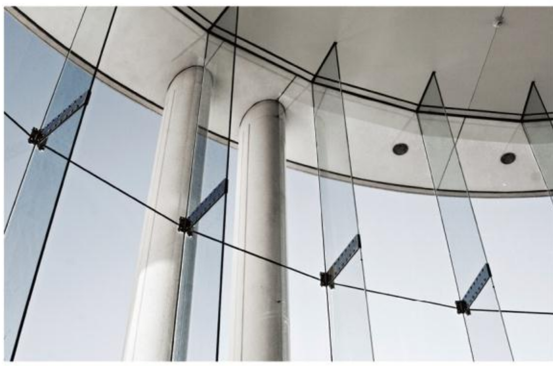

Windows and Building Envelope Research and Development:

Roadmap for Emerging Technologies

February 2014

Prepared by Energetics Incorporated for:
Windows and Building Envelope Research and Development
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DISCLAIMER

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COMMENTS

DOE is interested in feedback or comments on the materials presented in this document. Please write to:

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EXECUTIVE SUMMARY

The U.S. buildings sector, which consists of over 85 million existing residential and commercial buildings, accounts for approximately 40% of the United States' primary energy consumption and 39% of U.S. carbon dioxide emissions (Energy Information Agency 2013d; Office of Energy Efficiency and Renewable Energy 2011a). Due to the expected gross addition of over 1 million buildings each year, the number of buildings in the United States is projected to grow to over 100 million by 2035 (Energy Information Agency 2010; Energy Information Agency 2013a; Office of Energy Efficiency and Renewable Energy 2011h). However, existing buildings are projected to continue to dominate the market through that time. Efforts to reduce energy use in U.S. buildings will directly impact both residential homes and commercial businesses by saving money for both homeowners and business owners. The environmental impacts of energy use are also an important long-term economic consideration for businesses and homeowners. In particular, lower operating costs for businesses will translate to more competitive U.S. products and more jobs. Accordingly, President Obama, in his 2013 State of the Union address to the nation, issued a new national goal of reducing energy losses in buildings by 50% in the next 20 years (Remarks by the President 2013).

The U.S. Department of Energy (DOE) Building Technologies Office's (BTO's) mission is to improve the efficiency of existing and new buildings in both the residential and commercial sector through the development of high-impact energy efficiency technologies and practices. BTO aims to meet the national goal by developing and widely deploying tools and technologies that result from a variety of activities, including research and development (R&D), market stimulation, and codes and standards development. Next-generation windows and building envelope technologies have substantial technical potential to reduce energy consumption in buildings, but in order to significantly contribute to the goal the installed cost of high performance technologies must be reduced. As such, the windows and building envelope R&D community, including BTO, need to make a substantial and sustained commitment to R&D.

While the overall goal is clear, it is quite broad. As a result, a wide range of strategies may be needed to reach the goal and it is not always clear how to do so most effectively. What technology areas should R&D efforts focus on? What energy saving impacts will result? What is the specific market opportunity, new vs. retrofit or residential vs. commercial, for each approach? This R&D roadmap report aims to provide guidance to help answer these questions, focusing on windows and building envelope technologies. In many cases, it is not possible to develop a technology that will fit all possible use cases, which may appear to limit the energy-savings impact. However, the technological advances resulting in improved performance and/or cost reductions for one technology, material or process can often be leveraged for improvements in related technologies applicable to a wider market. Identifying these opportunities is critical to maximizing the impact of BTO's R&D investment.

Table 1 summarizes the windows and building envelope research areas that this report has identified as priority areas of interest. Figure 1 illustrates the how the staged payback and energy savings of these technologies compare. To avoid double counting of energy savings, this figure assumes that measures with lower projected cost of conserved energy are the first to capture their share of the market. Accordingly, this figure shows technology *staged* payback, which is longer than the unstaged payback for some technologies (e.g., dynamic windows) because a portion of energy savings are already captured by lower cost technologies.

Table 1. Summary of Priority Windows and Building Envelope Research Areas and R&D Cost and Performance Targets

Technology Description	Target Sector(s)	2025 Cost Target[1]	2025 Performance Target
Highest Priority R&D Areas			
Highly insulating windows	Commercial and Residential Sectors	Residential sector: Projected installed cost premium ≤$6/ft^2 compared to the 2010 standard base of windows Commercial sector: Projected installed cost premium ≤$3/ft^2 compared to the 2010 standard base of windows	Residential sector: R-10 windows with V_T>0.6. Commercial sector: R-7 windows with V_T >0.4. Highly insulating windows must be at comparable thickness and weight to the currently installed window base to enable retrofits.
Building envelope material	Commercial and Residential Sectors	Projected installed cost premium ≤$0.25/ft^2, including insulation material and associated labor, assuming an R-12/in performance to enable a payback period less than 10 years.	≥R-12/in building envelope thermal insulation material that can be added to walls to retrofit existing buildings and can also be applicable to other portions of the building enclosure (e.g., reduce the impact of thermal bridging between building components). The material must meet durability requirements and minimize occupant disturbance.
Air-sealing technologies (systems-level approach)	Commercial and Residential Sectors	Projected installed cost premium of ≤$0.5/ft^2 finished floor (25% of current average costs, including mechanical ventilation costs).	A system capable of concurrently regulating heat, air, and moisture flow to achieve the following performance specifications: Residential sector: <1 ACH50 Commercial sector: <0.25 CFM75/ft^2 (5-sided envelope)
High Priority R&D Areas			
Dynamic windows and window films	Commercial and Residential Sectors	Dynamic windows: Projected installed cost premium ≤$8/ft^2 compared to a standard IGU Dynamic window films: Projected installed cost premium ≤$2/ft^2 compared to a standard IGU	Demonstrate ΔSHGC > 0.4 with V_T bleached state > 0.6 for the residential sector and > 0.4 for the commercial sector.
Visible light redirection	Commercial Sector	Projected installed cost premium ≤$5/ft^2 compared to the cost of a standard window or blind installation including the costs of sensors and lighting controls.	Reduce lighting energy use by 50% for a 50-ft floor plate.
Highly insulating roofs	Commercial Sector	Projected incremental cost increase ≤$1/ft^2 compared to standard roof costs.	An energy use reduction equivalent to a doubling of current American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) R-values.

Each of the above technologies is discussed in more detail in this report including the potential energy savings opportunity if cost and performance targets are met and the technical and market challenges to reaching these targets, R&D milestones and activities, and the identification of the key stakeholders that will need to collaborate in order to reach the identified R&D goals. For each technology described, focus is given to improving performance, as well as specific strategies to reduce installed costs in order to increase the likelihood of mass-market adoption of the technologies that emerge from these R&D efforts.

[1] Cost targets in this report are quantified in order to provide a viable critical pathway from current technology R&D status to a cost target that, at scale, will facilitate mass-market technology adoption.

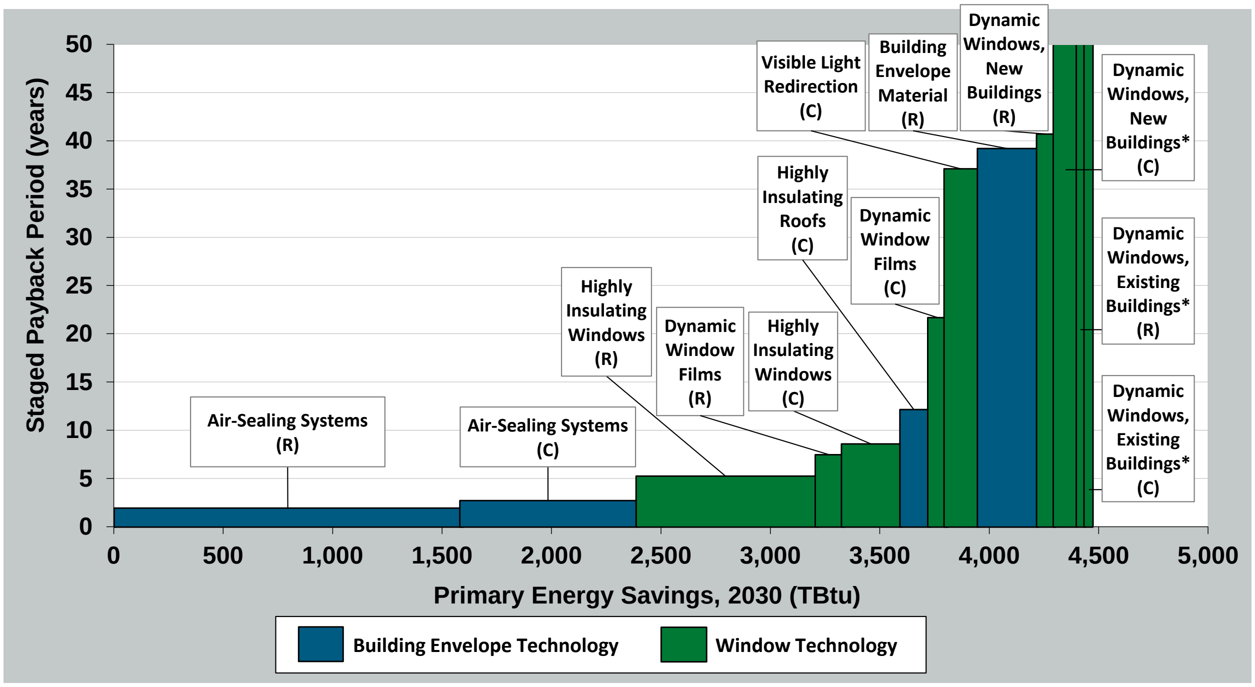

Figure 1. Staged maximum adoption potential and staged payback in 2030 for priority windows and building envelope technologies in the residential (R) and commercial (C) building sectors. Technologies with staged paybacks longer than expected technology lifetime are indicated with an asterisk (*).[2]

In addition to technical R&D activities, it is critically important that focus is also given to mitigating non-energy market drivers that may spur the mass-market adoption of these energy-efficient technologies. A discussion and summary of these barriers and their mitigation is presented in Chapter 5 and include:

- Reducing balance of system (BOS) costs and approaches to achieve those BOS cost reductions.
- Developing diagnostic technologies that will help make a business case for building energy upgrades and changes in building codes.
- Understanding methods for strengthening the business case for retrofits and developing appropriate and innovative business plans.

DOE looks forward to continuing to work together with researchers and technology developers in industry, academia, and the national laboratories in developing energy efficient building technologies and facilitating development of those that carry the greatest benefits today and in the years to come. While this roadmap does not cover all the important R&D areas, it will help facilitate and accelerate these efforts by identifying particular R&D milestones, final goals, and over-arching strategies necessary for the development of next-generation windows and building envelope technologies at a cost that enables mass adoption in commercial and residential buildings in the U.S. In addition, this roadmap aims to be a dynamic resource that will be updated as technologies develop and new technologies emerge. This report is intended to be a source of direction and focus to both public and private decision makers pursuing high-impact R&D that fosters participation from existing and new researchers as the next steps are taken to advance next-generation energy efficient windows and building envelope technologies.

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[2] Staged Maximum Adoption Potential (TBtu) assumes that measures with the lowest cost of conserved energy are the first to capture their share of the market to avoid double counting of energy savings. The staged maximum adoption potential represents the energy savings that would result if the technology is deployed only for all end-of-life replacements and new purchases, and does not include savings that result from other technologies with a lower cost of conserved energy. Accordingly, the staged payback of the higher cost technologies shown in this figure (e.g., dynamic windows) is longer than unstaged payback because a portion of projected energy savings are considered to be already captured by lower cost technologies.

1. INTRODUCTION

Background and Importance of Buildings Energy Consumption

The U.S. buildings sector accounted for approximately 41% of United States primary energy consumption in 2010; more energy than any other end-use sector. Residential and commercial buildings were responsible for 22 quadrillion Btu (quads) and 18 quads of energy, respectively. In 2010, 43% of U.S. residential building energy consumption (equal to 9.5 quads of energy) was consumed for space conditioning, including both heating and cooling. For perspective, the entire electric output of the nation's nuclear power plants was 8.4 quads in 2010 (Energy Information Agency 2013d). In the commercial buildings sector, lighting was the largest category of energy end use in 2010, consuming 20% of commercial building sector energy consumption (equal to 3.7 quads). Space heating and cooling also consumed significant portions of commercial building energy consumption in 2010. Space heating consumed 16% of commercial building energy consumption (equal to 2.9 quads), while space cooling consumed 14% of commercial building energy consumption (equal to 2.6 quads). By comparison, the U.S. aviation industry consumed 2.1 quads of energy in 2010 (Office of Energy Efficiency and Renewable Energy 2012). Space heating, space cooling, and lighting end uses across residential and commercial buildings consumed 21 quads of energy or nearly 52% of overall building energy consumption.

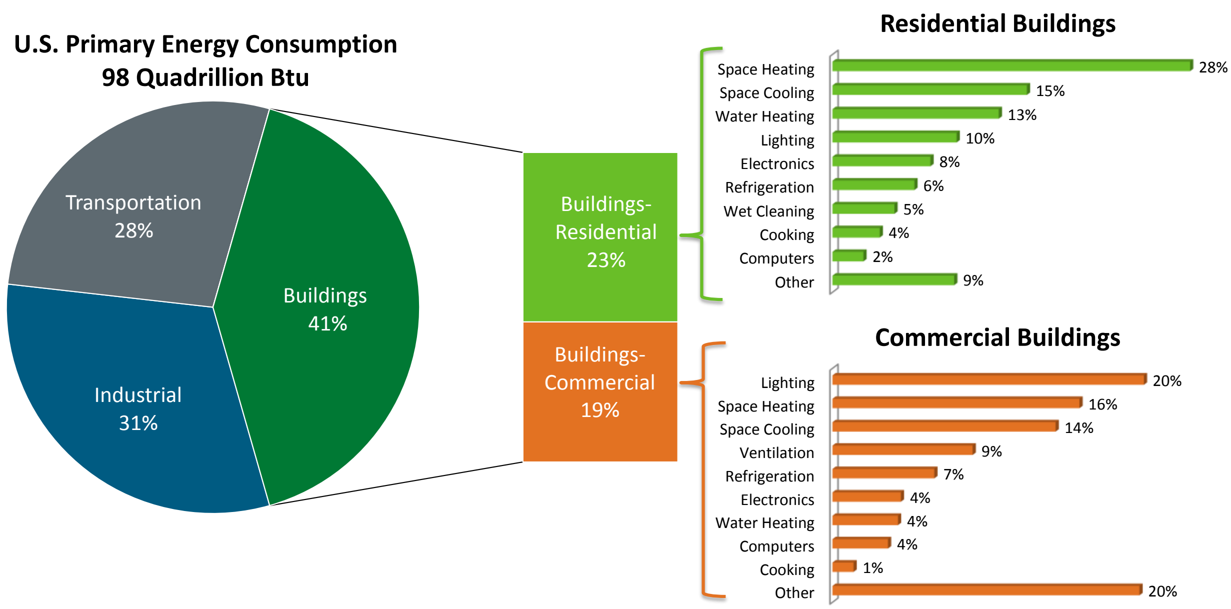


Figure 2. 2010 U.S. primary energy consumption (quads)[3]

Source: Energy Information Agency 2013d; Office of Energy Efficiency and Renewable Energy 2011b; Office of Energy Efficiency and Renewable Energy 2011e

[3] End uses labeled *Other* in residential buildings include small electric devices, heating elements, motors, swimming pool and hot tub heaters, outdoor grills, and any energy attributable to the residential buildings sector, but not directly to specific end-uses. *Other* end uses in commercial buildings include service station equipment, ATMs, telecommunications equipment, medical equipment, pumps, emergency electric generators, combined heat and power in commercial buildings, manufacturing performed in commercial buildings, and any energy attributable to the commercial buildings sector, but not directly to specific end-uses.

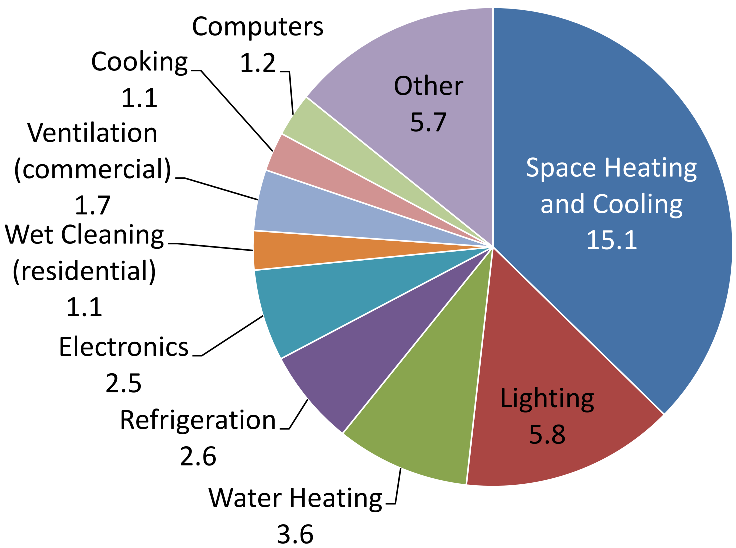


Figure 3. 2010 Commercial and residential primary energy end uses (quads)

Source: Office of Energy Efficiency and Renewable Energy 2011b; Office of Energy Efficiency and Renewable Energy 2011e

Building Technologies Office

BTO's mission is to improve the efficiency of existing and new buildings in both the residential and commercial sectors through the development of energy-efficiency technologies and practices. With this mission in mind, BTO aims to reduce building-related energy costs by developing and widely deploying tools and technologies to reduce building energy use by 50% by 2030 relative to the 2030 "business as usual" baseline energy use predicted by the EIA's *Annual Energy Outlook 2010* at a cost less than that of the energy saved.

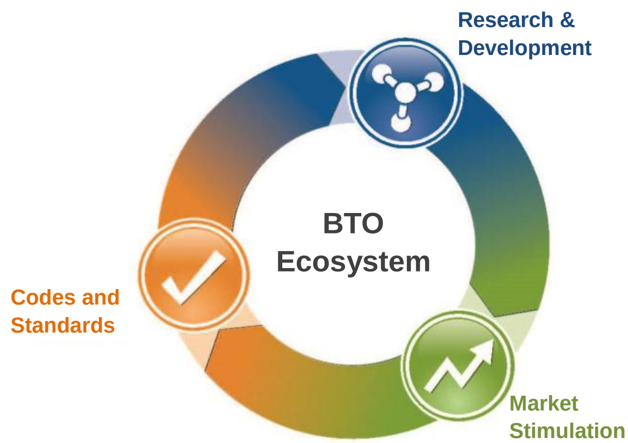


Figure 4. Integrated approach to BTO Program efforts

As illustrated in Figure 4, BTO employs a three-pronged integrated approach to achieve its mission and goal, focusing program efforts on (1) R&D, (2) market stimulation, and (3) codes and standards.

R&D efforts are focused on funding the development of next-generation, energy-efficient technologies for building technologies that have performance metrics equal or better than state-of-the art technologies at a cost that enables mass-adoption. Market stimulation efforts involve collaborating with industry partners and other key stakeholders to increase the adoption of energy-efficient technologies. Market barriers, including policy, financial, and communication barriers, are identified and mitigated in collaboration with BTO program partners. Finally, codes and standards efforts establish minimum energy use levels using a transparent public process, which is critical to raising the efficiency bar, enhancing industry competitiveness and profitability, and protecting consumer interests. All three strategies must be tightly integrated and are all equally important in order for BTO to reach its goal. The focus of this report is to develop a roadmap for the Windows and Buildings Envelope Research and Development Emerging

Technologies (ET) Program that will integrate with the Market Stimulation and Codes and Standards programs, and ultimately contributing to the larger BTO goals.

Emerging Technologies Program

The BTO ET Program funds research and development of energy-efficient and cost-effective building technologies in industry, academia, and the Department of Energy national laboratories. The portfolio includes technologies targeted at both new buildings and building retrofits for both the commercial and residential building sectors. The ET Program funds a wide-range of technologies, including solid-state lighting, space heating and cooling, windows and building envelope, water heating, modeling and tools, and sensors and controls.

The ET mission is to accelerate the research, development, and commercialization of emerging, high-impact building technologies that will impact the BTO program's overall 2030 goal. The overall BTO goal can be broken out into specific technology area goals. BTO analysis projects that if the overall BTO goal is met in 2030, buildings will consume over 20% less energy from heating, ventilation, and air conditioning (HVAC) and refrigeration due to improvements in the opaque portions of the building envelope (walls, roofs, foundation, and infiltration), accounting for 4.2 quads total energy savings. Along the same lines, improvements in windows will lead to 1.1 quads of energy savings due to reduced HVAC and refrigeration use. In total, BTO projects the use of cost-effective, energy-efficiency technologies could result in savings of 23.4 quads in 2030 (23% of these total savings are projected to result from improvements in windows and building envelope technologies). This breakdown is shown in Figure 5.

