impacts. That kind of framework would help organize activities of behavior researchers, and where PIER wants to focus

Many (arguably most) important decisions made regarding IAQ and occupants' exposures to pollutants indoors are predominately made by occupants and building operators. Occupants' and building operators' decisions and actions affect and often dominate the most important determinants of indoor air quality: ventilation regimes and pollutant source generation indoors. Actions by occupants commonly defeat the intent of codes and building design, construction, and operations professionals, resulting in exposure to hazardous pollutants emitted from building materials, furnishings, equipment, and sources associated with occupant activities.

Ventilation rate reductions are often the target for achieving low-energy commercial buildings. In residential buildings, building and duct tightness and insulation are major targets too. This was the case of responses to the early and late 1970s energy crises. As ventilation rate reductions are implemented, indoor pollutant sources will more strongly influence indoor air quality.

Building occupant and operator behavior strongly determine the most important factors affecting indoor air quality including the nature and strength of indoor pollutant sources, building design, construction, operation, and use. The selection and use of products, equipment, and procedures for cleaning, maintenance, and cooking; personal hygiene and cosmetics; pest control; and many other occupant-influenced and controlled activities have important implications for indoor air quality and exposure to indoor pollutants. Many pollutants from these common sources are among the most important, from a health perspective.

Occupants often control ventilation and thermal conditions. These, in turn, affect dilution and exhaust ventilation, as well as the emission source strengths and the impacts on exposed individuals.

Cleaning and maintenance practices are strongly influenced (if not almost completely controlled) by behavioral factors. The impacts of cleaning and maintenance are strongly determined by the selection and use of equipment and materials, frequency and thoroughness, and timing in relation to occupancy and ventilation system operation. Maintenance also includes selection and timing of filter replacement, ventilation system adjustment, and repairs.

In spite of the recognized importance of building occupant and operator behavior, there is a paucity of research on the effects of behavior on indoor air pollutant exposures resulting in health effects. Much of the relevant existing research on building occupant and operator behavior focuses on operation of equipment such as ventilation systems, exhaust systems, etc. and their effect on energy use.

National Academy of Sciences studies in the early 1980s documented the importance of behavior on energy conservation and use. [305]

The need for research in this area is strongly related to the lack of such research historically. While there is a substantial amount of research on the relationship between behavior and energy use going back more than 40 years (NAS 1984; 1985), there is a paucity of research on

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[305] Paul C. Stern and Elliot Aronson, Editors, Energy Use The Human Dimension. Committee on Behavioral and Social Aspects of Energy Consumption and Production, Commission on Behavioral and Social Sciences and Education, National Research Council. ISBN [0-309-11694-5] 250 pages, 6 x 9, (1984) http://www.nap.edu/catalog/9259.html.

behavior and IAQ. Much of what we know is by inference from studies that were not designed to enhance our understanding of behavior and how to influence it.

Efforts to accelerate the achievement of NZEBs are at risk of increasing IEQ problems, as was seen in the responses to the energy crises of the 1970s. Focusing on technology alone brings with it the danger of its misuse and abuse with undesirable health outcomes. There is a need to learn how to most effectively market good IEQ behavior and to develop a NZEB marketing plan that addresses IEQ as well as comfort and low energy use and cost.

Identify any specific regulatory or policy-related needs

Most regulatory needs for behavioral factors are related to controlling access to ventilation system operation in centralized systems; supplementing available information to inform occupants of the impacts of their behavior on indoor air quality and health; and identifying pollutants and their sources of significance for health. An important illustration of the effectiveness of regulatory policy is the restriction on smoking in public spaces. No such restriction exists in single-family dwellings, so many children of smoking parents are exposed to environmental tobacco smoke at concentrations well established as hazardous to the children's health. Recent California data indicate that a large percent of parents go outside the home to smoke (http://www.healthpolicy.ucla.edu/pubs/files/secondhandsmokepboct2011.pdf), although indoor surfaces may still be contaminated with the smoke, which can lead to third-hand smoke (remissions and reaction by-products) (Matt et al. 2004), http://tobaccocontrol.bmj.com/content/13/1/29.abstract. Also, new California law allows apartments to restrict smoking.

Guideline needs

Activities associated with pollutant sources can be identified and information can be provided to assist those engaged in such activities to understand the hazards associated with the activities and the measures that can be taken to minimize pollutant generation and exposure.

While it may be politically difficult to restrict smoking in private residences, it is important for smokers to be aware of the hazards posed to those around them by their smoking indoors. This is especially true for children of smokers. There is evidence that such information can influence smokers' behavior.

Behavior is the dominant factor in the selection of low or no emission materials. The use of solvents pesticides and other hazardous materials is often carried out in contradiction of instructions for use ("use in a well-ventilated space," "avoid inhalation," "avoid dermal contact," etc.). Consumer choices are often dominated by functions of products relative to the consumer's needs and do not always include any or adequate consideration of health consequences. More public awareness of the implications of selection of building materials and consumer products can be achieved with publication and dissemination of fact sheets, consumer advisories, and public service announcements.

Nongovernmental organizations serving asthmatics have been reasonably effective in "selling" the correct behavior messages for those whose acute and chronic health condition is most sensitive to harmful exposures. Other populations at risk, such as children and the elderly, should be provided more guidance to inform their behaviors that influence indoor air quality and pollutant exposure.

Ventilation system operation failures are often attributable to occupant/operator behavior that stems from a lack of knowledge or understanding. Examples include use of exhaust ventilation during such activities as cooking and bathing to reduce moisture accumulation or supply of outdoor air during cleaning, hobby, personal hygiene, and other activities involved in the use of potential sources of indoor air pollutants.

High Priority Research Projects: Behavior Group

Identify key behavior determinants of IEQ- and energy-related behavior at various decision points:

Investigate occupant and operator habits and their effects on IEQ and energy use in various building types, including residential (single-family dwelling and multifamily dwelling), schools, daycare, retirement homes, and offices, among others. Consider a white paper on the behavioral issues related to energy-related IEQ?

(Related project from Ventilation group): Assess the impacts of weatherization in multifamily buildings, e.g., inter-floor differences in radon due to stack effects, IAQ differences due to changes to ventilations systems, building shells, and occupant behavior.

Description: Objectives and General Approach

There are two very broad categories of research falling under this area: (1) improving the base of knowledge about how human behavior impacts energy and IEQ in buildings, and (2) improving our understanding of what key "agents" in the process—including owners, builders, designers, operators and users—know about the impacts of their decisions and actions and about how they consider those impacts when acting.

In all of the categories of impacts described above, there exist the following elements related to behavior:

- It is essential to develop a better understanding of what is known or understood by the decision maker or "agent" about the actual impacts of their decision / action on energy or IEQ performance. Decision makers include designer, building owner, operator, or occupant.

- Research needs to be conducted to determine how does an agent obtain information about energy and IEQ impacts. We need to find out if the state can improve the accessibility of information available to these agents.
- Research should study the question of what bases (if any) agents consider energy and IEQ impacts. We also need to learn what other elements are being considered.

In spite of the recognized importance of building occupant and operator behavior, there is a paucity of research on the effects of behavior on indoor air pollutant exposures resulting in health effects. Much of the relevant existing research on building occupant and operator behavior focuses on operation of equipment such as ventilation systems, exhaust systems, etc. and their effect on energy use.

A process should be established to develop communication between engineers and behavioral and social scientists (e.g., a wiki may be needed).

