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Building America Research-to-Market Plan

November 2015

Prepared by Confluence Communications and Energetics Incorporated for:
The Building America Program
Residential Buildings Integration
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Office of Energy Efficiency and Renewable Energy
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Executive Summary

This report was prepared by the U.S. Department of Energy's (DOE's) Building America program, the research, development, and demonstration (RD&D) arm of the Residential Buildings Integration (RBI) Program, within the DOE Office of Energy Efficiency and Renewable Energy's Building Technologies Office (BTO). For more information on any of these programs, please visit the website links provided above.

This report presents the *Building America Research-to-Market Plan* (Plan), including the integrated *Building America Technology-to-Market Roadmaps* (Roadmaps) that will guide Building America's RD&D activities over the coming years. The Plan and Roadmaps will be updated as necessary to adapt to research findings and evolving stakeholder needs, and they will reflect input from DOE and stakeholders.

Building America developed the Plan and Roadmaps to help tightly focus program efforts on developing effective solutions to building science problems that work so well for the housing industry that they become standard practice. Effective RD&D activities that are well coordinated with industry and deployment programs will fill critical research and information gaps to enable rapid market adoption of high-performance home technologies and best practices.

Successful implementation of these roadmaps will involve the following:

- Using codes and standards improvements as end points for the greatest long-term market impact.
- Engaging key industry and market stakeholders in the RD&D process to ensure market relevance.
- Providing clear program objectives for each critical challenge.
- Developing cost-effective, high-performance solutions that are practical and profitable for builders and home improvement contractors.
- Linking RD&D efforts with market deployment programs and codes and standards initiatives.
- Disseminating best practices and lessons learned using the Building America Solution Center (BASC) and other deployment tools and websites.
- Managing technical and business risks to minimize problems of adoption.

Continuing to provide clear program objectives—as supported by the Plan and the Roadmaps—focuses program resources on the highest-priority activities in order to achieve concrete, measurable results. Linking research activities with market deployment activities and codes and standards initiatives helps to ensure RBI activities are coordinated efficiently and collectively impact the market. Refining the Plan and the Roadmaps over time will ensure accountability and responsiveness to changing market conditions and stakeholder value.

For more information on how to participate in the Building America program or to access program updates, visit the Building America website.

Acknowledgements

This plan was built on the shoulders of leading building science experts and dedicated industry professionals who have helped build the modern building science profession. Building America Teams and their many industry partners have shown the housing industry over the past 20 years that it is possible to create better, healthier, more durable homes for Americans that save energy and cost less to own. We cannot name them all here, but we appreciate their many contributions to the field and their many lessons learned along the way. Now, with this plan, we have the opportunity to define a clear path forward for Building America and the housing industry, with sound building science and engineering best practices, toward the smarter and healthier high-performance homes of the future.

We wish to thank all those who provided input to this plan, including those who responded to the Request for Information with thoughtful comments and the many dedicated professionals who participated in the three expert meetings and the Better Buildings Residential Network stakeholder webinar. Your many intelligent and diverse contributions helped ground this plan in reality and keep us on track.

We also wish to thank the national laboratory technology leads who provided invaluable technical leadership and support to DOE for development of the technology-to-market roadmaps, including Roderick Jackson, PhD, Oak Ridge National Laboratory; Iain Walker, PhD, Lawrence Berkeley National Laboratory; and Jon Winkler, PhD, National Renewable Energy Laboratory. We also thank Michael Baechler, Pacific Northwest National Laboratory, for his thoughtful review and input, and Sam Rashkin, Chief Architect of BTO, for challenging us every step of the way to make the plan compelling, clear, and focused.

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Introduction

The long-term goal of the Building Technologies Office (BTO) is to develop and deploy technologies and systems to save the nation $200 billion annually in energy-related costs through a 50% reduction in building energy consumption. To deliver on this goal, BTO employs a three-pronged strategy for advancing building technologies and practices, referred to as the BTO Ecosystem:

1. Research & Development (R&D) of advanced technologies, primarily through the Emerging Technologies (ET) Program;
2. Market Stimulation of Innovations through the Residential Building Integration (RBI) and Commercial Building Integration (CBI) Programs; and
3. Codes and Standards development and implementation through the Building Energy Codes and Appliance and Equipment Standards Programs to raise minimum industry standards once higher-performance technologies are proven cost effective at scale.

The ET Program is BTO's primary R&D program, and it supports projects that lead up to commercialization of advanced building technologies. However, commercially available equipment and materials are often underutilized in the field because of building integration issues and market barriers. BTO addresses these challenges for residential buildings through its RBI Program, which works within the BTO Ecosystem to stimulate market adoption of whole-house energy-saving innovations.

The goals of BTO's RBI Program include the following:

1. By 2020, develop and demonstrate cost-effective technologies and practices that can reduce the energy use intensity (EUI) of new single-family homes by 60% and existing single-family homes by 40%, relative to the 2010 average home EUI in each climate zone, with a focus on reducing heating, cooling, and water heating loads.
2. By 2025, reduce the energy used for space conditioning and water heating in single-family homes by 40% from 2010 levels.

RBI's Building America program conducts applied research, development, and demonstration (RD&D) in residential buildings, in many cases linking technologies from the ET Program to the Building Energy Codes and Appliance and Equipment Standards Programs through demonstration projects that cost-effectively integrate these emerging technologies into residential building systems. Building America projects are led by U.S. Department of Energy (DOE) national laboratories and expert building science teams, in partnership with leading industry stakeholders (i.e., builders, contractors, manufacturers, and others).

DOE selects strategic Building America projects that can simultaneously develop and demonstrate better technologies and practices while overcoming critical market barriers to adoption, such as real and perceived technical and business risks and codes and standards limitations. DOE also prioritizes projects that can leverage influential early adopters in order to stimulate market adoption. Building America industry partnership teams then demonstrate that the high-performance technical solutions and best practices featured in the projects are low risk and can lead to added business benefits.

Voluntary above-code programs (e.g., Zero Energy Ready Home [ZERH], ENERGY STAR for New Homes, and Home Performance with ENERGY STAR [HPwES]) and participating early adopters effectively follow Building America's proven innovations to industry. This results in greater market penetration and adoption of energy-saving technologies and practices in new high-performance homes and existing home improvements, ultimately paving the way for better industry standards and advanced building codes.

Results from Building America projects, including proven innovations and lessons learned from RD&D projects, as well as best practice guidance culled from the Building America project portfolio, are made available through technical reports and the Building America Solutions Center (BASC). The BASC is a repository for Building America's best practices to help builders, contractors, installers, raters, and others in the building industry apply the latest results from Building America teams and national laboratories. Currently funded Building America research projects are detailed on the Building America website.

Building America Program Strategy

Problem Summary

Despite significant advancement of energy-efficient home technologies and best practices, including voluntary market advances and adoption of advanced codes such as International Energy Conservation Code (IECC) 2012, large technology and information gaps remain. These gaps prevent further advancement and mainstream adoption of the high-performance home technologies and systems for both new and existing homes that are needed to achieve DOE's energy-savings goals.

A highly fragmented and resource-constrained housing industry (e.g., ~100,000 home builders and remodelers[1]) lacks the skills and funds to invest in research, which has led to gaps in market adoption. Increased energy performance brings new technical challenges and can increase risk to builders and contractors. Real and perceived risks associated with adopting new technologies, combined with a general lack of understanding by housing industry stakeholders of business models that can create profit from improved home performance, prevent quick uptake of new energy-saving technologies and design approaches. Without proof that these new technologies and business models are safe, effective, and provide real business benefits, the market will not move forward with energy efficiency at the rate required to meet DOE's long-term energy-savings goals.

Furthermore, the housing industry is at a critical juncture in its ability to deliver homes that safely and effectively meet increasingly demanding performance requirements in building energy codes. For example, before substantial additional insulation and air-sealing requirements can be responsibly adopted into future advanced building energy codes and home energy upgrade programs, these risks must be better managed by the housing industry.

Quite simply, the housing industry is now facing a "building science imperative," where timely advances in knowledge, technology, and standard practices are urgently needed to ensure that homes, especially high-performance homes, do not incur additional risk of building failures.

Program Strategy Overview

Recent Building America planning efforts have focused on clearly identifying the biggest remaining research and information gaps preventing broad market adoption of proven high-performance home technologies in both new construction and home improvement markets. The results of these planning efforts are the focus of this *Building America Research-to-Market Plan* (Plan). The Plan sets specific program objectives over the coming years with three integrated and strategic *Building America Technology-to-Market Roadmaps* (Roadmaps), corresponding to the remaining critical technical challenges highlighted in Figure 1.

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[1] Carlos Martin and Stephen Whitlow, *The State of the Residential Construction Industry*, produced by Abt Associates Inc., Bethesda, MD (Washington, DC: Bipartisan Policy Center, 2012). http://bipartisanpolicy.org/wp-content/uploads/sites/default/files/State%20of%20the%20Residential%20Construction%20Industry_Formatted_8-31.pdf.

Figure 1. The Building America Technology Roadmap overview illustrates the evolution of energy use in homes over time and provides context for the Building America Research-to-Market Plan and the three Building America Technology-to-Market Roadmaps described in this report.

The roadmaps were developed with input from stakeholders and building science experts (described in the Building America Research-to-Market Plan Development Process section of this document) and will be periodically calibrated with additional input to ensure continued market relevance and value and add increasing detail. The roadmaps are integrated to ensure strong links between Building America's RD&D results, RBI deployment programs (i.e., ZERH, Better Buildings, and HPwES), and BTO codes and standards initiatives.

Program Objectives

The Building America program strategy enables market adoption of high-performance home technologies and best practices at scale—i.e., throughout the new home construction and home improvement markets—so that the housing industry and future energy codes can responsibly promote energy efficiency. The strategy focuses on developing and demonstrating solutions to the following three critical technology challenges, and on improving the ability of the housing market infrastructure to adopt these innovations:

- **High-Performance, Moisture-Managed Envelope Solutions.** The tighter the building enclosure, the less it can dry when needed. Building America will provide high-performance construction and retrofit solutions that manage moisture risks, reduce mold potential, and improve building durability. Moisture-managed, high-performance building assemblies will have increased insulation, reduced infiltration, reduced risk of condensation, and adequate drying potential year-round.

- **Optimal Comfort Systems for Low-Load Homes.** High-performance homes have dramatically lower heating and cooling requirements. Building America will provide efficient heating, ventilation, and air conditioning (HVAC) equipment and distribution system solutions for high-performance homes with low thermal loads, including optimal efficiency, managed airflow, and relative humidity (RH) control at all part-load conditions. Optimal comfort systems will effectively mitigate humidity and comfort risks due to reduced airflow and longer periods without HVAC operation that result from lower thermal loads in high-performance homes.
- **Optimal Ventilation and Indoor Air Quality (IAQ) Solutions.** Tighter building enclosures lead to less natural infiltration of fresh outside air. Controlled mechanical ventilation is required in modern homes to allow energy-efficient, tight construction while maintaining or improving occupant comfort and IAQ. Building America will provide smart ventilation systems and non-ventilation (i.e., source control) solutions for improved IAQ, with minimized energy penalties.

Why These Objectives Matter for New Home Construction

Because modern building envelopes do not dry out as easily as old, inefficient structures, the risks associated with unmanaged moisture is higher within modern building assemblies. In addition, homes cannot be energy efficient by today's standards without controlling air infiltration losses through tighter construction. Furthermore, tighter residential building envelopes need controlled fresh air ventilation to ensure acceptable IAQ, as is standard for all commercial buildings. The laws of physics have not changed; air, moisture, and heat still flow in and out of buildings according to the laws of thermodynamics. However, building materials, equipment, and construction practices have changed substantially over the last century.

Innovation in building materials and equipment and changing consumer expectations about comfort (e.g., mass market adoption of central air conditioning) have transformed the way modern buildings are constructed and perform. However, the housing industry's understanding of how these changes affect building performance has evolved slowly because "tried and true" builder know-how has traditionally developed over centuries of trial-and-error experience. Today, the old design "rules of thumb" no longer apply. Modern building envelope assemblies are much less tolerant of design and installation flaws. They must be better designed and constructed to control thermal, air, and moisture flows in and out of the structure.

Three primary factors have led to this "building science imperative":

- Innovative labor-saving building materials, such as gypsum board and oriented strand board (OSB) sheathing, have changed the way building envelopes behave. Market introduction of new materials that reduce air infiltration (i.e., house wraps and adhesives) have also contributed to the reduced drying potential of building assemblies. Even new homes not considered energy efficient by today's standards are tighter and less forgiving to moisture intrusion than older homes.
- The dramatic increase in central air conditioning, even in colder climates, has significantly changed the thermal conditions inside homes throughout the United States during much of the year. These relatively new operating conditions have fundamentally changed thermal, air, and moisture dynamics in homes.
- The latest building energy codes (i.e., IECC 2009, IECC 2012, and IECC 2015) require significantly increased airtightness and insulation levels. When designed and installed properly, these new requirements are cost effective and improve comfort and energy efficiency. However, design and installation problems persist throughout the industry, leading to increased risk of failing to meet higher-performance requirements or—worse yet—durability problems.

The new home construction industry has not completely caught up with the new "building science imperative" and faces challenges in delivering homes that safely and effectively provide higher levels of performance. If these performance issues are not solved, energy-efficient homes will have comfort and durability problems, builders will not exceed current code requirements, and energy codes will not promote increased energy efficiency.

Why These Objectives Matter for the Existing Home Improvement Market

The existing home retrofit industry faces the same risks as the new construction industry, with the following additional challenges:

- Air-sealing and insulating are often the most cost-effective measure for improving the energy and comfort performance of homes. However, air-sealing and insulating change the building's thermal, air, and moisture flows. Consequently, these measures must be accompanied with actions to ensure safe operation of existing combustion appliances, fresh air ventilation for acceptable IAQ, and moisture management in upgraded envelope assemblies. These additional requirements can be more difficult to address in existing homes because of costs and potential problems accessing hidden pipes, ducts, wiring, and equipment.
- The costs of retrofitting an existing home to the same performance level as new construction can be cost prohibitive, in light of the required additional pre-retrofit testing and extra costs for removing old materials and equipment. Uncertainty about these additional costs prior to beginning a job increases the business risk.
- Retrofit measures occasionally exacerbate HVAC system design or installation flaws that were not noticeable prior to the retrofit. This also increases risk and/or costs associated with improving the building, which is another significant entry barrier for home energy retrofit businesses.

In addition to the solutions needed for new construction, the home performance retrofit industry needs the following:

- Envelope air-sealing solutions that effectively (1) manage moisture risks and (2) reduce the costs of testing and removing old materials.
- Low-cost HVAC upgrade solutions that can effectively manage reduced loads without short-cycling or loss of humidity control.
- Low-cost ventilation systems that are suitable for retrofitting and compatible with existing construction and HVAC distribution systems.

Past Building America work has focused on both new and existing homes, and though many research results apply to both, a preponderance of the program's work has been specific to new construction. In 2016, Building America will undertake a deliberate research planning effort in the three roadmap areas to specifically address the RD&D needs of the home performance retrofit market. This effort will align future research projects more completely with the needs of the retrofit and home improvement markets.

Building America Research-to-Market Plan

Overview

Building America developed the Plan to provide a clear strategic framework for guiding future program investments and setting project objectives for overcoming the highest-priority RD&D challenges facing the high-performance housing industry. The Plan describes the three integrated Roadmaps, which each address one of the three major integrated technical challenges.

