How Building America Research Is Removing Major Roadblocks to High-Performance Homes

Preprint

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Presented at the 2018 ACEEE Summer Study on Energy Efficiency in Buildings
Pacific Grove, California
August 12–17, 2018

Suggested Citation

Burkett, Lena and Eric Werling, 2018. "How Building America Research Is Removing Major Roadblocks to High-Performance Homes: Preprint." Golden, CO: National Renewable Energy Laboratory. NREL/CP-5500-71179. https://www.nrel.gov/docs/fy18osti/71179.pdf.

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Operated by the Alliance for Sustainable Energy, LLC

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Conference Paper
NREL/CP-5500-71179
September 2018

Contract No. DE-AC36-08GO28308

NOTICE

This work was authored in part by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Building Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

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How Building America Research Is Removing Major Roadblocks to High-Performance Homes

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ABSTRACT

Today the U.S. housing industry is critically challenged to deliver homes that safely and effectively meet demanding new performance requirements of homeowners and modern building codes. The housing industry must learn to better manage real and perceived risks that can impact occupant health, comfort, and building durability. But it is clear from decades of applied research through the U.S. Department of Energy (DOE) Building America Program that many building energy-efficiency and performance improvements will not be adopted by the market or industry standards if the costs and perceived risks of change outweigh the known benefits, especially when the benefits do not accrue directly to businesses that must take those risks.

In 2015, Building America published a new integrated strategy designed to tackle these adoption risks of high-performance homes. The Building America Research-to-Market Plan, including three integrated Technology-to-Market Roadmaps, has guided Building America research and development activities over the past three years to tightly focus program efforts on solving the major roadblocks to high-performance homes, improving the housing market's ability to adopt innovations that address them. The three Building America Roadmaps are: A) high-performance, moisture-managed envelope solutions, B) optimal comfort systems for low-load homes, and C) optimal ventilation and indoor air quality (IAQ) solutions.

This paper outlines these key technical and market risks that impede adoption of high-performance home systems and technologies and highlights 16 recent Building America projects that strategically attack these risks with real-world advancements in applied building science, engineering, and construction practices.

Introduction and Background

The mission of the DOE Building Technologies Office (BTO) Residential Buildings Integration (RBI) Program is to accelerate energy performance improvements in existing and new residential buildings to achieve optimal whole-house energy performance. This includes a 40% reduction in energy used for space conditioning and water heating in single-family homes by 2025 (DOE 2016).

Despite significant advancement of energy-efficient home technologies and best practices, including voluntary market advances and adoption of advanced building energy codes such as International Energy Conservation Code (IECC) 2012 and 2015, big challenges to achieving RBI's energy-savings goals remain.

As with every technology, substantially increased performance targets bring new challenges and risks. Increasing energy performance targets for homes have brought new technical challenges, application hurdles, and potential risks for builders and contractors, including uncertainty about the performance of new building materials and systems, moisture management in insulated buildings, comfort control challenges as loads are reduced, and risks of poor IAQ in tighter homes. Without proof that new building materials and systems are durable, safe, and effective and provide real business benefits, the market is very slow to move forward with energy efficiency. Overcoming these real and perceived risks is critical to meeting RBI's long-term energy-savings goals.

Further, 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. For example, before home energy upgrade programs and future advanced building energy codes can responsibly adopt substantial additional insulation and air-sealing requirements, the housing industry must better manage moisture durability and IAQ risks.

In 2015, Building America developed a strategic plan for overcoming these building science challenges. The resulting Building America Research-to-Market Plan (DOE 2015) was developed with assistance from experts at four DOE national labs and considering inputs from a wide array of industry stakeholders through a public request for information, then further refined through three expert workshops, one for each of the three strategic roadmaps included in the plan. The remainder of this paper describes each of the three roadmaps and the major roadblocks to innovation they are designed to address, followed by highlights from Building America funded projects awarded to address roadmap objectives.