Step 1: The human issues from zero energy building (ZEB) will emerge over time, and an effort has to be made to find them before they blow up in everyone's faces; for example, through a highly publicized cluster of serious health events in ZEBs.

Some of this effort should be analytical work by toxicologists, combustion and ventilation engineers, etc. Some of it should involve careful monitoring of pilot buildings, first without and then with, real occupants. Some of it should probably involve creation of a stakeholder council of ZEB occupants and operators whose job it should be to anticipate concerns and make sure they are evaluated before they blow up. Zero energy building technical experts should engage these people in discussion as early as feasible in the process of developing ZEB technologies.

Step 2: Monitor and evaluate human behavior during the move to NZEBs. It is reasonable to predict that ZEBs will not be operated according to engineering specifications. They will require more careful monitoring and optimization than conventional buildings, but building managers and occupants are not ready to provide it. They will also require people to learn new behaviors, and not everyone will learn them. People will behave adaptively to the challenges they see, and there will be surprises. This means that in pilot buildings, there will need to be research on how managers and occupants actually do "drive" the buildings, because they will surely do some things the engineers have not anticipated, and some of those things will defeat the purposes of the ZEB engineering, cause avoidable negative health or comfort consequences, or both.

Step 3: Provide labeling and education that shows people how to do common things and use common products differently in ZEBs. It might be possible to anticipate the behavioral changes that will be needed, for example, with cleaning products that are usually used with high levels of ventilation, but it may not be easy to induce the behavioral changes. So there are research needs here, both for how the products should be used and on what it would take to get people to use them properly.

It is recommended that an advisory council including occupants be created along with a program of pilot monitoring and testing of ZEBs. This should create an on-going dialogue between these two activities (monitoring and testing) and with building designers and experts.

There is also a need for behavioral research of many kinds, only a few of which can be identified right now. More dialogue could produce better predictions, but behavioral observation will also be needed. And there should be an effort to anticipate show-stoppers on the human side: things that could besmirch the reputation of the whole ZEB movement.

Some questions that need to be answered:

- Why do people operate buildings in specific ways, e.g., energy or IEQ wise, or both?
- How to most effectively communicate appropriate behaviors; or, what kinds and means of communication are most effective in influencing the behaviors of different types of building operators, including facility operators, homeowners, and other occupants?
- What are the potential means (smart grid info, "smartphone" messaging, web access, barcode scan linked info, etc.) to deliver information when its needed to those whose decisions most influence building operation related to IEQ?
- What are the most convincing types of messages, i.e., the means to deliver adoption of "right" behaviors?
- How to reach under-served segments and high-risk segments of the population, and how to shift their awareness and decisions (note: low-income and some ethnic groups are hard to reach and influence). Mention CBSM (community based social marketing).

Related R&D Application Categories

It is not merely rhetorical to state that behavior is significant for all categories of potential research. The use of technology is strongly dependent on the activities of building occupants and operators.

Co-funding or Leverage Opportunities

The California Energy Commission is funding research to determine ventilation rates for energy (low-energy) or net zero energy buildings (NZEB).

There are several social science academic societies and groups within them with a strong interest in behavior. These include the American Sociological Society (especially the Environmental Division) and the American Psychological Society.

This area is ripe for funding by the National Science Foundation and for a review project by the National Research Council.

Several projects in progress or in the planning stage could be used as models or as platforms to obtain necessary data on human behavior aspects, e.g.,

a) DOE: LBNL studies of residential and commercial buildings; ORNL studies of Low Income Weatherization impacts on IEQ

b) Northwest Energy Efficiency Portland, Oregon: Planned project to evaluate residential ventilation system use and performance. Contact: Charlie Stevens.

c) British Research Establishment project on PassivHaus demo homes in Wales that will be studying behavior, IAQ, energy use: http://www.building4change.com/page.jsp?id=795

d) Dutch projects on HRV use: Bogers et al., *Proceedings of Indoor Air 2011*

e) Dutch RIVM/BBA projects, contact JaapBalvers, ab-bba@binnenmilieu.nl Active House demonstration projects, Measuring Life By Real People, http://www.activehouse.info/knowledge/measuring-life-real-people.

f) CPUC EE Strategic Plan and Action Plans have a marketing component (surveys and market development) that could include IEQ-related items.

TOPIC AREA: CROSS-CUTTING

PRIORITY RESEARCH: ASSESSMENT AND BENCHMARKING

Specific Regulatory or Policy-related Needs

As progress is made toward increasing the numbers of net-zero energy buildings, it is important to create a process to measure progress and identify changes, not only in energy efficiency or energy use intensity (EUI), but also the concomitant changes in the indoor environment. Identifying benchmarks for energy efficiency is relatively easy since energy consumption by sector can be obtained from utility companies through existing reporting mechanisms. But benchmarking and monitoring changes in IEQ presents substantial challenges due to the complexity of the indoor environment and the large number of variables relevant to assessing IEQ.

Why the Research Area Is Considered a Priority

Health and Safety Issues. Assessment and benchmarking are closely related priority research needs. Current information is absent or greatly lacking on IEQ and its determinants in most existing buildings in California, except for new single-family homes and K–12 classrooms. For example, pollutant source emission rate and ventilation rate are key determinants of IEQ, but we lack representative data for IEQ and such key factors in most building types. This is largely due to a lack of sufficient studies of various building-occupancy types and sizes, as well as the variations around the State. It is also related to the lack of affordable assessment methods and metrics.

The 2002 Research Roadmap Report, *Energy-Related Indoor Environmental Quality Research: A Priority Agenda*, ranked as high priority the need for benchmark studies including of small and medium commercial buildings. Since that time, there have been some studies of California portable classroom school buildings, as well as a single study of small and medium commercial buildings (SMCB). The SMCB Study found that among the building types studied (seven retail establishments; five restaurants; eight offices; two gas stations, hair salons, healthcare facilities, grocery stores, dental offices, and fitness gyms; and five other buildings), there are significant indoor air quality problems.[306][307] These problems are often associated with the diverse pollutants related to the specific building type (e.g., cosmetic products in hair salons; fine particulate matter in hair salons, restaurants, and dental offices) The researchers are also reported ventilation system deficiencies (design or operational) in most of the buildings studied, many due to inappropriate equipment selection or deficiencies in ventilation system operation.

Sixteen (43 percent) of the buildings were not designed to provide mechanically supplied outdoor ventilation air or did not do so. In some cases the air handling unit was a residential

[306] Bennett, Wu, and Trout, 2011; Indoor Environmental Quality and Heating, Ventilating, and Air Conditioning Survey of Small and Medium Size Commercial Buildings: Field Study. CEC-500-2011-043

[307] Bennett et al. 2012, Ventilation, Temperature, and HVAC Characteristics in Small and Medium Commercial Buildings (SMCBs) in California. *Indoor Air* (accepted for publication)

rather than a commercial model, thereby it failed to meet applicable ventilation standards. Low-efficiency air filters were frequently observed. The air exchange rate averaged 1.6, with a standard deviation of 1.7 exchanges per hour, and was similar between buildings with and without mechanically supplied outdoor air, indicating that small and medium sized commercial buildings have significant leakage, in contrast to California homes. Compared against Title 24 standards, healthcare establishments, gyms, offices, hair salons, and retail stores were ventilated below the required rates, not meeting Title 24 ventilation requirements; restaurants and gas stations had rates above the standard, meeting ventilation requirements." (*op cit*)

Indoor/outdoor ratios of ultrafine particulate matter and particulate matter smaller than 2.5 microns were less than 1.0 in most buildings; exceptions were restaurants, hair salons, and dental offices, which have known indoor sources. The average black carbon ratio was 0.72, indicating that the building shell and heating, ventilation, and air-conditioning system provided partial protection from outdoor particulates. Aldehydes and volatile organic compounds were measured. The majority of buildings had formaldehyde levels above the Office of Environmental Health Hazard Assessment 8-hour reference exposure level. (*op cit*)

"Recommendations based on this study's finding are: (1) require a mandatory inspection to confirm that appropriate mechanically supplied air is supplied; (2) increase formaldehyde source control; and (3) require increased air filter efficiencies." (*op cit*)

While these findings are strongly suggestive of the need for Energy Commission or other agency actions, they also suggest the need for more studies of the building types included in the study, as well as other small and medium commercial building types not included.