The Roadmaps are designed to achieve the following:

- Engage key industry and market stakeholders in the Building America RD&D process.
- Provide clear program objectives for each critical challenge.
- Develop solutions that are practical and profitable for builders and home improvement contractors.
- Clearly define RD&D efforts, market deployment programs, and codes and standards initiatives, as well as how they are linked.
- Develop best practices and lessons learned to be shared in the BASC and through other deployment tools and websites.
- Use codes and improvements in standards as end points for the greatest long-term market impact.
- Manage technical and business risks to minimize problems of adoption.
- Achieve optimal performance and cost effectiveness.

Defining clear program objectives in the Plan and the Roadmaps will focus program resources on the highest-priority activities in order to achieve strategic, concrete, measurable results. The process of developing and refining the Plan and Roadmaps over time will ensure accountability and responsiveness to changing market conditions and stakeholder value.

The Roadmaps and Plan will also help RBI effectively coordinate within the BTO Ecosystem to help achieve BTO's technology-to-market goals for residential buildings. Linking the Roadmaps' applied RD&D and market engagement activities to BTO's advanced R&D (i.e., Emerging Technologies) will help build a more efficient innovation pipeline for the housing industry. Linking research activities with market deployment activities and codes and standards initiatives within the BTO Ecosystem helps to ensure BTO residential program activities are coordinated efficiently and collectively impact the market.

Anticipated DOE-funded activities referenced in these roadmaps are subject to change based on program planning and congressional appropriations, and they may be altered to include other innovative activities likely to achieve the same or greater impact.

Building America Research-to-Market Plan Development Process

Draft Roadmap Development

Building America, with support from four DOE national laboratories—Lawrence Berkeley National Laboratory (LBNL), the National Renewable Energy Laboratory, Oak Ridge National Laboratory (ORNL), and the Pacific Northwest National Laboratory—developed three initial draft roadmaps in the winter and early spring of 2015, as shown in Figure 2.

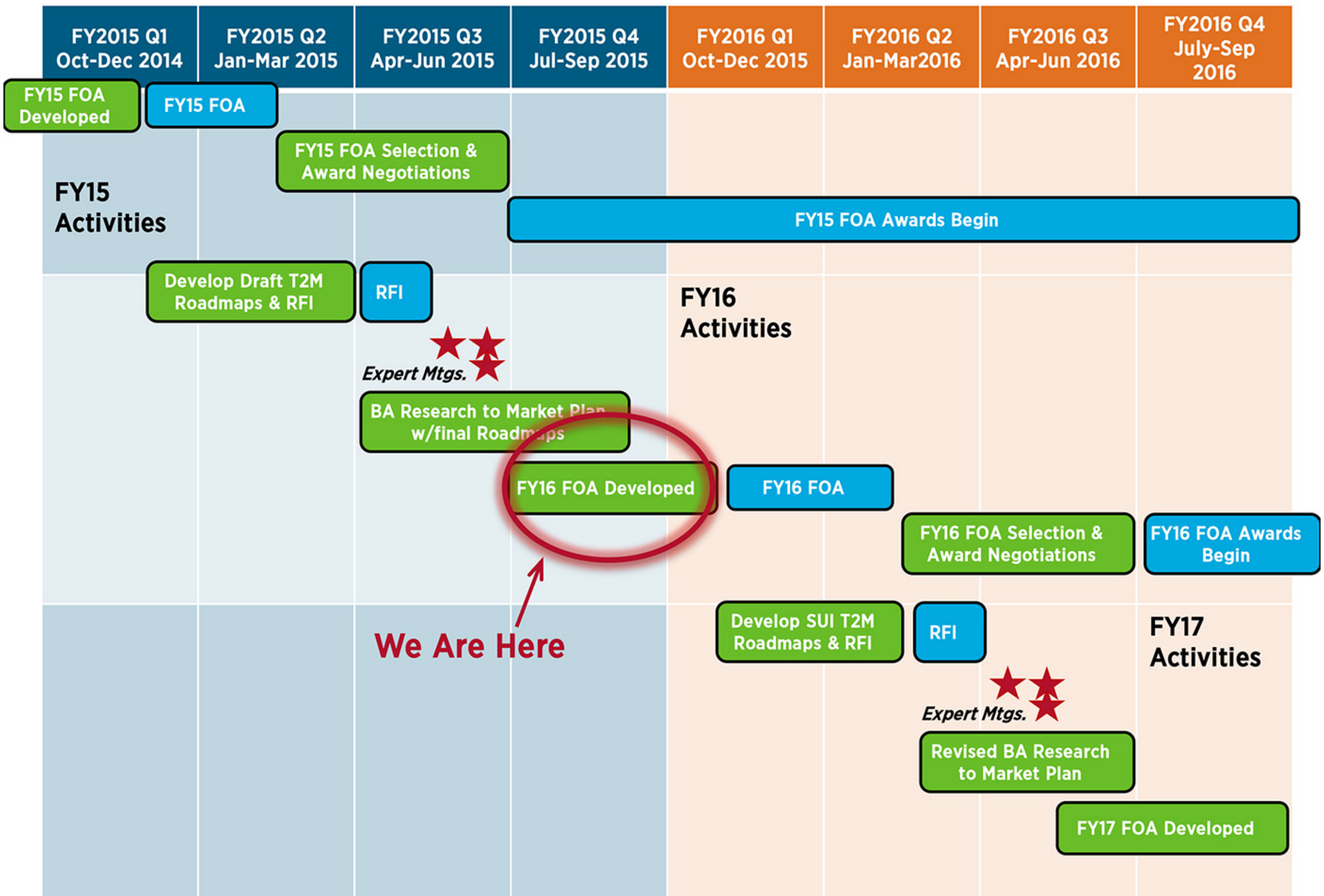

Figure 2. Building America Fiscal Year (FY) 2015 to FY 2017 planning timeline

The planning schedule links development of the draft roadmaps to stakeholder engagement, finalization of the *Technology-to-Market Roadmaps* and the *Research-to-Market Plan*, and ultimately formulation of the RD&D needs and gaps to be addressed in Building America Funding Opportunity Announcements (FOAs). Figure 3 illustrates the anticipated FOA schedule for implementing Building America projects supporting the roadmaps detailed in the Plan. Note that all planned future FOAs are tentative, subject to congressional appropriations as well as annual reassessment of progress and strategic and policy considerations.

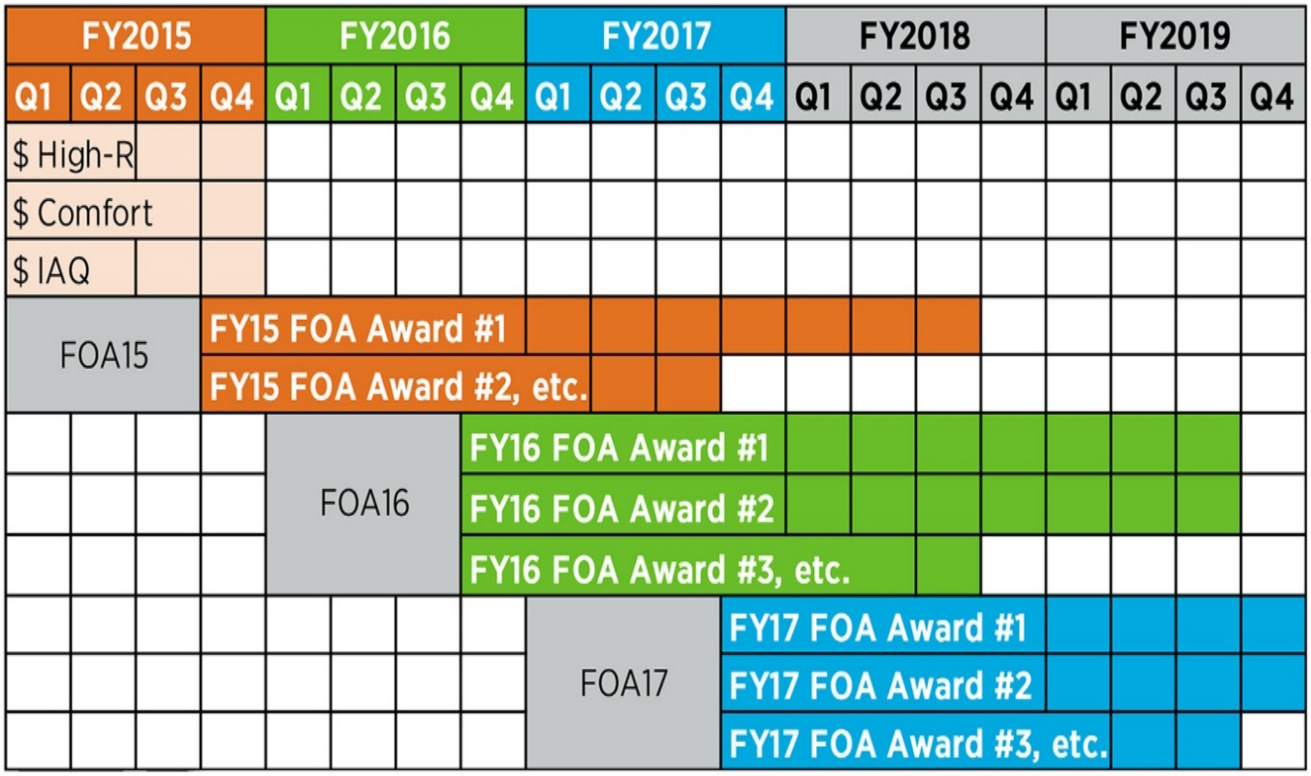

Figure 3. Building America planned FOA schedule (subject to appropriations and program planning activities)

Request for Information and Public Review Process

On April 3, 2015, a Request for Information (RFI) was posted by DOE, focused on soliciting industry feedback to the draft Plan and the associated Roadmaps. Twenty-one organizations responded to the RFI; these responses included 193 individual comments from four different types of organizations:

- **Consultant**: Provides services such as design, execution, repair, operation, maintenance, technology, and recommendations to clients.
- **Manufacturer**: Manufacturer of building materials, equipment, or products.
- **National Laboratory**: DOE laboratory.
- **University**: Educational institution.

Consultants provided the most comments of any organization type, but each organization type provided a balanced variety of comments. Each respondent commented on at least one of the four different categories that were outlined in the RFI:

- **Category 1 – General**: General comments about the proposed Building America Research-to-Market Plan, which incorporates the three integrated Roadmaps.
- **Category 2 – Envelope**: Technology-to-Market Roadmap A: High-Performance, Moisture-Managed Envelope Systems.
- **Category 3 – HVAC**: Technology-to-Market Roadmap B: Optimal Comfort Systems for Low-Load Homes.
- **Category 4 – IAQ**: Technology-to-Market Roadmap C: Optimal Ventilation Systems and IAQ Solutions for Low-Load Homes.

The individual comments received were balanced across the four categories. The individual comments were pulled from the responses and sorted as one of four comment subcategories:

- **Missing from roadmap**: Reference to a recommended activity or objective that was missing from the draft roadmaps.
- **Recommended revision**: Recommended revision or clarification of an existing activity or objective in the draft roadmaps.
- **Sequence/timing of roadmap**: Recommended revision or clarification of the timing or sequencing of the draft roadmap objectives or activities.
- **Stakeholder engagement**: Recommendation of stakeholders that should be included in the Building America planning and implementation process.
- **Other concerns**: Any other concerns regarding the Building America program planning efforts.

Comments were organized and reviewed by DOE and national laboratory staff, and then prepared for discussion in industry expert meetings, which are discussed in the next section.

2015 Industry Expert Meetings

As a follow-on activity to the public review and RFI period, DOE hosted three expert meetings, one for each of the three roadmap areas, in April and June 2015. These meetings brought together experts in each technology area to review the draft roadmaps and comments collected during the RFI and public review period and to provide valuable expert feedback as part of the DOE roadmap revision process.

Following the expert meetings, DOE revised the roadmaps and the associated narratives to produce the plan presented in the remainder of this document.

Planned Revision Process

The Plan and the associated Roadmaps are living documents. As RD&D projects are completed and market dynamics evolve, the Plan and the Roadmaps must also evolve. An iterative review and revision process will be undertaken each year to ensure that the Plan and Roadmaps continue to be market relevant and properly guide and inform Building America activities. In 2016, Building America plans to undertake a similar roadmapping process to the one used in 2015 to develop this plan and these roadmaps, with a distinct focus on home performance retrofit technical needs in the three roadmap areas. This process is expected to include a public review period in mid-2016, along with expert meetings to finalize revisions to the Plan and Roadmaps in 2016. These Building America stakeholder engagement activities will be separate from, but coordinated with, other RBI stakeholder engagement efforts related to stimulating the markets for home energy upgrades.

2015 Building America Technology-to-Market Roadmaps

The following section presents the three roadmaps in detail, providing the following for each:

- Narrative description of the roadmap and its key technology areas, including discussion of the primary technology and market gaps.
- Roadmap graphic depicting the key components or "blocks" (see roadmap key below).
- For each individual roadmap block:
    - The Goal/Outcome of the roadmap block, and
    - Detailed Action Plan, listing activities DOE anticipates funding to achieve the roadmap block objectives (subject to appropriations and policy considerations).
- References.

The following key (Figure 4) is presented for use in interpreting the roadmaps:

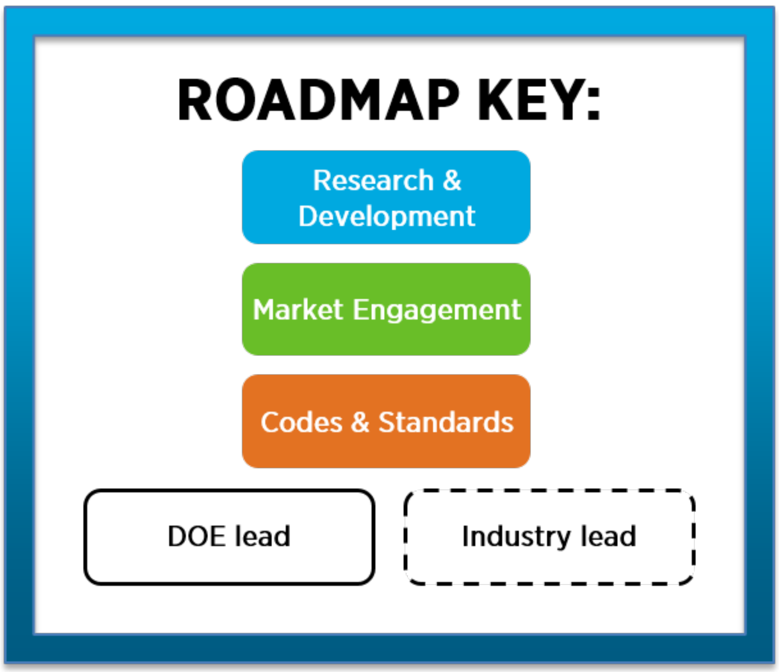

Figure 4. Roadmap key

It is important to note that the anticipated DOE-funded activities listed for each roadmap block are subject to change based on congressional appropriations, program policy considerations, and the relative merits of proposals received in response to related Building America FOAs. These detailed action plans may be altered at any time to address other challenges that arise and to include other innovative activities likely to achieve the same or greater impact.