A. High-Performance Moisture-Managed Envelopes Roadmap

High R-value (high-R) building envelope assemblies (i.e., foundation, walls, and roof) exceeding IECC 2012 insulation requirements offer the biggest remaining opportunities for home energy savings, according to several analyses by DOE national laboratories. Heating and cooling loads still 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 Oak Ridge National Laboratory, 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, building designers rarely select advanced envelope systems. Current solutions are expensive and/or unfamiliar to many designers, builders, contractors, and code officials and therefore perceived as risky. Further, the dominant perceived risk is durability specifically related to condensation and moisture accumulation in building materials and assemblies. In addition, some high-R envelope solutions are limited by International Residential Code (IRC) barriers (e.g., fire and structural codes).

The Building America Research-to-Market Plan (DOE 2015) presents detailed evidence that real and perceived risks of moisture problems in insulated building assemblies prevent adoption of high-performance building envelope assemblies. *Figure 1* shows the High-Performance Moisture-Managed Envelopes Roadmap, with project markers pointing to one or more roadmap objective that each funded project was selected to address. The end goal of this roadmap is to resolve or mitigate 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. The data, guidance, and research and design tools developed in accordance with this roadmap will help the industry confidently identify and specify the least-cost high-R building assembly designs that can best manage moisture durability risks 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).

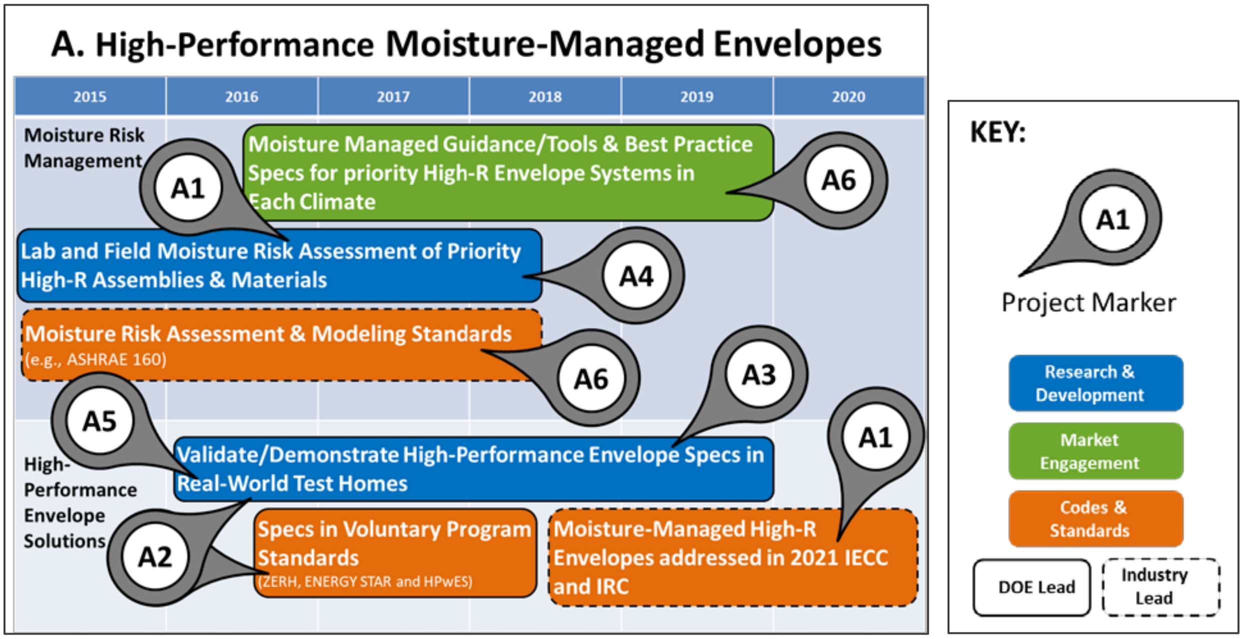

Figure 1. Building America Envelope Roadmap

Highlights of Building America Funded Envelope Roadmap Projects

A1. Structural Support of Windows in Walls with Continuous Insulation (Home Innovation Research Labs)