There is a paucity of reported assessments of building performance with respect to IEQ generally, and specifically in relation to low-energy buildings. The number of building types included and the number of buildings of each type studied was small and cannot be considered necessarily representative of that type of building. Larger numbers of buildings in each type are still required, as are studies of other types that have not yet been studied.

Additionally, there is a strong consensus that there is a need for better metrics for IEQ. In particular, such metrics could be used in benchmarking studies but would have very wide potential for use by professional practitioners involved in commissioning, auditing, assessing, and evaluating building performance. Indoor environmental quality and IAQ are comprised of many discrete and interrelated elements, components, or factors. Those who measure even the most common indoor environmental characteristics use divergent metrics, resulting in a lack of comparability. More development of criteria for comparison of results of measurements is needed, but such comparisons will necessarily require standardized or equivalent measurement methods.

An example of the need for improved metrics is building ventilation rates, either outside air per occupant or per unit area, or outside air changes per space or building volume. Outside air ventilation is widely considered one of the most common "indicators" of indoor air quality, although by itself, without regard to sources, it cannot sufficiently characterize the quality of the indoor air to provide those using it with a strong indicator of indoor air quality. It certainly is not able to indicate whether indoor air is healthy or comfortable without knowledge of the pollutants and their source strengths or the thermal conditions, both indoors and out.

Similarly, concentrations of indoor air pollutants are commonly measured and compared with standards, guidelines, threshold values, or other concentration values. Yet single pollutant concentrations are widely recognized as inadequate as indicators of human health effects since indoor air is commonly composed of hundreds of chemicals. Efforts to identify important indoor pollutants in individual buildings are limited by the absence of an integrated measure. There are many advocates of the use of total volatile organic compounds (TVOC) as an indicator, but there is wide agreement that it cannot be used as an indicator of health.

There is a severe lack of information on perinatal and early childhood exposures. There is abundant evidence that these exposures are among the most important in terms of lifelong health. (Section 40451 of the Health and Safety Code from SB25, Environmental Health Protection: Children, requires a focus on protection of children's environmental health protection in California.)

Specific Regulatory or Policy-related Needs. Title 24, building retrofit, and other building energy programs need benchmark data in order to help evaluate the effects of program implementation and updates on IEQ and health risks. Benchmark data need to be updated periodically to help evaluate compliance with building standards and health-based guidelines for IEQ. In addition, benchmark data help identify other trends that can affect IEQ, such as changes in building practices, occupant and operator behavior, and consumer and building product emissions.

Bennett et al. (2011) provide a number of recommendations that suggest regulatory action by the Energy Commission or, in some cases, either Cal-OSHA, ARB, or state and local building code adoption and enforcement agencies. [308] Title 24 and provisions of building codes are clearly not being met in many of these buildings. The problem of code enforcement is not new, having been noted shortly after the adoption of the first round of Title 24 California Residential Building Energy Efficiency Standards when the Energy Commission convened a committee to investigate the problem of Building Energy Efficiency Standards enforcement. [309]

Beyond that, it may be necessary to include strengthening of licensing requirements for State-licensed architects and registered professional engineers who are responsible for the designs of these buildings. Such buildings typically require a licensed architect or engineer to sign the plans submitted for a building permit, and all such buildings are required to be permitted for construction in California.

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[308]Bennett, Wu, and Trout, 2011; Indoor Environmental Quality and Heating, Ventilating, and Air Conditioning Survey of Small and Medium Size Commercial Buildings: Field Study. CEC-500-2011-043

[309], Hal Levin, one of the authors of this report, was a member of the Commission's committee on enforcement of its Building Energy-Efficiency Standards

There needs to be a mechanism put in place to collect information on the energy and IEQ performance of buildings.

Guideline Needs. Green building programs can use benchmark data to evaluate the performance of buildings they have certified and ways to improve their programs. Comparisons among different green building programs and conventional building programs, in terms of IEQ and its determinants, energy efficiency, life-cycle cost, and market value are also needed to evaluate program performance and product value.

Guidelines for design, construction, operation, and maintenance of specific small and medium commercial buildings may be able to reduce the occurrence of the types of problems observed in the SMCBS.

Guidelines for inspection and enforcement actions may also be useful in assisting those responsible for compliance with building codes, standards, and regulations to execute their duties more effectively.

Guidelines for health-relevant concentrations of most indoor air pollutants are unavailable for the vast majority of compounds found in indoor air.

High-Priority Research Projects

Identify, develop, and demonstrate the metrics for tracking and comparing IEQ. Consider a graded approach).

Monitor IEQ and its determinants initially, and then periodically, in all major building sectors, to improve estimates of long-term IEQ and health risks and energy performance, as well as to help refine program design and implementation, for all major residential building types.

Additional (Low- to Medium-Priority) Projects

Assess IEQ and its determinants initially, and then periodically, in all major building sectors:

Initiate a small and medium commercial building study (SMCB) follow-up study. This should include small and medium commercial sector problems in more buildings of the types studied, plus in additional building types.

Survey indoor exposure of children in early life (initial days and weeks and months in the home)

Monitor long-term IEQ and mitigation performance, e.g. radon, formaldehyde, symptoms, exposures, etc.

Investigate indoor, outdoor, and personal exposures near major outdoor sources, such as roadways, rail yards, power plants, and agricultural pesticide users.

Assess IEQ (identify the metrics – could be a graded approach) and its determinants initially and then periodically in all major building sectors, to improve estimates of long term IEQ and health risks and energy performance and to help refine program design and implementation, for all major residential building types:

Description: Objectives and General Approach

A white paper should be produced to review methods of benchmarking IEQ and its determinants in all major building types. It should include an assessment of appropriate metrics for IEQ and personal and indoor exposure along with recommendations for building types and population groups where benchmarking is perceived to be most needed or where it appears to be lacking.

Pilot and field studies should be conducted to obtain initial benchmarking data on high-priority building types and population groups. These could be based on populations-at-risk or buildings-at-risk (known or believed to have poor IEQ). Once a substantial number of low-energy or NZEB buildings are produced, they will need benchmarking. Recommended best practices and periodic benchmarking updates for residential and commercial buildings should also be developed.

This topic also requires the establishment of a data repository. The organization hosting the data repository might also be tasked to develop and make available tools to analyze the data. These tools could range from those intended for researchers or policy-makers to those intended for use by builders or building occupants.

There is a need to extend the work done in the SMCBS to more buildings in the types already studied and to more building types.