Roadmap A: High-Performance, Moisture-Managed Envelope Solutions

Introduction

High-R-value (high-R) building envelope assemblies (i.e., foundation, walls, and roof) exceeding IECC 2012 are the biggest potential home energy-saving measures, according to several analyses by DOE national laboratories. Heating and cooling loads account for nearly 50% of home energy use, and significant end-use savings cannot be achieved without major improvements in building envelope performance. Based on a prioritized building envelope technologies assessment, the BTO Emerging Technologies Program, with analysis support from ORNL, determined that high-R building envelope assemblies in new and existing homes can decrease energy use by about 2.75 quads per year, which is nearly 3% of the energy consumed in the United States. However, advanced envelope systems are rarely selected by building designers. Current solutions are expensive and/or unfamiliar to many designers, builders, contractors, and code officials and therefore perceived as risky. Furthermore, the dominant perceived risk is durability specifically related to condensation and moisture accumulation in building assemblies. In addition, some high-R envelope solutions are limited by International Residential Code (IRC) code barriers (e.g., fire and structural).

Evidence of the real and perceived risk of moisture problems in insulated building assemblies, which can prevent adoption of high-performance building envelope assemblies, includes the following:

- BTO Building Energy Codes Program input, based on Office of Energy Efficiency and Renewable Energy (EERE) discussions with key IECC stakeholders regarding the major perceived risk of increased R-values in IECC.
- Building America Envelope Standing Technical Committee and expert meeting reports identifying moisture risk in high-R walls as the highest technical priority.[2]
- Field, laboratory, and modeling studies showing the risk of moisture issues in insulated building assemblies, such as increased moisture content of sheathing.[3]

Roadmap Overview

The end objective of this roadmap is the resolution of perceived cost and risk barriers to broad market acceptance of optimized, high-R building envelope systems. This will require addressing both knowledge gaps about moisture risk management and validating performance of priority high-R envelope systems.

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[2] Baker, *Expert Meeting Report: Cladding Attachment Over Exterior Insulation*; Levy et al., *Expert Meeting Report: Advanced Envelope Research for Factory Built Housing*; Lstiburek, *Enclosures STC*; Lstiburek, Ueno, and Boucher, *Enclosure Standing Technical Committee Strategic Plan, v. 2011a*; Ojczyk, Huelman, and Carmody, *Expert Meeting Report: Foundations Research Results*; Ojczyk, Carmody, and Haglund, *Expert Meeting Report: Windows Options for New and Existing Homes*; Ueno and Van Straaten, *Expert Meeting Report: Interior Insulation Retrofit of Mass Masonry Wall Assemblies*.

[3] Chandra et al., *Alleviating Moisture Problems in Hot, Humid Climate Housing*; Home Innovation Research Labs, *Characterization of the Moisture Performance of Energy-Efficient and Conventional Light-Frame Wood Wall Systems*; Hun et al., *Effects from the Reduction of Air Leakage on Energy and Durability*; International Energy Agency, "Annex 14, Condensation and Energy"; International Energy Agency, "Annex 24, Heat, Air, and Moisture Transfer Through New and Retrofitted Envelope Parts (Hamtie)"; Lepage and Lstiburek, *Moisture Durability with Vapor-Permeable Insulating Sheathing*; Lepage, Schumacher, and Lukachko, *Moisture Management for High R-Value Walls*; Pallin et al., *Risk Assessment of Energy-Efficient Walls*; Pallin, "Risk Assessment of Hygrothermal Performance – Building Envelope Retrofit"; Nielsen, *Use of FMEA – failure modes effects analysis on moisture problems in buildings*; and Wiehagen and Kochkin, *High-R Walls for Remodeling: Wall Cavity Moisture Monitoring*.

To accomplish this goal, the roadmap focuses on two main areas:

1. ***Moisture risk management***, including RD&D to develop data, guidance, and tools—both research and design tools—that result in better industry standards and codes for managing moisture durability risks of insulated building assemblies. These data, guidance, and tools will help industry confidently identify and specify the least-cost high-R building assembly designs that are least likely to encounter moisture problems in each climate zone. They will also provide a comprehensive and compelling basis for building codes to adopt requirements for building envelope assemblies that are both energy efficient and moisture durable (i.e., high-performance, moisture-managed building envelopes).
2. ***High-performance envelope systems***, developing and effectively disseminating best practice guidance and specifications for envelope systems with optimal thermal performance and minimal risk (e.g., moisture risk, structural risk, and fire risk) based on validated performance and accepted industry standards.

Note: The anticipated DOE-funded activities listed for each roadmap block are subject to change based on congressional appropriations, program policy considerations, and the relative merits of proposals received in response to related Building America FOAs. These detailed action plans may be altered at any time to address other challenges that arise and to include other innovative activities likely to achieve the same or greater impact.

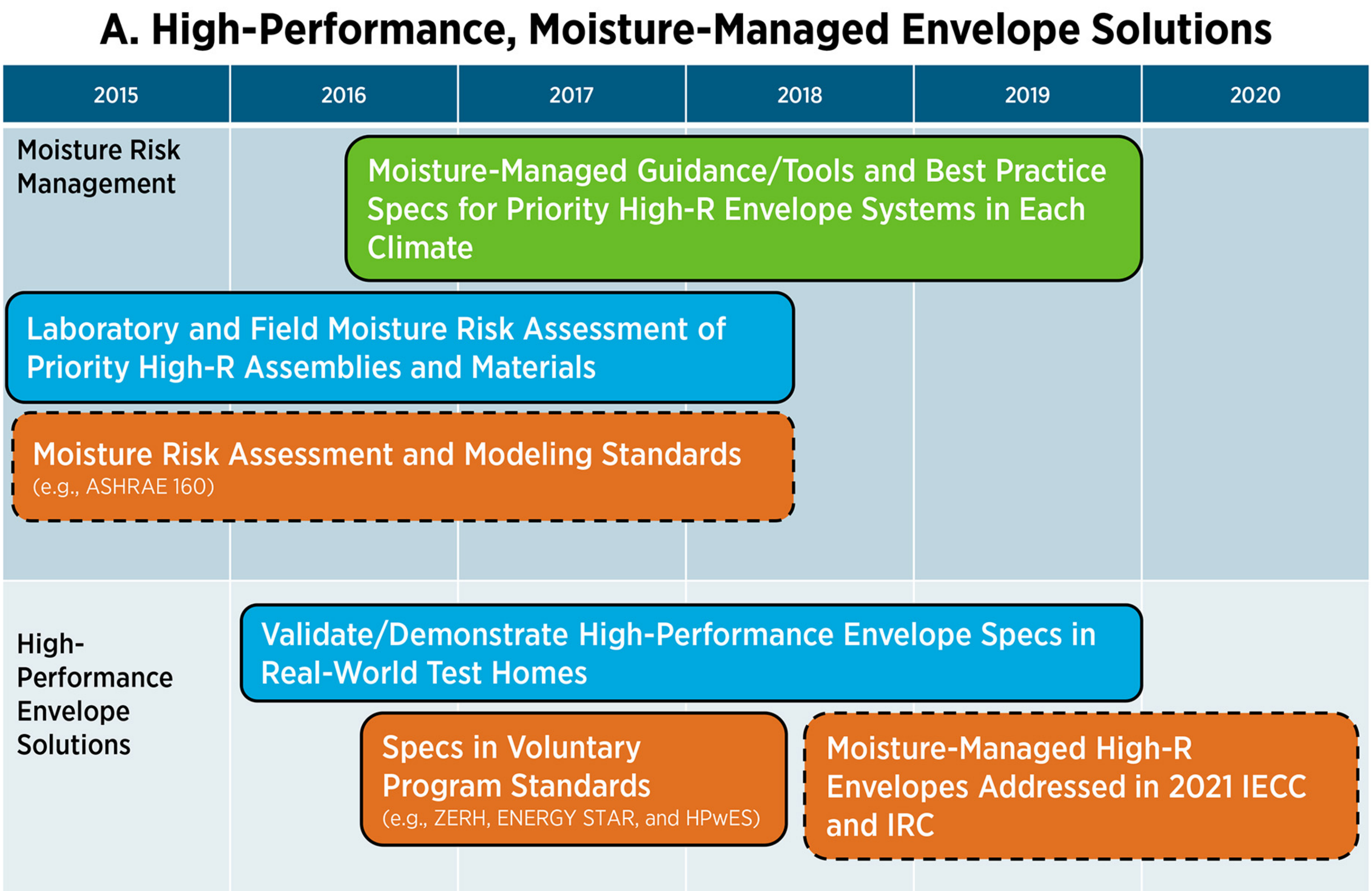

Figure 5. Roadmap A: High-Performance, Moisture-Managed Envelope Solutions

Moisture Risk Management

This section of the roadmap seeks to resolve the remaining knowledge gaps regarding the moisture durability of insulated envelope systems, and to develop the data, guidance, and tools needed to facilitate rapid industry adoption of high-performance, moisture-managed envelope systems. This R&D will evaluate the hygrothermal performance of high-R building envelope assemblies for new construction and envelope retrofits that have high deployment success potential, using both field tests and laboratory evaluations to calibrate and improve simulation tools. The improved tools will be used to conduct risk analyses that will help identify designs that are least likely to encounter moisture problems in each climate zone. The resultant combination of field tests, laboratory evaluations, and improved simulations will be leveraged to improve industry guidance, specifications, tools, and standards to increase industry confidence in high-performance envelope system designs and their ability to manage moisture durability risks.

Based on decades of R&D, including substantial contributions by Building America program participants, much is known about how to design and construct high-performance building assemblies that are both energy efficient and durable. High-performance building assembly best practices have been shown to both (1) cost-effectively reduce heating and cooling loads by more than 30% compared to current building code benchmarks and (2) effectively protect building envelope systems from the risks associated with moisture accumulation, especially in terms of the durability of building assemblies and materials. R&D has also helped to characterize the dominant moisture sources and loads in buildings, including (1) penetration of bulk water (i.e., precipitation) through compromised envelope components, (2) moist air infiltration through cracks and penetrations, (3) vapor diffusion through permeable building materials, and (4) moist indoor air that becomes a problem when it condenses on cool interior surfaces.

It is also known that moisture will eventually overcome any moisture control layer from either the inside or the outside because of design flaws, construction defects, material imperfections, excessive moisture loading, and/or repeated exposure to the elements over time. The inevitable wetting of building materials requires that durable building assemblies are designed such that vulnerable building materials are able to dry when they get wet (i.e., drying potential).

These multiple moisture control challenges are complex and often at odds; for example, some moisture-resistant materials can trap moisture inside building assemblies, exposing vulnerable building materials to prolonged dampness and resultant durability risk.

Building America has documented examples in every major climate zone of proven high-performance envelope system designs that are energy efficient, effectively control all these moisture pathways, and are cost effective over the life of the components. However, these durable system designs often require additional first costs or effort, and many in the residential building industry are still not confident that energy efficiency, moisture management, and low-cost designs are simultaneously achievable. This lack of industry confidence has been observed by both Building America experts and DOE Building Energy Codes Program staff, who report that key IECC stakeholders believe moisture durability risk increases with added insulation. Although insulation levels affect moisture dynamics in building assemblies, R-value is by no means a simple causal factor in moisture durability risk. Many other parameters affect moisture risk, including the permeability of materials, envelope air leakage, internal moisture sources, and other factors.

Experts have observed that this heightened perception of moisture durability risk is due to several factors, including a lack of design standards or criteria for estimating and managing moisture durability risks, uncertainty about the drying potential of new materials and assemblies due to insufficient data, and concern about increased construction defect litigation related to moisture problems in buildings. Designers, builders, contractors, and building scientists are currently forced to use “professional judgment” regarding design decisions and modeling input parameters, based on general moisture control principles and professional experience.

Before mainstream designers, builders, and contractors can confidently and reliably select durable, high-R building envelope assemblies, they will need solutions that help them to manage this complexity without compromising design flexibility. They also will need confidence that best practice guidance and tools lead to better design decisions. In short, they need credible "expert" assistance, based on sound research and demonstrated performance in real-world houses. However, insufficient expertise exists in the building workforce, and hiring experts is an additional cost in a highly cost-competitive industry. Furthermore, even building science experts cannot definitively resolve every design problem.

It is impractical to physically measure the moisture performance of every possible envelope system in each climate and account for reasonable variation in every influencing parameter. There are millions of possible variations in construction details and climate stressors. Therefore, validated solutions that enable fair comparisons of envelope assemblies and components will require improved analysis tools and standards for estimating probabilistic moisture durability risk (e.g., >97.5% confidence interval that no moisture problems will occur), calibrated by laboratory and field tests of priority envelope assemblies and systems.

Building science experts and stakeholders have made recent progress in developing building moisture risk assessment modeling tools (e.g., WUFI) and standards (e.g., ASHRAE Standard 160). However, further efforts will be required to instill industry confidence in these tools and standards. For example, ASHRAE Standard 160 has been severely criticized by industry stakeholders for being overly conservative, and consequently it is not widely used. Critiques include the fact that using the assumptions in the standard can yield "false positive" failures of building envelope components that are known to be relatively low risk. In addition, ASHRAE Standard 160 does not address air leakage as a moisture source, does not accurately assess internal moisture loads in buildings, and uses pass-fail criteria that are not state of the art. Furthermore, using ASHRAE Standard 160 (and WUFI) does not help users fully understand the risks associated with building envelope material selection; it simply provides standardized assumptions about moisture loads and acceptance criteria for performing quantitative moisture analysis of building envelope components such as a wall assembly. Probabilistic distributions of widely varying moisture loads in real houses will also be required before the standard can be used to provide accurate risk assessments. In addition, validated performance of building assemblies and calibration of moisture models to field measurements will be required before trustworthy estimates can be made of the risk associated with any given building component selection.

Laboratory and Field Moisture Risk Assessment of Priority High-R Assemblies and Materials

Goal/Outcome:

Success will be achieved when sufficient data exist to improve and validate models, design guidance, and tools for ensuring moisture durability of building envelope assemblies by climate zone, along with industry-accepted metrics for calibrating moisture durability risk (e.g., 97.5% confidence interval that no moisture problems will occur).

Detailed Action Plan:

DOE-Funded Activities (subject to appropriations and other policy considerations):

- Data collection to better define boundary conditions that influence interior temperature/RH conditions and moisture durability risk (i.e., material/assembly properties and typical moisture loads by climate zone and occupancy).
- Laboratory and field measurements of priority building assemblies in priority climate zones to improve and validate moisture durability risk analysis protocols, metrics, and tools.
- Field measurements in real-world test houses in priority climate zones to validate moisture durability risk analysis results, leading to development of validated guidance and decision support tools for housing industry professionals.
- Produce a listing of laboratory-/field-validated priority building envelope components and assemblies that minimize moisture risk for each climate zone, along with their relative degree of risk (e.g., >97.5% confidence interval that no moisture problems will occur).

Related Industry Activities:

- Builder and contractor partners work with Building America teams and laboratories to support field testing in real-world homes.
- Stakeholders provide feedback on priority building envelope components and assemblies to be tested.

Moisture Risk Assessment and Modeling Standards
(e.g., ASHRAE 160)

Goal/Outcome:

Success will be achieved when validated risk assessment protocols have been adopted into industry standards (e.g., ASHRAE Standard 160), enabling buildings science experts and industry professionals to reliably analyze and manage moisture durability of insulated building envelope systems and consistently select durable, high-performance envelope assemblies/systems in each climate zone, meeting acceptable risk criteria (e.g., >97.5% confidence interval that no moisture problems will occur).