Continuous insulation (CI) is an uninterrupted layer of insulation that spans all structural support elements of a building (e.g., studs or beams) without thermal bridges. CI has been shown to be a highly effective insulation and moisture mitigation solution, but research is needed to overcome industry concerns and code restrictions around window installation in walls using CI. Home Innovation Research Labs will establish performance criteria and conduct comprehensive testing to evaluate the structural performance of CI walls with windows of varying shapes and sizes, insulation thicknesses, and installation methods. The results of the study will validate and demonstrate various window installation methods for walls with CI and will provide data and justification to enable inclusion of these methods in applicable codes and standards. Evaluation of the structural performance of additional window installation methods will inform future industry guidance and energy codes, enabling wider adoption of CI in both new construction and retrofitted residential buildings.

A2. Aerosol Sealing in New Construction (Center for Energy and Environment)

Whole-house envelope air sealing minimizes the uncontrolled flow of heat, air, and moisture between indoors and outdoors and is essential to the energy efficiency, comfort, and IAQ of residential buildings. Center for Energy and Environment and partners will field-test and optimize an innovative new method for whole-house air sealing using an aerosol sealant. This aerosol sealant method is already a proven duct sealing solution and can reduce time and labor costs by simultaneously measuring, locating, and sealing leaks. Center for Energy and Environment and builder partners will perform iterative field tests in 20 homes to identify the optimal integration of this aerosol-based air-sealing method into production home building practices to achieve better airtightness at a lower installation cost than typical air sealing. If integrated into the production building process, this method will radically improve quality assurance of envelope sealing and significantly reduce labor costs compared with traditional air-sealing approaches.

A3. Validation Study of Experimental Insulating and Air-Sealing Technology for Enclosed Roof Cavities (Building Envelope Materials)

Air sealing and insulating attics of existing homes can result in significant energy savings and comfort improvement. However, cathedralized or flat roofs with enclosed cavities are difficult and expensive to insulate and air seal, requiring removal of the ceiling surface or roof sheathing. The goal is to develop a minimally invasive retrofit insulation technology for enclosed roof cavities that will not create potential moisture damage issues on the interior surface of the roof sheathing. This technology involves a controlled micro injection of spray polyurethane foam into roof bays via the exterior soffit. Field tests in existing homes will validate and optimize the approach to ensure that performance goals of <1 perm in a 2-inch thickness and an increase of at least R-12 in the roof bays are met.

A4. Monitoring of Unvented Roofs with Diffusion Vents and Interior Vapor Control in a Cold Climate (Building Science Corporation)

Moisture is a common concern in unvented attics with air and vapor permeable fibrous insulation. This moisture typically accumulates at the roof ridge and can lead to mold and structural damage. Building Science Corporation and partners are evaluating a vapor control membrane, or diffusion vent, which could substantially reduce the risk of moisture issues in roof assemblies with this type of fibrous insulation. This solution is field-tested in a cold climate new construction test house over three winters with varying levels of air leakage and interior humidity to validate performance under real-world conditions. This project's moisture-managed fibrous insulation solution can achieve code and above-code performance (R-49) while reducing insulation material costs up to 80% and potentially decreasing heating, ventilating, and air conditioning (HVAC) energy use by 10% or more by locating the HVAC and duct system in the conditioned attic.

A5. Experimental Integrated Zero Energy Ready Retrofit Solution for Multifamily Renovations (Rocky Mountain Institute)

The project goal is to develop a building delivery system that provides a cost-effective zero energy ready retrofit solution to precipitate the market transformation needed to accelerate the wide scale adoption in the US market. The project will design and field-test a standardizable, transferable, climate zone-specific, integrated envelope and mechanical retrofit solution to reduce energy use intensity (EUI) by 50% in multifamily buildings. The energy performance, cost, constructability, and installation time will be evaluated, and retrofit risks will be observed and reported to further inform industry design and innovation. The project results will be used to develop guidelines to enable the broader industry to engineer and offer such retrofit packages.