A number of small pilot or intervention studies might be used to test various approaches to addressing the deficiencies identified in the SMCBS. Following are a few possibilities of ways to follow-up on the findings and recommendations of the SMCBS:

<u>Inspection procedure and maintenance</u>

A building inspection procedure should include a determination of whether the heating, ventilation, and air-conditioning units meet the Title 24 requirement for mechanically supplied outdoor air at the required rate (excepting the case where the natural ventilation option can be demonstrated through a code check and inspection to meet the same ventilation rates). This could best be accomplished by adding an inspection of the HVAC unit to the required elements of the required inspection associated with finalizing the building permit. In some cases, it was clear that noncommercial HVAC units were installed in commercial buildings. Improved labeling of equipment might limit this problem. However, specific packaging and labeling requirements for California requirements may be burdensome for manufacturers with markets in other states.

The Energy Commission could collaborate with a single or a small number of permit issuing jurisdictions to adopt the provisions requiring "…that an HVAC contractor complete a test and balance procedure that included a certification of mechanically supplied outdoor airflow rate." Building inspectors would inspect a small percentage, for example 5 percent, of buildings to verify that the measured flow rate as declared by the HVAC contractor was the actual measured mechanically supplied outdoor air flow rate. Additionally, during the inspection, the inspector would confirm that filters are accessible.

Annual maintenance and inspection should be required. The authority already exists under Cal/OSHA's ventilation rule. This could be enforced by a requirement for an annual inspection certified by a letter from a licensed HVAC inspector.

Buildings built prior to 1978 generally do not have mechanically supplied outdoor air. To address this, one recommendation would be to require buildings be brought up to date in the current Title 24 standards at change of ownership. This might include a requirement that ventilation units provide mechanically supplied outdoor air. It might also be required that buildings be brought up to Title 24 standards when ownership is transferred or when a new lease is signed.

Provide some instruction to the new building operator at change of ownership or new lease. Introduce a building exchange tax that could then support development of either educational materials or provide free education classes to help operators understand the importance of maintaining an HVAC system. Ideally, some sort of inspection should be required; however, this is likely not to be cost effective or feasible.

Commissioning (or recommissioning) existing buildings at transfer of ownership, requiring that HVAC units be upgraded to include mechanically supplied outdoor air meeting current ventilation standards.

There was a surprising finding of a high prevalence of low-efficiency filters in the SMCBS. While measured particulate matter levels were generally not above regulatory limits, it would still be beneficial to decrease particulate matter levels by increasing the efficiency of filters. It was apparent that there were particulate matter sources in restaurants, hair salons, and dental offices. These types of buildings, along with other building uses, are anticipated to have high particulate matter sources that would particularly benefit from the use of higher efficiency filters.

Additionally, the outdoor $PM_{2.5}$ levels were very high for the buildings monitored in the Central Valley of California, as expected. While the buildings did not have any indoor sources, and had relatively low indoor/outdoor ratios, they still had some of the higher indoor levels of the non-source buildings in the study sample. Buildings in areas with typically high outdoor levels would also be good candidates to benefit from the use of higher-efficiency filters.

Field testing could be done of a requirement for use of higher-efficiency filters in buildings in locations that are likely to generate significant particulate matter, and buildings in regions with high outdoor levels. It is acknowledged that this would increase costs. However, studies have indicated that higher-quality filters last longer and require less labor associated with frequency of replacement, negating some of the cost increases. [310].

Related R&D Application Categories

Many of the other research topics will have substantial overlap and connection to this topic.

Co-funding or Leverage Opportunities

Many of the experimental activities under this topic could be co-funded by a variety of potential partners, including building technology companies, public and private research organizations at the national level, and others.

U.S. EPA, DOE, HUD, NIOSH, CDC, National Center for Healthy Housing.

Various low-energy and zero energy building projects in California, U.S., and abroad. Energy and/or IEQ projects by California State and local government, universities, and utilities in new and existing buildings.

ASHRAE and HVAC manufacturers.

CHPS and local school districts.

American Lung Association and HMOs.

Building Owners and Managers Association (commercial buildings).

Apartment and condominium owners associations.

Related Work

PIER/ARB/: Small and Medium Commercial Building Study: mail survey and field study.[311][312][

DOE/ORNL: Weatherization Assistance Program IAQ study.[313]

PIER/DOE/LBNL: Healthy Zero Energy Buildings (HZEB, commercial), Healthy Home (multifamily), and RESAVE (residential) projects.[314][315]

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310 Fisk, Faulkner, et al, 2002. Performance and costs of Particle Filtration Air Filtration Technologies. *Indoor Air*, 12(4), 223–234.

311Sherwin et al., 2011. http://www.arb.ca.gov/research/single-project.php?row_id=64912

312Bennett et al., 2011. http://www.arb.ca.gov/research/single-project.php?row_id=64797.

313Tonn B, May 2011. Study design and preliminary results: www.nwcouncil.org/energy/rtf/.../DOE-ORNL-WAP_IAQ_Study.pdf.

314http://eetdnews.lbl.gov/nl29/eetd-nl29-4-pco.html

NRC Canada, Institute for Research in Construction: air cleaner test method.[316]

CMHC EQuilibrium Sustainable Housing Demonstration Initiative.[317]

NRC Canada: Field Study on Indoor Air Quality, Ventilation and Health.[318]

CETEC International pilot benchmarking assessment of IEQ and productivity in buildings.[319]

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[315] http://hzeb.lbl.gov/; http://apartmentenergy-ieqretrofits.lbl.gov/projects; http://resave.lbl.gov/

[316] http://www.nrc-cnrc.gc.ca/eng/ci/v16n3/14.html

[317] http://www.cmhc-schl.gc.ca/en/inpr/su/eqho/

[318] http://www.nrc-cnrc.gc.ca/eng/projects/irc/air-initiative/fieldstudy.html

[319] http://www.cetec-foray.com.au/RiskeNews/eissue32.htm

TOPIC: CROSS-CUTTING

RESEARCH PROJECT: PROGRAM EVALUATION

Specific Regulatory or Policy-related Needs

To achieve the program goals regarding IEQ, an evaluation and feedback mechanism is needed to promote continuous improvement of IEQ measures and to avoid the many pitfalls of technology change and behavioral change. Any strategy for implementing improved technologies and practices for providing good IEQ will need to include outreach and feedback from the users. The design and operation of Californian buildings will change drastically over the next 30 years and beyond, assuming that the move to low-energy buildings accelerates and energy prices continue to rise. Indoor environmental quality research will produce measures and practices to solve and prevent IEQ problems in both low-energy buildings and conventional buildings, but those measures are not likely to be perfectly implemented on the first attempt. The measures will need continuous improvement based on lessons learned, and they will need to be integrated with other building processes and programs.

It is also critical, given the interconnection of all the project areas, the funding limitations, and constant changes in our knowledge base, that the overall progress and effectiveness of the strategies in IEQ Research Roadmap itself be revised periodically. A revision is advised every 3–5 years.

Description: Objectives and General Approach

The objective is to help develop a continuous improvement process for this IEQ R&D program, in order to efficiently meet program goals. Research in this area should start with a review and assessment of successful program evaluations for RD&D and IEQ programs. A program evaluation process for one or more high-priority IEQ measures would then be developed. The numerous stakeholders and actors who determine the deployment and effectiveness of those IEQ measure would be consulted, through interviews, surveys, and focus groups. This feedback would be used to identify key issues that still need to be addressed, and to identify the appropriate metrics to track progress. Overall integration of the IEQ R&D effort would also be evaluated to improve linkages among different projects and collaboration with other research groups.