Detailed Action Plan:

DOE-Funded Activities (subject to appropriations and other policy considerations):

- Develop protocols and metrics for evaluating the moisture durability risk of building envelope components, applicable to both retrofits and new construction, including provisions for calibrating the metrics to measured data.
- Analysis to determine which boundary conditions (i.e., material/assembly properties and typical moisture loads) most affect moisture durability risk (i.e., key influencing parameters), and how they vary as a function of building type, usage, and climate.
- Improve hygrothermal simulation tools (i.e., WUFI) so they can adequately address the effects of air leakage in building assemblies, and pursue other improvements as needed.
- Develop/improve standards for hygrothermal analysis (e.g., ASHRAE 160) that specifically define empirically validated moisture loads to be applied when performing moisture durability risk analysis. Moisture loads that need quantification and validation include water leakage, internal moisture generation, construction moisture, and air leakage.
- Work with key organizations such as ASHRAE and ASTM International to develop moisture modeling accuracy standards similar to those utilized for energy modeling, such as ASHRAE Guideline 14 (Measurement of Energy and Demand Savings).

Related Industry Activities:

- Industry experts develop consensus of the major parameters that influence moisture durability.
- Industry experts reach consensus on moisture risk evaluation protocols and metrics.
- Manufacturers measure material properties of new materials entering the marketplace and add these properties to existing databases. This activity will enhance the ability of hygrothermal models to accurately reflect the moisture performance of envelope systems.
- Standard committees improve ASHRAE Standard 160 to address key stakeholder concerns.
- Standard committees incorporate vetted moisture modeling protocols in ASHRAE and ASTM standards as appropriate.

Moisture-Managed Guidance/Tools and Best Practice Specs for Priority High-R Envelope Systems in Each Climate

Goal/Outcome:

Success will be achieved when best practice guidance and tools (e.g., design support and "expert systems"), validated by credible R&D findings, are used and trusted by building science experts and/or industry professionals to confidently select moisture-durable, high-performance building envelope systems, stimulating broad market adoption of high-R building assemblies.

Detailed Action Plan:

DOE-Funded Activities (subject to appropriations and other policy considerations):

- Develop model specifications and guidance for managing moisture risk in priority high-performance envelope systems, to be posted in the BASC, for use by key stakeholders such as builders, retrofit contractors, educators, and voluntary programs. Specs will meet acceptable risk criteria (e.g., >97.5% confidence interval that no moisture problems will occur), based on moisture risk management analysis and research.
- Develop decision support tools (i.e., "expert systems") that guide users (i.e., building science consultants, Home Energy Rating System [HERS] raters, builders, and/or retrofit contractors) through envelope assembly design and specification processes to more confidently and efficiently design high-performance, moisture-managed envelope assemblies and systems, meeting both energy efficiency specifications and acceptable risk criteria (e.g., >97.5% confidence interval that no moisture problems will occur).
- Activities that leverage educational opportunities to aid builders and contractors to understand and utilize best practice guidance and tools in their design decision processes.

Related Industry Activities:

- Stakeholders vet and provide feedback on proposed moisture risk management guidance and decision support tools for relevance and practical application.
- Manufacturers, builders, and industry organizations collaborate on the development of best practice guidelines.

High-Performance Envelope Solutions

This section of the roadmap builds on the previous section by addressing validation in real-world houses and strategic promotion of the high-performance, moisture-managed envelope solutions with the greatest potential for market adoption and energy savings at scale. Building America will validate the performance of selected solutions in real-world houses with Building America partners. Best practice guidance and specifications will be developed and posted in the BASC for the priority envelope systems proven to achieve high thermal performance and minimal risk for each climate. These validation, demonstration, and dissemination activities are all designed to instill industry confidence in the performance of these systems, encourage their use by mainstream builders, and support their integration into voluntary program requirements and building codes.

Encouragement and/or adoption by relevant codes, such as IECC and IRC, are necessary for proven moisture-managed high-R envelopes to achieve full market adoption. This section of the roadmap discusses the collection of data and demonstrated performance that will most likely encouraged this code adoption.

Validate/Demonstrate High-Performance Envelope Specs in Real-World Test Homes

Goal/Outcome:

Success will be achieved when a critical mass of high-performance envelope specifications for each climate have been validated and demonstrated in real-world houses so that builders and retrofit contractors can confidently select the appropriate balance between cost and risk to reliably achieve highly efficient and durable envelope performance. These solutions must effectively manage key performance risks (e.g., moisture, structure, and fire), be feasible in typical construction and/or home retrofit applications, and be cost competitive when whole-building life cycle performance is considered.

Detailed Action Plan:

DOE-Funded Activities (subject to appropriations and other policy considerations):

- Conduct field demonstrations with Building America partners in real-world homes to validate the performance of optimal high-performance envelope systems for new and existing homes in each climate zone. Develop best practice guidance for each major validated envelope system to be included in the BASC.
- Conduct field demonstrations to validate the performance and cost effectiveness of emerging technologies such as R-7+ windows, window attachments, spray-applied air barrier systems, and other advanced materials as they are developed and made commercially available. Develop best practice guidance for each major validated new technology to be included in the BASC.
- Evaluate other performance issues such as the quality of construction during the installation of windows, insulation, air and vapor barriers, and cladding systems.

Related Industry Activities:

- Builders, manufacturers, and industry experts participate in expert meetings and contribute to comprehensive lists of high-performance envelope systems, deployment issues, and risk mitigation strategies.
- Manufacturers collaborate with Building America teams to validate the performance of emerging technologies through field demonstrations.

Specs in Voluntary Program Standards

(e.g., ZERH, ENERGY STAR, and HPwES)

Goal/Outcome:

Success will be achieved when moisture management and other risk mitigation strategies identified by Building America research have been fully validated and incorporated into moisture-durable, high-performance envelope specifications for ZERH and ENERGY STAR–certified homes' specifications and checklists, other high-performance home programs, and home improvement program guidance and specifications (e.g., HPwES).

Detailed Action Plan:

DOE-Funded Activities (subject to appropriations and other policy considerations):

- Technical support for the incorporation of high-performance, moisture-managed envelope requirements and strategies in ZERH and ENERGY STAR–certified homes' specifications and checklists, including vetting with program partners and analysis support as needed.

- Technical support for HPwES and other home improvement programs to facilitate adoption of high-performance, moisture-managed envelope improvement specifications, including vetting with program partners and analysis support as needed.

Related Industry Activities:

- Independent high-performance new home programs and certification organizations incorporate high-performance, moisture-managed home specifications from ZERHs, ENERGY STAR–certified homes, and/or the BASC.
- Independent home performance programs and certification organizations incorporate moisture management and risk mitigation guidance and specifications from the BASC and/or HPwES guidance.

Moisture-Managed High-R Envelopes Addressed in 2021 IECC and IRC

Goal/Outcome:

Success will be achieved when IECC and IRC model building codes are modified to include moisture management and higher performance requirements, such as the selection of building envelope systems based on Building America recommendations and/or adding ASHRAE Standard 160 analysis compliance pathways.

Detailed Action Plan:

DOE-Funded Activities (subject to appropriations and other policy considerations):

- Develop a comprehensive and compelling basis for model building codes to adopt provisions that encourage high-performance, moisture-managed envelope assemblies that are proven to be energy efficient, moisture durable, and cost effective.
- Develop guidance for addressing hybrid insulation strategies in the building codes, such as addressing the recommended ratio of permeable to impermeable insulation as appropriate.
- Develop specific recommendations to modify 2021 IECC and IRC model building codes to address moisture management and other identified gaps for high-performance envelope assemblies, introduced to the code change process through the BTO Building Energy Codes Program or other means as appropriate.
- Support development of effective outreach and training materials for both builders and code officials in the form of BASC guidance and code compliance briefs. These activities will be coordinated with the BTO Building Energy Codes Program as appropriate.

Related Industry Activities:

- Industry experts and key stakeholders reach consensus and support recommendations for moisture-managed building envelope components.
- IECC and IRC code hearings vote to include Building America recommendations.

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Roadmap B: Optimal Comfort Systems for Low-Load Homes

Introduction

The installed performance of HVAC systems, especially distribution system effectiveness and latent performance (i.e., humidity control), is typically suboptimal in American homes, and it is often significantly compromised because of design and/or installation defects. Compromised HVAC system performance can result in energy waste, building durability problems, and occupant discomfort. These can be critical risks in low-load homes, which often have lower HVAC system airflows and/or less operation time. Distribution system and RH optimization are not often ensured by manufacturers or regulated by codes or standards, and current solutions are labor-intensive and/or expensive.

Evidence that comfort (i.e., HVAC) system performance problems can be significant and may prevent adoption of high-performance home technologies and systems includes the following:

- BTO Building Energy Codes Program input, based on EERE discussions with key IECC stakeholders regarding the major perceived risk of comfort problems in tighter homes (IECC 2012/2015).
- Building America Space Conditioning Standing Technical Committee and Expert Meeting reports have identified air distribution issues, high RH, and equipment sizing problems as the highest technical priorities for ensuring comfort in low-load homes.[4]
- Numerous studies have found significant comfort risks related to latent performance and distribution effectiveness in low-load homes, and additional studies have concluded that typical HVAC systems can operate inefficiently because of installation errors and undetected operational faults.[5]

Roadmap Overview

High-performance, low-load homes face unique space conditioning challenges that are not adequately addressed by current HVAC design practices. Furthermore, equipment suitable for optimal performance in low-load homes is not yet commonly used by builders and HVAC contractors. Low-load home comfort systems must address (1) effective part-load temperature and humidity control during all occupied times, and (2) effective air distribution and temperature control throughout the occupied spaces in a home. The goal is to ensure HVAC designers and builders have the tools necessary to design and install optimal comfort system solutions that address the needs of high-performance, low-load homes.

This roadmap seeks to guide critical RD&D efforts needed to ensure that residential equipment selection procedures adequately address year-round comfort control and temperature uniformity throughout the home. Previous Building America research, coupled with simulation studies and field test experiments, will be used to supplement existing comfort system design approaches to meet the needs of low-load homes. The improved comfort system design process will be validated using field demonstrations, and necessary revisions will be made.

Additional roadmap efforts will focus on meeting the equipment needs of low-load homes. By collaborating with manufacturers and conducting field demonstrations, Building America–funded activities in this roadmap

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[4] Arena, *Expert Meeting*; Brand, *Expert Meeting Report*; Brand, *Building America Expert Meeting*; Dentz, *Expert Meeting Report*; DOE, *Building America*; Lstiburek and Pettit, *Building America Expert Meeting*; Lstiburek and Pettit, "Final Report"; Martin and McIlvaine, *Space Conditioning;* Martin and McIlvaine, "Space Conditioning"; Building America Technology to Market Roadmap Experts' Workshop: Optimal Comfort Systems for Low-Load Homes, meeting minutes; Rudd, *Expert Meeting*; and Stecher, *Expert Meeting Report.*

[5] Brown et al., *Residential Low-Load HVAC*; Burdick, *Distribution and Room Air*; Domanski, Henderson, and Payne, *Sensitivity Analysis*; Downey and Proctor, "13,000 Air Conditioners"; Kerrigan and Norton, *Evaluation of Performance*; Poerschke and Stecher, *Simplified Space Conditioning*; Puttagunta, *Low-Load Space Conditioning*; Rudd et al., *Residential Dehumidification System Research*; and Stecher and Poerschke, *Simplified Space Conditioning.*

will help to ensure the space conditioning requirements of low-load homes can be satisfied with off-the-shelf equipment. The roadmap will also develop best practice guidelines to help practitioners make optimal design and equipment selection decisions, so that the resulting system installations achieve the expected efficiency.

The end objective of this roadmap is to set a course for RD&D, standards, and market stimulation that will reduce the barriers to designing and installing high-performance space conditioning systems in low-load homes that meet occupant comfort expectations during all occupied hours so they will be voluntarily adopted by industry and ultimately addressed in building codes.

The roadmap focuses on two main areas:

1. ***System design*** ensuring occupant comfort is maintained uniformly throughout the home for the entire year.
2. ***Smart systems and equipment*** capable of efficiently and consistently conditioning low-load homes are available on the market.

Note: The anticipated DOE-funded activities listed for each roadmap block are subject to change based on congressional appropriations, program policy considerations, and the relative merits of proposals received in response to related Building America FOAs. These detailed action plans may be altered at any time to address other challenges that arise and to include other innovative activities likely to achieve the same or greater impact.

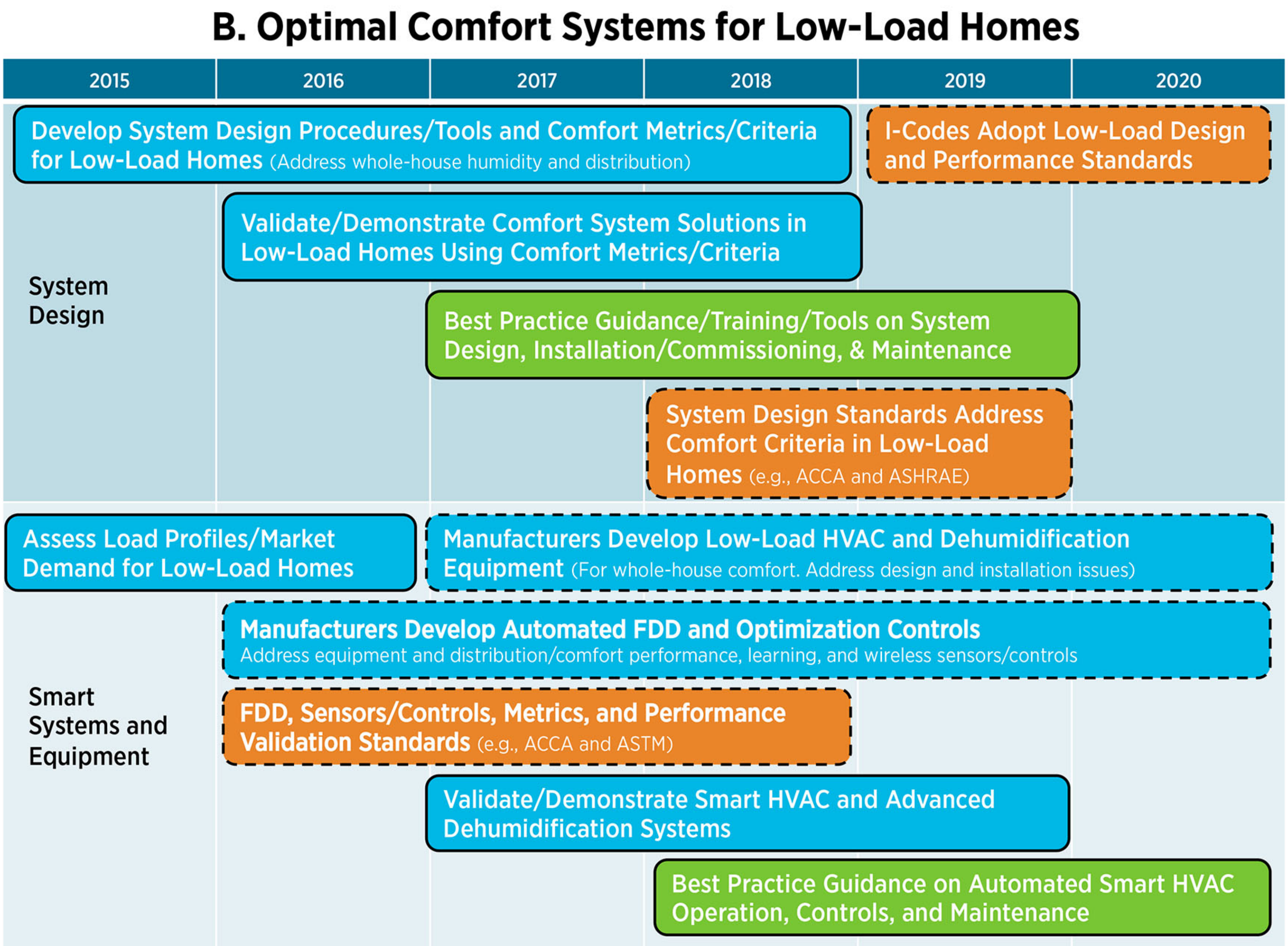

Figure 6. Roadmap B: Optimal Comfort Systems for Low-Load Homes

System Design

As a home's envelope improves, peak and seasonal sensible cooling loads are reduced, which leads to smaller air conditioners, shorter peak cooling seasons, and lower system airflow rates. However, because of internal gains and fresh air ventilation, latent loads are not reduced as much as sensible loads, making indoor humidity control at part-load cooling conditions a critical need. Elevated indoor humidity levels, particularly during non-summer cooling conditions, have been observed in several field[6] and simulation-based studies.[7] Current equipment sizing procedures do not explicitly address the selection of residential dehumidification equipment. Industry experts agree that explicit humidity control will be a critical need to ensure year-long comfort in low-load homes.[8]

Addressing the challenge of air distribution in low-load homes is needed because low airflow rates susceptible to insufficient air mixing can lead to poor temperature distribution and reduced comfort. Challenges associated with adequate air mixing in low-load homes have also been well demonstrated.[9] Research has shown current system design procedures may need to be revised to meet the needs of low-load homes.[10]

Low-load homes may not require conventional distribution systems, and space conditioning distribution may be accomplished via point-source systems or in combination with a distributed ventilation system.