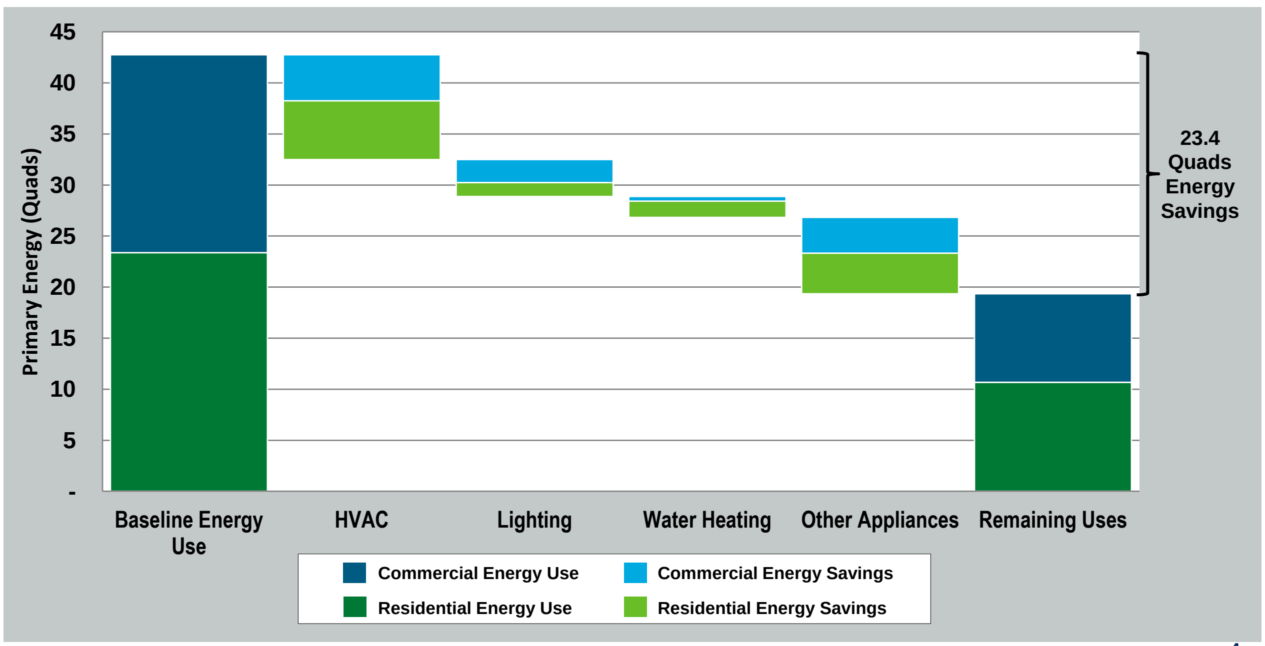


Figure 5. Overall BTO energy savings goal in 2030 shown by commercial and residential building market segments[4]

[4] Savings from building envelope and window technologies are included in HVAC, except for savings from daylighting technologies, which are included in the form of reduced lighting energy consumption. Lighting energy savings result when daylighting sensors and controls are able to turn off lights automatically when daylight enters a building. Non-daylighting fenestration technologies will only reduce lighting energy load if there are associated lighting sensors and controls. The lighting energy savings are not accounted for because sensors and controls for fenestration technologies are not included in the R&D targets, except for visible light redirection.

Figure 6 shows a notional timeline that would need to occur in order to achieve the 2030 BTO goal. This report's focus is on developing the roadmap, including quantitative metrics, to inform the upcoming R&D activities. Market entry would need to occur no later than 2025 to give ample time for scale-up and deployment efforts.

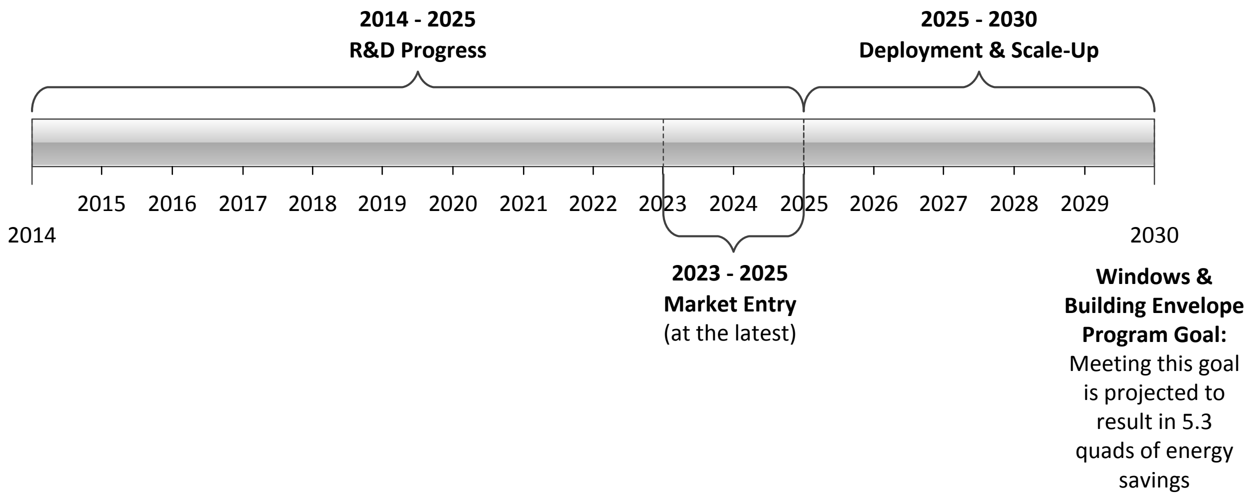


Figure 6. Notional timeline of anticipated building technology R&D progress

Role of Windows and Envelope Technologies in Reducing Building Energy Consumption

Next-generation windows and building envelope technologies, such as those identified in this report, have substantial potential to reduce energy consumption in buildings. However, to make significant progress toward the program goal, any next-generation technologies must be developed with a specific emphasis achieving a market-acceptable installed cost to facilitate mass-market adoption. Both transparent and opaque components of the envelope protect building occupants from undesirable external environmental conditions. Alternatively, the envelope can be constructed to take advantage of desirable external conditions by providing natural lighting or ventilation. Both strategies may reduce the use of energy consuming machinery in buildings. A complementary strategy employed by ET is to fund R&D for more efficient machinery (e.g., more efficient heating, ventilation, and air conditioning [HVAC] systems or more efficient lighting). A successful example of the role R&D can play to successfully stimulate product innovation is described on the next page.

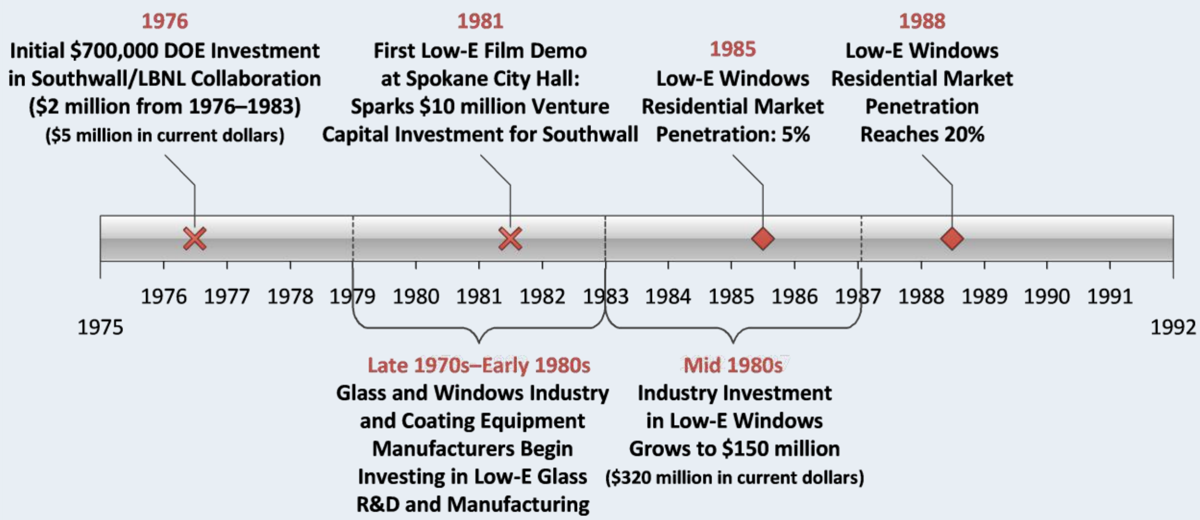
The Low-E Window R&D Success Story†

The development of low-emissivity ("low‑E") windows in the late 1970s to 1980s offers an excellent case study to show how government funded R&D and seed investments can make a significant impact on the market adoption of energy-efficient technologies and, ultimately, the nation's energy consumption. Low-E windows use a transparent coating that blocks infrared radiation to keep heat outside the building on hot days and keep it inside the building on cold days.

From 1976 to 1983, the U.S. government spent $2 million ($5.5 million in current dollars) to initiate window research at Lawrence Berkeley National Laboratory (LBNL) and support research into low-E window technologies. During that same time period, a start-up company called Suntek Research Associates (later renamed Southwall Technologies) was formed by a group of Massachusetts Institute of Technology students to develop low-E window technology. This fledgling company was unable to obtain adequate private-sector investment because of the perception that low-E technology was unproven and risky, particularly for a company of that size. However, DOE saw great promise in the technology and granted the company $700,000 ($1.95 million in current dollars) in initial R&D funding on the condition that the company collaborate with a national laboratory. The company chose to partner with LBNL, a collaboration that proved to be very fruitful, as Southwall was then able to develop the Heat Mirror transparent film (released in 1981), the first low-E window technology to become a commercial product.

At that point, the major window and glass manufacturers became more interested in low-E technology and accelerated their investment in low-E research, coating manufacturing, and window products. A major glass and window manufacturer stated that "DOE-funded efforts in the late 1970s and early 1980s were important factors in the critical decisions that led them to make [the] major capital investments" (Romm 1996) necessary to begin producing low-E glass and windows. By the mid-1980s, industry investment in low-E manufacturing facilities had grown to $150 million ($320 million in current dollars), and **"**virtually every major window and glass company offered a low-E product**"** (Romm 1996).

Low-E windows rapidly increased market share, accounting for 20% of residential window sales by 1988. Further adoption of these energy-efficient windows was driven by the introduction of ENERGY STAR® window standards in 1998, to the point where today, low-E windows command a >80% market share of residential windows and a >50% market share of commercial windows in the United States. Ultimately, DOE-sponsored research investments into this technology helped generate net savings of more than $8 billion ($10.7 billion in current dollars) by 2000.



† This case study summary is adapted from the "Case Studies on the Government's Role in Energy Technology Innovation: Low-Emissivity Windows" by Jeffrey Rissman and Hallie Kennan of the American Energy Innovation Council. The full case study can be found at: americanenergyinnovation.org/wp-content/uploads/2013/03/Case-Low-e-Windows.pdf.

Windows and Building Envelope R&D Program Roadmap Workshop

A collaborative *Windows and Building Envelope R&D Program Roadmap* workshop was held on April 5, 2013 in Washington, DC, in order to lay the basis for this roadmap report. This facilitated workshop provided a structured forum for participants to discuss challenges and identify and prioritize research directions, goals, and metrics for the windows and building envelope community. Participants (see full participant listing in Appendix A; also summarized in Figure 7) included researchers, industry leaders, and other experts in the windows and building envelope community.

Following introductory remarks and presentations from DOE staff, the workshop began with a series of overview presentations focused on relevant issues within the following areas:

1. Residential Windows: *Highly Insulating Residential Windows using Smart Automated Shading* (Christian Kohler, LBNL)
2. Residential Building Envelope: *Residential Envelopes: Future Market Needs* (Eric Werling, Building Technologies Office, Residential Buildings Program)
3. Commercial Building Envelope: *Energy Efficient Integrated FRP-Confined Sandwich Roof for Commercial Buildings* (An Chen, University of Idaho)
4. Commercial Windows: *Dynamic Control in Commercial Fenestration* (Guillermo Garcia, Heliotrope Technologies)

Following these plenary presentations, the workshop participants split into four breakout discussion groups, with each group focusing on one of the aforementioned topic areas. During the breakout sessions, each of the four groups prioritized R&D topic areas for building window technologies and building envelope technologies. Each discussion group identified the technical challenges associated with each priority R&D topic. Workshop participants then participated in an additional discussion session to identify the metrics, milestones, and roadmap/action plans associated with each R&D topic area. The final discussion session allowed for workshop participants to discuss relevant crosscutting perspectives, including soft costs, diagnostics, filtration issues, aesthetics, the role of the contractor or architect, indoor air quality (IAQ), soundproofing, and thermal comfort. The workshop concluded with presentations from breakout group representatives summarizing results.

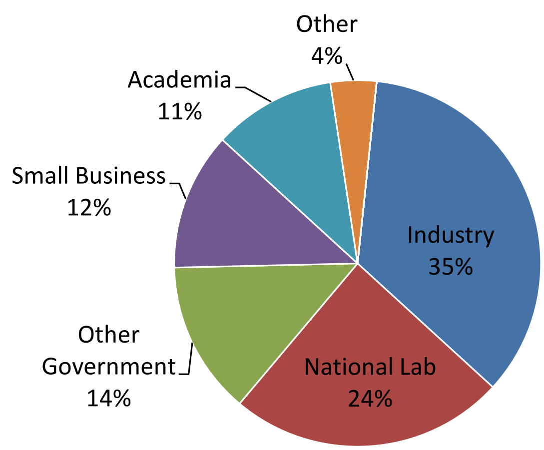


Figure 7. Composition of R&D roadmap workshop participants

The results that emerged from the breakout group discussions form the basis of this report. The International Energy Agency (IEA) has conducted a similar exercise to identify performance and cost roadmaps for key building envelope and window technologies (International Energy Agency 2013). The IEA publication identifies similar focus areas to the ones identified in this report, with comparable performance and cost targets.

Organization and Purpose of the Roadmap

This roadmap focuses on R&D for windows and building envelope technologies. It is the result of collaboration with prominent researchers and leaders in the field, and aims to prioritize BTO's investments in developing the next generation of high-performance, cost-competitive windows and building envelope technologies. While it does not cover all relevant areas in depth, it does highlight some ideas of particular importance. By identifying opportunities and the barriers inhibiting progress, it is hoped that this roadmap will inform the strategic direction of BTO in soliciting and selecting innovative technology solutions to overcome technical barriers and ultimately help fulfill the BTO mission and goal.

Chapter 2 of this roadmap provides an introduction to the BTO Prioritization Tool, which has been utilized throughout this report to compare investment opportunities by evaluating energy savings potential and cost effectiveness. Chapter 3 details technology roadmaps for emerging windows technologies, while the focus of Chapter 4 is an analogous examination of emerging building envelope technologies. When appropriate, each chapter identifies technologies relevant to the residential and commercial building sectors. In addition, important stakeholders relevant to the technology's development are also identified in each chapter, as concerted action by all stakeholders will be critical to realizing BTO and ET goals. Chapter 5 provides an overview of important crosscutting market drivers and challenges including soft costs, building diagnostics and infiltration issues, aesthetics, the role of the contractor or architect, acoustics and soundproofing, and building occupant thermal comfort. While the focus of this report is R&D, these crosscutting market drivers are very important to facilitate the market adoption of any technologies that are the result of focused R&D efforts and should be integrated into R&D projects as early as possible.

Ultimately, success may require long-term, high-risk research and public-private collaborations between academia, national laboratories, government, and private industry. This roadmap is a dynamic resource to assist in this process, and as such it will continue to change and be refined and/or expanded as the market develops and as technology breakthroughs emerge.

2. Impact of Windows and Building Envelope Technologies on Building Energy Consumption

Introduction to the Prioritization Tool

BTO has developed a comprehensive tool, called the Prioritization Tool (Farese 2012a), to compare investment opportunities by evaluating their energy savings potential and cost effectiveness. BTO uses the Prioritization Tool to perform sensitivity analyses and to inform programmatic decisions and targets. The tool provides an objective framework for most energy-saving measures and scenarios, as well as methodology, comparing long-term benefits and end-user costs applied to various markets, end-uses, and lifetimes. The methodology for this tool has been described in detail elsewhere (Farese 2012b). In brief, more than 500 building energy efficiency measures have been identified and input into the tool by defining key metrics for each measure to describe energy efficiency performance, cost, market penetration, and lifetime. These energy efficiency measures cover a spectrum of market opportunities, including residential and commercial buildings, new and existing buildings, as well as industrial and outdoor applications. Each measure is analyzed both individually and in the context of the full portfolio of measures using stock and flow dynamics, technology diffusion, and a staging framework.

The tool outputs include:

- **Market size (TBtu)**: The energy consumption associated with a building component (e.g., windows), within a particular buildings market segment (e.g., commercial, residential, new or existing buildings).
- **Payback period (years)**: Equal to the installed costs of an energy efficiency measure divided by the projected annual energy savings. Payback period is assessed in the year 2030.
- **Technical potential (TBtu)**: Existing stock is instantly replaced with the new measure. The technical potential represents the theoretical maximum energy savings available if the technology is implemented in the U.S. buildings sector.
- **Unstaged maximum adoption potential (TBtu)**: A 'stock and flow' model accounting for unit replacement, elimination, or addition. The unstaged maximum adoption potential represents the energy savings that would result if the technology is deployed only for all end-of-life replacements and new purchases.
- **Staged maximum adoption potential (TBtu)**: Measures with the lowest cost of conserved energy are the first to capture their share of the market to avoid double counting. The staged maximum adoption potential represents the energy savings that would result if the technology is deployed only for all end-of-life replacements and new purchases. It does not include savings that result from other technologies with a lower cost of conserved energy.

This analysis framework provides one method to better understand the opportunities for energy-efficiency technologies in buildings in the light of BTO's overall goal of reducing energy consumption in buildings by 50% by 2030. The tool allows for the evaluation of "what if" scenarios when pursuing potential competing energy efficiency measures and it ultimately helps BTO create technology roadmap and Funding Opportunity Announcements (FOAs) objectives. However, the methodology is only framed in terms of the levelized cost of conserved energy, which is defined as the incremental investment in the technology divided by the present value of the energy saved over the baseline energy use.[5] Other market drivers (thermal comfort, indoor air quality, aesthetics, etc.) are not accounted for and can certainly impact the adoption of energy-efficiency technologies, especially for first adopters. Additionally, the tool does not accurately capture the benefit of non-efficiency or enabling technologies, such as building energy storage or building energy modeling.

As shown in Figure 3, within the U.S. buildings sector, 37% of primary energy is used for space heating and cooling. Table 2 and Table 3 show the energy lost through windows (both conduction and solar heat gain) and opaque building envelope components from heating and cooling in both the residential and commercial building sectors in 2010 and projected for 2035. This data suggests that the building envelope components that can have the most impact on energy savings in the residential sector are infiltration, conduction through windows, and walls. In the commercial sector, the most impactful components are infiltration and conduction through windows, followed by infiltration and conduction through walls. However, it is noted that in cooling-dominated climates, solar heat gain from windows has a significant energy impact in both the sectors. This data does not account for the impact of window technologies on reducing lighting loads.

Table 2. Primary Energy Consumption Attributable to Fenestration and Building Envelope Components in 2010 (Quads)[6]

Building Component	Residential		Commercial	
	Heating	Cooling	Heating	Cooling
Roofs	1.00	0.49	0.88	0.05
Walls	1.54	0.34	1.48	-0.03
Foundation	1.17	-0.22	0.79	-0.21
Infiltration	2.26	0.59	1.29	-0.15
Windows (Conduction)	2.06	0.03	1.60	-0.30
Windows (Solar Heat Gain)	-0.66	1.14	-0.97	1.38

Source: Office of Energy Efficiency and Renewable Energy 2011b; Office of Energy Efficiency and Renewable Energy 2011d; Office of Energy Efficiency and Renewable Energy 2011e; Office of Energy Efficiency and Renewable Energy 2011g

[5] Discount rates are used to calculate a range of present values, from 3% (inflation), to 6%–10% (historic rates of returns on bonds and securities), to 20%–40% (rates observed to govern some decisions). The default discount rate is 7%.

[6] A negative value indicates the building component *reduces* heat load.

Table 3. Primary Energy Consumption Attributable to Fenestration and Opaque Building Envelope Components Projected for 2035 (Quads)6

Building Component	Residential		Commercial	
	Heating	Cooling	Heating	Cooling
Roofs	0.92	0.55	0.80	0.04
Walls	1.42	0.37	1.35	-0.02
Foundation	1.08	-0.24	0.72	-0.16
Infiltration	2.09	0.65	1.18	-0.11
Windows (Conduction)	1.90	0.03	1.46	-0.23
Windows (Solar Heat Gain)	-0.61	1.26	-0.89	1.03

Source: Office of Energy Efficiency and Renewable Energy 2011c; Office of Energy Efficiency and Renewable Energy 2011d; Office of Energy Efficiency and Renewable Energy 2011f; Office of Energy Efficiency and Renewable Energy 2011g

Table 4 shows the stock of residential buildings in 2010 and what is projected for 2035. Similarly, Table 5 shows the total floorspace of new and residential commercial buildings in 2010 and projected to 2035. These tables show the number of residential buildings or commercial floorspace built prior to 2010 and the number of buildings and commercial floor space built post-2010. For both the residential and commercial building sectors, the number of buildings built prior to 2010 continues to be the majority of overall buildings even past the year 2035. This is important to note in light of the overall BTO goal, which encompasses both new and existing buildings. Retrofitting existing buildings often requires different, more challenging technologies at different price points than the energy-efficient technologies that can be used for new buildings. However, because existing buildings dominate the market in 2010 and will continue to do so for the foreseeable future, all of the priority R&D areas discussed herein must be applicable to retrofitting existing buildings.

Table 4. New and Existing Residential Buildings in 2010 and 2035.[7]

	Number of Buildings (millions)	
	Pre-2010 Buildings	Post-2010 Buildings
2010	81.7	1.2
2035	52	51

Source: Energy Information Agency 2013a; Energy Information Agency 2013b

Table 5. New and Existing Commercial Building Floorspace in 2010 and 2035.[8]

	Total Floorspace (billion ft^2)	
	Pre-2010 Buildings	Post-2010 Buildings
2010	79.3	1.8
2035	52.8	50.2

Source: Energy Information Agency 2010; Energy Information Agency 2013c

[7] Numbers in this table assume a building lifespan of 70 years in order to account for changes in building stock from year to year. Apartment buildings are excluded from the estimates in this table.
[8] Numbers in this table assume a building lifespan of 70 years in order to account for changes in building stock from year to year.

Prioritization Tool Results

BTO has used the Prioritization Tool (PT) to analyze a wide range of windows and building envelope technologies. The results for technologies at development level[9] 3, 2, or 1 that are most relevant to the roadmap R&D targets are summarized graphically in Figure 8, Figure 9, Figure 10, and Figure 11 below, and are also shown in more detail in Table 34 and Table 35 in Appendix C. These figures and tables show the market size (TBtu), technical potential (TBtu), the unstaged maximum adoption potential (TBtu), and staged maximum adoption potential (TBtu) for each technology. The applicable buildings market segment, residential (R) and/or commercial (C) is shown on the x-axis label. The PT results use present-day costs of the installed measures, assuming significant market adoption, as described in more detail in (Farese 2012b).