A6. Building Science Advisor (Oak Ridge National Laboratory)

Oak Ridge National Laboratory is developing an innovative new design tool that will put building science expert advice in the hands of designers and building professionals to manage moisture risk in high-R walls. The Building Science Advisor will provide building science knowledge and advice based on expert experience, field measurements, laboratory tests, and probabilistic computer simulations. This tool will enable users to confidently select assembly characteristics that achieve their design goals with the least moisture durability risk. Links to design-specific guidance will also be provided to help users manage any remaining risk. This tool will further enable DOE's BTO to meet its long-term energy goal of a 50% reduction in building energy consumption.

B. Optimal Comfort Systems Roadmap

The installed performance of HVAC systems, especially distribution system effectiveness and latent load 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 relative humidity (RH) optimization are not often ensured by manufacturers or regulated by codes or standards, and current solutions are labor-intensive and/or expensive.

The Building America Research-to-Market Plan presents detailed evidence that suggests comfort (i.e., HVAC) system performance problems can be significant and might prevent adoption of high-performance home technologies and systems (DOE 2015). High-performance, low-load homes face unique space conditioning challenges that current HVAC design practices do not adequately address. Further, builders and HVAC contractors do not yet commonly use equipment suitable for optimal performance in low-load homes. Low-load home comfort systems must address: (1) effective part-load temperature and humidity control during occupied times and (2) effective air distribution and temperature control in occupied spaces. *Figure 2* shows the Optimal Comfort Systems Roadmap, with project markers pointing to one or more roadmap objective that each funded project was selected to address. The primary goal of this roadmap is to ensure HVAC designers and builders have off-the-shelf equipment and system design tools necessary to cost-effectively design and install optimal comfort system solutions that address the needs of high-performance, low-load homes, which are substantially more airtight than typical homes.