Design guidance on alternative distribution system designs is needed. Currently, there is not an established method to quantify and compare the comfort associated with a particular system design. Additionally, because of complex system design and interaction issues in low-load homes, using peak design conditions to design systems may no longer be appropriate.

Comfort systems that address the low-load, high-performance homes must be thoroughly vetted and demonstrated in order for the industry to implement these solutions. Successful demonstrations are critical to achieving market acceptance and improving ease of installation. As the industry transitions from conventional air distribution systems, learning best practice installation techniques for new system designs will be key to accelerating market adoption.

It is critical that designers follow appropriate standards when designing comfort systems for low-load homes.[11] A majority of HVAC contractors do not follow current system design standards.[12] Additionally, numerous field and simulation-based studies have shown that installed systems operate sub-optimally because of poor installation and design practices.[13]

Ensuring best practice guidance is utilized by the workforce is a key challenge. Informational content and delivery mechanisms must be individually tailored for the intended audience. It is also critical for consumers to recognize the importance of a systems-based approach to HVAC design.

Existing system sizing and design standards should be revised to include the dehumidification design calculations necessary to select dehumidification equipment. New standards must be developed, or existing standards must be revised, to resolve distribution system needs and issues unique to low-load homes, including simplified/limited air distribution systems, point-source equipment, and multi-zone systems. As the international codes (International Mechanical Code [IMC] and IECC) mandate increased energy efficiency and trend toward low-load designs, it will be critical that they also adopt low-load comfort system design standards to ensure homes meet occupant comfort expectations, and commissioning/performance standards to ensure potential energy savings are realized.

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[6] Kerrigan and Norton, *Evaluation of Performance;* and Rudd et al., *Residential Dehumidification System Research.*
[7] Rudd et al., *ASHRAE RP-1449*; and Fang, Winkler, and Christensen, "Using EnergyPlus."
[8] DOE, *Building America*; and Rudd, *Expert Meeting*.
[9] Poerschke and Stecher, *Simplified Space Conditioning*; and Burdick, *Distribution and Room Air.*
[10] Arena, *Analyzing Design*.
[11] DOE, *Building America*.
[12] Burdick, *Strategy Guideline*; and DOE, *Building America*.
[13] Domanski, Henderson, and Payne, *Sensitivity Analysis.*

Develop System Design Procedures/Tools and Comfort Metrics/ Criteria for Low-Load Homes (Address whole-house humidity and distribution)

Goal/Outcome:

Success will be achieved when improved and/or lower-cost standardized system design procedures are developed that effectively address thermal comfort optimization in high-performance homes, including supporting tools with minimal inputs that provide comparable/improved results relative to traditional methods, and comfort metrics/criteria that enable designers to effectively address space conditioning issues unique to low-load homes.

Detailed Action Plan:

DOE-Funded Activities (subject to appropriations and other policy considerations):

- Develop/validate a multi-zone building model to assess thermal comfort distribution and evaluate simplified comfort system solutions.
- Investigate the feasibility and need for alternative comfort metrics.
- Investigate simplified space condition systems for low-load homes.
- Develop thermal comfort metrics and criteria to evaluate systems.
- Develop a part-load calculation procedure and supplemental dehumidification equipment selection procedure.
- Develop annual simulation/design tools to ensure year-round, well-distributed temperature and humidity control.

Related Industry Activities:

- Manufacturers create tools to assess comfort and air distribution in low-load homes.

Validate/Demonstrate Comfort System Solutions in Low-Load Homes Using Comfort Metrics/Criteria

Goal/Outcome:

Successfully validate low-load home design procedures and demonstrate optimal comfort solutions in real-world low-load homes, including the measured energy and comfort performance of optimal comfort system designs in various house types and climates.

Detailed Action Plan:

DOE-Funded Activities (subject to appropriations and other policy considerations):

- Evaluate and demonstrate low-load solutions through ARIES field testing of manufactured and Habitat for Humanity homes and FSEC field testing of Habitat for Humanity homes and the Flexible Residential Test Facility.
- Collect field data on simplified space conditioning solutions.
- Gather and analyze field data on a mini-split heat pump and transfer fan distribution system in a low-load manufactured home.
- Assess the ease of installation of simplified space conditions for low-load homes.

- Demonstrate and validate low-load home comfort system design solutions using Building America unoccupied test houses and DOE ZERHs. Collected field data and lessons learned will be used to develop BASC content and validate system design procedures and tools.
- Learn and document best practice installation techniques to minimize installation costs and improve the likelihood of achieving expected performance.

Related Industry Activities:

- Pacific Gas and Electric Company laboratory home study investigating mini-split heat pump performance in retrofit homes.

Best Practice Guidance/Training/Tools on System Design, Installation/Commissioning, & Maintenance

Goal/Outcome:

Success will be achieved when best practice guidance on optimal comfort system design, quality installation, and low-cost/reliable commissioning procedures for low-load homes are incorporated into BASC content, including system details and documentation, training content, and targeted informational videos as needed. BASC content is used by target industry audiences to improve designs, installation/commissioning, and operations/maintenance of comfort systems in high-performance homes, particularly through above-code programs.

Detailed Action Plan:

DOE-Funded Activities (subject to appropriations and other policy considerations):

- Develop/validate a multi-zone building model (design tool) to assess thermal comfort distribution and evaluate simplified comfort system solutions.
- Develop best practice guidelines on system design, installation/commissioning, and maintenance using previous information on system design methods unique to low-load homes, findings from field installations, and measured field results.
- Through the BASC, deliver best practice guidance targeted to HVAC contractors, builders, architects, engineers, and homeowners.

Related Industry Activities:

- Manufacturers, builders, and industry organizations collaborate on the development of best practice guidelines.

System Design Standards Address Comfort Criteria in Low-Load Homes (e.g., ACCA and ASHRAE)

Goal/Outcome:

Success will be achieved when new and/or revised system design standards (e.g. Air Conditioning Contractors of America Association, Inc. [ACCA] Manuals J, S, D, T, and E) are adopted that address unique aspects of high-performance, low-load homes.

Detailed Action Plan:

DOE-Funded Activities (subject to appropriations and other policy considerations):

- Support the development of load calculation and system design methods to select space conditioning equipment for year-round comfort.
- Support the development of the dehumidification design calculations necessary to select dehumidification equipment.

Related Industry Activities:

- ACCA, ASHRAE, and the Residential Energy Services Network (RESNET) support the adoption of system design standards for low-load homes.
- Industry standard committees revise existing standards or develop new standards to address distribution system needs and issues unique to low-load homes, including simplified/limited air distribution systems, point-source equipment, and multi-zone systems.
- Standard committees include the dehumidification design calculations necessary to select dehumidification equipment in system sizing and design standards.
- Standard committees incorporate load calculation and system design methods to select space conditioning equipment for year-round comfort into standards.

I-Codes Adopt Low-Load Design and Performance Standards

Goal/Outcome:

Success will be achieved when revised I-Codes and voluntary labeling programs incorporate design standards that enable optimal comfort systems for low-load, high-performance homes.

Detailed Action Plan:

DOE-Funded Activities (subject to appropriations and other policy considerations):

- Develop simple metrics that are quickly identifiable by code officials.
- Potentially develop an automated diagnostic system for verification of system performance, as this verification may be out of scope for code officials.
- DOE's ZERH and the U.S. Environmental Protection Agency's (EPA's) ENERGY STAR homes program requirements will be updated to require the documented use of the equipment sizing and air distribution design standards for low-load homes.

Related Industry Activities:

- ICC adopts equipment sizing and air distribution design standards for low-load homes.

Smart Systems and Equipment

Nearly 80% of the residential HVAC market is the replacement of existing equipment. Moreover, low-load new-construction homes are a fraction of the remaining 20%. Manufacturers that attended DOE's Building America Technology-to-Market Roadmap Expert Meetings on Optimal Comfort Systems for Low-Load Homes indicated there is not a technological barrier to manufacturing low-capacity equipment. However, manufacturers lack a clear understanding of where the new construction residential HVAC market is headed and are in need of a market assessment prior to offering low-capacity equipment.[14]

[14] DOE, *Building America*.

Additionally, manufacturers need a clearer understanding of the load profiles present in low-load homes.[15] The Building America Space Conditioning Standing Technical Committee identified the determination of total internal moisture gains in homes as the main priority under the RH control sub-topic.[16] Sensible and latent load profiles are less understood for low-load homes, but internal gains are known to make up a larger portion of the total load. Better understanding of occupant-related internal gains will not only help to inform system design methods, it will also help manufacturers optimize equipment for sensible and latent loads common to low-load homes.

The majority of the space conditioning equipment currently available on the market is oversized compared to the cooling, dehumidification, and heating loads that exist in high-performance, low-load homes. As building codes trend to high levels of efficiency, low-capacity HVAC options for new construction homes are limited.[17] In a survey by the Consortium for Advanced Residential Buildings (CARB) Building America teams of 941 multi-family or single-family attached dwellings, heating and cooling equipment was correctly sized 1% and 6% of the time, respectively. Additionally, more than 75% of the heating and cooling design loads were less than 12 kBtu/hr and 25 kBtu/hr (~2 tons) for the multi-family apartments and single-family attached homes, respectively. Equipment options are mostly limited to all-electric, inverter-driven air-source heat pumps to meet these needs.[18] Available low-capacity equipment is also challenging to interface with a distribution system. There is a need for manufacturers to offer central equipment in lower capacities with integrated (built-in) humidity control suitable for low-load, high-performance homes.

Residential comfort systems in the United States consume about 50% of an average home's energy.[19] More than 60% of these systems are not operating optimally.[20] Additionally, more than 20% of them experience at least one failure a year.[21] Numerous field and simulation-based studies have shown installed systems operate sub-optimally because of installation faults.[22] A majority of faults identified at start-up can be corrected, while issues related to poorly designed distribution systems are harder to correct. Lstiburek and Pettit suggest that initial priority should be given to identifying faults at start-up and less focus spent on identifying efficiency loss over time.[23] Researchers have estimated that advanced monitoring of residential loads presents a potential of 12% energy savings.[24] In addition, fault detection and diagnostics (FDD) could achieve 15%–30% energy savings.[25] Furthermore, advanced control techniques could enable residential comfort systems to interact with demand response programs.

Homeowners are unlikely to know about or respond to performance issues until their HVAC system fails completely. FDD and control systems are needed to call attention to comfort system issues before they become major failures. This early intervention will reduce excess energy consumption, minimize overall repair costs, and improve occupant comfort. Few automated controls, sensors, diagnostics, and fault correction systems exist for residential comfort systems. Furthermore, residential service providers have little experience with these control systems. Developing a standard set of fault codes, developing a standardized language to communicate faults to homeowners, and including sensing and diagnostic requirements in code language were identified as the key priorities. This standardization will enable contractors to diagnose and service equipment for different systems from different manufacturers.

A critical step to achieve broad market penetration of FDD capabilities is the development of communication standards and performance validation standards for FDD tools. The potential benefits of proper system

[15] DOE, *Building America.*
[16] Martin and McIlvaine, "Space Conditioning."
[17] Brown, *Review*; and Puttagunta, *Low-Load Space Conditioning.*
[18] Puttagunta, *Low-Load Space Conditioning.*
[19] U.S. Energy Information Administration, "Residential Energy."
[20] Lstiburek and Pettit, *Building America Expert Meeting.*
[21] Downey and Proctor, "13,000 Air Conditioners."
[22] Domanski, Henderson, and Payne, *Sensitivity Analysis.*
[23] Lstiburek and Pettit, *Building America Expert Meeting*.
[24] Ehrhardt-Martinez, Donnelly, and Laitner, "Advanced Metering."
[25] Architectural Energy Corporation, *HVAC Fault Detection.*

installation have been well documented.[26] Developing a standard set of fault codes and including sensing and diagnostic requirements in code language were identified by Lstiburek and Pettit as the key priorities to gaining market penetration of FDD tools.[27]

Successful demonstrations are critical to achieving market acceptance and improving the application of smart systems. Findings from field demonstrations will help contractors best apply the technology and manufacturers to understand how to improve next-generation products. Advanced controls will be a new technology when introduced to the market. As envisioned, these technologies will require interaction with technicians in the field. These interactions may involve accessing diagnostic codes, but they could also include remote communication, troubleshooting through decision analysis, accessing manufacturer data, and diagnosis of the controls themselves. In addition, controlled demonstrations will be needed to validate energy performance. Service providers may view the technology as a risk, or even as a threat. Market adoption will require demonstrations, guidance, and outreach to enhance the technologies' credibility through proven performance and give creative providers the means to develop technical approaches and business plans for broad market deployment.

Best practice guidance and outreach activities are needed to gain traction among HVAC contractors and homeowners.

Assess Load Profiles/Market Demand for Low-Load Homes

Goal/Outcome:

Complete a market assessment for single-family detached housing, outlining new construction trends, the influence of voluntary labeling programs, and current/needed comfort system solutions for high-performance homes. Develop latent and sensible load profiles needed for optimal comfort system design in low-load, high-performance homes.

Detailed Action Plan:

DOE-Funded Activities (subject to appropriations and other policy considerations):

- Conduct a literature review and assessment of existing data for internal latent gains.
- If necessary, develop a field test protocol and implementation plan to measure internal latent gains.