Figure 8 shows PT results for select windows technologies. These results are shown in more detail in Appendix C, Table 34. Among these window technologies, the technical potential impact of R-10 window development is greatest, equal to just greater than 2 quads of energy savings by the year 2030. However, the staged max adoption potential of R-10 windows is only 234 TBtu, which indicates that R-10 windows will need considerable cost reductions in order to achieve these energy savings (the staged max adoption potential adjusts the unstaged max adoption potential to avoid double-counting energy savings from measures of overlapping markets and the max adoption potential accounts for savings of the lowest cost measures first). Window attachments, including energy-efficient low-E storm windows, cellular shades, and low-E window films, have sizable technical potential savings with reasonable payback periods. However, other than the automated window attachments, which require integration with low-cost sensor and control technologies, these products are in need of market-driving initiatives in order to accelerate adoption, rather than the R&D that is focused on in this roadmap. Dynamic windows, on the other hand, are much more costly, particularly in the commercial sector. Daylighting technology's technical potential is more limited and adoption is limited by high costs.

Figure 9 shows PT results for a wide array of building envelope technologies, covering a broad range of energy savings potential and payback periods. These PT results are shown in more detail in Appendix C, Table 35. A variety of thermal insulation materials are shown, of which R-6/in sheathing with sealing has the largest staged max adoption potential and lowest payback period. The figure clearly shows that VIPs in walls in existing buildings have the greatest potential to save energy with a technical potential of 1,099 and 575 TBtu in residential and commercial buildings, respectively. However, the unstaged and staged[10] maximum adoption potential data show that VIPs will have limited market penetration without a substantial reduction in cost. This trend is observed for other thermally insulating building envelope components as well, suggesting that the focus of R&D for these technologies should be on installed cost reduction. On the other hand, roofing technologies for the commercial sector, including cool roofs and thermally insulating roof technologies, have technical potentials of 90 and 100 TBtu, respectively, but they also have substantial market penetration in part because of a short payback periods. Figure 10 shows

[9] Level 1 is defined as early stage R&D (i.e., lab bench scale, beyond basic science), level 2 is defined as late stage R&D (cost reduction and performance improvements still needed, but technology may be available to early adopters), and level 3 is defined as early deployment (energy savings are not yet proven in a whole building context).

[10] Staged Maximum Adoption Potential (TBtu) assumes that measures with the lowest cost of conserved energy are the first to capture their share of the market to avoid double counting. The staged maximum adoption potential represents the energy savings that would result if the technology is deployed only for all end-of-life replacements and new purchases, and does not include savings that result from other technologies with a lower cost of conserved energy.

building wrap technologies that offer substantial savings potential with relatively low payback periods, especially in the residential sector, but building wrap technologies do not provide system-level control of heat, moisture, and air that would increase functionality over today's technologies and increase deployment and energy savings impact. Finally, Figure 11 shows PT results for highly insulating commercial building roofs that have relatively small savings potential and thus require performance improvements in order to enable more substantial energy savings (Farese 2012b).

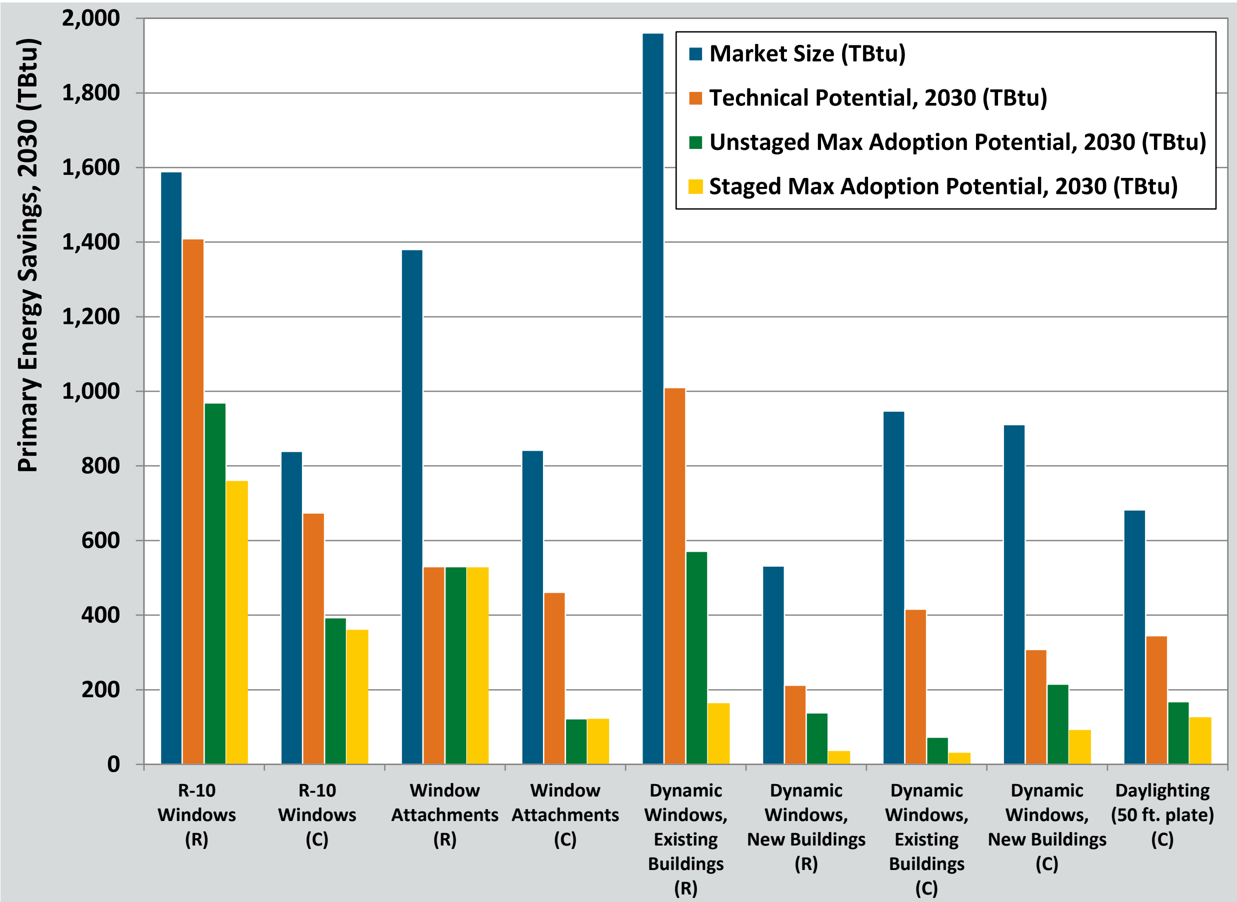


Figure 8. Prioritization tool analysis results for select windows technologies at development levels 1, 2, or 3

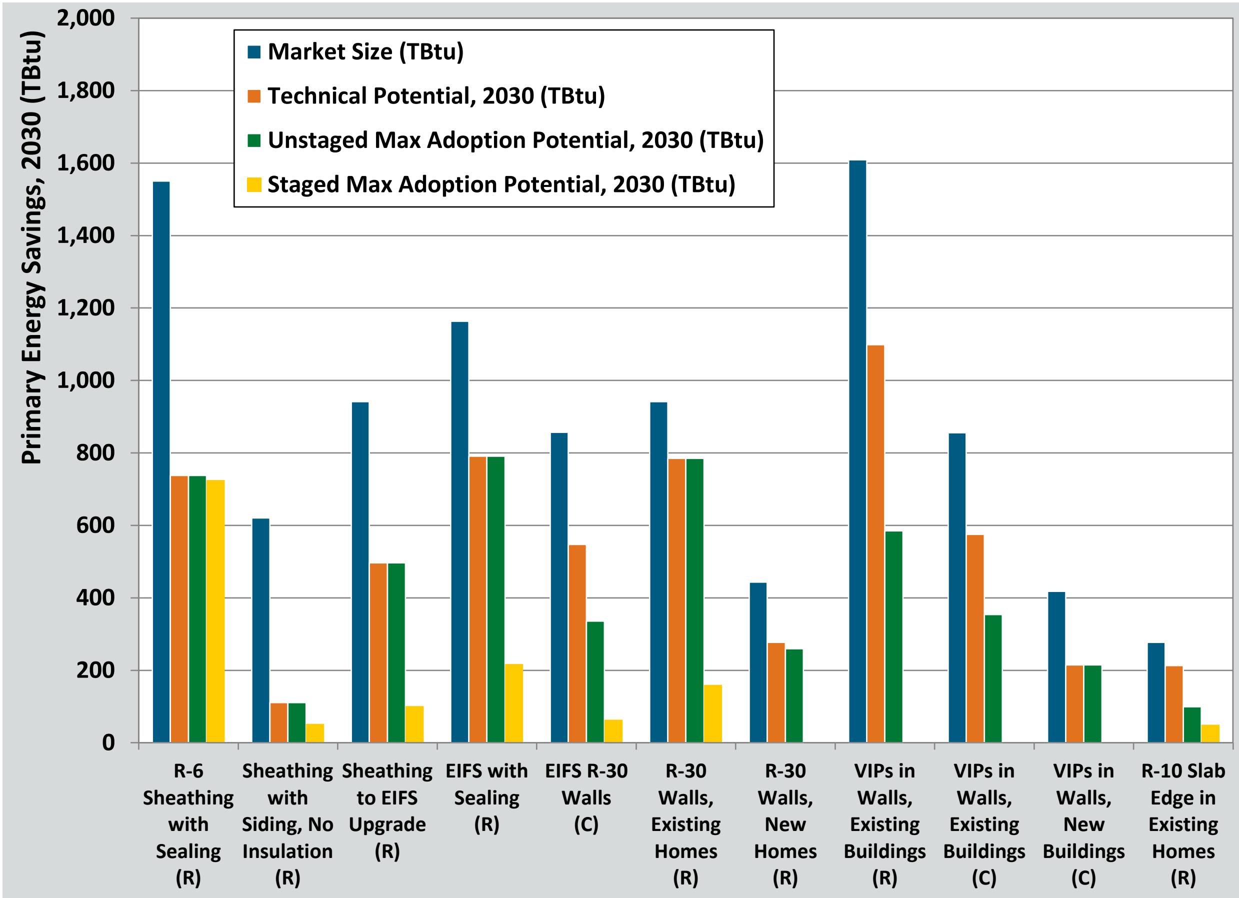


Figure 9. Prioritization tool analysis results for select thermal insulation materials at development levels 1, 2, or 3

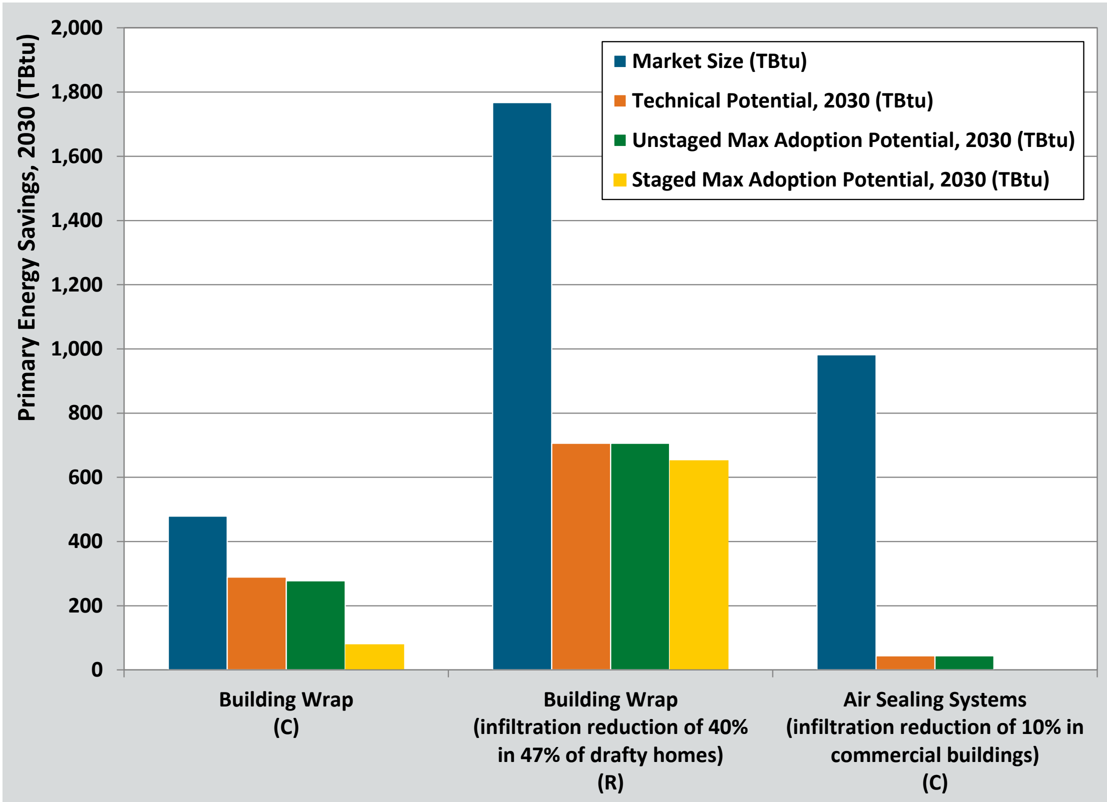


Figure 10. Prioritization tool analysis results for select air-sealing system technologies at development levels 1, 2, or 3

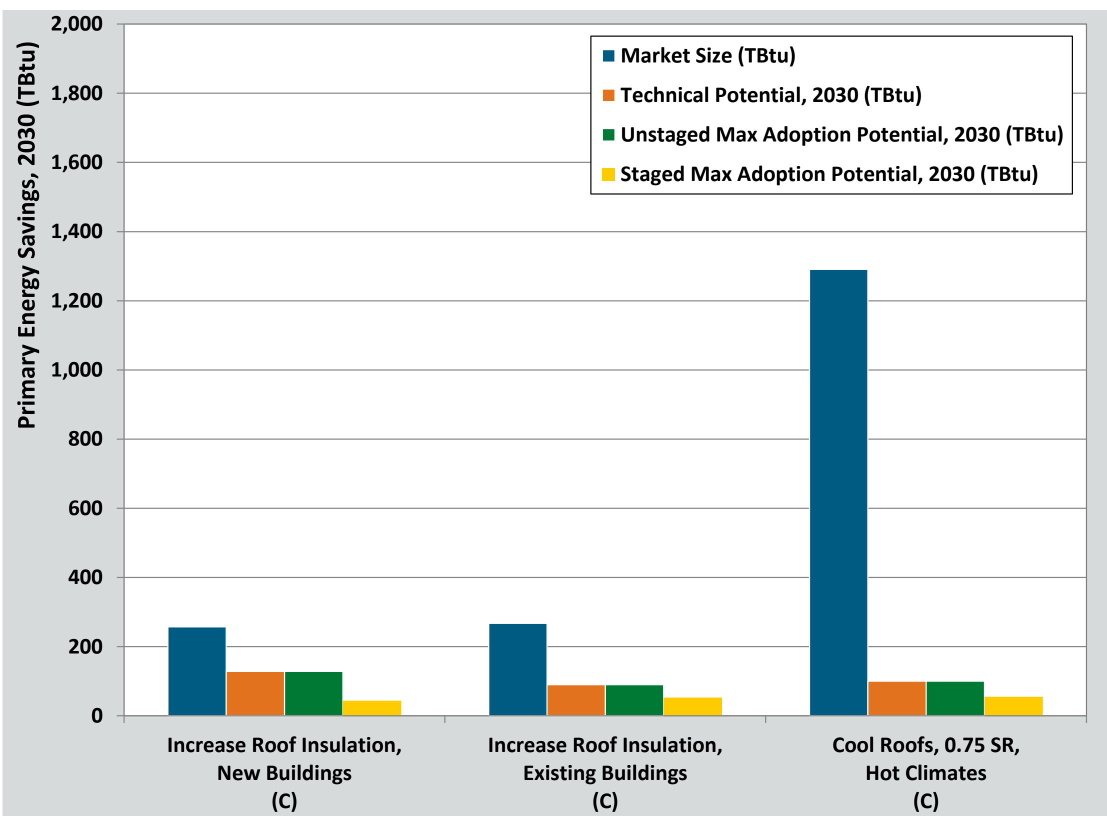


Figure 11. Prioritization tool analysis results for select commercial roofing technologies at development levels 1, 2, or 3

3. ROADMAP FOR EMERGING WINDOWS TECHNOLOGIES

Priority R&D Topics Summary

Improving building energy performance will require R&D to produce low-cost advanced materials and window technologies that can be easily and cost-effectively installed into new building construction and existing retrofits. The mission of the BTO ET Program is to accelerate the research, development, and commercialization of emerging, high-impact building technologies. This roadmap report aims to contribute to this mission by identifying technology R&D opportunities and barriers.

Taking into consideration traditional development schedules, window R&D topics will need to be identified and initiated in the near future in order to have technologies ready for mass-market adoption by 2030. These designs will need to be applicable to both new buildings and retrofits. Numerous topics can be pursued; however, BTO internal analysis and stakeholder engagement indicates that the following areas will have the largest potential for energy savings. These topics, which will be individually expounded in more detail, are summarized in the table below:

Table 6. Residential and Commercial Window Priority Research Topics[11]

Technology Description	Target Sector(s)	2025 Cost Target[12]	2025 Performance Target
Highest Priority R&D Area			
Highly insulating windows	Commercial and Residential Sectors	Residential sector: Projected installed cost premium ≤$6/ft^2 compared to the 2010 standard base of windows Commercial sector: Projected installed cost premium ≤$3/ft^2 compared to the 2010 standard base of windows	Residential sector: R-10 windows with V_T>0.6.[13] Commercial sector: R-7 windows with V_T >0.4.[13] Highly insulating windows must be at comparable thickness and weight to the currently installed window base to enable retrofits.
High Priority R&D Areas			
Dynamic windows and window films	Commercial and Residential Sectors	Dynamic windows: Projected installed cost premium ≤$8/ft^2 compared to a standard IGU Dynamic window films: Projected installed cost premium ≤$2/ft^2 compared to a standard IGU	Demonstrate ΔSHGC > 0.4 with V_T bleached state >0.6 for the residential sector and >0.4 for the commercial sector.[13]
Visible light redirection	Commercial Sector	Projected installed cost premium ≤$5/ft^2 compared to the cost of a standard window or blind installation including costs of sensors and lighting controls	Reduce lighting energy use by 50% for a 50-ft floor plate

[11] There is a wide range of technologies that can be used to reduce energy consumption in buildings; however, because of limited R&D funds BTO must prioritize its investments for technologies with the greatest energy savings potential. Thus, while BTO will be investing in a wide range of technologies, the majority of its focus will be on highest priority R&D areas.

[12] Cost targets in this report are quantified in order to provide a viable critical pathway from current technology R&D status to a cost target that, at scale, will facilitate mass-market technology adoption.

[13] Visible transmission should be sufficient to provide a market-acceptable level of daylighting in the relevant sector without negatively impacting lighting load. Visible transmission performance targets are based on center-of-glass measurements.

Table 2 shows the energy lost (conduction and solar heat gain) through windows and opaque building envelope components in 2010 and Table 3 shows the projected loss for 2035. In 2010 in the residential sector, conduction through windows accounted for 2.06 quads of lost energy used for space heating, but offset cooling loads by 0.03 quads. Along those same lines in the commercial sector, conduction through windows accounted for 1.60 quads of energy lost in space heating, offset by 0.30 quads of cooling loads. In the residential sector, solar heat gain through windows accounted for 1.14 quads of energy lost from space cooling, but provided 0.66 quads of heating energy. Similarly in the commercial sector, solar heat gain through windows accounted for 1.38 quads of energy lost from cooling, but offset heating loads by 0.97 quads. The projected trends are similar for 2035. In aggregate, this data suggests that in both the residential and commercial sectors the most impactful strategy for reducing energy lost through windows is to focus on reducing energy losses resulting from conduction through windows. However, strategies focused on mitigating solar heat gain are clearly needed in cooling-dominated climates. In addition, the development of these highly insulating windows can also be integrated with other next-generation technologies, such as dynamic fenestration systems, daylighting systems, controls, and building integrated photovoltaics (PV).

Table 7. Roadmap Target Prioritization Tool Analysis Results for Window Technologies, Including Highly Insulating Window Technologies, Dynamic Window Technologies, and Visible Light Redirection Technologies

Window Technologies					
Roadmap Target Technology Description	Market Size[14] (TBtu)	Technical Potential[15], 2030 (TBtu)	Unstaged Max Adoption Potential[16], 2030 (TBtu)	Payback in 2030 (years)	Prioritization Tool Measure Number[17]
Highest Priority: Highly Insulating Windows					
R-10 windows (R)	1,589	1,409	969	5.3	421
R-7 windows (C)	780	599	263	8.3	422
Dynamic Window Technologies					
Dynamic window films (R)	257	121	121	7.2	651
Dynamic window films (C)	133	79	79	21	652
Dynamic windows, existing buildings (R)	1,961	1,010	571	10	401
Dynamic windows, new buildings (R)	532	212	138	12	400
Dynamic windows, existing buildings (C)	947	416	73	22	402
Dynamic windows, new buildings (C)	911	308	215	21	399
Visible Light Redirection Technologies					
Visible light redirection (C)	682	345	168	10	816

[14] Market Size represents the energy consumption associated with a building component (e.g., windows), within a particular buildings market segment (e.g., commercial, residential, new or existing buildings).
[15] Technical Potential assumes existing stock is immediately replaced with the new measure. The technical potential represents the theoretical maximum energy savings available if the technology is implemented in the U.S. buildings sector (free of practical constraints such as financing and deployment considerations).
[16] Unstaged Maximum Adoption Potential (TBtu) assumes a 'stock and flow' model accounting for unit replacement, elimination, or addition. The unstaged maximum adoption potential represents the energy savings that would result if the technology is deployed only for all end-of-life replacements and new purchases.
[17] Detailed sources for each measure number are shown in Appendix C.