For example, implementation of improved ventilation systems depends on proper system design, installation, inspection, commissioning, and operation and maintenance. In other words, the entire building process from concept, site selection, and feasibility study through occupancy, use, and renovation or adaptive re-use is relevant to the mandate and overall goals of the Energy Commission’s regulatory and research functions. Metrics and review procedures would be used to identify potential problems in the technology and the practices at each stage of the life cycle. Those results would be used to set up demonstration programs for elimination or mitigation of the problems, to develop best practices guidelines, and to train building professionals and trades.

Why the Research Area Is Considered a Priority

Health and Safety Issues. Indoor environmental quality measures will be needed in various energy-efficiency programs to mitigate potential adverse health impacts and obtain health and human performance co-benefits (non-energy benefits). However, to do so effectively and to maintain credibility with the building community and the public, systematic evaluation of the IEQ mitigation efforts and the supporting R&D efforts will be needed. The interaction of various IEQ determinants in buildings requires systems analysis, including feedback from building studies and surveys.[320]

Guideline Needs. Research and development of project areas that involve guidelines would benefit from project evaluation. Both the Energy Commission, the CPUC, and the electric and gas utilities also need to know how IEQ measures will affect energy usage in the real world.

High-Priority Research Projects

Program evaluation applies to all of the other project areas and would integrate all of the priority topics in the Research Roadmap. It is especially connected to the benchmarks and metrics project areas. Critical needs for developing program evaluation are as follows:

- Identify and assess methods and model programs for assessing progress of projects related to IEQ and its determinants. Determine data needs and database needs for evaluations.
- Identify opportunities to partner with stakeholders and programs to incorporate IEQ factors in program evaluation and market evaluation, e.g., in energy-efficiency programs at State agencies and energy utilities.
- Identify and periodically revise strategies for achieving healthy low-energy buildings in accordance with the 2020/2030 time frame of the Strategic Plan.

Related R&D Project Areas and Topics

All categories, but the initial focus should be on high-priority or time-sensitive issues so that measures can be incorporated into standards and guidelines.

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[320] Cole RJ. Environmental Issues Past, Present & Future: Changing Priorities & Responsibilities for Building Design. World Sustainable Building Conference 2011. Helsinki, Finland. http://www.sb11.org/sb11-helsinki/home.html. Or http://www.youtube.com/watch?v=gX-pStsIFx8.

Related Work

NIH: Partnerships for Environmental Public Health.[321]

Harvard University: Indoor environmental indicators of self-reported health symptoms.[322]

Colorado State University: Evaluation of Green Home Weatherization Programs and Remodeling Programs.[323]

Intelligent Energy Europe: funding to determine skill needs and training gaps for the building sector.[324]

iiSBE Sustainable Building Challenge: This international program obtains design and performance data and building performance criteria for buildings entered into the competition from around the world. A reasonably high level of documentation is required to include in a submitted entry.[325]

The CPUC plans to conduct program evaluation for various elements of the State Energy Efficiency Strategic Plan.

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321 http://www.niehs.nih.gov/research/supported/programs/peph/about/evaluation/index.cfm.

322 Adamkiewicz G, Spengler JD, et al., 2011. Healthy Homes Conference 2011, Denver, CO. http://www.healthyhomesconference.org/presentations/Tuesday/7E-2_%20Key%20Contaminents%20in%20Indoor%20Air.pdf.

323 Kawamura S, 2010. An Evaluation of Green Home Weatherization and Remodeling Programs: What is Being Done to Promote Occupant Health and Recommendations for Best Practices. National Healthy Homes Conference 2010.

324 IEE, August 12, 2011 press release. http://ec.europa.eu/energy/intelligent/files/press-releases/bus_press_release_eaci_final_en.pdf.

325 International Initiative for a Sustainable Built Environment, Sustainable Building Challenge. Formerly the Green Building Challenge. http://iisbe.org/sb_challenge.

APPENDIX B:
Building Processes Linking IEQ, Health, and Building Energy Use

Table B1. Building Processes Linking IEQ, Health, and Building Energy Use

Process	Link to Energy	Link to IAQ and Health
Outside air ventilation	Energy used to transport and thermally condition air	Serves to dilute indoor-generated pollutants, but also brings outdoor pollutants and moisture into the building Associated with improved symptoms, respiratory health, perceived air quality, and work performance In some climates: inadequate ventilation leads to increased humidity, condensation, mold, and possibly allergens and vermin in houses. Window opening may bring in noise and pollutants, create drafts, and create a security issue.
Heating	Energy used to heat and transport air	Affects thermal comfort Risk of combustion product entry to indoor air Affects emission rates of pollutants, especially VOCs, formaldehyde, and lighter SVOCs Affects occupant response to pollutant exposures
Air-conditioning	Energy used to cool, dehumidify and transport air	Affects thermal comfort Risk of microbiological contamination of wetted surfaces. Risk of condensation on occupied space surfaces when warm air enters cooled interior. Associated dehumidification may help prevent moisture problems and microbiological contamination Associated with increased health symptoms Can be a source of unwanted noise Can reduce pollutant emissions of VOCs Can reduce moisture content of air and condensation

Process	**Link to Energy**	**Link to IAQ and Health**
Particle filtration	Energy used to overcome airflow resistance May save energy by preventing fouling and obstruction of heating and cooling coils and ductwork	Reduces indoor particle concentrations with indoor or outdoor origin Reduces soiling of surfaces Filters can be odor sources Filters, if wet, can be contaminated microbiologically
Humidification	Energy used to evaporate water	Affects comfort Potential source of microbiological and chemical pollutants in the HVAC system May lead to condensation and microbiological growth on occupied space surfaces Linked to respiratory illnesses from humidifier contaminants Possible link to person-to-person respiratory illnesses transmission
Air recirculation	Energy used to transport air	Enables filtration of recirculated air Causes dispersion of indoor pollutants Reduces concentrations of indoor pollutants near sources Potential source of noise in occupied space
Building pressure control	Energy used to transport air Sealing moisture pathways	Affects pollutant and moisture transport through building envelope, ductwork, and among rooms May prevent or cause moisture problems in building envelope Affects infiltration-related drafts and comfort problems Can cause back drafting of combustion appliances
HVAC maintenance	Improves HVAC system operation, expected to normally save	May improve ventilation, air distribution, thermal comfort, humidity control, and pressure control Lack of maintenance may lead to microbial contamination and combustion safety problems

Process	Link to Energy	Link to IAQ and Health
	energy	
HVAC cleaning	Cleaning of coils reduces air pressure drops and improves heat transfer, potentially reducing HVAC energy use	May reduce, or temporarily increase, pollutant emissions from HVAC systems Debris, microbiological contamination, and poor draining from cooling coil drain pans are associated with increased respiratory symptoms
Space cleaning	Minor energy use for cleaning	May reduce indoor odors and resuspended particles Cleaning compounds can be indoor pollutant sources Workstation cleanliness has been associated with reduced symptom reports and with lower dust fungal loads.
Water leaks	Degrades thermal performance of building envelopes May increase dehumidification energy	Increases indoor microbiological contamination, including fungi and bacteria Affects presence, survival and pathogenicity of viruses Linked to increase in respiratory symptoms and asthma and other allergy symptoms
Occupant behavior	Reducing outdoor air ventilation rates to reduce fan energy and heating or cooling energy use	Reduces potential dilution and removal of pollutants Reduces energy used at power plants, resulting in cleaner outdoor air available for ventilation
Indoor pollutant source removal or reduction	Often energy neutral; except when source or its replacement consumes	Reduces indoor pollutant concentrations May improve IEQ by reducing loading on air filters, air cleaners, and interior surfaces