Related Industry Activities:

- Manufacturers and industry organizations collaborate on the market assessment and identification of current trends and demands.

Manufacturers Develop Low-Load HVAC and Dehumidification Equipment (For whole-house comfort. Address design and installation issues)

Goal/Outcome:

Success will be achieved when a diverse and competitive selection of HVAC and humidity control equipment is on the market and enables the housing industry to meet the space conditioning needs of low-load homes throughout the United States.

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[26] Domanski, Henderson, and Payne, *Sensitivity Analysis.*

[27] Lstiburek and Pettit, *Building America Expert Meeting*.

Detailed Action Plan:

DOE-Funded Activities (subject to appropriations and other policy considerations):

- Provide the necessary market information to the manufacturers to improve the availability of low-capacity equipment.

Related Industry Activities:

- Manufacturers develop a variety of HVAC equipment and distribution systems that are suitable for low-load homes and include integrated humidity control.
- Manufacturers ensure the compatibility of low-load central systems with conventional distribution systems, or they develop innovative distribution systems.

Manufacturers Develop Automated FDD and Optimization Controls

Address equipment and distribution/comfort performance, learning, and wireless sensors/controls

Goal/Outcome:

Success will be achieved when onboard or third-party automated controls, FDD, and fault correction equipment are readily available in the market, enabling designers and home energy professionals to ensure "smart" HVAC systems are properly installed and performing to expectations at start-up, at installation, and throughout the product's lifetime.

Detailed Action Plan:

DOE-Funded Activities (subject to appropriations and other policy considerations):

- Identify the following in the short term:
    - Applications (uses) that may be served by advanced controls and diagnostics.
    - Use cases for meeting applications.
    - Potential technology and service solutions that will meet the use cases.
    - Potential business cases that may incorporate the technologies.
- Develop areas where DOE RD&D can contribute to technology development.
- Applications that may be met with existing business models should be the subject of guidance documentation and outreach activities.
- Demonstrate technologies and service models in Building America projects.
- Vet all solutions, including prioritized technologies, with industry on an ongoing basis.
- Support adoption of technologies, as well as technology-based and service-based business models.
- Business models that may be promoted with industry to lend credibility and provide guidance for the adoption of new approaches.

Related Industry Activities:

- Manufacturers prioritize technologies for further development to meet applications that fit promising business models.
- Manufacturers develop sensors, controls, and supporting software platform for automated FDD and optimization.
- Manufacturers commercialize technologies.
- HVAC contractors implement service-based business models with support from Building America.

FDD, Sensors/Controls, Metrics, and Performance Validation Standards (e.g., ACCA and ASTM)

Goal/Outcome:

Success will be achieved when metrics and performance standards are developed and adopted that enable industry to objectively evaluate the capability, accuracy, and applicability of sensors, controls, and FDD tools applied to smart HVAC equipment.

Detailed Action Plan:

DOE-Funded Activities (subject to appropriations and other policy considerations):

- Support development of metrics and performance validation standards.
- Support adoption of metrics and performance standards by ACCA and ASTM.

Related Industry Activities:

- Manufacturers develop a variety of FDD tools.
- ACCA and ASTM develop metrics and performance validation standards with support from Building America teams.

Validate/Demonstrate Smart HVAC and Advanced Dehumidification Systems

Goal/Outcome:

Successful demonstration and performance validation of smart HVAC and advanced dehumidification systems, leading to increased demand for these smart products, especially in low-load, high-performance homes.

Detailed Action Plan:

DOE-Funded Activities (subject to appropriations and other policy considerations):

- Establish field test protocols/methods of test to assess FDD tools and smart HVAC equipment performance.
- Test automated FDD and commissioning tools to assess ease of installation, ease of use, and capabilities in identifying installation faults and/or poor system design.
- Perform field tests to validate equipment performance using Building America unoccupied test houses and real-world test houses, such as DOE ZERHs.

Related Industry Activities:

- ACCA and ASTM develop metrics to evaluate FDD tools and smart HVAC equipment.
- Manufacturers develop the diverse set of product offerings that is required to assess a range of products.
- Manufacturers and installers collaborate on testing to ensure field installations are performing as expected.

Best Practice Guidance on Automated Smart HVAC Operation, Controls, and Maintenance

Goal/Outcome:

Success will be achieved when best practice guidance on automated, smart HVAC system operation, control, and maintenance for low-load homes is incorporated into BASC content, including documentation, training content, and targeted informational videos. Success may be measured by the use of BASC content by target industry audiences to improve operations/maintenance of comfort systems in high-performance homes, particularly through above-code programs.

Detailed Action Plan:

DOE-Funded Activities (subject to appropriations and other policy considerations):

- Assess currently available products in this space.
- Develop best practice guidance for currently available products.
- Develop best practice guidelines on automated, smart HVAC operation and controls using previously collected field data.
- Deliver best practice guidance targeted to HVAC contractors, builders, engineers, and homeowners via the BASC.

Related Industry Activities:

- Manufacturers develop a diverse set of FDD and commissioning tools, smart HVAC equipment, and advanced dehumidification systems.

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Roadmap C: Optimal Ventilation and IAQ Solutions

Introduction

Basic mechanical ventilation has become standard in new homes, building codes, and home performance and weatherization programs. However, current applications and standards do little to optimize either IAQ or IAQ system-related energy performance. For example, heat recovery is not required or encouraged in ASHRAE Standard 62.2, and it is less commonly specified. In addition, current ventilation solutions are limited by climate, sensor and control technologies, pollutant source control methods, and the system costs the market will bear.

However, even optimized ventilation solutions do not guarantee acceptable IAQ. This ventilation caveat is clearly stated in the scope of ASHRAE Standard 62.2. Acceptable IAQ requires addressing the sources of indoor pollutants through elimination or removal. Then, dilution ventilation can be more effectively applied to address general pollutants that cannot be eliminated or removed effectively at their sources, such as occupant-generated pollutants.

Finally, it is clear from decades of research and market experience through Building America and other programs that energy efficiency and high-performance homes will not be adopted by the market or industry standards if they cause IAQ problems. Furthermore, good IAQ and healthy home features have been shown to be a powerful driver for energy efficiency and improved home performance.

Evidence that improved IAQ can encourage adoption of high-performance home technologies and systems includes the following:

- Decades of IAQ research has shown that acceptable IAQ can be confidently ensured only with control of indoor pollutant sources. This has led to adoption of the building science community adage, "build tight and ventilate right." Evidence supporting this approach includes studies that show increased health risks in houses with inadequate ventilation,[28] as well as studies linking increased health risks to specific indoor pollutants.[29]
- IAQ risk is not directly associated with increased airtightness. In fact, there is strong evidence that high-performance homes (i.e., homes that have been built 10 or more times as airtight) have better IAQ than typical homes.[30]
- IAQ and health benefits are major drivers of demand for energy-efficient houses and features.

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[28] Bornehag et al., "Association between ventilation rates in 390 Swedish homes and allergic symptoms in children"; Sundell et al., "Ventilation rates and health: multidisciplinary review of the scientific literature"; and Wargocki et al., "Ventilation and health in non-industrial indoor environments: report from a European Multidisciplinary Scientific Consensus Meeting (EUROVEN)."

[29] AirAdvice for Homes, "AirAdvice for Your Home"; EPA, "Care for Your Air: A Guide to Indoor Air Quality"; Health Science Associates, "Industrial Hygiene & Safety: Indoor Air Quality & Mold/Fungi"; and Milner et al., "Home energy efficiency and radon related risk of lung cancer: modeling study."

[30] Breysse et al., "Health Outcomes and Green Renovation of Affordable Housing"; Coulter et al., "Liabilities of Vented Crawl Spaces And Their Impacts on Indoor Air Quality in Southeastern U.S. Homes"; Emmerich et al., "Air and pollutant transport from attached garages to residential living spaces"; Jacobs, "Health Outcomes of Green and Energy-Efficient Housing"; Kovesi et al., "Heat recovery ventilators prevent respiratory disorders in Inuit children"; Leech, Raizenne, and Gusdorf, "Health in occupants of energy efficient new homes"; Noris et al., "Indoor environmental quality benefits of apartment energy retrofits"; and Weichenthal et al., "A randomized double-blind crossover study of indoor air filtration and acute changes in cardiorespiratory health in a First Nations community."

Roadmap Overview

This roadmap seeks to guide RD&D to ensure that the development of best practices, specifications, and standards for existing home retrofits and high-performance new home construction accounts for the effects that the building and its systems may have on the health of occupants and the durability of the building itself, while minimizing energy usage. The end objectives of this roadmap are smarter ventilation and IAQ solutions, more flexible and robust industry standards (e.g., future editions of ASHRAE 62.2), and IAQ valuation methods that enable market adoption of high-performance homes with optimal IAQ and minimal energy use. These will ease adoption of good IAQ by the housing industry and increase the attractiveness of high-performance homes to the public. The roadmap provides more detailed objectives by focusing on improving technologies and industry standards in the following three areas:

1. ***Targeted pollutant solutions*** that better control known indoor contaminants of concern, near their emission source(s), to allow for improved IAQ without increasing dilution ventilation requirements. Ideally, if all known contaminants of concern are controlled at their sources, very little dilution ventilation will be required to maintain acceptable IAQ.
2. ***Smart ventilation technology solutions*** that optimize the balance between IAQ and energy and account for other variables that affect IAQ, such as occupancy, exhaust fan (e.g., dryer and range hood) operation, indoor and outdoor temperature, RH, and outdoor pollutant levels (e.g., ozone and particles).
3. ***IAQ valuation*** that facilitates standardized, quantified assessments of home IAQ to encourage more informed and objective design decisions regarding IAQ measures. One promising approach being considered in this roadmap is the development of a standardized scale for scoring home IAQ, similar to energy scores (e.g., HERS Index). A standard IAQ scoring system could encourage better-informed choices about IAQ and provide a way to incent building industry stakeholders to provide healthier, more durable homes. IAQ valuation will also make pollutant measurements more meaningful and may lead to real-time IAQ controls that effectively respond to indoor environmental conditions.

Note: The anticipated DOE-funded activities listed for each roadmap block are subject to change based on congressional appropriations, program policy considerations, and the relative merits of proposals received in response to related Building America FOAs. These detailed action plans may be altered at any time to address other challenges that arise and to include other innovative activities likely to achieve the same or greater impact.

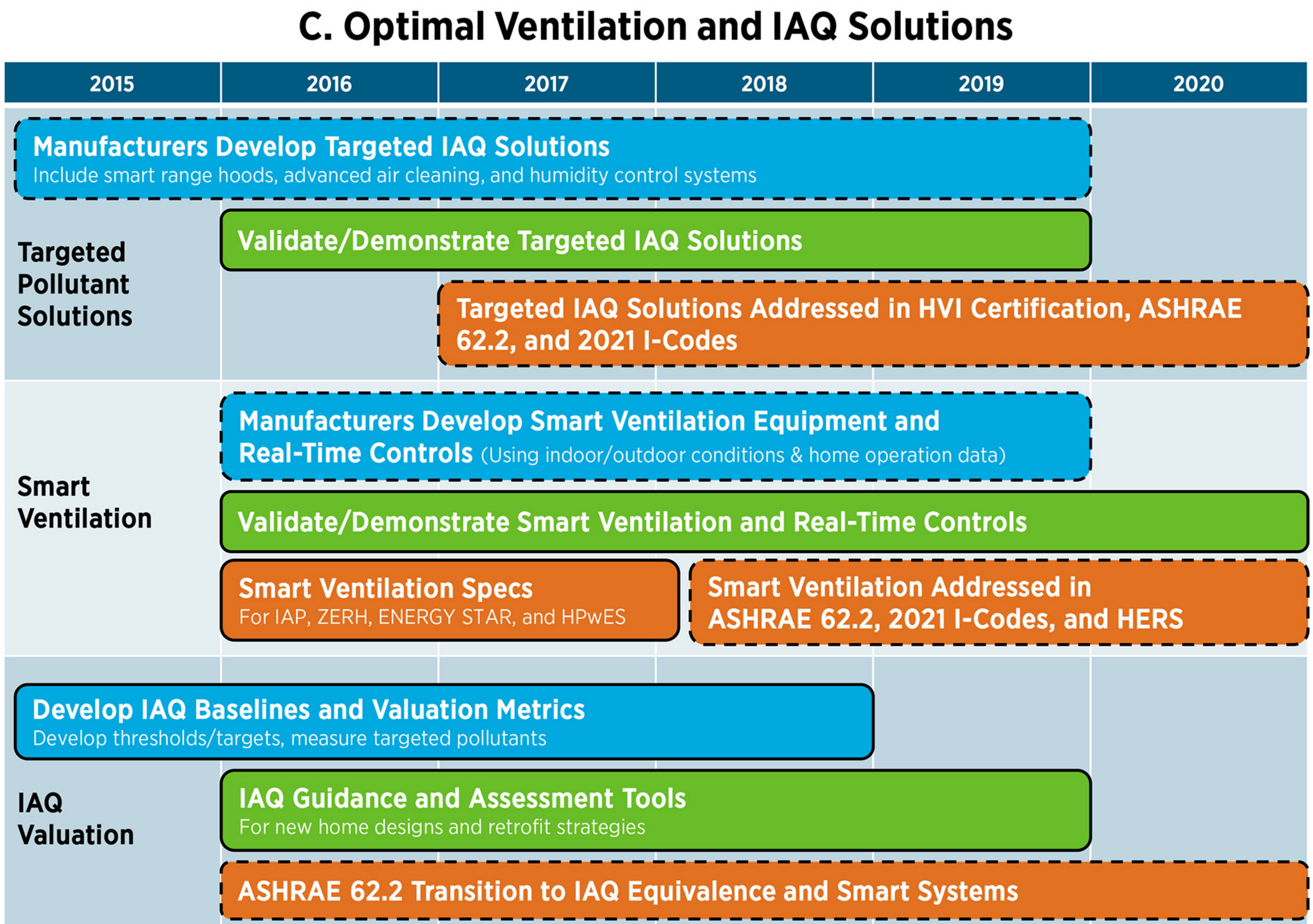

Figure 7. Roadmap C: Optimal Ventilation and IAQ Solution

Targeted Pollutant Solutions

It is well established that IAQ can best be managed in both new and existing homes through the following approaches:

- Reduce emissions and entry of contaminants into the home (source control).
- Efficiently exhaust contaminants at the location and time of generation/emissions (task ventilation).
- Provide fresh outdoor air to dilute remaining contaminants emitted from all indoor sources (general ventilation).
- Remove contaminants from indoor air and/or from ventilation air (filtration and air cleaning).

This IAQ management strategy addresses specific contaminants in situations where the source of the contaminant is known and controllable (e.g., localized). It also addresses sources that generate a variety of contaminants that are impractical to control directly (e.g., outdoor air, new materials and coatings, and improperly venting combustion appliances). This roadmap focuses on both types of contaminant sources by considering gaps in both targeted pollutant solutions and practical pollutant control approaches. The roadmap prioritizes Building America RD&D investments by focusing on the IAQ management gaps that will have the greatest impact on IAQ in U.S. houses.

Targeted pollutants in this roadmap were identified by recent research into the relative health risks of common IAQ pollutants. Figure 8, adapted from Logue et al., summarizes the estimated aggregate health damage of chronic exposure to known indoor air contaminants for the U.S. population. That analysis shows estimated disability-adjusted life years (DALY)—a measure that includes the cost of premature death and morbidity—caused by various air pollutants in residences.