Table 7 summarizes the BTO prioritization tool analysis for window technologies, including highly insulating windows, dynamic windows, and visible light redirection technologies. Figure 12 shows technical potential and unstaged maximum adoption potential for the window technology roadmap targets. This figure shows that highly insulating windows (R-10 for residential and R-7 for commercial buildings) have the greatest potential to save energy with a combined technical potential of 2,008 TBtu in the residential and commercial sectors. The large drop in energy savings for the unstaged maximum adoption potential illustrates that windows are expected to penetrate the market slowly because replacement windows require a substantial upfront cost. However, achieving the installed cost target for R-10 windows is expected to increase the rate of retrofit because the payback period is reduced to 5.3 and 16 years for the residential and commercial sectors, respectively. The technologies that focus on controlling solar heat gain, such as dynamic window films and dynamic windows, have a technical potential of 200 and 1,946 TBtu, respectively in the residential and commercial sectors. However, the energy savings for dynamic windows includes savings that result from controlling SHGC and from improving the window's R-value from a base value of 1.61 (1.86 for commercial windows) to an R-value over 3 for a replacement dynamic window.[18] Approximately 61% of the technical savings potential is a result of improving the R-value in the window, while 39% is from the ΔSHGC. Additionally, dynamic windows have a larger market than highly insulating windows because dynamic windows can save energy with both conduction and SHGC, while insulting windows only address conduction losses. The high cost of state-of-the-art dynamic windows limits the market penetration, and as a result R&D activities are primarily focused on relative cost reductions. Both Table 7 and Figure 13 show that achieving the target will lead to market-acceptable payback periods in 2030 for some markets, but that the payback period is still projected to be greater than 20 years in some cases. In general, the costs for commercial windows are expected to be higher than residential windows because of the added structural requirements, as illustrated graphically in Figure 13.

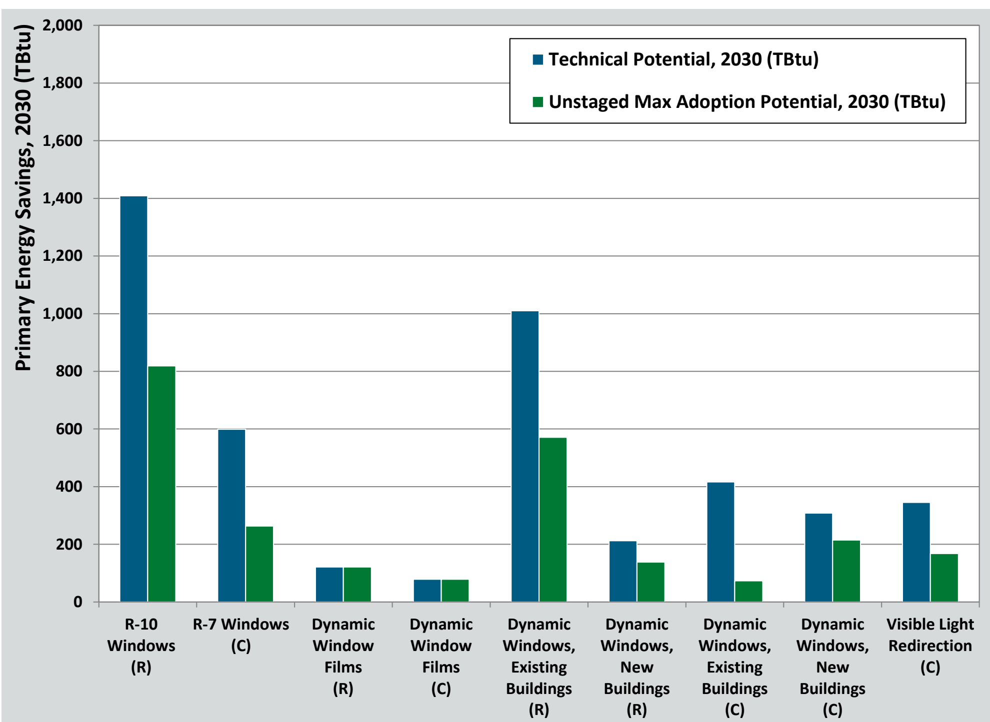


Figure 12. Prioritization tool analysis results for window technologies roadmap targets, including highly insulating windows, dynamic windows, and visible light redirection technologies

[18] View Dynamic Glass IGU data sheet: viewglass.com/pdf/IGU_DataSheet_US.pdf.

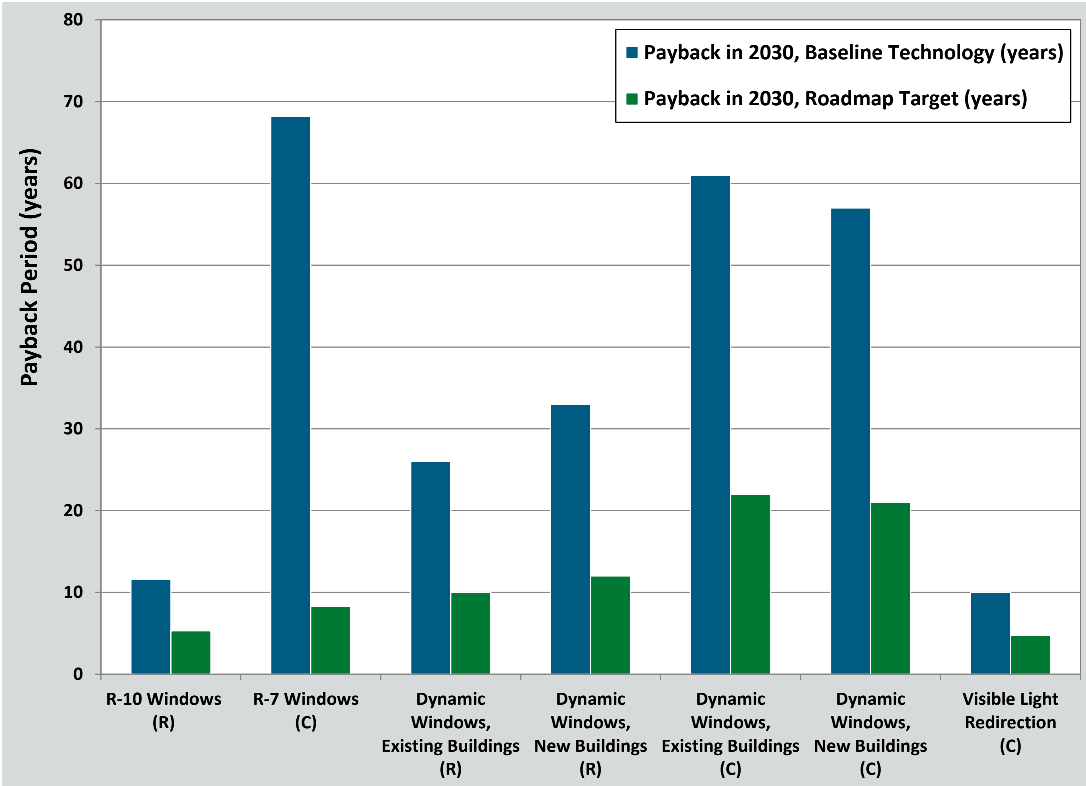


Figure 13. Comparison of payback periods for baseline technologies and technologies that achieve the roadmap cost and performance targets[19]

Crosscutting Barriers for Next-Generation Window Technologies

The key crosscutting challenges to innovative R&D for next-generation window technologies include the availability of high-performance materials, innovative manufacturing processes to reduce costs, and the ability to integrate new technologies into existing building systems.

- **Materials** – Increased costs of high performance materials may lead to greater up-front costs that must be passed down the supply chain to building owners. Additionally, while technically feasible, advanced concepts for high-performance windows may be hindered by the potentially limited availability of high-performance, next-generation materials.
- **Manufacturing** – Manufacturing costs must be lowered in order to facilitate mass-market adoption of next-generation window technologies. As such, technology development should proceed forward cognizant of the need to transition to automated, high-throughput manufacturing and installation processes that can be used for custom and large sized components.
- **System integration** – The inability to integrate new technologies into current system configurations (retrofits) and then demonstrate improved system performance is a significant challenge. Appropriate test methods and standards are lacking to ensure or prove the integrated performance of systems with capabilities that are not found in today's windows.

[19] The payback for R-7 window technology is based on a cost premium of $25/ft^2. This cost is an estimate that is between the costs of R-10 windows and R-5 windows shown in Appendix C.

Windows Highest Priority R&D Topic 1: Highly Insulating Windows

Overview

Highly insulating windows have the potential for substantial energy savings relative to existing windows, which typically possess R-values ranging from R-1 (single glass) to R-3 (double glazing with low-E) and R-4 (triple or quadruple glazing). R-factors are a measure of thermal conductivity; a higher R-value signifies a more insulating window.[20] For example, BTO internal analysis shows that the technical potential of R-10 windows is 2 quads by 2030, but the unstaged and staged[21] maximum adoption potential by 2030 is only 1.4 and 0.23 quads, respectively, because the stock of existing windows is slow to turn over.

The targeted outcome for R&D is a cost-effective, highly insulating window with reduced installation cost. Separate cost and performance targets have been identified for windows in the residential and commercial sectors. In the residential sector, the target is to develop R-10 windows with less than $6/ft^2 installed cost premium over the 2010 installed base of windows (R-1.61 for residential windows). In the commercial sector, the target is to develop R-7 windows with less than $3/ft^2 installed cost premium over the 2010 installed base of windows (R-1.86 for commercial windows). In both cases, sufficient V_T must be maintained to provide daylighting, approximately >0.6 for the residential sector and >0.4 for the commercial sector, based on center-of-glass measurements. The weight and thickness of these windows must be comparable to the existing stock of windows to enable retrofits of existing buildings. Commercial windows must also meet much more demanding structural tests (design pressures, deflection limits, torsion, and other hurricane ratings, operability, etc.) as well as very different market demands for design flexibility, durability, and integration into different wall facades in order to ensure market acceptability.

The R&D roadmap for moving toward next-generation residential and commercial window deployment is shown in Table 11. Key technical and market barriers preventing achievement of this target are discussed below, while detailed R&D barriers are also discussed in Table 9.

- **Performance improvement needed for highly insulating windows –**
    - Glass/glazing: high performance glass and glazings require next-generation, low-E coatings; multi-pane glazing systems; and highly insulated translucent panels. Durability improvements are needed for vacuum glazing edge seals to maintain gas retention and soft low-E coatings to maintain performance over the expected lifetime of a window.
    - Frames: For typical window frames, the glass R-value drops significantly at the IGU edge. Improved frame materials can reduce demand for ultra-high-performance glass and lead to super-low-conductivity frames. Advanced window frames should be able to pass

[20] A similar metric to the R-value (units: ft²·°F·hr/Btu) is the U-factor, which is generally presented as the inverse of the R-value ($U = \frac{1}{R} = \frac{k}{L}$, where k is material thermal conductivity and L is the material thickness). U-factors express the insulation value of windows, while R-values are used to express the insulation value of both window and opaque building envelope elements (i.e., walls, roofs). As such, R-values are used throughout this report in order to use a consistent metric across window and envelope technologies.

[21] Staged Maximum Adoption Potential (TBtu) assumes that measures with the lowest cost of conserved energy are the first to capture their share of the market to avoid double counting. The staged maximum adoption potential represents the energy savings that would result if the technology is deployed only for all end-of-life replacements and new purchases, and does not include savings that result from other technologies with a lower cost of conserved energy.

long-term air infiltration and structural requirements in order to gain a high-performance window label.

- **Window construction cost reductions –** Cost reductions are needed for the overall assembly of triple-glazed units with a thin glass middle layer, krypton gas fill[22], and multiple low-E coatings. Cost savings will likely come from manufacturing advances that enable automated, high-throughput product manufacturing and installation while still being able to produce custom sizes required in diverse building applications.
- **Amenability to retrofits –** Highly insulating windows must be developed at reduced or at least comparable thickness and weight to the currently installed window base so that they are amenable for commercial and residential building retrofit applications. A bulky/heavy window is also more costly to transport.
- **Simplified window installation** – Window installation is currently labor intensive, expensive, and variable. In order to enable mass-scale and possibly automated retrofits, window installation must be simplified to be "snap-in" or "dummy-proof." Effectively, the entire window system, including all components and insulation, must be easily installed with the "snap-in" capability.

BTO internal analysis shows that if the R&D roadmap cost and performance targets are achieved, the payback period would be reduced from 12 to 5.3 years and 66 to 8 years for the residential and commercial sectors, respectively. BTO projections show that energy savings from highly insulating windows would become even more substantial beyond 2030 as the installed base of windows turns over. Windows are generally a once-in-a-lifetime purchase, and as such the diffusion of new window technologies into the market will take longer than other energy-efficiency technologies.

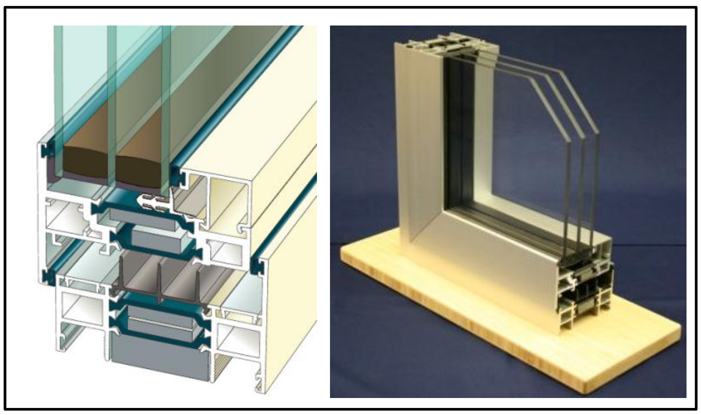


Figure 14. R-5 window, schematic diagram (left) and commercial product (right) (images courtesy of Alcoa/TRACO)

Figure 15 (with corresponding data shown in Table 8) shows the results of an economic sensitivity analysis for highly thermally insulating residential windows, considering the projected impacts of high ($18/ft^2), medium ($12/ft^2) and low ($6/ft^2) installed cost premiums. The payback period is more heavily dependent on the installed cost of the window than on the R-value. For example, the payback of R-10 windows decreases by a factor of 3 when reducing the installed cost premium from $18/ft^2 to $6/ft^2.

[22] Due to its higher molecular mass, krypton is a more effective insulator than argon ($k \propto \frac{c_v}{\sigma}\sqrt{\frac{T}{MW}}$, where k = thermal conductivity, c_v = constant volume specific heat capacity of gas, σ = molecular radius, T = temperature and MW = molar mass of gas). The thermal conductivity of krypton is 0.0053 Btu/ft²·°F·hr, while the thermal conductivity of argon is 0.0093 Btu/ft²·°F·hr.

Alternatively, the reduction in payback period is less than 1 year when comparing R-10 technology to R-7 technology at the same cost premium.

Analogous economic sensitivity analysis for highly insulating commercial windows in shown in Figure 16 with corresponding data presented in Table 8. The market size, and corresponding technical potential, for highly insulating commercial windows is less than half of that of the residential sector, due in large part to the reduced heating and cooling load in commercial buildings relative to homes (refer to Figure 2). Additionally, the performance target for commercial windows is lower than for residential windows because of the more stringent structural requirements, as discussed above. However, in order to maintain acceptable payback periods, the cost target in the commercial space is lower than for the residential space. Like the residential sector, the impact of cost reduction of commercial windows, even for existing technologies, such as R-5 windows, is likely to have a greater impact on energy savings than developing more insulating IGUs. For example, the payback of R-7 windows decreases from 33 to 8 years when the installed cost premium is reduced from $12/ft^2$ to $3/ft^2$. Alternatively, the difference in payback period is less than 2 years when comparing R-7 technology to R-5 technology for a $6/ft^2$ installed cost premium.

The technology and manufacturing advances needed to achieve low-cost highly insulating windows and window components will also impact window technologies that are closer to market. R-5 windows are commercially available today for both the residential and commercial building sectors, but are not yet cost-effective. Likewise, R-7 residential windows have a technical potential of 1,271 TBtu compared to 1,409 TBtu for R-10 windows and are expected to become commercially available earlier, making them potentially more impactful towards the overall BTO 2030 goal. The data in Table 8 shows a relatively small difference in the technical and unstaged maximum adoption potentials for R-7, R-8.5, and R-10 residential windows. This suggests that the R&D effort to increase a window's R value from 7 to 10 is less impactful in the *short-term* than pushing the state-of-the-art technology to R-7. Similar trends are observed when comparing the technical and unstaged maximum adoption potential for R5 and R7 commercial windows.

Table 8. Primary Energy Savings from Highly Insulating Windows (R-7, R-8.5, R-10) in the Residential and Commercial Sectors

Insulating Window Performance Target	Market Size (TBtu)	Technical Potential, 2030 (TBtu)	Unstaged Max Adoption Potential, 2030 (TBtu)
Residential Building Sector			
R-7	1,731	1,271	646
R-8.5	1,731	1,352	687
R-10	1,731	1,409	716
Commercial Building Sector			
R-3	780	360	158
R-5	780	528	232
R-7	780	599	263

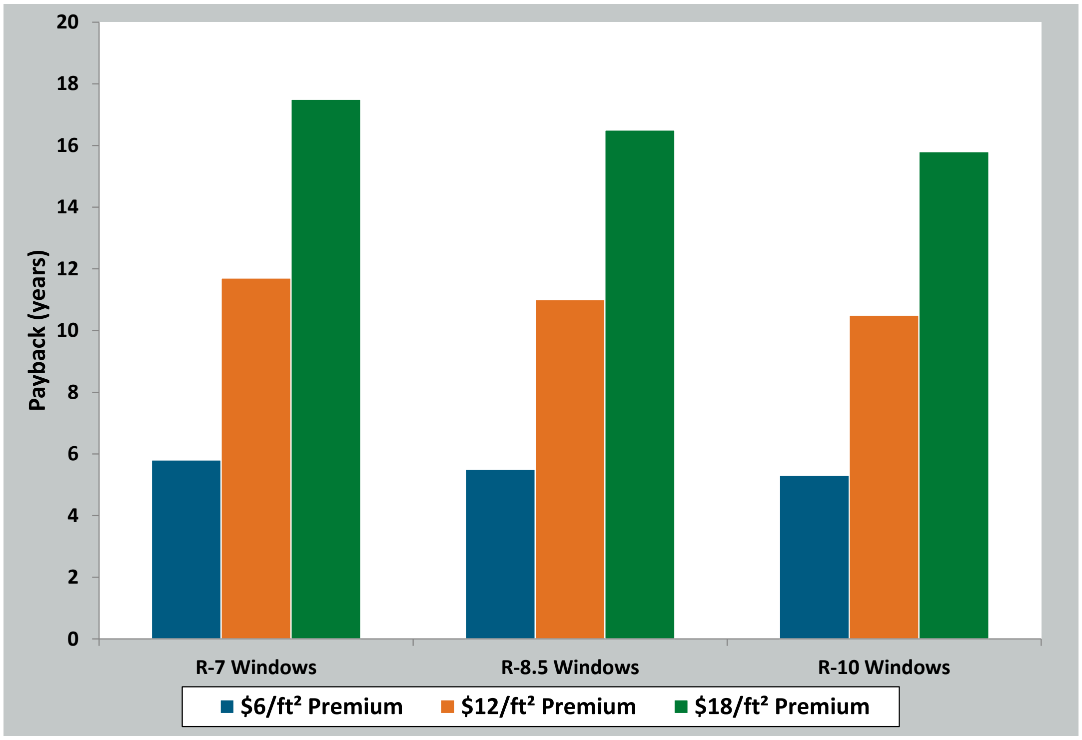


Figure 15. Sensitivity analysis of simple payback time for highly insulating windows (R-7, R-8.5, R-10) in the residential sector

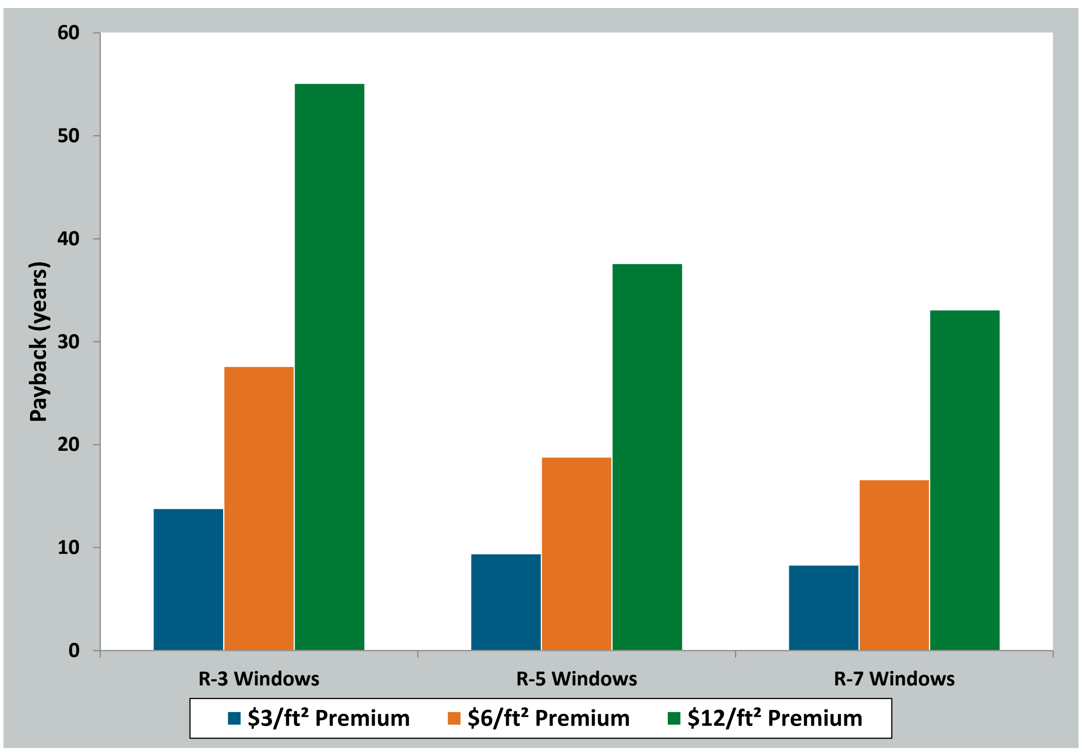


Figure 16. Sensitivity analysis of simple payback time for highly insulating windows (R-3, R-5, R-7) in the commercial sector

Technical Barriers and Challenges

Table 9. Technical Barriers and Challenges to the Development and Cost-Reduction of Highly Insulating Windows

Topic/Barrier		Description
R&D Barriers	Low-cost, inert gases for multilayer insulated glazings	• Krypton is currently too expensive for mass adoption in windows
	Cost-effective, improved performance vacuum insulated glass (VIG)	• Expansion/contraction of interior/exterior lites (i.e., panes of glass) to increase VIG durability
	Novel materials and designs for aesthetically pleasing windows and window films	• Multilayer reflections need to be reduced while controlling glare and maintaining visible light transmittance (V_T) to achieve market-acceptable aesthetics
	Improved performance framing materials	• The R-factor of a highly insulated frame needs to be reduced by a factor of two • Low-cost materials to increase the R value at the glass/frame interface while achieving higher durability and stability specifications • Highly insulating frame technology that meets the North American Fenestration Standard (NAFS-12) governing windows, doors, and skylights (NAFS 2012).
	Performance improvements are needed for existing high-performance technologies	Technologies in need of performance improvements include: • Spacer system for thin center lite triple • Pillars, edge-effect conductivity • Thermal simulation methods (3-D) • Improved durability for soft-coat, low-E coatings
Manufacturing and Scale-Up Barriers	New equipment and manufacturing methods	Innovative and new cost-effective manufacturing methods are needed for: • High-precision automated manufacturing processes capable of handling triple-pane windows with thin glass • Manufacturing processes capable of handling custom-size and large-size windows • VIG manufacturing processes

Market and Deployment Barriers

Table 10. Market and Deployment Barriers to the Adoption of Highly Insulating Windows

Market/Deployment Barrier	Description
Codes and Enforcement	A lack of code enforcement could hinder market deployment. More stringent and regularly enforced building energy codes that support the use of highly insulating (>R-7) windows will drive demand.
Consumer Education	Readily available and easy to understand information must be made available to consumers interested in the latest in energy-efficient window technology.