Process	Link to Energy	Link to IAQ and Health
	energy or affects heat transfer from indoors to outdoors. May reduce HVAC and filter maintenance needs May reduce the need for additional ventilation	
Envelope insulation and tightness	Reduce heat gain and loss	Reduces moisture and pollutant intrusion Changes dew point location; could be beneficial or harmful Reduces infiltration that provides air exchange where proper means are not in use Reduces garage pollutant intrusion
Crawl space or slab seals	Reduces heat gain and loss Vapor intrusion	Reduces moisture intrusion Changes dew point location Reduces infiltration that provides air exchange where proper means are not in use and Reduces intrusion of vapor and pollutants
Windows and skylights: ventilation, lighting	Reduces unwanted heat loss, heat gain, and air leakage Reduces need for electric illumination Can be source of unwanted air and water leakage Can be a source of desirable ventilation Back up or	Dilutes indoor-generated pollutants Associated with improved symptoms, respiratory illness, perceived air quality, and work performance Brings outdoor pollutants and moisture into building In some climates: inadequate ventilation leads to increased humidity, condensation, mold, and possibly allergens and vermin Can provide natural lighting and beneficial views to outdoor Can be source of noise intrusion

Process	Link to Energy	Link to IAQ and Health
	replace ventilation for mechanical systems	
Gaseous air cleaning	Energy used to overcome airflow resistance Reduced energy when indoor air is recirculated	Reduces indoor gas concentrations with indoor or outdoor origin Reduces SVOCs Filters can be odor sources Filters, if wet, can be contaminated microbiologically Chemical reactions on filters can be sources of cleaner or fouler air

APPENDIX C: Process for Updating the 2002 IEQ Research Roadmap

In consultation with Energy Commission staff, the following scope for this update of the IEQ Research Roadmap was established:

- Limit research planning to the period of 2011–2030, based on the 2030 target for commercial NZEBs.
- Limit the IEQ issues to health, thermal comfort, occupant satisfaction, worker and student performance, acoustics, building energy use, and the building systems and practices affecting energy use. The quality of indoor lighting was excluded due to limited funding and the complexity necessary to characterize lighting effects on humans.
- Focus on efforts to achieve zero energy buildings that are now under way and are anticipated to increase in the coming decade.
- Focus on retrofits of existing commercial and residential buildings.
- Limit building types to residences, non-industrial commercial buildings (excluding health care buildings), and schools.
- Include the design, construction, operation, and maintenance phases of a building's life.
- Include a portfolio of different RD&D products, ranging from new information to applied products for implementation by industry or decision makers.

The starting point was to review the 2002 Research Roadmap, *Energy-Related Indoor Environmental Quality Research: A Priority Agenda*, and update its table on energy-IAQ-health linkages for various building processes. A limited review was conducted of major IEQ and energy-efficiency RD&D programs in North America and Europe and of major IEQ research since 2001.

Over 170 IEQ experts, building science experts, and stakeholders in the United States and a few other countries were contacted to help imagine what future NZEBs and low-energy buildings would look like, and to identify the high-priority IEQ research areas of the future. In addition, 10 health scientists with extensive backgrounds in indoor air and environmental quality and health were surveyed, to help prioritize research needs based on potential benefits to public and worker health, and the major health concerns related to IEQ were considered. The individuals surveyed included physicians, epidemiologists, and physical scientists with strong scientific or professional experience in indoor environmental health. The participants were asked to consider the following (based on their opinions only), to identify the top priority indoor environmental health problems or illnesses resulting from these problems:

Identify health effects that you consider are the highest priority. List your top five in rank order of the most important health effects.

The poll participants were asked to consider the following criteria in determining the importance of a health hazard:

- Number of people affected and potentially affected.
- Severity of the health effects/illness (and consider both medical treatment and degree of disability for morbidity, plus mortality).
- Disability Adjusted Life Years (DALY): Age and number of years of disability or lost life.
- Recoverability from the health effects/illness.
- Mitigation potential for the causes of the health effects/illness.
- Mitigation potential for the effects of the health effects/illness.
- Possible additive or synergistic effects of multiple pollutant exposures, e.g., smoking, environmental tobacco smoke (ETS), radon, asbestos, mold.
- Level of uncertainty in unit health risk (for a given pollutant or disease) and in California exposures.

The responses covered a broad range of issues and varied in terms of their focus on the problems or the illnesses. Some of the responses were overlapping or subsets of others, so the tabulated numerical results are difficult to interpret confidently. The results of the poll are summarized as follows:

- The most commonly listed illness was asthma, which received a far stronger ranking than any other individual illness. There was a cluster of comments about communicable disease, upper respiratory infections and other respiratory illness, allergy, and cancer (including but not limited to lung cancer).
- Also mentioned were influenza (to the extent that it is airborne), hypersensitivity pneumonitis, rhinosinusitis, sick building syndrome (SBS), discomfort, and non-communicable disease. Sarcoidosis (inflammation of the lymph nodes, lungs, liver, eyes, skin, or other tissues) was also mentioned.
- Among the indoor hazards most frequently identified, the highest ranked were environmental tobacco smoke, modern chemicals (flame retardants, pesticides and other organic compounds), pollutants from nearby roadways, and dampness/moisture.
- Mold was also identified by several experts. Endotoxins and mycotoxins were mentioned in connection with moist conditions.
- Dryness was mentioned in connection with mucosal irritation and infectious airborne disease transmission.

- Other hazards mentioned were radon, indoor combustion, and outdoor air ventilation less than 10 percent (of space supply air).

A public workshop was held by the Energy Commission in late July 2011 to solicit input from various stakeholders to identify information and research needs on energy-related indoor environmental quality (IEQ) through 2030.[326] The focus was on research and development needs as California moves aggressively to zero net energy buildings and increased retrofitting of existing buildings, as identified in the Energy Commission's Integrated Energy Policy Reports.[327][328] Energy Commission staff presented background information regulatory and policy drivers on IEQ, including building energy-efficiency standards (Title 24), environmental review regulations, and the governor's green jobs policy. We presented preliminary assessments of IEQ-energy linkages, major IEQ research since 2001, future scenarios in achieving zero energy buildings, IEQ research gaps, and potential research projects. Comments from the workshop were used to supplement a draft analysis of research needs and possible projects to meet those needs.

An Advisory Panel consisting of experts from the fields of indoor air quality, thermal comfort, and building science was then assembled. The panel members and their affiliations are listed in Appendix D. Prior to their meeting, the members received a copy of the ranking criteria (shown in Table C1), the draft research areas and specific topics, and the research needs and background information on the project.

The Panel met in late September 2011 for two days. During extensive discussion of the research areas, they recommended adding several specific research topics and voted on a list of proposed research topics and projects. Their votes were considered in prioritizing and grouping the research priorities. The panel members, the Contract Manager, and other selected experts were asked to review and comment on the draft research topic priorities. Subsequently, the draft final report and revised summaries of priority research topics were sent for review and comment to panel members, selected Energy Commission staff, and other experts in various fields. The comments of these reviewers were considered in preparing the final report.