The IAQ management gaps associated with these targeted pollutants of concern (i.e., targeted pollutant solutions) were then identified. They were categorized according to the building science knowledge and technology development needed before practical solutions that address these contaminants will be commercialized and adopted efficiently at scale in U.S. housing markets. The primary targeted pollutant solutions addressed in this roadmap include the following:

- Combustion Pollutant Control (PM 2.5, moisture, CO, NOx, and misc.).
- Smart Range Hoods (PM 2.5, acrolein, moisture, CO, NOx, and misc.).
- Advanced Filtration (PM 2.5).
- Humidity Control (moisture).

Three priority pollutants of concern identified in Figure 8—second-hand smoke (SHS), radon, and formaldehyde—are not targeted directly by Building America roadmap activities, because source reduction strategies and policies outside the scope of Building America are needed to fully address these health risks. SHS and radon are being addressed through other federal activities (including the Healthy Homes Program of the U.S. Department of Housing and Urban Development [HUD] and the EPA Indoor Environment Program). Formaldehyde is not a primary focus of the Building America roadmap because indoor formaldehyde emissions can more effectively be addressed by controlling material constituents of the most significant indoor sources—manufactured wood products[31]—and will be covered by federal regulation in the near future. This objective is beyond the scope of the Building America program. However, formaldehyde may be controlled to a lesser extent with general ventilation as a secondary control strategy, and the Building America roadmap will consider the impact of general ventilation on formaldehyde concentrations as part of the Smart Ventilation Solutions and IAQ Valuation strategies. The effectiveness of general ventilation to control formaldehyde has been reported in two recent studies.[32] The need for additional attention to formaldehyde is also being assessed in a current study of new, energy-efficient homes in California with mechanical ventilation.[33]

[31] EPA, "Formaldehyde Emission Standards for Composite Wood Products."
[32] Hult et al., *Formaldehyde and acetaldehyde exposure mitigation in US residences*; Lajoie et al., "The IVAIRE project."
[33] "Healthy, Efficient, New Gas Homes," Lawrence Berkeley National Laboratory.

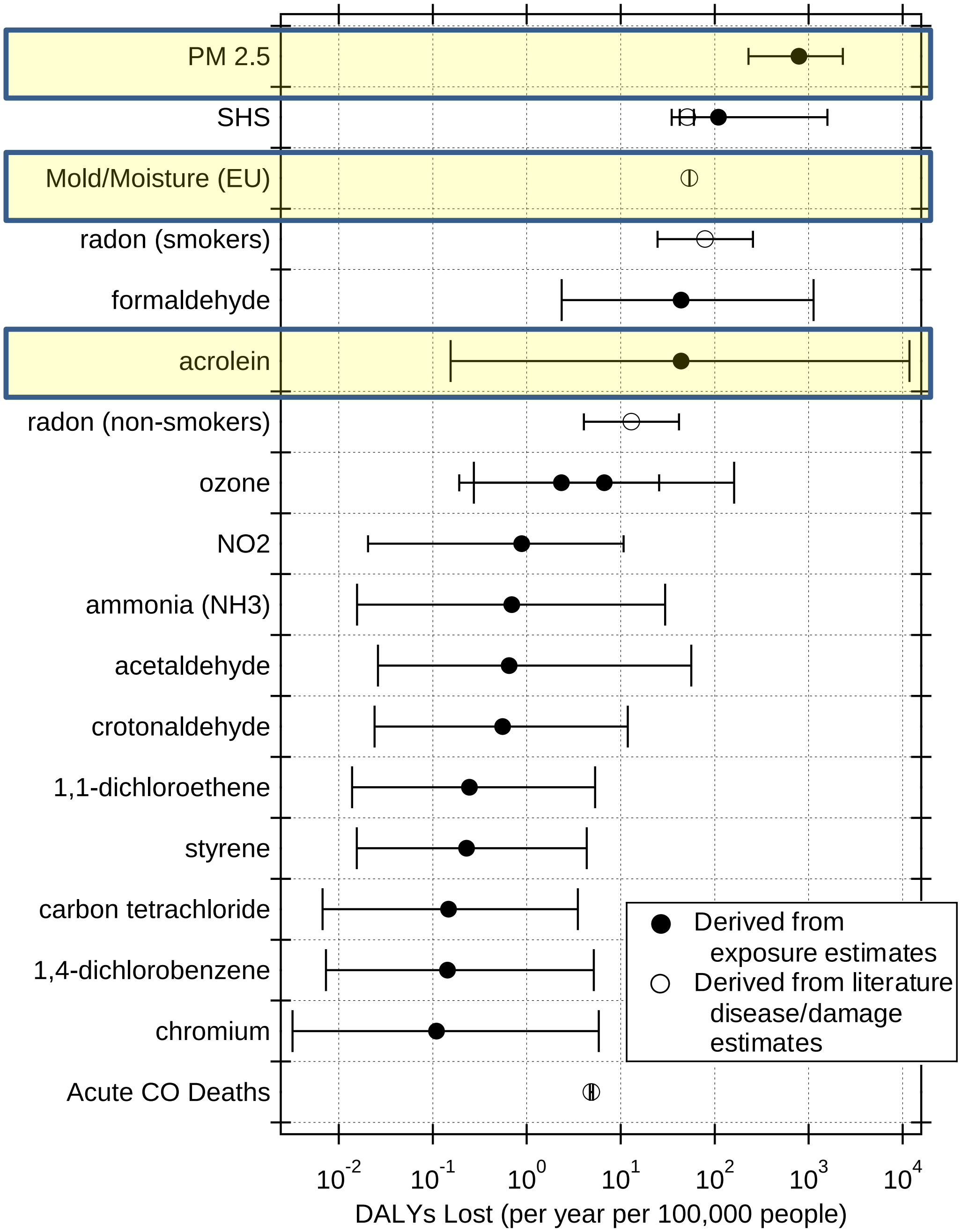

Figure 8. Estimated disability life years lost per 100,000 people per year due to chronic (long-term) exposure to indoor air pollutants[34]

Combustion Pollutant Control

Unvented or improperly vented combustion heating appliances can be a major source of moisture and air pollutant emissions inside existing homes. Energy retrofits that tighten building envelopes may create unsafe conditions in which existing exhaust fans depressurize spaces containing natural draft appliances, resulting in combustion product spillage. Many variations of combustion appliance safety (CAS) testing procedures exist,

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[34] Values are based on the work of Logue et al., "A Method to Estimate the Chronic Health Impact of Air Pollutants in U.S. Residences," and de Oliveira et al., *EnVIE Wp3 Technical Report – Characterization of spaces and sources.*

yet none explicitly identify their safety objectives. Complicated procedures and variability in results across procedures adds to the confusion. Cheaper, more reliable CAS testing procedures will reduce retrofit costs, reduce health risks and business risks, improve IAQ, and enhance the market value of home energy retrofits to occupants.

Smart Range Hoods

Cooking emits pollutants from gas combustion and electric heating elements, as well as from the cooking process itself. The most effective and efficient way to reduce occupant exposure to cooking-related pollutants is to capture and remove them as they are being emitted (e.g., by using a vented range hood). Research indicates that many existing homes lack any kitchen ventilation. Kitchen ventilation is not routinely used even when it is available, and range hoods vary widely in their ability to efficiently capture cooking pollutants, even when they meet ASHRAE 62.2 minimum airflow requirements. Because range hoods are not currently rated for their effectiveness in capturing pollutants, users have no means to differentiate products based on performance, and standards cannot specify a requirement for related IAQ performance. Efforts are underway to develop an ASTM consensus standard method of test for range hood performance, along with the associated laboratory testing.

The availability of capture efficiency and automatic operation performance test results will enable the specification of minimum performance requirements, first in high-performance home programs, then in codes and standards. It is anticipated that EPA's Indoor airPLUS (IAP) specification will be an early adopter and that ASHRAE 62.2 will be the first standard to require improved range hood performance, with later adoption by IRC/IMC. There is a need to provide technical support and assistance to these codes and standards bodies.

Advanced Filtration

Particle filtration is a particularly important strategy because particles cause the most aggregate chronic health damage of any class of indoor air pollutants. Particles are emitted from various indoor activities such as cooking and cleaning, but they may also come from outdoors. Manufacturers are already developing effective, low-energy filtration products and working on efficient air cleaners for gaseous pollutants. However, standards do not require or encourage their use, nor are all filtration products equally effective. Consumer confusion about filtration and air cleaning product benefits is common.

While standard tests and metrics are available for distinct filtration products (e.g., minimum efficiency reporting value [MERV] rating mechanical media particle filtration), system-level performance assessment has not been standardized. In addition, standards have not been developed to allow comparison of different filtration and air cleaning product benefits. Improved whole-house filtration and air cleaning may require new R&D products that will necessitate laboratory and field evaluation before standards can specify or give credits for their use.

Humidity Control

Humidity is the top IAQ concern for many builders because visible mold or damaged materials are easily observed by occupants and have an immediate impact on home performance (in contrast to long-term health effects), as well as substantial potential business risk. The *Optimal Comfort Systems for Low-Load Homes Roadmap* described in this document addresses humidity control technologies, primarily focused on HVAC systems. This IAQ roadmap focuses on the relationship between home ventilation and humidity.

The building industry needs better understanding of the varying impacts of ventilation on indoor moisture in homes, as well as access to better solutions for reliably managing both IAQ and indoor moisture. Currently, builders in humid climates resist applying minimum ventilation standards for fear of introducing humidity problems. Specifically, the industry needs guidance and specifications on how to meet ASHRAE 62.2 ventilation requirements and avoid humidity problems. Until this major ventilation system challenge is resolved, optimal ventilation strategies will be resisted by the building industry. Findings and solutions developed in this roadmap will be coordinated with Roadmap B: *Optimal Comfort Systems for Low-Load Homes*.

Manufacturers Develop Targeted IAQ Solutions

Include smart range hoods, advanced air cleaning, and humidity control systems

Goal/Outcome:

Manufacturers develop targeted IAQ solutions, including smart range hoods with high capture efficiency (e.g., >80% at 100 cfm) and automatic operation, practical and effective combustion safety solutions for home retrofit applications, advanced filtration and air cleaning equipment, and improved humidity control systems and approaches.

Detailed Action Plan:

DOE-Funded Activities (subject to appropriations and other policy considerations):

- Conduct research to better characterize typical pollutant levels in homes and the key variables that influence them, such as climate, system type, and construction/installation quality.
- Develop strategies for tight new homes and retrofitted existing homes to effectively handle makeup air for large exhaust systems (e.g., high-capacity range hoods), especially in homes with fireplaces or other combustion appliances that take their combustion air from the home, and strategies to provide adequate exhaust venting for economizers.
- Determine moisture generation rates/criteria for acceptable humidity and assess humidity impacts of ventilation standards.
- Develop standard testing and rating procedures for range hoods, air cleaning, and related sensor/control technologies.
- Encourage manufacturers to develop and market high-capture-efficiency auto-operation range hoods.
- Encourage manufacturers to develop and market whole-house filtration and gas-phase cleaning technology.

Related Industry Activities:

- Manufacturers develop pollutant-based ventilation controls and accurate, durable sensors that are maintenance-free.
- Manufacturers develop high-capture-efficiency range hoods (e.g., min. 80%) and auto-operation controls.
- Manufacturers develop range exhaust integrated with whole-house ventilation systems.
- Manufacturers develop high-efficiency whole-house filtration and gas-phase air cleaning technology.
- Manufacturers develop filtration systems that provide a reliable method of informing the homeowner when maintenance is needed.
- Home Ventilating Institute (HVI) will support product certification.
- Building Performance Institute (BPI), ACCA, and others will support the development of installer training materials.

Validate/Demonstrate Targeted IAQ Solutions

Goal/Outcome:

Field-validated IAQ solutions are widely available and specified by industry; these solutions improve IAQ and allow for a wider range of energy-optimized ventilation solutions as well as provide more flexibility in achieving IAQ targets.

Detailed Action Plan:

DOE-Funded Activities (subject to appropriations and other policy considerations):

- Conduct laboratory and field testing of range hood capture efficiency.
- Collect field data on ventilation standard (e.g., ASHRAE 62.2) compliance rates and the impact of ventilation strategies and standard compliance on IAQ in both new and retrofitted homes. This includes investigating the necessity for regional variation in ventilation and humidity controls, as well as exploring opportunities for using ventilation to control humidity in homes.
- Perform validation and demonstration of IAQ and humidity controls in both new and retrofitted homes, in collaboration with manufacturers.

Related Industry Activities:

- RESNET and others provide field surveys of compliance rates.
- Manufacturers collaborate on validation and demonstration of IAQ and humidity controls.
- ACCA and BPI can help develop quality assurance/quality control test procedures, documentation, etc. for installers, in collaboration with key manufacturers.
- ASHRAE and/or ASTM will collaborate on the development of testing requirements and new/improved standards.
- HVI will collaborate on certifications and ratings.

Targeted IAQ Solutions Addressed in HVI Certification, ASHRAE 62.2, and 2021 I-Codes

Goal/Outcome:

Better IAQ solutions are available to the housing industry for improving IAQ in all homes, without significant energy or humidity control penalties, through improved targeted IAQ pollutant requirements in codes and standards.

Detailed Action Plan:

DOE-Funded Activities (subject to appropriations and other policy considerations):

- Improve combustion appliance safety for home energy retrofit programs (e.g., the Weatherization Assistance Program and HPwES) and other applications.
- Support the addition of range hood or down-draft capture efficiency minimum standards and automatic operation requirements for kitchen ventilation in EPA’s IAP.
- Support development of rating methods for range hood capture efficiency and automatic operation through collaboration with ASTM, ASHRAE, and HVI.
- Collaborate with equipment manufacturers, rating agencies, and potential users such as ASHRAE 62.2 and the ENERGY STAR and IAP programs on the development of certifications and labeling for IAQ solution technologies.

Related Industry Activities:

- ASTM (and possibly ASHRAE) develops rating methods for range hood or down-draft capture efficiency and automatic operation.
- ASHRAE adds capture efficiency and automatic operation requirements for kitchen ventilation to Standard 62.2, with a future compliance date in ASHRAE 62.2 to give manufacturers time to develop equipment. Ensure that ASHRAE 62.2 requirements are developed for both existing/retrofitted homes and new construction.

- HVI performs certification and labeling of humidity control equipment.
- HVI adds range hood and down-draft capture efficiency to ratings/product certification and labels.
- ASHRAE 62.2 considers outdoor air quality.
- IRC/IMC adds capture efficiency and automatic operation requirements for kitchen ventilation.

Smart Ventilation

Smart ventilation is intended to significantly reduce the energy associated with whole-house ventilation, which is primarily used for conditioning air to meet IAQ requirements. Prior research efforts (and developed ventilation controls) have shown that smarter ventilation controls can theoretically achieve equivalency to ASHRAE 62.2 whole-house ventilation requirements while allowing for time shifting of ventilation to save energy and power. Smarter ventilation may also be used to reduce indoor concentration of outdoor contaminants.

The following approaches will be developed under this roadmap to minimize ventilation-related energy and/or improve IAQ: (1) accounting for ventilation provided by other systems (e.g., kitchen/bathroom exhaust, clothes dryers, economizers, and natural draft appliances in the living space), (2) modulating ventilation with occupancy, (3) integrating ventilation with filtration, and (4) using other control strategies (e.g., outside temperature and/or humidity control).