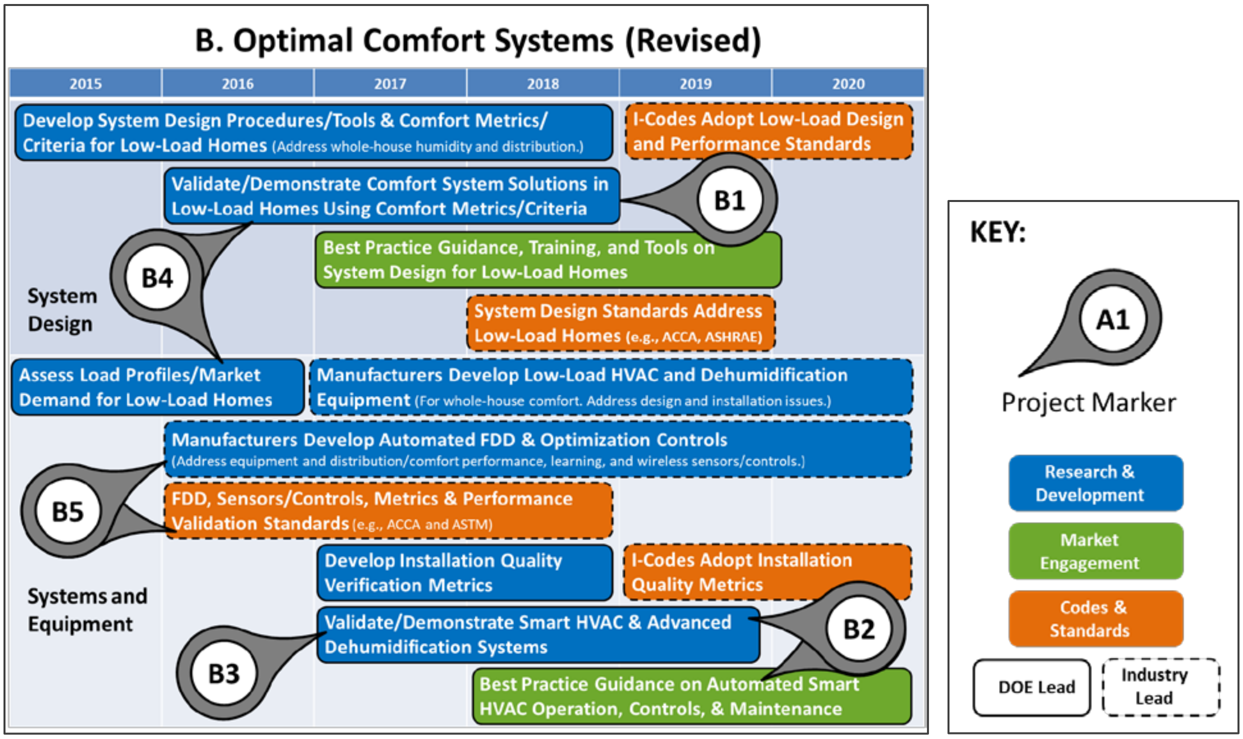

Figure 2. Building America Comfort Roadmap

Highlights of Building America Funded Comfort Roadmap Projects

B1. "Plug-n-Play" Air Delivery System (IBACOS)

IBACOS investigated a simplified residential air delivery system as a solution to air distribution and comfort delivery issues being encountered in low-load production-built homes. The system is assembled in the field from a simple kit of parts with a limited number of small-diameter components. This project included developing a straightforward and intuitive design methodology for the system and companion guidance documents to enable a technician to quickly produce the equivalent of an engineered design using the simplified air delivery system components. The system is easily integrated within the home's conditioned space, is installed with less error and waste, and offers predictable performance to help provide comfort in low-load homes (Beach 2017).

B2. Integrated HVAC Control Methods for Supplemental High Efficiency Mini-Split Heat Pumps in Existing Homes (Florida Solar Energy Center)

Using a high efficiency mini-split heat pump to supplement an existing central system can result in significant energy savings. Previous Florida Solar Energy Center (FSEC) research documented 34% average heating and cooling energy savings for Florida homes with this approach. However, optimized performance requires integrated control of these two systems. The current project focuses on using one centrally located mini-split heat pump as the primary system, while only using the existing, lower efficiency central system as needed, with an integrated controller developed for this project that is expected to enable additional savings and improve comfort. Best practice guidance for optimum design, installation, system control, and central system replacement at end of life will be developed to foster mainstream adoption of the approach.

B3. Advanced HVAC Equipment Design Strategies for Optimal Efficiency and Humidity Control (Home Innovation Research Labs)

This project will develop and validate an integrated solution to improve IAQ, comfort, humidity control, and energy performance for low-load homes in hot-humid and mixed-humid climates. The solution is based on a central air-conditioning system that is specifically redesigned and optimized to meet both sensible and latent loads and designed to simplify the transition to high-performance ventilation and humidity control systems. The project strategy is to optimize the central system across all key design metrics, including effective temperature and humidity control, without the need for additional dehumidification equipment, to ease transition across the entire value chain, reduce comfort risks, and decrease costs to install and operate the system.

B4. Physics-Based Interval Data Models (Fraunhofer USA Center for Sustainable Energy Systems)

This project will develop and validate models that use communicating thermostat data and interval electricity and gas data to remotely evaluate and identify residential retrofit opportunities. This scalable remote performance assessment tool will enable utility energy efficiency programs to leverage the dramatic growth in the installed base of communicating thermostats to automate, simplify, and customize retrofit opportunity assessment, customer acquisition, and energy performance evaluation. This tool can significantly improve program efficiency by: (1) identifying the 20% of homes that would benefit most from insulation, air sealing, and/or heating system upgrades; (2) more accurately predicting the energy savings of the upgrade measures; and (3) radically increasing the fraction of site audits that lead to energy conservation measures.

B5. HVAC Quality Installation (National Renewable Energy Laboratory)

While it is well known that poor installation can significantly impact the efficiency and performance of HVAC systems, the industry needs to better understand the effect of residential air-conditioning and heat pump faults to develop solutions to prevent or fix them. This project: (1) uses advanced, physics-based computer models to simulate HVAC system performance across the U.S. housing stock with and without faults and (2) assesses the ability of smart automated verification system tools to discern fault states in the laboratory. Better understanding of both the magnitude of savings potential from fault correction and the accuracy and capabilities of available diagnostic systems will help the industry adopt and/or improve these technologies.