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326 http://www.energy.ca.gov/research/notices/index.html#07282011.

327 http://www.energy.ca.gov/2009_energypolicy/index.html. p. 227 et seq.

328 Achieving Energy Savings in California Buildings, Saving Energy in Existing Buildings and Achieving a Zero-Net-Energy Future, Draft Staff Report. Pub # CEC-400-2011-007-SD. Posted July 11, 2011.

Table C1. Ranking Criteria

1) Likely Magnitude of IEQ Impacts from Energy Measure (Adverse or Beneficial)	Topic addresses problems with high likelihood and large magnitude of IEQ impacts from particular energy-efficiency practices (current and potential future) that will result in potential health and comfort concerns
2) Potential Benefits to Health, Comfort, Performance in Protecting IEQ	Potential for a convincing outcome that will lead to effective action by regulators, designers, occupants, operators, or more than one of the above
3) Strength of Energy Linkage and Potential Benefits	The potential energy benefits or strength of the linkage to energy
4) Feasibility of Study	Potential for a successful study with a clear outcome
5) Likelihood of Results Being Used	Potential for study results to lead to effective action by either regulators, designers, occupants, operators, or more than one of the above
6) Opportunities for Leveraging or Synergies	Potential to take advantage of synergies and opportunities from other projects
7) Potential to be "Game Changing"	The extent to which the project can lead to a "game-changing" or "critical path" outcomes, such as an affordable IEQ monitoring technique, an effective mitigation method, integration of IEQ protection into building design and operation, or a major shift in decision-maker awareness

APPENDIX D: Expert Advisors

Advisory Panel (Met September 29–30, 2011, to review and revise research topics list and to indicate their priority research recommendations):

- Rick Diamond, Lawrence Berkeley National Laboratory (Sept 30 only)
- William J. Fisk, Lawrence Berkeley National Laboratory
- Peggy Jenkins, California Air Resources Board
- Mike Lubliner, Washington State University
- Marla Mueller, California Energy Commission
- William Orr, Collaborative for High Performance Schools (Sept 29 only)
- Brett Singer, Lawrence Berkeley National Laboratory
- Mark Mendell, Lawrence Berkeley National Laboratory
- Antoinette Stein, Collaborative for High Performance Schools

Experts Interviewed by Phone

- Jeffrey Siegel, University of Texas, Austin
- Mithra Moezzi

Experts providing input by email:

Paul Stern
Eduardo de Olivera Fernandes
Jennifer Logue
Max Sherman, LBNL
Steve Selkowitz, LBNL
Judy Heerwagen
Cindy Sage
Michael Lipsett
Hugo Destaillats
Loren Lutzenhiser
Torben Sigsgaard
Bill Rose
Susan Lum
Peder Wolkoff
Ole Johansson
Myrto Petreas
Martha Brook
Paul Marmion
Kaz Kumagai
Ren Anderson
Bill Turner
John Randell
Karen Earhardt-Martinez
Tom Dietz
Bruce Wilcox
Linda Wigington
Paul Francisco
Matt Berges
Arlene Blum
David Miller
Cathleen Fogel
Mark Jackson

APPENDIX E: Energy Commission and Other IEQ and Energy-Related Programs and Policies in California

The Energy Commission is required to set standards for energy efficiency for both new and existing buildings and for new appliances.[329] It must consider indoor air quality problems in setting energy-efficiency standards for buildings and appliances.[330] Further, it must comply with the California Environmental Quality Act by considering potential impacts of such standards on human health and safety and by mitigating any significant adverse impacts.[331]

In recent years, the need for more-efficient buildings has grown due to climate change legislation and policy under California's AB 32 Global Warming Solutions Act of 2006. Green buildings with increased energy efficiency were identified as a major target for reducing greenhouse gas (GHG) emissions in the AB 32 Scoping Plan.[332][333] Improved indoor air quality was one of several co-benefits expected from the plan's green building element.

California Strategic Energy Efficiency Plan

In order to meet AB 32 goals, the Energy Commission is working with the California Public Utilities Commission and various stakeholders to implement the California Strategic Energy Efficiency Plan.[334]The Strategic Plan has four major goals, also known as the Big Bold Energy Efficiency Strategies:

- All new residential construction in California will be zero net energy by 2020
- All new commercial construction in California will be zero net energy by 2030
- Heating, Ventilation and Air-Conditioning (HVAC) will be transformed to ensure that its energy performance is optimal for California's climate
- All eligible low-income residential customers will be given the opportunity to participate in the low-income energy-efficiency program for existing homes by 2020

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[329] AB 758, Chapter 470, Statutes of 2009. PRC Sec. 381.2 and 385.2. http://www.energy.ca.gov/ab758/.

[330] AB 4655 (Tanner; PRC 25402.8).

[331] CEQA. PRC Sec. 21000 et seq. http://ceres.ca.gov/ceqa/.

[332]ARB, 2008.Climate Change Scoping Plan. See Final version, 5/11/09, pp. 57 et seq. and Vol. 1, Appendix C, pp. C-138 et seq.http://www.arb.ca.gov/cc/scopingplan/document/scopingplandocument.htm.

[333]ARB, 2011.Green Building Strategy.http://www.arb.ca.gov/cc/greenbuildings/greenbuildings.htm.

[334]CPUC, September 2008. The California Energy Efficiency Strategic Plan. http://www.californiaenergyefficiency.com/docs/EEStrategicPlan.pdf.

A building is considered a net zero energy building when the societal value of energy consumed by the building over the course of a typical year is less than or equal to the societal value of the on-site renewable energy.[335]

The Energy Commission staff recently outlined its plan for achieving net zero energy building (NZEB) goals and the issues related to IEQ, based on a series of public workshops in 2011.[336][337] This plan focuses on a variety of areas:

- Various measures for new residential buildings will be phased in through the 2013, 2017, and 2020 building standards. These will include reduced infiltration, ventilative cooling, thermal mass, passive solar measures, and performance verification and acceptance testing. The 2013 standards are currently at the public review stage.
- Additions and alterations of existing residences will receive more attention in the standards. Building energy performance ratings will address combustion safety testing and IEQ metrics.
- New commercial buildings (2013 standards) will be required to confirm compliance with building codes, CalGreen building standards, and acceptance testing requirements at the design review stage. CalGreen building standards include mandatory and voluntary (reach) standards for IEQ, such as moisture control, low-formaldehyde and low-VOC materials, air filtration, acoustical control, exterior wall shading, and commissioning.[338]
- New commercial buildings (2013 standards) will be required to have improved design, installation, and verification of demand controlled ventilation systems, laboratory exhaust hoods, and commercial kitchen hoods.

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335 Zero Net Definitions Team, 2011. June 6 Draft. A Zero Net Energy Definition for Residential and Commercial Buildings.http://www.engage360.com/index.php?option=com_k2&view=item&task=download&id=44&Itemid=295&lang=en.

336 Brook M, 2011. Summary of IEQ Related Updates to the 2013 Building Energy Efficiency Standards. Presentation at PIER Workshop on IEQ Research Roadmap, July 28..

337California Energy Commission, 2011. Title 242013 Building Energy Efficiency Standards Pre-Rulemaking, Staff Workshops presentations, April-November, 2011. http://www.energy.ca.gov/title24/2013standards/prerulemaking/documents/

338 CalGreen, California Green Building Standards, 2010Code, CCR, Title 24, Part 11. http://www.documents.dgs.ca.gov/bsc/calgreen/2010_ca_green_bldg.pdf.