Table 11. Highly Insulating Windows R&D Technology Roadmap

Topic Description: Highly Insulating Windows

1) Residential Windows: R-10 window with sufficient V_T to provide daylighting, approximately >0.6 based on center-of-glass measurements and a ≤$6/ft^2 projected installed cost premium compared to 2010 standard base windows (R-1.61).
2) Commercial Windows: R-7 window with sufficient V_T to provide daylighting, approximately >0.4 based on center-of-glass measurements and ≤$3/ft^2 projected installed cost premium compared to 2010 standard base windows (R-1.86).

For both the residential and commercial sectors, the weight and thickness of these windows must be comparable to the existing stock of windows to enable retrofits of existing buildings.

	Roadmap Action Plan Activities	Milestones
Near Term (<5 yrs)	• Develop durable VIG materials, such as flexible edge seals • Improve advanced frame materials and designs • Develop multi-pane glazing systems, including non-VIG • Develop a high-performance, low-E coating that can withstand higher manufacturing temperatures • Develop spacer design for triple pane systems with thin glass • Optimize low-conductivity edge seal/pillars • Develop highly insulating translucent panels	• Residential: R-7 window ≤$10/ft^2 projected installed cost premium by 2018 • Commercial: R-5 window ≤$8/ft^2 projected installed cost premium by 2018 • ASTM International/industry standard for durability passed • Commercial and residential window structural requirements met
Mid Term (6 – 9 yrs)	• Optimize durable VIG materials, such as flexible edge seals • Optimize advanced frame materials and designs • Optimize multi-pane glazing systems, including non-VIG • Optimize a high-performance, low-E coating that can withstand higher manufacturing temperatures • Optimize spacer design for triple pane systems with thin glass	• Residential: R-10 window ≤$10/ft^2 projected installed cost premium by 2021 • Commercial: R-7 window ≤$8/ft^2 projected installed cost premium by 2021 • ASTM International/industry standard for durability passed • Commercial and residential window structural requirements met
Long Term (9 – 12 yrs)	• Field demonstrations to prove payback • Scale-up and optimize manufacturing	• Residential: R-10 window ≤$6/ft^2 projected installed cost premium by 2025 • Commercial: R-7 window ≤$3/ft^2 projected installed cost premium by 2025

Benefits and Impacts

Factor	Impact	Description
New Buildings	High	Drive higher use of these products to impact other aspects of building design (e.g., reduced HVAC size daylight optimization)
Retrofit Buildings	High	Energy impacts would not be as high for retrofits as new buildings because retrofits do not always allow capturing of all potential benefits (e.g., HVAC size reduction, daylight capturing). However, the large number of existing buildings may offset that difference on a national or global scale
Industry Competitiveness	High	Manufacturers would strive to improve their product performance in their portfolios to stay competitive
Cost Reduction	High	Residential: The payback period for currently available R-10 windows is estimated at 12 years. Meeting cost reduction targets will reduce payback to 5 years. Commercial: The payback period for currently available R-10 windows or R-7 windows is estimated to be greater than 50 years. Meeting the roadmap cost reduction targets will reduce payback to 8 years.

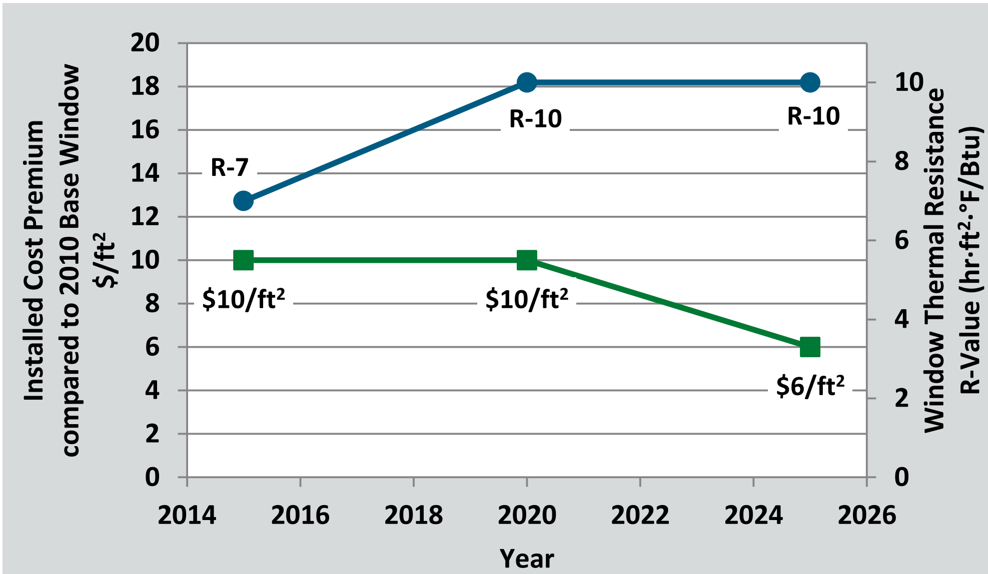


Figure 17. Highly insulating window installed cost and performance targets (residential sector)[23]

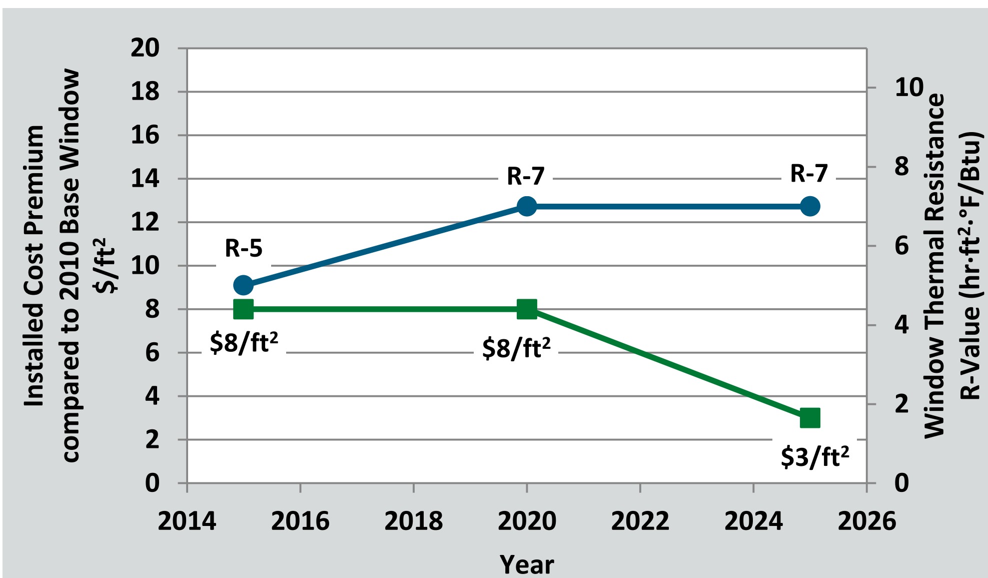


Figure 18. Highly insulating window installed cost and performance targets (commercial sector)[24]

[23] Residential sector highly insulating window: baseline installed cost premium = $29/ft^2. Source: BTO Prioritization Tool, Measure 421. References of all Prioritization Tool measures are located in Appendix C.

[24] Commercial sector highly insulating window: baseline installed cost premium = $29/ft^2. Source: BTO Prioritization Tool, Measure 422. References of all Prioritization Tool measures are located in Appendix C.

Windows High Priority R&D Topic 1: Dynamic Windows or Window Films

Overview

Dynamic window and shade technologies improve window energy performance by adding beneficial solar heat gain in cold climates to offset heating and by reducing solar heat gain in the hot climates to reduce cooling loads. The pioneers in the field of dynamic fenestration systems produce electrochromic and thermochromic windows. For example, SageGlass and View are producing products today on a small scale and thermochromic fenestration technologies from Pleotint and Ravenbrick have also recently become commercially available. However, today's state-of-the-art dynamic fenestration systems are too expensive for mass adoption in either the commercial or residential sectors. While improving the performance of these dynamic systems is desirable, it is critical to drastically reduce the installed cost by focusing on materials cost, improved manufacturing processes, and the ease of installation.

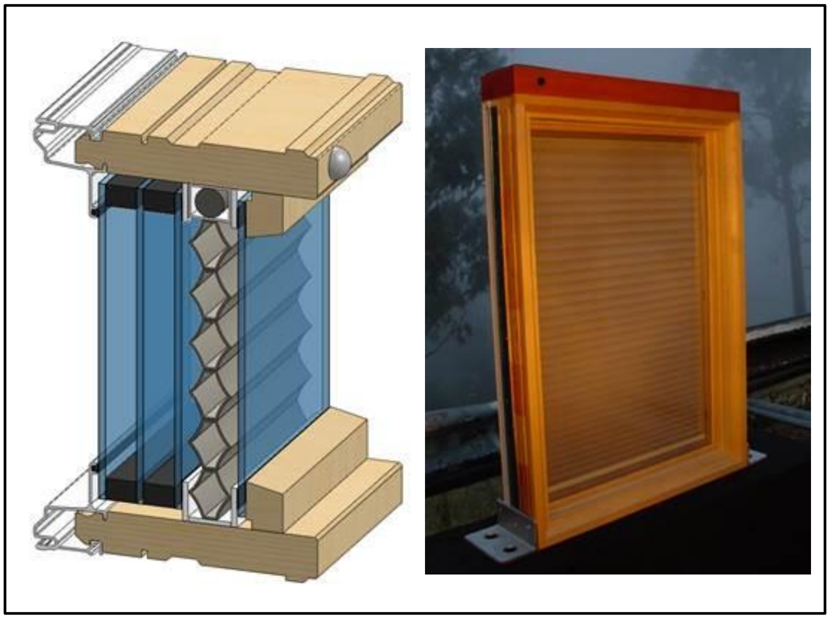


Figure 19. Highly insulating, dynamic windows with automated shading, schematic diagram (left) and prototype (right) (images courtesy of LBNL)

Recent advances in materials science and chemistry have led to the investigation of dynamic window films that can be used to retrofit existing fenestration or can be incorporated into IGU manufacturing (Environmental Energy Technology Division 2012; ITN Energy 2013; Office of the Vice President 2011). Similarly, these new chemistries allow dynamic window functionality to be incorporated into existing glass or IGU manufacturing lines, reducing capital investment for manufacturers, and reducing risks.

Automated energy-efficient window attachments, such as those that are insulating and reflective, are competitive with dynamic windows in that they are also capable of modulating solar heat gain to offset heating and cooling loads. BTO internal analysis presented in Chapter 2 shows that today's manually operated insulating and reflective interior window attachments are cost effective for residential buildings. Exterior window attachment technologies also have great potential for energy savings. Energy-efficient window attachment technologies do not require government R&D investment into next-generation technologies, but instead would benefit from efforts to drive the market towards increasing adoption.

Recently, BTO has used prioritization tool analysis to identify the value proposition from an energy savings potential perspective for dynamic window technologies across the building sector. Electrochromic windows with a $\Delta SHGC \sim 0.4$ ($SHGC_{bleached} = 0.46$ to 0.47 and $SHGC_{tinted} = 0.09$) represent today's state-of-the-art dynamic window technologies.[25] While there are commercially (or near commercially available) dynamic window technologies that are able to hit the performance targets for replacement windows, there are no dynamic window film technologies on the market that can do so. Window films are particularly appealing for retrofitting existing buildings, particularly in hot climates that are dominated by cooling loads.

BTO prioritization tool analysis shows that today's state-of-the-art electrochromic windows have the potential to save 1,222 and 724 TBtu from the residential and commercial sectors by 2030, respectively, if all the windows in new and existing buildings are replaced, regardless of the cost of the windows. This accounts for the energy savings achieved from the $\Delta SHGC$ as well as possible improvements in the window R-value, not accounting for additional savings from daylighting.[26] Approximately 61% of the technical savings potential is the result of increasing the R-value in the window to approximately 3, achievable with double glazing with low-E, and 39% of the savings is from the $\Delta SHGC$. The most impactful energy savings market for dynamic window technologies (relative to static windows with similar insulating properties) is in hot climates where solar heat gain through windows contributes to 1.14 and 1.38 quads of lost space cooling energy in the residential and commercial sectors, respectively. Note that energy savings from daylighting technologies can be especially large in commercial buildings because recent changes to building energy codes now require automatic daylight controls in many more spaces.

The R&D target for dynamic windows or window films is the development of a technology that is either actively or passively controlled with a V_T in the bleached state > 0.6 for the residential sector and > 0.4 for the commercial sector. The V_T in the bleached state for a double pane IGU with state-of-the-art dynamic window technologies is approximately 0.6.[27] As for highly insulating windows, the V_T targets for dynamic windows are guidelines intended to provide sufficient daylighting. In the case of the commercial sector, it is extremely difficult, if not impossible, to achieve both $V_T = 0.4$ and $\Delta SHGC = 0.4$. We expect to require $V_T > 0.4$ in order to achieve the $\Delta SHGC > 0.4$. However, BTO is interested in technologies with comparable energy savings and market penetration in the commercial sector that can be achieved with $\Delta SHGC < 0.4$ and $V_T \leq 0.4$. The R&D energy savings performance target is mostly unchanged relative to the state-of-the-art performance ($\Delta SHGC > 0.4$). Instead, the focus of R&D for dynamic windows and window films is on installed cost reductions. The R&D cost target is $\leq\$8/ft^2$ and $\leq\$2/ft^2$ installed cost premium (at scale) over a standard IGU installation for dynamic windows and

[25] View Dynamic Glass panes are available with SHGC ranging from 0.09 to 0.46 (viewglass.com/pdf/IGU_DataSheet_US.pdf), while SageGlass panes are available with SHGC ranging from 0.09 to 0.47 (glassolutions.co.uk/sites/default/files/products/documents/SageGlass%20Product%20Guide.pdf).
[26] The energy savings for dynamic windows includes savings from SHGC and from an improvement in the window R-value from a base value of 1.61 (1.86 for commercial windows) to an R-value over 3.
[27] View Dynamic Glass panes are available with V_T in the bleached state equal to 0.58 (viewglass.com/specifying-your-dynamic-glass.php), while SageGlass panes are available with V_T in the bleached state equal to 0.62 (sageglass.com/sageglass/double-pane-glazing/).

window film technologies, respectively. BTO internal analysis shows that achieving the R&D roadmap installed cost target of $<\$8/\text{ft}^2$ premium over existing IGUs, including the cost of sensors and controls, for dynamic windows reduces the payback periods to a minimum of 10 years for new residential buildings and a maximum of 22 years for new commercial buildings. Similarly, achieving the R&D cost target of $\leq\$2/\text{ft}^2$ installed cost premium for dynamic window films leads to a reduction in the payback period to 7 and 21 years in the residential and commercial building sectors, respectively. Note that the dynamic windows and window film targets discussed herein do not prescribe whether the technologies operate by electrochromic, thermochromic or other mechanisms. The technical and market barriers to achieving the cost and performance targets for dynamic windows are discussed below.

Technical Barriers and Challenges

Table 12. Technical Barriers and Challenges to the Development and Cost Reduction of Dynamic Windows or Window Films

Topic/Barrier		Description
R&D Barriers	Improved materials performance	• Color control in visible- and low-contrast ratio in the infrared (IR) • Spectral and thermal truncation • Glare mitigation • Switching speed (particularly to reach fully dark [block-out])
	Materials cost reductions	• Transparent, conducting materials (e.g., transparent conducting oxides such as indium tin oxide) • Photovoltaics, batteries, and actuators to improve the ease of installation of electrochromic technologies
	Daylighting performance improvement	• Solar hear gain modulation without adverse impacts on daylighting • Ability to redirect or reflect, not absorb, light to reduce thermal damage in window and surrounding structures

	Coating manufacturing processes	• Reduce cost of glazing coating processes
		  ○ Coatings with improved yields, durability, and quality
		  ○ Faster deposition methods
		  ○ Alternatives to indium tin oxide

	Customized product manufacturing at high throughputs	• Ability to produce fabricator-friendly products that are adaptable to a range of sizes. • Lacking mass production technologies (homogenizes electric field, reduced irising) for electrochromic materials

Market and Deployment Barriers

Table 13. Market and Deployment Barriers to the Adoption of Dynamic Windows or Window Films

Market/Deployment Barrier	Description
Cost	High upfront costs are dependent on overcoming materials constraints and close integration with existing value channels in the fenestration industry.
Acceptance	Architect, fabricator, and consumer acceptance will be critical to market deployment. Consumer adoption is dependent on the integration of wireless devices for each window with manual override capabilities and the integration with operable window designs.
Lack of Standardization	Dynamic window technology needs to be standardized in order for consumers to make more informed decisions. Testing and certification costs are a barrier to broader standardization.

Table 14. Dynamic Window and Window Film R&D Technology Roadmap

Topic Description: Windows or window films capable of automatically modulating solar heat gain with installed cost premium targets of ≤$8/ft^2 and ≤$2/ft^2 for windows and window films, including sensors and controls, over a standard IGU. Performance targets for both windows and window films are ΔSHGC > 0.4 with V_T bleached state >0.6 for the residential sector and >0.4 for the commercial sector. V_T targets are guidelines and are intended to be sufficient for daylighting.

	Roadmap Action Plan Activities	Milestones
Near Term (<5 yrs)	• Identify abundant, low-cost materials with low contrast, high ΔSHGC, V_T in the clear state sufficient for daylighting and fast switching speeds • Identify low capital production equipment and low-cost manufacturing processes • Achieve smart automation for active dynamic solutions (automated home energy monitoring) • Realize a non-hard-wired power solution for retrofits	• Dynamic windows: Demonstration of bench-scale dynamic window (ΔSHGC >0.4 with V_T sufficient for daylighting) manufacturing process at installed costs ≤$25/ft^2 (including sensors and controls) • Dynamic window films: Demonstration of bench-scale dynamic window film (ΔSHGC >0.4 with V_T sufficient for daylighting) manufacturing process with projected installed costs ≤$15/ft^2 (including sensors and controls)
Mid Term (6 – 9 yrs)	• Improve performance of next-generation materials • Develop next-generation production and manufacturing processes • Collaborate with the Institute of Electrical and Electronics Engineers to develop wireless communication protocol	• Dynamic windows: Demonstration of dynamic window (ΔSHGC >0.4 with V_T sufficient for daylighting) manufacturing process for areas >10 ft^2 with a projected installed cost premium ≤$15/ft^2 compared to a standard IGU (including sensors and controls) • Dynamic window films: Demonstration of dynamic window film (ΔSHGC >0.4 with V_T sufficient for daylighting) manufacturing process for areas >10 ft^2 with a projected installed cost premium ≤$8/ft^2 compared to a standard IGU (including sensors and controls)
Long Term (9 – 12 yrs)	• Integrate window with energy storage, energy generation and control technologies • Achieve complete control of visible to near-IR electromagnetic spectrum	• Dynamic windows: Dynamic window (ΔSHGC >0.4 with V_T sufficient for daylighting) manufacturing process demonstrated for areas >30 ft^2 with a projected installed cost premium ≤$8 ft^2 compared to a standard IGU (including sensors and controls) • Dynamic window films: Window film (ΔSHGC >0.4 with V_T sufficient for daylighting) manufacturing process demonstrated for areas >30 ft^2 with a projected installed cost premium ≤$2/ft^2 compared to a standard IGU (including sensors & controls)

Benefits and Impacts

Factor	Impact	Description
New Buildings	High	Market driver through increased sales, especially if required by code
Retrofit Buildings	Medium	Dependent on capacity for wiring or availability of wireless solutions, window films will be more impactful in the retrofit space than replacement windows
Industry Competitiveness	High	Dynamic solutions are the next-generation solution, but they must be competitive domestically, otherwise other countries will seize technology leadership
Cost Reduction	High	The high cost of the state-of-the-art technology is the largest market barrier for dynamic window technologies. For residential buildings, present-day dynamic window payback period is estimated at 26 to 33 years. Meeting cost reduction targets will reduce payback to 10 to 12 years. For commercial buildings, present-day dynamic window payback period is estimated at 57 to 61 years. Meeting cost reduction targets will reduce payback to 21 to 22 years.