C. Optimal Ventilation and IAQ Solutions Roadmap

Mechanical ventilation has become standard in new homes and is addressed in building codes as well as voluntary home energy efficiency and weatherization programs. However, current ventilation applications and standards do little to optimize IAQ and IAQ system-related energy performance. For example, heat recovery is not required or encouraged in ASHRAE Standard 62.2 or most building codes, and it is less commonly specified. In addition, the effectiveness of current ventilation solutions is limited by climate, sensor and control technologies, pollutant source control methods, and system costs. Even the best ventilation solutions do not guarantee acceptable IAQ. This 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, in addition to dilution ventilation to address general pollutants that cannot be eliminated or removed effectively at their sources.

In addition, 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. Further, good IAQ and healthy home features have been shown to be a powerful driver for energy efficiency and improved home performance. The Building America Research-to-Market Plan presents detailed evidence that improved IAQ can encourage adoption of high-performance home technologies and systems (DOE 2015).

Figure 3 shows The Optimal Ventilation and IAQ Solutions Roadmap, with project markers pointing to one or more roadmap objective that each funded project was selected to address. This roadmap seeks to guide research and development to ensure that the development of best practices, specifications, and standards for existing home retrofits and high-performance new home construction account for the effects that the building and its systems might have on the health of occupants and the durability of the building itself while minimizing energy usage. The roadmap's end objectives are smarter ventilation solutions and IAQ valuation methods that enable market adoption of high-performance homes with optimal IAQ and minimal energy use.

The roadmap covers three key technology 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; (2) *smart ventilation technology solutions* that optimize the balance between IAQ and energy by using dynamic control based on occupancy, exhaust fan (e.g., dryer and range hood) operation, or indoor/outdoor temperature, RH, and pollutant levels; and (3) *IAQ valuation* that facilitates quantified assessments of home IAQ to encourage more informed and objective design decisions regarding IAQ measures.