Using controls based on occupancy presents a significant opportunity to reduce the energy costs associated with ventilation if no one is home. However, occupancy controls are not easy to develop because current sensor technologies are limited in their ability to reliably determine that no one is home (i.e., accurately and continuously sensing occupancy in all rooms). In addition, many occupancy-sensing approaches, such as motion detection, may not work when people are sleeping or sitting still. One approach to addressing this issue is to be conservative and go to 50% flow rather than completely off when a home is unoccupied. Another approach would be to use real-time control based on higher exposure limits (that do not exceed acute levels) during unoccupied times. Other occupancy challenges include pets and long-term occupancy sensor reliability. However, there is reason to believe that if targets are set and there is a reasonable credit for changing ventilation with occupancy, industry will catch up and develop sensors.

Another aspect of real-time control is the ability to ventilate less if outdoor air quality conditions are poor. Specifically, when outdoor ozone or particle levels are high, ventilating less can actively improve IAQ. These new capabilities would require development of controls with internet connectivity that could obtain outdoor pollutant data from external sites and respond accordingly without the need for on-site ambient measurements.

Smart ventilation and real-time controls are a developing area, and some preliminary open-source algorithms and systems are already in development, primarily via simulation. In order to increase market acceptance, field measurements are needed to validate the operation of algorithms and to confirm the maintenance of acceptable or improved IAQ. These field tests should be performed in both new and existing retrofitted homes.

In addition to validation of the laboratory-developed smart ventilation approaches, the market needs independent evaluation of commercially available proprietary systems that claim to save energy and/or improve IAQ. A similar approach is needed for sensor evaluation to provide a level playing field in the market by determining whether manufacturers’ claims are true and providing unbiased guidance to industry and the public.

Currently, compliance software for ventilation standards and home energy ratings does not have the capability to account for the energy savings of smart ventilation systems. This is a major barrier to adoption of smart ventilation technology that will be targeted in the roadmap.

In addition to adoption by industry standards (i.e., ASHRAE 62.2) and voluntary standards (e.g., EPA’s ENERGY STAR for Homes Program), this roadmap will encourage adoption of smart ventilation by minimum performance building codes. Today, ASHRAE Standard 62.2 is used by both voluntary and compulsory building codes, and its user base is increasing as compliance methods and technologies become more widely available and affordable. This adoption model can be applied to smart ventilation as well. However, ASHRAE

62.2 does not currently include metrics, performance standards, or diagnostics that account for the full benefits of smart ventilation systems or even that show that a system complies with relevant code requirements. This roadmap will develop and encourage adoption of standardized approaches to account for smart ventilation.

Building America validation studies and voluntary programs such as ENERGY STAR can provide the data and early market demonstration necessary to pave the way for consideration in future editions of ASHRAE 62.2 and later building codes. In this way, smart ventilation will eventually become available in all homes.

Manufacturers Develop Smart Ventilation Equipment and Real-Time Controls (Using indoor/outdoor conditions & home operation data)

Goal/Outcome:

Manufacturers develop and promote smart ventilation systems for new and existing homes that save energy, provide as good or better IAQ as homes meeting current standards, and increase durability by avoiding levels of pollutants (mainly moisture) that may be damaging to building components and materials.

Detailed Action Plan:

DOE-Funded Activities (subject to appropriations and other policy considerations):

- Develop smart ventilation system control algorithms and technologies ready for use by ventilation system manufacturing partners.
- Identify key pollutants and/or other indicators that correlate with key pollutants but are easier to measure; i.e., proxies for good/bad IAQ or high/low pollutant concentrations.
- Develop a catalog of the most prevalent indoor and outdoor pollutants in homes so that manufacturers can develop sensors and controls to address the most prevalent IAQ problems in homes. EPA/Occupational Safety and Health Administration/CARB standards for pollutants can be used as a basis for indoor levels.
- Develop and analyze options for smart ventilation, such as temperature, RH, occupancy, outdoor pollutants, sensors, and control capabilities.
- Expand smart ventilation humidity control to include cold climates, not just high-humidity climates.
- Collaborate with industry on well-supported, open-source communication and controls protocols.
- Develop protocols for using Web-based air quality and weather data.
- Establish standards and protocols for evaluating sensors and control systems.
- Develop algorithms for smart controls that respond to measured pollutant concentrations.
- Create a manufacturing base for smart ventilation/IAQ equipment.
- Collaborate with industry to develop technology for sensors and controls.

Related Industry Activities:

- Manufacturers and installers collaborate with Building America on technology development, field tests, and the evaluation of smart ventilation controls and systems.
- Manufacturers develop smart ventilation equipment based on the algorithms and control strategies developed through this roadmap.
- Software designers collaborate with Building America on well-supported, open-source communication and controls protocols.
- Manufacturers develop low-cost pollutant sensors and controls that are low/zero maintenance and operate reliably for >25 years and/or have fault detection and communication.

- Manufacturers develop smart pollutant control technologies that go beyond the current source control and dilution methods.

Validate/Demonstrate Smart Ventilation and Real-Time Controls

Goal/Outcome:

Smart ventilation systems are proven to improve IAQ and energy performance in new and existing/retrofitted homes, such that the market has confidence to adopt these new strategies.

Detailed Action Plan:

DOE-Funded Activities (subject to appropriations and other policy considerations):

- Develop test methods for sensor accuracy and long-term performance.
- Develop metrics and evaluation procedures to allow comparison of different smart ventilation system approaches in order to provide a basis for eliminating poorly performing systems and promoting systems that provide good IAQ, as well as to demonstrate that systems deliver on their promised performance.
- Evaluate performance metrics though laboratory and field testing.
- Conduct field studies to examine the efficacy of temperature control, humidity control (in both humid and dry climates), and pollutant sensing.
- Conduct field studies to evaluate the IAQ and energy performance of smart ventilation systems in a range of homes including tight new construction, leakier older homes, and high-performance homes such as those developed in the Building America program and ZERHs.
- Demonstrate smart ventilation systems to encourage industry adoption.

Related Industry Activities:

- Conduct a research project that investigates IAQ sensing (ongoing: ASHRAE).
- Evaluate smart ventilation approaches in the Pacific Northwest in the context of acceptability for utility program support (ongoing: Bonneville Power Administration [BPA], LBNL, Ecotope, and Washington State University for BPA).
- Home energy analysis software developers optimize control algorithms for existing/retrofitted, standard construction, and high-performance homes, including single-family and multi-family buildings.

Smart Ventilation Specs

For IAP, ZERH, ENERGY STAR, and HPwES

Goal/Outcome:

Specifications for smart ventilation systems are incorporated into voluntary program requirements, including into energy analysis tools used by these programs.

Detailed Action Plan:

DOE-Funded Activities (subject to appropriations and other policy considerations):

- Conduct field studies of smart ventilation that will provide insight on acceptable specifications.
- Determine the adaptability of smart ventilation for high-performance new and retrofitted homes.

- Perform simulation-based analysis backed by field demonstrations to develop smart ventilation options or requirements for IAP, ZERH, ENERGY STAR, HPwES, and Passive House.
- Develop algorithms and calculation procedures to be adopted by energy rating systems (i.e., HERS) and related software programs to account for smart ventilation energy savings.
- Engage with HERS industry and software developers to provide them with the technological background information required to make related standards and software changes.
- Work with RESNET and rating tool developers to include smart ventilation.
- Work with HUD to help with/expand its current programs that focus on lead, moisture, and asthma.

Related Industry Activities:

- Conduct field studies of smart ventilation that will provide insight on acceptable specifications (ongoing: BPA).
- RESNET and rating tool developers collaborate with Building America to include smart ventilation.
- Passive House and utility programs collaborate with Building America to adopt smart ventilation approaches.
- Energy rating systems adopt algorithms and calculation procedures to account for smart ventilation energy savings.

Smart Ventilation Addressed in ASHRAE 62.2, 2021 I-Codes, and HERS

Goal/Outcome:

Adoption of provisions that encourage smart ventilation approaches in ASHRAE Standard 62.2 and the I-Codes and HERS.

Detailed Action Plan:

DOE-Funded Activities (subject to appropriations and other policy considerations):

- Develop the calculation procedures necessary to compare smart ventilation systems to minimum whole-house annual ventilation requirements such as those in ASHRAE 62.2.
- Develop metrics, performance standards, and diagnostics to show that a system complies with IAQ/ventilation standard and code requirements.
- Provide technical support to ASHRAE 62.2 to allow occupancy controls (or demand-controlled ventilation [DCV]).

Related Industry Activities:

- ASHRAE 62.2 committee continues its support of including smart ventilation (in terms of equivalence with its minimum standard) in ASHRAE 62.2.
- ASHRAE 62.2 adds pollutant-based ventilation control.
- ASHRAE 62.2 completes adoption of equivalent ventilation calculations.
- IECC, the International Green Construction Code, and then IRC incorporate ventilation requirements, including provisions for smart ventilation systems.

IAQ Valuation

Rating methods exist for energy efficiency, but there is no useful method for rating IAQ. This effort will allow an eventual transition from *smart ventilation* to *smart IAQ* and help the market to place objective value on IAQ. Creation of an IAQ metric will enable builders, contractors, and programs to market and receive credit for homes based on the robustness of IAQ controls. This hypothetical “IAQ score” will show the benefits of going beyond the minimum requirements (e.g., those in ASHRAE 62.2) and will be a valuable tool for high-performance home programs (e.g., EPA ENERGY STAR homes and the IAP program) to encourage better IAQ performance in addition to better energy performance.

The development of IAQ and valuation metrics will require the development of thresholds and targets for good IAQ. The DALY approach briefly introduced in the Targeted Pollutant Solutions section can serve as a base methodology, but population-level health effects by themselves are insufficient to develop a whole-house IAQ score, which will also need to consider variables such as non-health-related IAQ issues (e.g., odor and moisture), house characteristics, HVAC system type, and climate.

Builders have already commented that they like the IAQ score approach because it is something they can market and analyze in a "dollars per point" manner, just like they do with an Energy Score. Without this IAQ score, the motivation for builders to consider improving IAQ is limited. Without a quantitative metric, there is no way for them to get credit for addressing more than the individual measures asked for by consumers.

Initial concepts for the IAQ score are based on an assessment tool concept that combines features of the home with ventilation system characteristics (including diagnostics and assessments of durability and longevity). The IAQ score can be compared to other homes, using the health-based (DALY) analysis that allows comparisons and trade-offs between different elements that contribute to good IAQ.

These IAQ valuation efforts, including the proposed development of a standardized IAQ score, follow directly from other recent R&D efforts to analyze the benefits of various filtration system designs and qualities. A filtration credit to ASHRAE 62.2 has recently been approved for public review by the ASHRAE Standard 62.2 Committee, based on the estimated equivalence of various filtration approaches to the calculated benefits of whole-house ventilation as an indoor source particle reduction strategy. Filtration is a more robust particle exposure reduction measure than general dilution ventilation because it addresses particles from both indoor and outdoor sources and directly addresses the single most important indoor contaminant—PM2.5—from a public health cost perspective. However, it does not address all of the indoor contaminants that are addressed by ventilation. More work is required to expand the IAQ equivalence approach to address other known contaminants of concern. Two benefits of this strategy are the following:

- Using the ventilation equivalence approach allows comparison of different ventilation control strategies.
- Methods to use health impacts as the basis for the ASHRAE 62.2 standard (while still retaining moisture and odor control) will strengthen the health science basis for ASHRAE 62.2 and lead to broader adoption and support of the standard.

Develop IAQ Baselines and Valuation Metrics

Develop thresholds/targets, measure targeted pollutants

Goal/Outcome:

Metrics, calculation methodologies, and current home baselines are developed that can be used to objectively assess and quantify the IAQ of any home, including the development of a validated framework for IAQ scoring.

Detailed Action Plan:

DOE-Funded Activities (subject to appropriations and other policy considerations):

- Conduct in-home measurement of pollutants.
- Collaborate with industry on the development of a set of IAQ valuation metrics that factor in pollutant sources and mitigation strategies.

- Apply IAQ valuation metrics in field studies so that baselines can be developed, and then refine and validate the process.
- Add the background of informed metrics and calculations to move beyond checklists.
- Develop IAQ evaluation metrics, including for targeted pollutant sources and risk mitigation.
- Develop IAQ baseline scores using field studies to assess risks and baseline pollutant levels in homes.
- Work with industry to develop a set of IAQ valuation metrics that factor in pollutant sources and mitigation strategies.

Related Industry Activities:

- IAQ-related organizations (e.g., EPA, ASHRAE, and others) collaborate on the development of a set of IAQ valuation metrics that factor in pollutant sources and mitigation strategies.
- Physicians prescribe home IAQ upgrades.
- The health insurance industry recognizes the value of good IAQ and reduces premiums for homes with IAQ improvements.
- HUD expands its current programs that focus on lead, moisture, and asthma, with Building America support.

IAQ Guidance and Assessment Tools

For new home designs and retrofit strategies

Goal/Outcome:

Designers, builders, HERS raters, home improvement contractors, home performance consultants, and related programs have access to, and use, IAQ best practice guidance and tools to optimize IAQ measures in homes, leading to healthier homes with little or no energy penalty.

Detailed Action Plan:

DOE-Funded Activities (subject to appropriations and other policy considerations):

- Develop IAQ guidance for going beyond ASHRAE 62.2 minimum requirements.
- Develop IAQ guidance and solutions for retrofit homes.
- Redefine IAQ for sensitive sub-populations, using data on “ranges” so the target range changes based on the occupants’ sensitivity.
- Establish high-performance home requirements for Passive Homes, Zero Energy Ready Homes, and deep retrofit homes.
- Develop initial methodology that combines many aspects of Home IAQ into a single score and Beta-test this score in homes.
- For guidance, leverage existing content in the BASC.

Related Industry Activities:

- Third party “sustainable” programs (e.g., Living Building Challenge) develop ingredient labels for construction materials and “Red Lists” of restricted materials (based on EPA, European Union, and California requirements).
- Developers incorporate IAQ improvements into residential building energy analysis software.
- Public and private healthcare communities (e.g., associations of related medical specialists) support methods of identifying and comparing homes for IAQ and identifying ways of improving IAQ in a standardized manner.

- EPA works within the parameters of the Affordable Care Act on funding policy approaches that improve IAQ, such as allowing financing to improve public health measures in homes.

ASHRAE 62.2 Transition to IAQ Equivalence and Smart Systems

Goal/Outcome:

Changes to ASHRAE 62.2 reflect a health-based approach that allows for equivalence to be established between different systems and ventilation approaches, increasing design flexibility and encouraging better IAQ design decisions. This will enable smart ventilation systems to show compliance with the standard.

Detailed Action Plan:

DOE-Funded Activities (subject to appropriations and other policy considerations):

- Develop the formal calculation procedures needed to calculate equivalence for ventilation equipment and controllers.
- Support the transition to equivalence in ASHRAE 62.2.
- Collaborate with 62.2 compliance software manufacturers to include health equivalence and smart ventilation calculations.

Related Industry Activities:

- ASHRAE 62.2 transitions to health equivalence.
- ASHRAE 62.2 adds the formal calculation procedures needed to calculate equivalence for ventilation equipment and controllers.
- ASHRAE 62.2 adds a filtration option.
- Developers of 62.2 compliance software include health equivalence and smart ventilation calculations in their software.

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