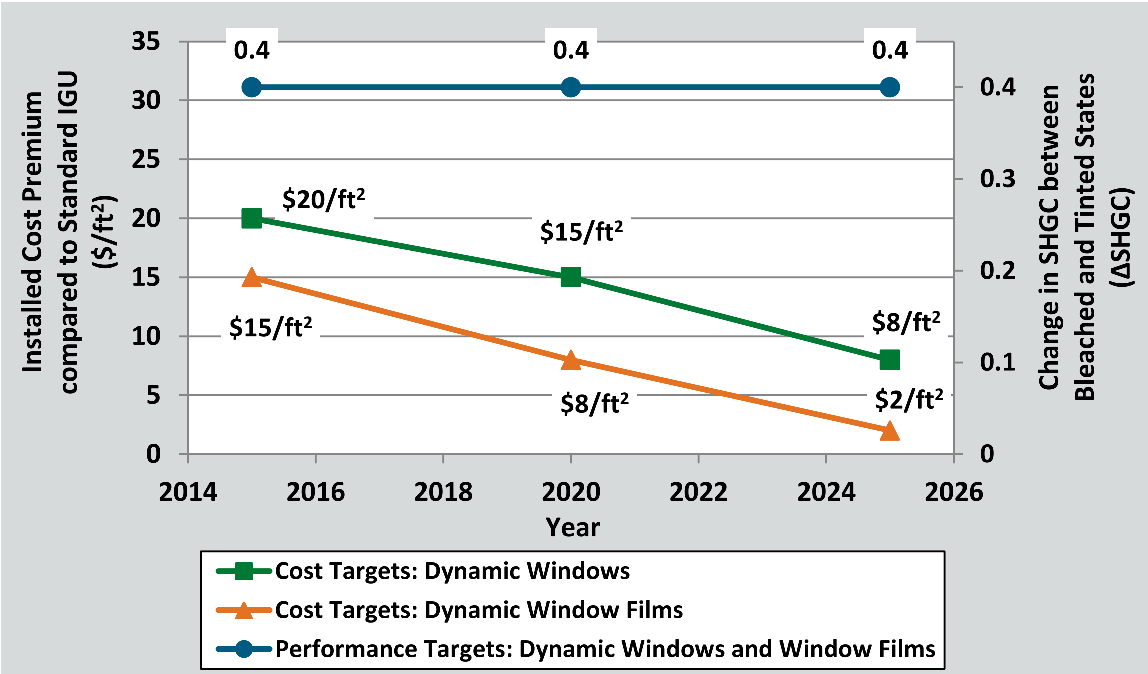


Figure 20. Dynamic window and window film installed cost and performance targets[28,29]

[28] Dynamic windows: baseline installed cost premium = $22/ft^2. Source: BTO Prioritization Tool, Measures 889, 890, 891, 892. References of all Prioritization Tool measures are located in Appendix C.

[29] Dynamic window films: cost of an insulating and reflective window attachment = $13/ft^2. Source: BTO Prioritization Tool, Measure 575, 576. References of all Prioritization Tool measures are located in Appendix C.

Windows High Priority R&D Topic 2: Visible Light Redirection

Overview

Window light redirection technology has the potential to reduce energy consumed for interior lighting in some types of commercial buildings. BTO internal analysis shows that existing daylighting technologies, such as light louvers and tubular daylighting devices, have a technical potential to save 345 TBtu in the commercial sector when integrated with lighting controls.[30] Market penetration of these devices is currently limited in part because of aesthetic issues. Next-generation light redirection technology distributes light into the interior of the building and provides shade when appropriate. The use of spectral coatings allows for further control of the amount of light and solar heat that penetrates through the window. Summer months, with high sun angles, allows less heat into buildings, while in winter months, with low sun angles, the light redirection technology allows both light and heat in.

The targeted outcome of R&D is a technology to reduce lighting energy by 50% for a 50-ft. floor plate, at an installed cost premium of ≤5/ft^2 over a typical window/blind installation (including the cost of lighting controls[31]). This will require new materials and simulation tools for product evaluation (e.g., glare and system integration). Daylighting technologies must be integrated with lighting controls to save energy. The R&D roadmap for a cost-competitive visible light redirection technology that can be widely deployed is shown in Table 17.

Figure 21. Picture of LightLouver unit product (left), interior view of Caltrans District 3 Headquarters atrium with LightLouver installed on clerestory windows (right). Visible light redirection technology intercepts and redirects sunlight onto the ceiling or deep into the interior of the building, reducing glare and electric lighting and mechanical cooling requirements.[32] (image courtesy of LBNL)

[30] Energy savings based entirely on lighting load.
[31] The cost of lighting controls, which is not the focus of R&D, is included in the cost target because daylighting technologies will only save energy if the lights get turned off.
[32] More information on the LightLouver product can be found at lightlouver.com/uploads/LightLouver_lunch_and_learn.pdf.

Technical Barriers and Challenges

Table 15. Technical Barriers and Challenges to the Development of Commercial Windows with Visible Light Redirection

Topic/Barrier		Description
R&D Barriers	Lack of new, cost-effective materials	• Deep light redirection efficiency at low cost and without glare is needed • Materials for dynamic controls are lacking (redirection, visible transmittance)
	Limited computational and experimental evaluation tools	• Demonstration to determine energy-savings impact versus season and time of day and appropriate integration with building controls and operation • Demonstration of market-acceptable performance with respect to glare and appearance of films
Manufacturing and Scale-Up Barriers	Development of cost-effective processing	• High-volume patterning processes • High-quality, thin-film coating technology

Market and Deployment Barriers

Table 16. Market and Deployment Barriers to the Adoption of Commercial Windows with Visible Light Redirection

Market/Deployment Barrier	Description
Architect Acceptance	Window aesthetics (e.g., quality of vision area), demonstration/assurance of performance, architectural flexibility, applicability to retrofit, and new construction will drive adoption
Occupant Acceptance	Cost, comfort, and aesthetics all impact consumer acceptance
Codes and Standards	Codes on daylighting are still developing and adoption and implementation will take time. ASHRAE 90.1-2010 has mandatory daylighting requirements for some spaces, and this requirement is being expanded in ASHRAE 90.1-2013 and the 2015 IECC. Daylighting requirements are also included in the green construction codes (ASHRAE 189.1-2011 and the 2012 International Green Construction Code), but adoption of these standards has been slow.

Table 17. Visible Light Redirection R&D Technology Roadmap

Topic Description: Reduce lighting energy use by 50% for a 50-ft floor plate with a projected installed cost premium of ≤$5/ft^2 over a typical window and blind installation (including the cost of lighting controls).

	Roadmap Action Plan Activities	Milestones
Near Term (<5 yrs)	• Develop light redirection materials research • Optimize simulation tools (product evaluation) • Demonstrate technology integration potential • Identify low capital production equipment and low-cost manufacturing processes	• Demonstrate a 25% lighting energy reduction with lab scale prototype • Simulations that demonstrate that prototype can achieve savings over a 25-ft floor plate with glare control (no downward daylight) • Macro-scale solution simulation capability to demonstrate micro- and macro-scale solutions • Manufacturing process demonstrated for areas >10 ft^2 at a projected installed cost premium of ≤$20/ft^2 (including for the cost of lighting controls)

Mid Term (6 – 9 yrs)	• Conduct prototyping and testing • Conduct initial prototype scale-up to areas larger than 10 ft^2 • Develop simulation tools (glare, system integration)	• Demonstrate a 35% lighting energy reduction with lab-scale prototype at >10 ft^2 • Simulations and experimental data that prototype can achieve savings over a 50-ft floor plate with glare control (no downward daylight)
Long Term (9 – 12 yrs)	• Achieve scale-up of potential new solutions • Optimize solutions with a combination of controls, dynamic solutions, and other approaches	• 50% potential lighting energy reduction for a 50-ft floor plate with glare control (no downward daylight) demonstrated in field tests • Dynamic panel manufacturing process demonstrated for areas >30 ft^2 at a projected installed cost premium of ≤$5/$ft^2$ (accounting for cost of lighting controls necessary to achieve 50% savings)

Benefits and Impacts

Factor	Impact	Description
New Buildings	High	Maximum likelihood of new buildings designed to take full advantage of the daylight redirecting solutions.
Retrofit Buildings	Medium	A subset of all existing building stock will benefit from a daylight redirecting retrofit, higher burden on lighting controls to dim or turn off electric lighting to claim benefit.
Industry Competitiveness	High	Daylight impacts occupant productivity and sense of well-being. Real estate owners will adopt redirection technology to reduce operating costs, but also to attract and retain tenants.
Cost Reduction	High	Increased market penetration is dependent on substantial cost reductions. Meeting the cost reduction target will reduce payback from 10 to 5 years.

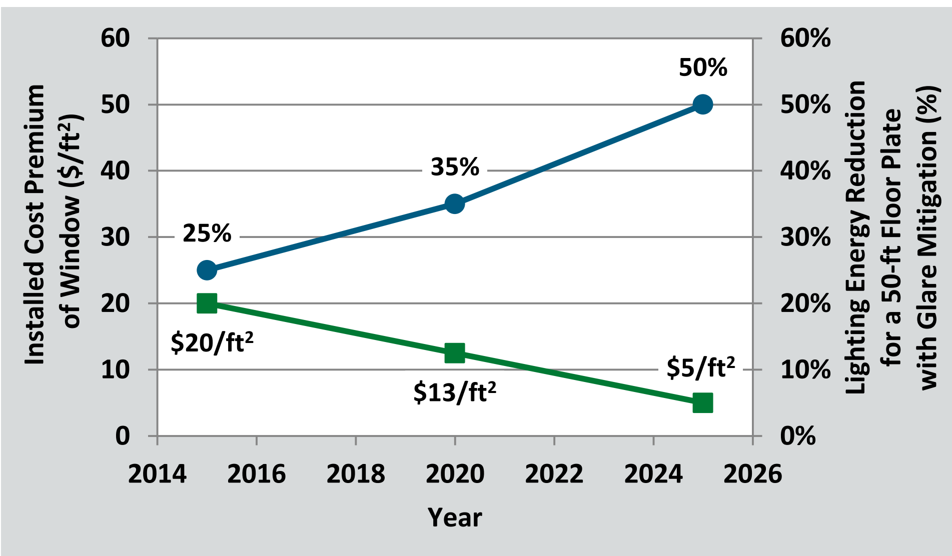


Figure 22. Visible light redirection technologies installed cost and performance targets

Early-Stage R&D Topic: Dynamic Windows with Energy Harvesting

Overview

In addition to the window technologies discussed earlier in this chapter, other less-mature emerging technologies have great potential for high impact and large energy savings if and when they are commercialized; however, associated with that potential are longer investment timelines and a greater technical risk. One such early-stage technology is discussed in more detail below.

Dynamic window performance has typically been defined as the dynamic control of solar transmittance, glare, solar gain, and daylighting at any time to manage energy, comfort, and view. However, dynamic windows may also be able to be augmented with energy harvesting technology (Chun-Chao 2012).

The targeted outcome for R&D on dynamic window energy harvesting is a technology with a power conversion efficiency (PCE) of 10% with the same performance goals for dynamic windows in the Dynamic Windows and Window Films section above. R&D will focus on new materials, packaging, and ensuring ease of integration (including electronic systems). Barriers to technology development are shown below and the R&D roadmap for this technology is shown in Table 20.

Technical Barriers and Challenges

Table 18. Technical Barriers and Challenges to the Development of Dynamic Windows with Energy Harvesting

Topic/Barrier		Description
R&D Barriers	Materials chemistry	• Materials chemistry issues (e.g., simple synthesis, achieving high-quantum efficiency) to be resolved for material cost-reduction and performance improvement gains
	Conductive materials	• High-performance electrolytes (conductivity) and robust active PV components (TCO and active layer transparency) are needed
	High system costs	• Low-cost, invisible interconnection schemes • Packaging and integration with highly insulating windows
	Durability	• Polymer degradation issues lead to lifetime, durability, and cycling concerns (Jorgensen 2008)
Manufacturing and Scale-Up Barriers	High manufacturing costs	• Manufacturing process needs to achieve defect tolerance with minimal resistive losses • Cost-effective, high-yielding production at a large scale
	Assuring quality and performance	• High visible transmittance (V_T >0.6 for residential sector and V_T >0.4 for commercial sector) without distortion.

Market and Deployment Barriers

Table 19. Market and Deployment Barriers to the Adoption of Dynamic Windows with Energy Harvesting

Market/Deployment Barrier	Description
Window Aesthetics	V_T >0.6 for residential sector and V_T >0.4 for commercial sector with power generation capability
Balance of System Costs	Opportunity to reduce BOS cost by coupling power generation capability to dynamic windows, automated window attachments, or sensors

Table 20. Dynamic Window with Energy Harvesting R&D Technology Roadmap

	Roadmap Action Plan Activities	Milestones
Topic Description: Dynamic windows with energy harvesting technology (e.g., transparent PVs or switchable dye PVs), with 10% PCE and a 10-year lifetime		
Near Term	• Develop proof-of-concept lab work for light-harvesting with other dynamic window functions (e.g., color change, switching, etc.) • Develop materials for the active layer, TCO, and electrolytes • Prototype packaging and simulations for orientation and installation	• PCE: 5% lab scale (3 in by 3 in glass sample) • Power buffering electrons • Aesthetics: V_T >50%–60% or selective color (delta change transmittance 40%) • Prototype with (ΔSHGC)*(V_T clear state) = 0.3 with V_T clear state >0.55
Mid Term	• Scale lab and work to larger areas • Develop solar harvesting laminates (e.g. flexibility) • Optimize packaging and ease of integration (retrofit, framing sizes, circuit design) • Integrate electronic systems (e.g., battery, super capacitor, and room framing)	• PCE: 8% lab scale (3 in by 3 in glass sample), 5% PCE scaled to 1 ft^2 glass sample • Durability: lifetime target of 5 years • Scalability: 1–2 ft^2 • Simultaneous heat gain and aesthetics with V_T >75%
Long Term	• Scale to full window sizes • Deploy more stringent codes for energized surfaces, certificates, and standardized testing	• PCE: 10% lab scale (3” by 3” glass sample), 8% PCE scaled to full window • Durability: lifetime target of 10 years • Scalability to full window size

4. Roadmap for Emerging Building Envelope Technologies

Priority R&D Topics Summary

Improving building energy performance will require R&D to produce cost-effective building envelope technologies such as insulating materials and air-sealing system technologies. To enable mass market adoption, these next-generation technologies must maintain or improve building enclosure durability, including moisture, fire, indoor air quality, acoustic, and structural requirements. In the case of retrofitting existing buildings, the installation must be fast and easy so that there is minimal impact on building occupants. The focus of this roadmap report is to accelerate these R&D efforts.

Table 21. Residential and Commercial Building Envelope Priority Research Topics

Technology Description	Target Sector(s)	2025 Cost Target[33]	2025 Performance Target
Highest Priority R&D Areas			
Building envelope material	Commercial and Residential Sectors	Projected installed cost premium ≤\$0.25/ft^2, including insulation material and associated labor, assuming an R-12/in performance to enable a payback period less than 10 years.	Building envelope thermal insulation material with R-value ≥R-12/in that can be added to walls to retrofit existing buildings and can also be applicable to other portions of the building enclosure (e.g., reduce the impact of thermal bridging between building components). The material must meet durability requirements and minimize occupant disturbance.
Air-sealing technologies (systems-level approach)	Commercial and Residential Sectors	Projected installed cost ≤\$0.5/ft^2 finished floor (25% of current average costs, including mechanical ventilation costs).	A system capable of concurrently regulating heat, air, and moisture flow to achieve the following performance specifications. • Residential sector: <1 ACH50 • Commercial sector: <0.25 CFM75/ft^2 (5-sided envelope)
High Priority R&D Area			
Highly insulating Roofs	Commercial Sector	Projected incremental cost increase ≤\$1/ft^2 compared to standard roof costs	An energy use reduction equivalent to doubling current ASHRAE R-values

Taking into consideration traditional development schedules, wall and roof R&D topics will need to be identified and initiated in the near term so that technologies are ready for mass-market adoption by 2030. These technologies will need to be applicable to retrofitting existing buildings in order to have the greatest energy savings impact, but can also be applicable to new construction. The R&D topic areas listed in Table

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33 Cost targets in this report are quantified in order to provide a viable critical pathway from current technology R&D status to a cost target that, at scale, will facilitate mass-market technology adoption.

21 apply to the entire building envelope space (applicable to both residential and commercial) and are anticipated to have the largest potential for energy savings. They will be expounded in more detail individually. When appropriate, topics that focus on the residential or commercial space are noted.

Table 2 shows the energy lost from heating and cooling for opaque building envelope components (walls, roofs, and foundations) and infiltration in 2010 and projected for 2035. In 2010 the largest contributors to heating energy loss in the residential and commercial sectors were infiltration (residential: 2.26 quads, commercial: 1.29 quads) and walls (residential: 1.54 quads, commercial: 1.48 quads). Overall, the space cooling energy lost for the opaque portions of the envelope is less substantial than the space heating energy loss in both the residential and commercial sectors. In the residential sector, infiltration accounts for the greatest space cooling loss (0.59 quads), followed by roofs (0.49 quads). Overall, the data in Table 2 show that walls and infiltration are the most substantial contributors to energy losses in both sectors.

Table 22. Roadmap Target Prioritization Tool Analysis Results for Building Envelope Technologies, Including Thermal Insulation Materials, Air-Sealing System Technologies, and Commercial Roofing Technologies

Building Envelope Technologies					
Roadmap Target Technology Description	Market Size[34] (TBtu)	Technical Potential[35], 2030 (TBtu)	Unstaged Max Adoption Potential[36], 2030 (TBtu)	Payback in 2030 (years)	Prioritization Tool Measure Number[37]
Building Envelope Material					
R-12/in building envelope thermal insulation material, with an installed cost premium ≤$0.25/ft^2 (R)	1,610	836	267	3.2	658
Air-Sealing Technologies (systems-level approach)					
Air-sealing systems that reduce air leakage to <1 ACH50 at a cost of ≤$0.5/ft^2 finished floor (R)	1,768	1,591	1,591	1.7	856
Air-sealing systems that reduce air leakage to ≤0.25 CFM75/ft^2 (5-sided envelope) at a cost of ≤$0.5/ft^2 (C)	982	805	805	2.7	834
Roofs for Commercial Buildings					
Highly insulating roof that doubles the R-value of existing ASHRAE standards with incremental cost increase ≤$1/ft^2 compared to standard roof costs (C)	257	129	129	12	741

Table 22 summarizes the BTO PT analysis for building envelope technologies, including building envelope materials, air-sealing technologies, and roofs. For building envelope materials, the roadmap target does not specify which wall surface the insulation material should be applied to, i.e., the insulation

[34] Market Size represents the energy consumption associated with a building component (e.g., windows), within a particular buildings market segment (e.g., commercial, residential, new or existing buildings).

[35] Technical Potential assumes existing stock is immediately replaced with the new measure. The technical potential represents the theoretical maximum energy savings available if the technology is implemented in the U.S. buildings sector (free of practical constraints such as financing and deployment considerations).

[36] Unstaged Maximum Adoption Potential (TBtu) assumes a ‘stock and flow’ model accounting for unit replacement, elimination or addition. The unstaged maximum adoption potential represents the energy savings that would result if the technology is deployed only for all end-of-life replacements and new purchases.

[37] Detailed sources for each measure number are shown in Appendix C.

material may be added to either the internal or external surface of the walls. However, the roadmap target is specifically focused on adding insulation to existing buildings, rather than new buildings.

The data from Table 22 is illustrated graphically in Figure 24, which shows technical potential and unstaged maximum adoption potential for the building envelope technology roadmap targets. This figure clearly shows air-sealing systems have the greatest potential to save energy with a combined technical potential of 2,396 TBtu in the residential and commercial sectors. Figure 25 compares the projected payback period of the roadmap target technologies with the existing baseline technologies. As illustrated in this figure, the technology with the greatest reduction in payback period is the R-12/in. thermal insulation material (which is compared against a baseline payback period that results from installing exterior insulation finish system (EIFS) technology, PT measure #660).

Figure 23. The VIP in the foreground has an R-value three times higher than the fibrous batt insulation in the background at one-third the thickness.