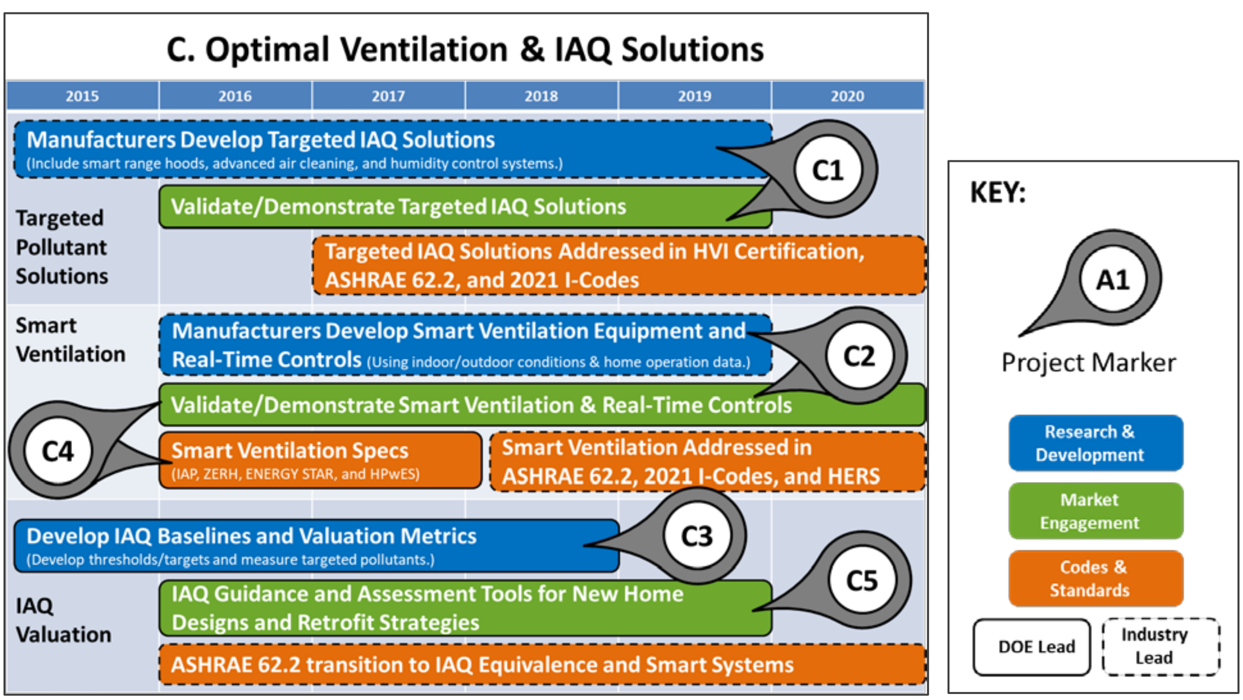

Figure 3. Building America IAQ Roadmap

Highlights of Building America Funded IAQ Roadmap Projects

C1. Development of the Industry's First Smart Range Hood (Newport Partners)

Kitchens are a principal source of some of the most harmful pollutants generated in the home. Kitchen range hoods can mitigate the impact of these pollutants, but range hoods can be ineffective at capturing pollutants and are often unused either because of noise or because occupants are unaware of when ventilation is needed. This project involves development and validation of a smart range hood that senses pollutants and automatically operates to remove the contaminants efficiently. The proposed smart range hood will be quiet (<1 sone), five times more energy efficient than today's ENERGY STAR® models, and price-point competitive with the intermediate market for standard kitchen range hoods. It will also capture nearly 100% of pollutants. By effectively addressing a major indoor pollutant source, this technology will enable residential building envelopes to be built tighter while still preserving healthy, acceptable IAQ.

C2. Ventilation Integrated Comfort System (Steven Winter Associates, Inc.)

Steven Winter Associates, Inc. will work to develop and validate an integrated energy recovery ventilation and heat pump system for residential buildings. The system will feature variable-speed fans to enable low-energy operation and precise control, providing balanced, distributed ventilation with heat recovery. This ventilation integrated comfort system will be tested in unoccupied and occupied homes to validate higher performance than other balanced heat recovery ventilation options. The system will enable balanced ventilation, improved IAQ, and RH control in tight homes for an installed cost that is $1,000–$2,000 less than separately installed, standard ducted ventilation and HVAC systems.

C3. Baseline IAQ Field Study in Occupied New U.S. Homes (FSEC and Pacific Northwest National Laboratory)

This national study is aimed at characterizing IAQ in recently built occupied homes. Researchers will closely monitor the use and performance of mechanical ventilation systems in these homes. Indoor and outdoor air will be sampled for formaldehyde, nitrogen oxides, carbon dioxide, and particulates. This work will help the industry understand how building characteristics and ventilation system design impact IAQ and which IAQ needs the available equipment is not meeting. This study is taking place in four climate zones (hot-humid, mixed-humid, marine, and cold) to identify any regional or climactic differences in IAQ or ventilation equipment.

C4. Smart Ventilation (Lawrence Berkeley National Laboratory)

The Smart Ventilation Project is a multiyear lab project to develop control strategies and algorithms for residential ventilation systems. The objectives are to reduce the energy associated with ventilation by 40% while maintaining equivalent IAQ compared with typical ventilation systems without smart controls. Smart ventilation also aims to reduce peak demand and intake of outdoor pollutants. Previous related work developed first-generation smart ventilation strategies and algorithms that are currently being commercialized, including the following control strategies: (1) time shifting ventilation to hours of the day when the energy required to condition the air is less and (2) taking into account the operation of other air moving systems, such as kitchen/bath exhausts, driers, and economizers. Current project work will extend this effort to investigate improved humidity control and synchronize ventilation system operation with home occupancy. This project includes modeling, laboratory testing, field experiments, and collaboration with ventilation equipment manufacturers.