The Strategic Plan was updated in 2011.[339]It incorporates measurement and continuous re-evaluation for updating of program elements. It has three major elements that are directly related to IEQ: commercial buildings, residential buildings, and HVAC.

- For commercial buildings, the California Public Utilities Commission (CPUC) developed with stakeholders a 2010–2012 Action Plan.[340] For new commercial buildings, the plan outlines measures that would progressively upgrade and expand mandatory (minimum) and voluntary energy standards and improve financial incentives, among other strategies. For existing commercial buildings, the plan measures include aggressive and progressive minimum energy codes and standards for buildings and plug loads, actions to increase Title 24 compliance, building commissioning, building operator training, and behavioral strategies, among others.
- For residential NZEBs, similar strategies would be used to meet the goal in 2020 for new homes, including increased whole-house retrofits and market transformation; a detailed action plan is under development.
- For HVAC in residential and small commercial buildings, strategies include improved quality installation and maintenance and development of new climate-appropriate HVAC equipment and controls, including system diagnostics.

The Energy Commission has also updated its Integrated Energy Policy Report recently. A staff draft report for these proceedings mentions various IEQ issues with building energy efficiency and supports the development and adoption of best practice guidelines and protocols for indoor pollutant testing.[341] It also supports strict adherence to relevant local, state, and federal guidelines in conjunction with home energy upgrades. Compliance with building standards is another challenge discussed in the report.

Building Retrofit Energy Standards

Existing buildings account for the greatest potential for energy-related greenhouse gas (GHG) reductions in the building sector. About two-thirds of California's homes and apartments – more than 8 million homes – were built prior to California's 1982 energy-efficiency standards,

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[339] CPUC, 2011.The California Energy Efficiency Strategic Plan, January 2011 Update. http://www.cpuc.ca.gov/NR/rdonlyres/A54B59C2-D571-440D-9477-3363726F573A/0/CAEnergyEfficiencyStrategicPlan_Jan2011.pdf.

[340]CPUC, 2010.Zero Net Energy Action Plan: Commercial Building Sector2010-2012. http://www.cpuc.ca.gov/NR/rdonlyres/6C2310FE-AFE0-48E4-AF03-530A99D28FCE/0/ZNEActionPlanFINAL83110.pdf.

[341]Brook M., B. Chrisman, P. David, T. Ealey, D. Eden, K. Moore, K. Rider, P. Strait, G. D. Taylor, and J. Wu. July 2011. Draft Staff Report: Achieving Energy Savings in California Buildings (11-IEP-1F).California Energy Commission, Efficiency and Renewables Division. Publication number: CEC-400-2011-007-SD. http://www.energy.ca.gov/2011publications/CEC-400-2011-007/CEC-400-2011-007-SD.pdf.

and a similar fraction of commercial buildings were built before the 1978 energy-efficiency standards. Only about three percent of all commercial buildings space is new or renovated in any given year in the United States.

The retrofitting or weatherization of existing buildings for energy efficiency has accelerated recently at the state and local level due to large increases in federal stimulus funding. The Energy Commission has leveraged over $800 million in federal, state, and private funding for improving energy efficiency in new and existing buildings, and has funded programs in various state and local agencies.[342][343]

In addition, the Energy Commission has authority under AB 758 (Skinner) to increase energy-efficiency savings in existing homes and other buildings, including those that are publicly owned.[344] The AB 758 Program is planning to develop markets and partnerships by 2012. Program measures will include energy audits, ratings, labels, and markets for retrofits and commissioning. The Energy Commission plans to develop statewide building ratings and upgrade requirements, such as whole-house retrofits and energy use disclosures, by 2014.

Other Programs and Policies

Several other State programs and policies that address building energy efficiency or climate change can also have implications for IEQ, as summarized below:

Residential Retrofit Programs.[345] The Department of Community Services Development (CSD) delivers about 50,000 home energy retrofits (weatherization) throughout California to low-income households annually. The federal Weatherization Assistance Program funds the State's low-income weatherization effort; federal stimulus funding will expand the program to another 43,000 low-income households per year. The CPUC requires investor-owned utilities to provide incentives for retrofits in single and multifamily residences. Municipal utilities have similar programs. All of these weatherization and incentive programs often involve HVAC and ductwork improvements, infiltration reductions, installation of ventilation fans, and improved insulation. They also address IEQ issues such as combustion appliance safety, moisture, and lead-based paint.

Property Assessed Clean Energy (PACE) Programs. Under AB 811 (Levine), municipal governments can provide loans for energy-efficiency work that are repaid through property

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[342]California Energy Commission, 2010.ARRA-Funded Energy Programs in California.http://www.energy.ca.gov/2010publications/CEC-180-2010-003/CEC-180-2010-003.PDF. See also: California State Energy Plan, http://www.energy.ca.gov/recovery/sep.html - efficiency.

[343]California Economic Recovery Energy-Related Programs. http://www.energy.ca.gov/recovery/.

[344] Skinner, Chapter 470, Statutes of 2009. http://www.energy.ca.gov/ab758/.

[345]ARB, 2011.AB 32 Scoping Plan, Building Retrofits. http://www.arb.ca.gov/cc/greenbuildings/retrofits.htm - cec.

taxes.[346] Such programs for residential and/or commercial buildings have been established in Sonoma County, Sacramento, Berkeley, Fresno, Keen, Riverside, Palm Desert, and soon in Los Angeles; private investors in some cases provided financing. The PACE residential program is on hold in other areas, pending proposed federal legislation (HR 2599) to resolve lending requirement issues.

SB 375 Land Use Planning. Under SB 375 (Steinberg), the state's metropolitan planning organizations must develop regional greenhouse gas reduction targets for passenger vehicles and plans to achieve those targets by 2020 and 2035.[347] These plans will affect local land use planning by encouraging mixed-use development, infill development, and increased building density. These changes will increase the proximity of buildings to pollutant and noise emissions from vehicle traffic, railroad traffic, and nearby buildings.

Commercial Building Energy Use Disclosure Program.[348] Under AB 1103 (Saldana), building owners or operators must provide prospective buyers, lessees, or lenders for commercial buildings with the building's energy consumption data and ratings for the past 12 months. Such disclosures will create market pressure to increase the energy efficiency of HVAC and other building systems that could affect IEQ. Proposed draft regulations set the initial compliance date at January 1, 2012.

Governor Brown's Clean Energy Jobs Policy.[349] The training of a green workforce has accelerated recently at the state and local level due to large increases in federal stimulus funding. This Green Jobs Policy further encourages the growth of green jobs by setting a timeline to make new homes and commercial buildings zero net energy and to make existing buildings more efficient.

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346 Streets and Highways Code, Sec. 5898.12 et seq.; California First Update on Federal PACE Issues, http://energycenter.org/index.php/public-affairs/property-assessed-clean-energy-pace See also: LBNL Policy Brief on Commercial PACE Programs, http://eetd.lbl.gov/ea/ems/reports/pace-pb-032311.pdf

347 http://www.arb.ca.gov/cc/sb375/sb375.htm.

348 Public Ressources Code Sec. 25402.10. http://www.energy.ca.gov/ab1103/.

349 http://www.jerrybrown.org/Clean_Energy. June 15, 2010.