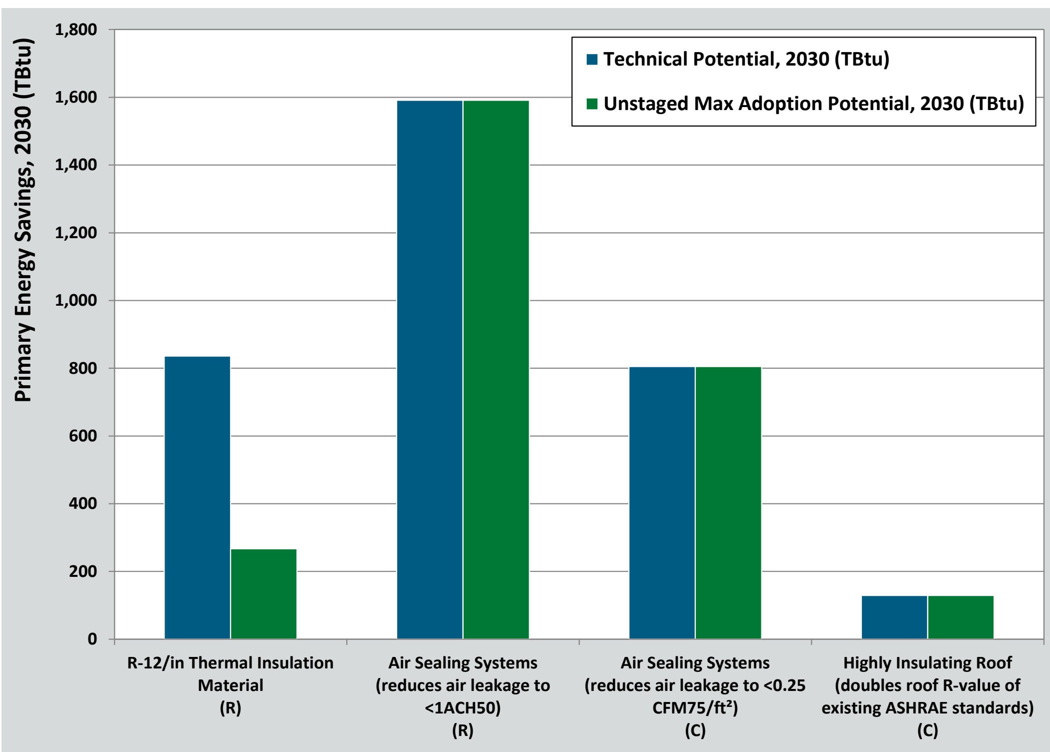

Figure 24: Prioritization tool analysis results for building envelope technologies roadmap targets, including thermal insulation, air-sealing, and roof technologies

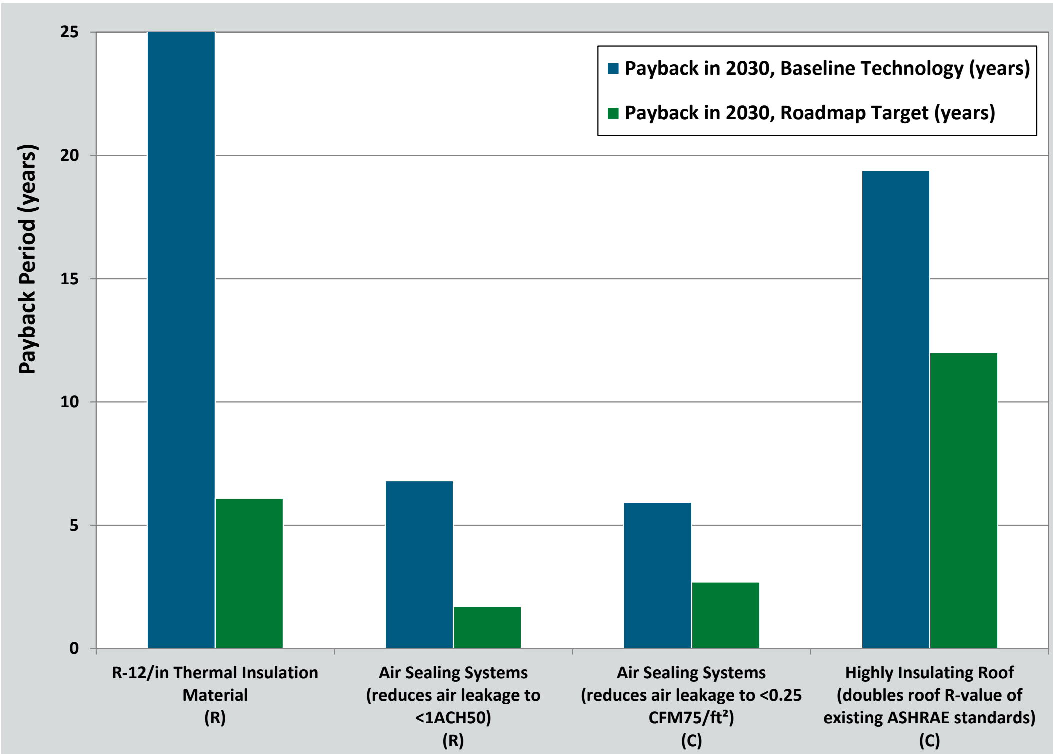

Figure 25: Comparison of payback periods for baseline technologies and technologies that achieve the roadmap cost and performance targets[38]

[38] The baseline technology for roofs is increased non-cool roof insulation for new commercial buildings.

Barriers for Next-Generation Building Envelope Technologies

The commercial and residential building sectors often have unique markets and consumers, which must be understood and analyzed in parallel with technology development to accelerate market penetration. Key barriers and challenges for next-generation building envelope technologies are summarized below:

Commercial Building Envelope

- **Envelope materials that enable smooth transitions between functional areas (roof and walls) to ensure high-level performance** – The composition/makeup of roof systems are often much different than wall materials. As such, the joints are abrupt, leading to thermal bridges and undesirable aesthetic characteristics, especially in large commercial buildings. Sealing between these envelope functions can be difficult during construction and often impossible during retrofits. As such, the development of envelope materials that can function both as walls and roofs is greatly desired to enable architecturally acceptable air seals between the roof and the walls.
- **Inadequate building design and diagnostics tools** – Computational tools are critically important for the design and construction of commercial buildings with energy-efficient envelope materials. As new technologies are developed, models and simulation tools must be updated to account for increased performance and durability. This is discussed in more detail in Chapter 5.
- **Lack of measurement technique for infiltration measurements in large-commercial buildings** – While blower door tests can be used to assess infiltration in residential buildings, no analogous technology exists for large-commercial buildings. As a result, commercial building codes do not include infiltration.

Residential Building Envelope

- **Lack of clear performance criteria and metrics** – As residential building envelope technologies are developed and put into service, it is often challenging to clearly define certain performance criteria, particularly in ways that are easily understood by homeowners. For example, building material durability, specifically moisture tolerance, and occupant comfort are both lacking metrics to adequately evaluate. The ability to easily verify cost metrics is also more challenging in this topic than others because of variations in existing residential buildings.

Figure 26. Fibrous glass loose fill insulation installed in a test attic in a climate simulator just prior to evaluating its R-value.

Crosscutting Commercial and Residential Building Envelope

- **Quick and easy building envelope retrofit solutions** – Energy-efficiency retrofits of commercial and residential buildings must be performed quickly. Commercial sector building occupants cannot afford to shut their business down and lose business for days or weeks. This effectively increases payback time for energy-efficiency measures. Similarly, consumers in the residential sector are more likely to perform energy-efficiency upgrades that do not disrupt their lives by requiring extensive construction. Building envelope retrofits that can be accomplished in less than 2 days also reduce labor costs, the most substantial cost driver for most building envelope retrofits.
- **Costly and complex installation methods –** The installation of building envelope technologies are dominated by labor costs associated with complex installation methods that are low-tech and generally done on a case-by-case basis. Novel manufacturing and installation methods that could reduce onsite installation costs have the potential to change the cost structure and reduce the overall installation cost for building envelope upgrades, specifically for existing buildings. Additionally, complicated construction reduces the speed at which buildings or building components can be erected and installed, which increases the possibility of installation errors that can negate any efficiency gains achieved from using advanced materials. High-quality standardized construction subcomponents (e.g., plug-and-play panels) may help reduce installation time and costs, as would the increased use of non-intrusive and non-destructive retrofit installation approaches. Furthermore, if materials and products can be developed with a high tolerance for error in installation, installation requirements can be less stringent and costly.
- **Lack of standardized test methods for evaluating envelope materials' performance metrics over service life for R-values, energy-efficiency performance, and other factors** – While there are a number of ASTM International standards for the evaluation of envelope assemblies, there is always a need to develop methods that better predict and confirm the behavior/performance of envelope material during a typical service life (ASTM 2013; TC 4.4 2013). That performance profile can be used to more accurately estimate the potential energy savings and other metrics as they relate to the envelope system.
- **Impractical performance verification of air and moisture infiltration/exfiltration** – The uncontrolled exchange of heat, air, and moisture are constant phenomena in building structures and significant influences on building energy consumption, as shown quantitatively in Table 2 (Woloszyn 2008). Existing flow verification measurement methods and tools need improvement before viable infiltrations/exfiltrations can be realized. The increased use of prescriptive packages may help show performance proof without having to consistently re-measure. In particular, there is also a great need for low-cost/no-cost uncontrolled heat and mass-flow diagnostics (e.g., test methods and characteristics).

Building Envelope Highest Priority R&D Topic 1: Envelope Insulation Material

Overview

A primary function of building insulation material is to control the flow of heat across the structure. More energy is lost through walls than any other building envelope component. Specifically, as shown in Table 2, 1.54 and 1.48 quads of space heating energy was lost through walls in the residential sector and commercial sectors, respectively, in 2010. Similarly, 0.34 of space cooling energy was lost through walls in the residential sector. Similar trends are projected for 2035. As a result, in order to have the greatest impact on energy savings, next-generation building envelope insulation materials must be applicable to walls and would ideally also be applicable to other parts of the envelope, such as the roof and foundation, both to increase the energy savings impact at a component level, but also increase energy savings by reducing thermal bridging when integrated throughout a building. The roadmap target does not specify which surface the insulation material should be applied to, i.e., the insulation material may be added to either the internal or external surface of the walls. In the design of new envelope systems to meet long-term goals, a holistic approach needs to be considered in order to achieve the desired energy, performance, and dimensional expectations. In particular, novel energy-efficient building envelope materials (i.e. with high R-values) that are designed to be simultaneously durable (structural, fire, and ultraviolet and moisture resistance) and energy efficient. Also desired, though at an earlier stage of development, are materials with dynamic properties (e.g., resistivity) to transfer heat or moisture and materials that are responsive to a variety of external conditions. For example, advanced polymeric material systems (e.g., fibers) could replace thick film systems. The development and adoption of any of these high-performance materials will require low-cost manufacturing processes and, to ensure wide-spread technology adoption, should enable fast and low labor-cost installation methods.

BTO internal analysis, detailed in Table 23 below, shows that the technical potential in 2030 for R-6/in, R-8/in and R-12/in thermal insulation materials for walls is 1101, 951, and 836 TBtu (assuming that in all cases 2 inches of insulation is added to existing walls). Because insulation upgrades to existing buildings typically happen infrequently, the unstaged maximum adoption potential for these technologies in 2030 is substantially reduced to 352, 304, and 267 TBtu respectively. This analysis does not account for additional energy savings if the thermal insulation is added to other components of the building envelope.

Table 23. Primary Energy Savings from Thermal Insulation Materials Added to Walls of Existing Buildings

Thermal Insulation Technology Performance Target	Market Size (TBtu)	Technical Potential, 2030 (TBtu)	Unstaged Max Adoption Potential, 2030 (TBtu)
Residential Building Sector			
R-6/in	1,610	836	267
R-8/in	1,610	951	304
R-12/in	1,610	1,101	352

Figure 27 shows a sensitivity analysis of a simple payback period for adding R-6/in to R-12/in thermal insulation materials to either surface (interior or exterior) of walls in existing buildings (assuming that 2 inches of material is added in all cases) at an installed cost premium range of $0.25/ft^2 to $0.75/ft^2 that includes both the insulation material and the associated labor costs. Much like the sensitivity analysis performed for highly insulating windows in Chapter 3, the data in Figure 27 show that the payback period is far more heavily dependent on the installed cost of the insulation than its insulating performance. For example, the payback of R-12/in insulation material is reduced by approximately a factor of 3 when the installed cost premium is reduced from $0.75/ft^2 to $0.25/ft^2. Alternatively, the reduction in payback period is approximately 2 years when comparing R-12/in to R-6/in technology at $0.25/ft^2. In all cases, the only installed cost premium that gives a payback period below 10 years is $0.25/ft^2. Labor costs for traditional interior or exterior insulation is $0.4 to $0.5/ft^2, depending on the insulation type, but not accounting for associated construction such as moving windows or electrical outlets (Kosny 2013). Thus, in addition to reducing material costs, the R&D performance target cannot be achieved unless new insulation materials enable low labor-cost, easy installation methods. Note that this analysis is performed in terms of $/ft^2, as opposed to $/ft^2*R, in order to isolate the impacts of installed cost and performance.

Table 23 clearly shows that additional primary energy savings can be achieved through higher-performance materials. However, the cost of those high performance products traditionally limits their market penetration. The BTO R&D roadmap performance target for building envelope insulation material is R-12/in in order to achieve a technical potential above 1,000 TBtu, but with an installed cost target that enables a simple payback period below 10 years. However, insulating materials with performance above R-12/in that can be applied to walls of existing buildings are highly desirable provided that the payback remains below 10 years. Additionally, in order to be acceptable for the market, any next-generation insulation material developed must maintain its performance over its service life, meet durability (existing fire, structure, moisture, and acoustic code) requirements, and minimize occupant disturbance as discussed in detail above.

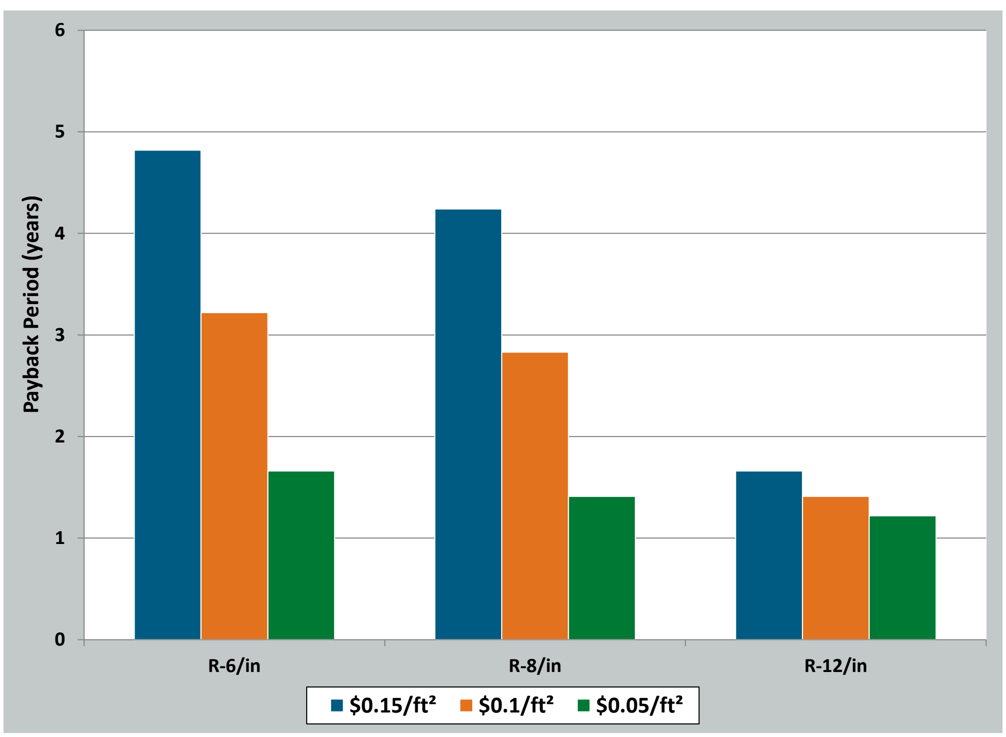

Figure 27. Sensitivity analysis of simple payback period for thermal insulation materials for a range of cost targets ($/ft^2), assuming 2 in of insulation material is applied

Barriers to technology development are discussed below, and the R&D roadmap for moving this technology forward is shown in Table 26.

Technical Barriers and Challenges

Table 24. Technical Barriers and Challenges to the Development of Envelope Insulation Materials

Topic/Barrier		Description
R&D Barriers	Development of low-cost materials	Core materials of particular importance include: • High R-values, such as low-cost nanoporous solids, with pore sizes that are less than the mean free path of air • Exceptional moisture/mold control • Low pressure alternate filler gas with reliable long-term performance
	IR radiation control	• New insulation systems need to take advantage of new materials and additives to effectively reflect thermal radiation
	Understanding of material failure modes, service-life test protocol	• A full identification analysis of how and on what timescale next-generation materials degrade • Tests against conditions designed to simulate the environments they would be subjected to during their period of service, testing conditions must be developed to enable improved correlation between testing and true performance
Manufacturing and Scale-Up Barriers	Integrated supply chain	• Low-cost manufacturing will be contingent on the emergence of an integrated supply chain of materials
	Modular manufacturing and standardization	• Modular manufacturing with greater material performance control for increased yields. • Seamless interfacing between elements of the manufacturing system will enable the production of low-cost, standardized products, simplifying installation and reducing soft costs

Market and Deployment Barriers

Table 25. Market and Deployment Barriers to the Adoption of Envelope Insulation Material

Market/Deployment Barrier	Description
System integration to envelope	Innovative insulation assemblies need to fit seamlessly into existing fabrication methods
Standardization of sizes	Novel insulation materials in existing form-factors will facilitate market adoption
Moisture management	Products with insufficient moisture management will have limited market adoption
Blowing agent restrictions	Low-cost blowing agents with low global warming potential
Lack of third-party verification of capabilities and flammability	Validating material performance by an independent party will lead to quicker utilization throughout the building industry

Table 26. Envelope Insulation Material R&D Technology Roadmap

Topic Description: Develop ≥R-12/in building envelope thermal insulation material that can be added to walls to retrofit existing buildings with a projected installed cost premium ≤$0.25/ft^2 (per service life R). The materials must meet durability (existing fire, structure, moisture, and acoustic codes) requirements and minimize occupant disturbance. This material must be applicable for wall insulation, but can also apply to other portions of the envelope to reduce the impact of thermal bridging.

	Roadmap Action Plan Activities	Milestones
Near Term (<5 yrs)	• Decrease IR transfer in the temperature range of 0°–100°C • Replace hydrofluorocarbon blowing agents with more environmentally benign materials without reducing R-per-inch values • Develop advanced vacuum insulation technology that is cost effective both in production and maintenance	• Candidate IR materials identified • Materials with R-values ≥R-6/in with moisture tolerance at a bench scale • Prototype of continuous manufacturing process for ≥R-6/in materials that can be produced and installed at a cost premium ≤$0.50/ft^2 compared to standard technology • Validated modeling tools for materials, components, and systems with techno-economic analysis
Mid Term (6 – 9 yrs)	• Develop new nucleating method(s) to increase initial nuclei population and control bubble coalescence • Design new composite resin system with higher radiation heat resistance and capability of internal (inert) gas generation • Develop test protocols for service life • Develop system integration approaches • Optimize core and barrier materials • Optimize next-generation vacuum insulation technology	• Materials with R-values ≥R-8/in and moisture tolerance demonstrated in a small field demonstration • Demonstration of the continuous manufacturing process for ≥R-8/in materials that can be produced and installed at a cost premium ≤$0.35/ft^2 compared to standard technology • Demonstration of building standards for performance of lifetime analysis • Demonstration of materials for internal and external applications
Long Term (9 – 12 yrs)	• Develop next-generation composite materials and assemblies that utilize multiple methods to mitigate heat transfer • Develop advanced vacuum insulation technology that is cost effective both in production and maintenance • Develop affordable advanced composite materials and assemblies that utilize multiple methods to mitigate heat transfer and reduce peak thermal load • Develop insulation with controllable conductivity and thermal mass	• Demonstrate a continuous manufacturing process for a ≥R-12/in material that can be produced and installed with a cost premium ≤$0.25/ft^2 compared to standard technology • Demonstrate materials with R-values ≥R-12/in and moisture tolerance in the field

Benefits and Impacts

Factor	Impact	Description
New Buildings	Med	Focus is on existing buildings, but the technology is expected to impact new buildings as well, specifically if added to code requirements.
Retrofit Buildings	High	Ease and cost of installation is key for high market penetration from re-siding and re-roofing
Industry Competitiveness	High	Increased energy conservation via thermal insulation will enhance the industry's competitiveness in emission and production cost controls
Cost Reduction	High	A large reduction in the payback period is needed for this technology to be cost-effective. Achieving the roadmap cost target is projected to reduce the payback period of R-12/in thermal insulation material to 3 years. If this target can be achieved, significant operating cost reductions from reduced building energy use will result.

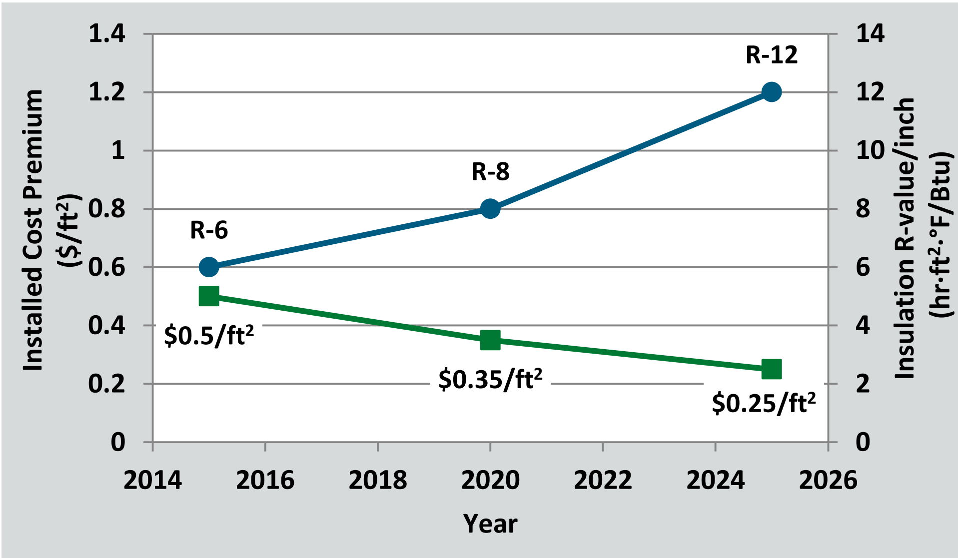

Figure 28. Envelope insulation material cost and performance targets[39]

[39] Baseline installed cost premium = $5/ft², which corresponds to the estimated cost premium of installing an exterior installation finishing system (EIFS, PT measure 660), compared to standard technology. The whole wall R-value of this technology is greater than R-30 (apps1.eere.energy.gov/buildings/publications/pdfs/building_america/high-r_value_walls_case_study_2011.pdf). This technology is just one of several technologies that could be used as a baseline to R-12/in insulation.

Building Envelope Highest Priority R&D Topic 2: Air-Sealing Systems

Overview

Uncontrolled heat, air, and moisture have a significant impact on energy usage. A comprehensive strategy for concurrently regulating these factors will be revolutionary and have a major impact on reducing overall building energy consumption. Specifically, Table 2 shows that in 2010 infiltration was responsible for 2.26 and 1.29 quads of space heating energy lost in the residential and commercial sectors, respectively, and 0.59 of space cooling energy was lost in the residential sector.[40] In aggregate, infiltration accounted for greater energy losses than any other component of the building envelope, including fenestration; 2035 projections show similar trends. As a result, air-sealing technologies are one of the top priority Building Envelope R&D areas. A next-generation air-sealing methodology will require new thought processes on how heat, air, and moisture flow are interrelated and how to best regulate them in order to improve overall building-level system performance, as opposed to a more traditional strategy that focuses on component improvements. The design of a systems-level approach to collectively address heat, air, and moisture issues has a number of cost and performance challenges, which are detailed below. Additionally, the inability of current technology to measure infiltration in large commercial buildings makes it difficult to define performance and cost targets in the space. The R&D roadmap for moving air-sealing systems into the market is shown in Table 30.