C5. IAQ Score (Lawrence Berkeley National Laboratory)

Healthy indoor environments are qualitatively valued by homeowners and buyers; however, there is no trusted quantitative method for rating and comparing homes for IAQ. Developing an IAQ score similar to energy scores for homes, such as the Home Energy Rating System Index, will enable homes with good IAQ to get credit for their better performance and will help establish a level playing field for valuation of IAQ by the housing industry. A metrics analysis will be used to create weighting functions that account for the variables that most affect home IAQ, including home and ventilation system characteristics, climate, and the resultant capability of the home to manage risks associated with health impacts of targeted pollutants, moisture risk, and odor. The proposed IAQ score will enable builders, contractors, buyers, and sellers to assess IAQ performance of specific homes and compare homes with different packages of IAQ-related features. We anticipate that a credible IAQ scoring system will lead to improved market valuation of home IAQ and enable cost optimization of IAQ features.

Conclusions

This paper summarized the three integrated roadmaps detailed in the Building America Research-to-Market Plan (DOE 2015) and the major roadblocks to innovation they are designed to address. Successfully addressing the majority of these roadmap objectives is expected to systematically break down the market barriers—mostly risks of adoption—that prevent high-performance homes from becoming the industry standard.

The 16 Building America funded projects highlighted in this paper were awarded in recent years to address these roadmap objectives. Figures 1–3 clearly show that the Building America project portfolio covers a substantial portion of the target roadmap objectives.

Yet most of these projects are not complete; this is a work in progress. We will not be able to measure long-term market results of this work for years to come. In the meantime, there are several indications that the Building America Program and the current research strategy are working.

Building America Case Studies Prove High-Performance Homes Are Market-Ready

The National Renewable Energy Lab (NREL) evaluated Building America's research results in 2016, documenting successes and remaining knowledge gaps (Farrar 2016). The case study review shows that 23 new demonstration homes among six climate zones achieve 23%–81% EUI reduction relative to 2010 EUI baselines. Eight of these homes have an EUI at least 60% less than the average EUI of single-family homes in 2010, meeting BTO's 2020 target (DOE 2016) Another six of these homes came very close to reaching this target, with EUI values that are 50%–59% less than the baseline for their climate. The case study review also shows that 16 existing home retrofits among six climate zones achieved 23%–51% savings compared with pre-retrofit EUI. Twelve of these homes have post-retrofit EUI at least 40% lower than the 2010 consumption of an average home in their climate, meeting or exceeding BTO's 2020 goal for existing homes (DOE 2016). These initial findings indicate that Building America is well on the way to meeting these targets for several climate regions based on measured data.

Independent Evaluation of Building Science Innovation Showed Big Market Impacts

An impact study by Industrial Economics, Incorporated (IEc) evaluated four building practices that Building America has advanced since 1995: (1) air tightness, (2) duct tightness, (3) envelope insulation, and (4) thermal bridging. A Delphi panel was convened to estimate how much of the total energy savings of these practices could be attributed to Building America's work. Overall, the panel determined that 66% of the modeled energy savings from the four practices could be attributed to the Building America Program. This study performed a retrospective cost-benefit analysis, comparing the economic benefits of Building America's work on these practices with the overall Building America funding (including on other technologies and practices) during that time frame. This analysis showed the benefit-to-cost ratio of the Building America Program to be 5.4 to 30.1 (IEc 2018).

Industry Interest in Building Science Knowledge and Tools Is Growing Rapidly

In 2012, Building America launched the Building America Solution Center, an interactive resource for high-performance home construction. It is based on the substantial library of building science knowledge and best practice guidance developed by Building America researchers over nearly two decades. The Solution Center helps builders, contractors, code officials, and industry professionals put into practice lessons learned from Building America-sponsored research on hundreds of high-performance residential building science topics. Researchers and practitioners can dig deeper into subjects in a library of nearly 1,000 technical reports, articles, code documents, and case studies. The Solution Center has grown to include more than 230 best practices guides offering step-by-step illustrated instructions for installing high-performance home measures. Today, the resource continues to skyrocket in popularity, growing from about 77,000 users in 2013 to more than 298,000 users in 2017. That's an increase of 287%! In total, Solution Center users are now approaching the 1 million mark, with 911,000 users and nearly 2 million page views since the launch.

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