BTO internal analysis is shown in Table 27 for pre-2010 and post-2010 residential buildings. For pre-2010 residential buildings, the technical potential ranges from 1,237 to 1,679 TBtu, depending on the technology performance. For post-2010 buildings, the technical potential ranges from 507 to 633 TBtu, suggesting that the greatest energy-savings opportunities for air-sealing system technologies are in existing buildings. Furthermore, it is expected that the technical potential for a next-generation technology that can *simultaneously* control heat, air, and moisture flow will be greater than the baseline numbers presented here.

Table 27. Primary Energy Savings from Air-Sealing System Technologies for New and Existing Buildings in the Residential Sectors

Air-Sealing System Technology Performance Target	Market Size (TBtu)	Technical Potential, 2030 (TBtu)	Unstaged Max Adoption Potential, 2030 (TBtu)
Residential Building Sector, Existing Buildings (pre-2010)			
3 ACH50	1,768	1,237	1,237
1 ACH50	1,768	1,591	1,591
0.5 ACH50	1,768	1,679	1,679
Residential Building Sector, New Buildings (post-2010)			
1 ACH50	760	507	346
0.5 ACH50	760	633	433

The objective of developing a R&D roadmap target for residential buildings is to develop a cost-effective air-sealing system that prevents uncontrolled heat, air, and moisture flow in the envelope. To aid in

[40] In 2010, infiltration offset 0.15 quads of space cooling loads in the commercial sector.

determining a roadmap performance and cost target, a sensitivity analysis was run, with results shown in Figure 29 and Figure 30. This sensitivity analysis varies simple payback period for air-sealing technologies (3 ACH50 – 0.5 ACH50) for pre-2010 and post-2010 buildings in the residential building sector, respectively. The analysis shows that current technologies achieving <3 ACH50 have payback periods less than 5 years at 75% of current installed cost premiums. Moreover, the difference in payback periods for a system achieving 3 ACH50 and 1 ACH50 at 50% or 25% of the current average installed costs[42] is less than 2 months. Thus, there is little economic benefit to pushing the performance from 3 ACH50 to 1 ACH50. However, Table 27 shows that systems that can achieve 1 ACH50 have an unstaged maximum economic adoption potential for pre-2010 residential buildings that is 350 TBtu higher than systems that can achieve 3 ACH50. But increasing performance further from 1 ACH50 to 0.5 ACH50 only increases the unstaged maximum adoption potential by 88 TBtu. A 0.5 ACH50 system also has much longer payback times than a 1 ACH50 system because of higher current costs. Accordingly, to achieve less than a 5 year simple payback period, the installed cost premium must be reduced by greater than 50%.

The desired technology must reduce air leakage to ≤ 1 ACH50 at a cost of < $0.5/ft^2 finished floor, including mechanical ventilation. At this target, the payback period is 1.7 years in pre-2010 buildings and 3 years in post-2010 buildings. This 2025 air-tightness goal is not significantly tighter than some existing high performance home requirements such as the DOE Challenge Home and the Passive House.[41] The sensitivity analysis results shown in Figure 29 show that the marginal benefit of setting a goal below 1 ACH50 is more than offset by the costs to achieve this level of air tightness. The target goal was thus set to 1 ACH50 in order to result in a target with a more economically viable solution.

While this sensitivity analysis is useful in informing performance and cost targets, it is critical to note that these technologies do not directly capture the benefit of the proposed R&D target because there is no single existing technology capable of simultaneously controlling heat, air, and moisture. An integrated technology capable of achieving this would certainly have an increased energy savings impact relative to the state-of-the-art technologies, but to achieve substantial market penetration in the residential sector, the payback period of such a technology should be less than 5 years.

[41] The DOE Challenge Home (eere.energy.gov/buildings/residential/ch_index.html) requires an air-tightness of 1.5 ACH50 in climate zone 8, while the Passive House (passivehouse.us/passiveHouse/PassiveHouseInfo.html) requires 0.6 ACH50 in all climate zones.

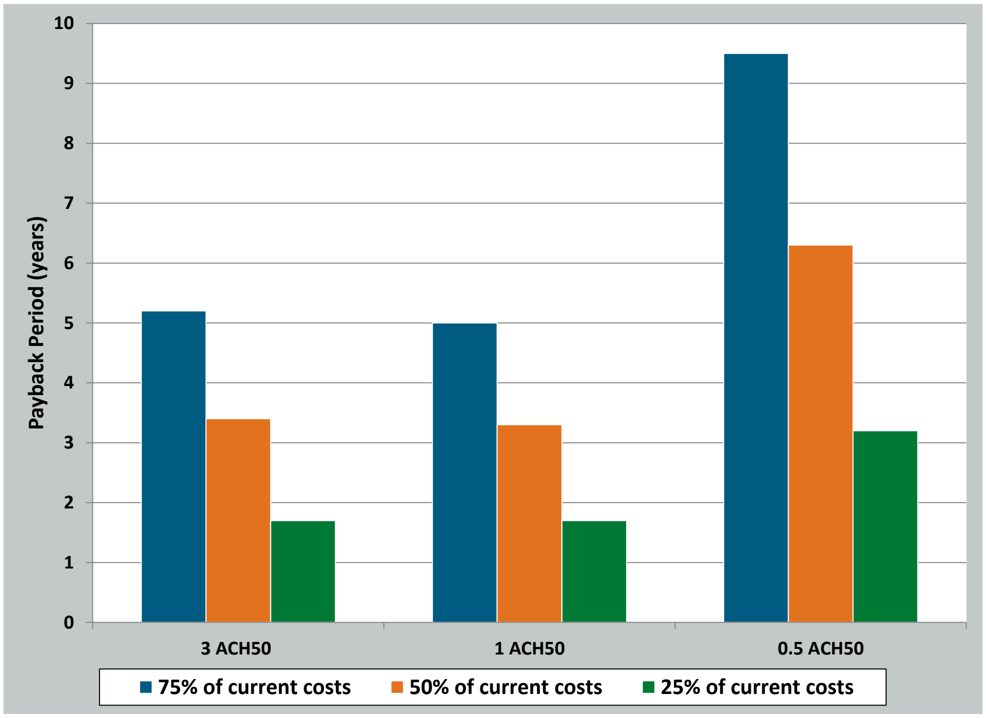

Figure 29. Sensitivity analysis of simple payback period for air-sealing technologies (3 ACH50 – 0.5 ACH50) for pre-2010 buildings in the residential building sector[42]

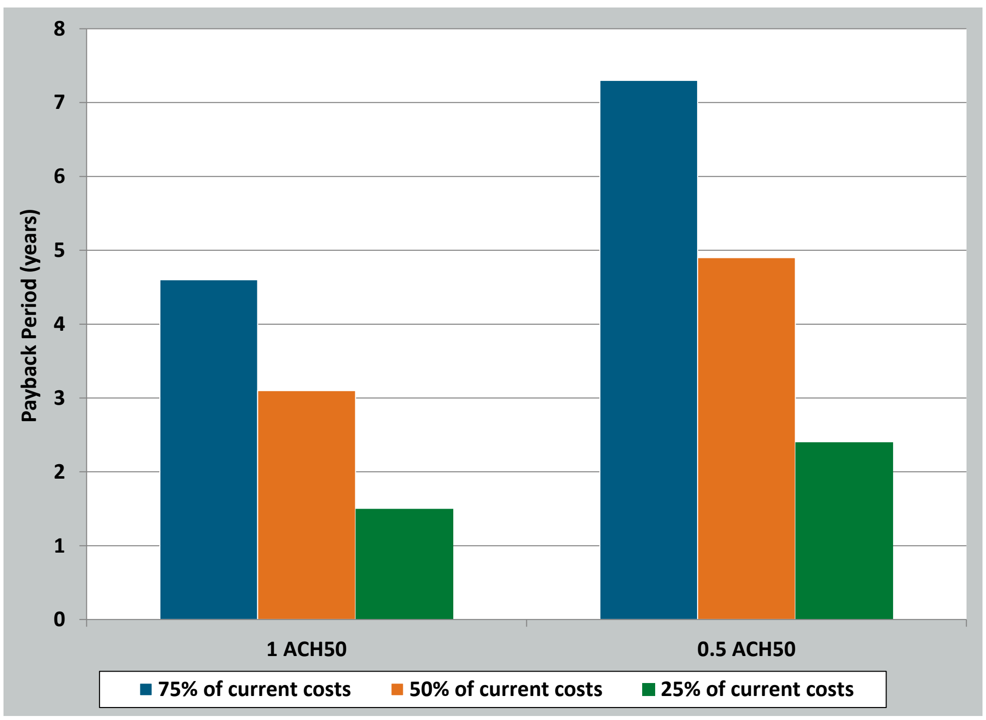

Figure 30. Sensitivity analysis of simple payback period for air-sealing technologies (1 ACH50 and 0.5 ACH50) for post-2010 buildings in the residential building sector

[42] Current average costs for air-sealing technologies are available at the National Renewable Energy Laboratory measure database. The average cost for 0.5 ACH50 technology was linearly extrapolated from 1 ACH50 costs. nrel.gov/ap/retrofits/measures.cfm?gId=10&ctId=376&scId=6160&acId=6164.

Table 28 shows the BTO analysis for air-sealing systems in new and existing commercial buildings. In this case, the baseline tightness (1.38 CFM75/ft^2 5-sided envelope) is a national average for buildings in the commercial sector (Emmerich 2011). Table 28 shows the impact of reducing leakage by 10% to 1.24 CFM75/ft^2 (achieved by sealing large, concentrated leaks using today's cost-effective technologies) and by roughly 80% to 0.25 CFM/ft^2 (requires sealing more smaller, more distributed leaks). The technical and unstaged maximum adoption potential varies substantially between these two cases, from 44 to 805 TBtu. In addition, it is expected that the technical potential for a next-generation technology that can *simultaneously* control heat, air, and moisture flow will be even greater than these baseline numbers.

Table 28. Primary Energy Savings from Air-Sealing System Technologies for New and Existing Buildings in the Commercial Sectors

Air-Sealing System Technology Performance Target	Market Size (TBtu)	Technical Potential, 2030 (TBtu)	Unstaged Max Adoption Potential, 2030 (TBtu)
Commercial Building Sector, New and Existing Buildings			
1.24 CFM75/ft^2	982	44	44
0.25 CFM75/ft^2	982	805	805

Emmerich (2011) reports a national average tightness for 227 U.S. commercial and industrial buildings of 1.38 CFM75/ft^2, and that tighter buildings are generally found in colder climates (Emmerich 2005). This metric is dominated by the tightness of existing buildings, which dominate the commercial building floorspace (Table 5). Table 28 shows the BTO internal analysis for new and existing commercial buildings with 1.38 CFM75/ft^2 being used as the baseline tightness (Emmerich 2011, Bohac 2013). Not surprisingly, new buildings are tighter. For example, the current ASHRAE 189.1 standard requirement is 0.4 CFM75/ft^2.[43] In addition, the Army Core of Engineers recently set a maximum building envelope air leakage requirement of 0.25 CFM75/ft^2 (USACE 2012).

A study by Bohac (2013) shows that existing cost-effective air-sealing technologies, such as foam sealing of wall/roof joints and exterior weather-stripping, leads to an average leakage reduction of 10% in commercial buildings (26,927 to 246,365 ft^2) in cold climates. These measures are most impactful for leaky buildings with large, concentrated leaks that are inexpensive to seal. Table 28 shows that the technical potential and unstaged maximum adoption potential of achieving this level of leakage reduction (from 1.38 to 1.24 CFM75/ft^2) with existing technologies is only 44 TBtu. Bohac's analysis shows that the cost of sealing these large, concentrated leaks is $0.17 per 5-sided envelope, leading to a simple payback of approximately 6 years. This analysis shows that while sealing commercial buildings with existing technologies is economically attractive, there is a relatively small energy savings potential.

In order to determine R&D cost and performance metrics for an air-sealing system, we have considered the opportunity for reducing the national average tightness of commercial buildings from 1.38 CFM75/ft^2 (Emmerich, 2011) to 0.25 CFM75/ft^2, an 83% reduction. This requires both sealing large, concentrated leaks with existing, cost-effective approaches, as discussed above, and sealing more dispersed and difficult-to-find leaks. Table 28 shows that the technical and unstaged maximum potential for this technology measure is 805 TBtu. Assuming an average cost of $0.5/ft^2 (5-sided envelope) for achieving this 83% leakage reduction, the 2030 simple payback is 2.7 years. We assume that the cost sensitivity is not linear because of the costs of sealing different leakage sources. The cost of sealing large, concentrated

[43] More information can be found at ashrae.org/resources--publications/bookstore/standard-189-1

leaks is not expected to change substantially from the cost metrics presented in Bohac's analysis (~$0.17 per 5-sided envelope), but instead that the majority of costs will be the result of sealing more dispersed, costly leaks needed to achieve the final performance target.

In addition, the size and design of U.S. commercial buildings varies substantially, from small main-street storefronts to large office buildings in major cities. While blower-door tests can be used to measure infiltration in small commercial buildings, there is no comparable technology for measuring infiltration in large commercial buildings, limiting the data available to analyze this opportunity. Clearly, a technology capable of measuring infiltration losses in large commercial buildings is a technology-development opportunity that would be extremely impactful for reducing building energy losses. This opportunity is discussed in more detail in Chapter 5. Like the residential sector, the analysis we present here does not directly capture the benefit of the proposed R&D target because the technology is not capable of simultaneously controlling heat, air, and moisture.

Technical Barriers and Challenges

Table 28. Technical Barriers and Challenges to the Development of Cost-Effective Advanced Air-Sealing Technologies

Topic/Barrier		Description
R&D Barriers	System simplification	High cost for three separate systems to control heat, air, and moisture, viable integrated systems will be more cost effective
	Selective sealing with spray-applied sealers	Existing spray-sealing technologies need improved sealing capabilities at reduced costs
	Inadequate quality control and verification of completeness during application process, inadequate visual or other indicators of installation flaws	Techniques that can be used during application to ensure consistent implementation—simple, non-destructive techniques to quickly and properly detect flaws and remediate
Manufacturing and Scale-Up Barriers	Manufacturing quality control to ensure performance	Single control systems will require screening upon being manufactured to ensure consistent viability during service life
	A coordinated systems approach is inhibited by the sequence of building trades involved in installations	Improved coordination between different trades involved in the installation of environmental control equipment could enable a systems approach
	Inability to install and seal the system immediately after or during construction	System installed (e.g., sealed) after or during construction in order to mitigate all of the flaws created during construction

Market and Deployment Barriers

Table 29. Market and Deployment Barriers to the Adoption of a Systems-Level Approach to Air-Sealing

Market/Deployment Barrier	Description
System price-point	Systems-level approaches need to show value-add benefits beyond that of the individuals systems installed together
Climate dependent air and moisture barrier co-location	Sealing solutions must have the capability to be added "à la carte," depending on the environment conditions they will be installed in
Low-cost verification and validation	Low-cost validation techniques need to be performed prior to or immediately after the completion of building construction so that remediation can be applied more cost-effectively
Variability of Market	Different builders vary in their product choices and solutions, solutions are different for new and existing construction
Inspector Training	Improved inspector training to ensure consistency in application and validation

Table 30. Air-Sealing Systems R&D Technology Roadmap

Topic Description: Develop a systems-level approach to prevent uncontrolled heat, air, and moisture flow in the envelope at an appropriate price point to facilitate mass-market adoption in the commercial and residential sectors. Develop a system with air leakage <1 ACH50, at a cost of ≤$0.5 per ft^2 finished floor for use in residential buildings and a system with air leakage <0.25 CFM75 per ft^2 (5-sided envelope), at a cost of ≤$0.5 per ft^2 (5-sided envelope) for use in commercial buildings. Costs include mechanical ventilation costs.

<table>
<tr><th colspan="2">Roadmap Action Plan Activities</th><th>Milestones</th></tr>
<tr><td>Near Term (<5 yrs)</td><td>• Develop improved (i.e., reduced leakage) integrated sealing at joints and interfaces between assemblies
• Perform accelerated performance tests
• Collect air-sealing cost data and develop a database of envelope sealing costs</td><td>• Establishment of a database of envelope sealing costs to complement existing databases of leakage levels
• Commercial buildings: Air-sealing systems for new and renovated buildings with air leakage reduced to 0.25 CFM75 per ft^2 5-sided envelope (USACE 2012), at a projected installed cost of ≤$1.25 per ft^2 5-sided envelope (Bohac 2013)
• Residential buildings: Air-sealing systems with air leakage reduced to 5 ACH50, at a projected installed cost of ≤$0.9 per ft^2 finished floor (National Residential Efficiency Measures Database 2013)</td></tr>
<tr><td>Mid Term (6 – 9 yrs)</td><td>• Develop methods to reduce installation cost of self-adhering field-applied air barriers by 25%
• Develop methods to reduce installation cost of fluid-applied air barriers by 25%
• Develop envelope joint sealing methods and technologies to improve leakage rates by 15% with projected installed cost of 85% of current industry standard mean
• Develop and implement leakage testing technologies to cost-effectively test portions of in-situ building envelopes to enable quality assurance during construction sequence
• Develop a listing of key air leakage sites so that the applicator knows where to focus efforts
• Determine a method to air seal in a retrofit application that does not require the disassembly of the entire envelope component
• Develop products that can be installed in a variety of environmental conditions</td><td>• Commercial buildings: Air-sealing systems with air leakage reduced to 0.25 CFM75 per ft^2 5-sided envelope (USACE 2012) at a projected installed cost of ≤$0.75 per ft^2 5-sided envelope (Bohac 2013)
• Residential buildings: Air-sealing systems with air leakage reduced to 3 ACH50, at a projected installed cost of ≤$0.5 per ft^2 finished floor (National Residential Efficiency Measures Database 2013)</td></tr>
<tr><td>Long Term (9 – 12 yrs)</td><td>• Develop methods to reduce installation cost of self-adhering field-applied air barriers by 50%
• Develop methods to reduce installation cost of fluid-applied air barriers by 50%
• Develop envelope joint sealing methods and technologies with to improve leakage rates by 25% with projected installed cost of 65% of current industry standard mean
• Develop and commercialize air-sealing technologies with improved cost and performance including self-detecting, self-repairing, integrated, and other novel air-sealing methods
• Develop new techniques to apply to retrofit applications</td><td>• Commercial buildings: Air-sealing systems with air leakage reduced to 0.25 CFM75 per ft^2 5-sided envelope at a projected installed cost of ≤$0.5 per ft^2 5-sided envelope (including mechanical ventilation costs) (Bohac 2013)
• Residential buildings: Air-sealing systems with air leakage reduced to 1 ACH50, at a projected installed cost of ≤$0.5 ft^2 finished floor (including mechanical ventilation costs) (National Residential Efficiency Measures Database 2013)</td></tr>
</table>

Benefits and Impacts		
Factor	**Impact**	**Description**
New Buildings	Med	Envelope infiltration can offset the benefits of other energy efficiency technologies.
Retrofit Buildings	High	Large energy savings from potential stock of existing buildings—the systems-level approach is an additional capability beyond the state-of-the-art technology, which may further extend energy-savings potential.
Industry Competitiveness	High	A systems-level approach is a capability beyond what is available from currently available technologies; this system will redefine the state-of-the-art for the industry.
Cost Reduction	Medium	Cost reductions will enable wider adoption, but many existing building-wrap technologies are currently cost competitive. However, today's technologies do not provide a systems-level approach to controlling heat, air, and moisture flow in the envelope. A systems-level approach that achieves the technology cost and performance targets is projected to lower payback to below 3 years.

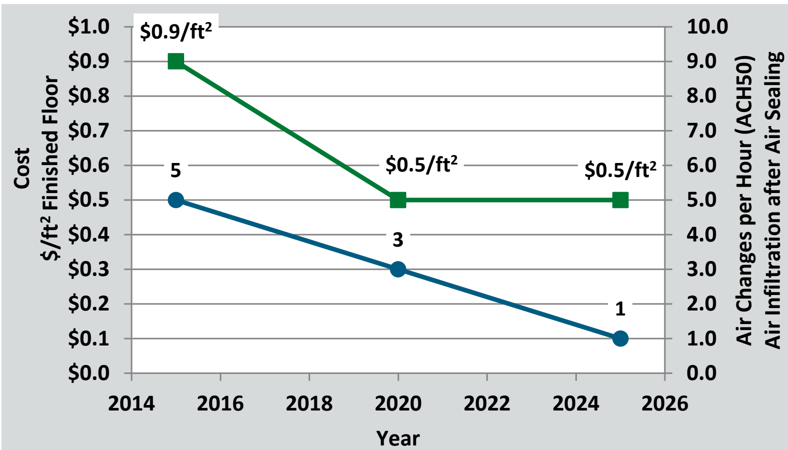

Figure 31. Air-sealing systems installed cost and performance targets (residential sector)[44]

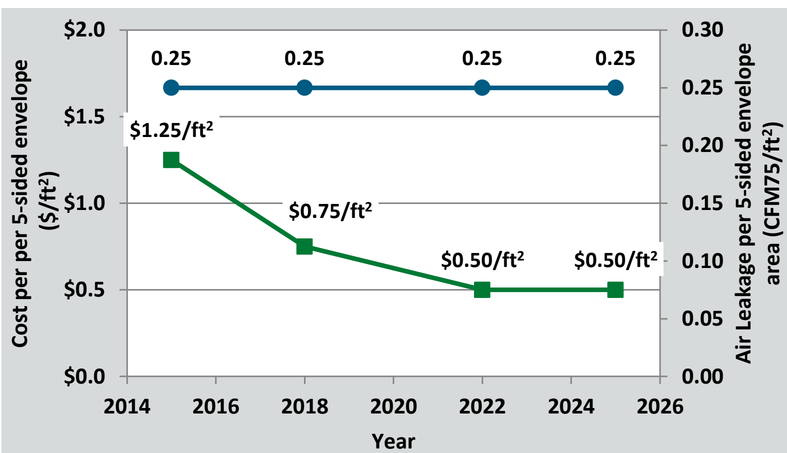

Figure 32. Air-sealing systems installed cost and performance targets (commercial sector)[45]

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[44] Residential air-sealing: baseline cost of infiltration reduction = $1.5/ft². Source: BTO Prioritization Tool, Measure 391. References of all Prioritization Tool measures are located in Appendix C.

[45] Air tightness and improvement cost data from cited literature are used as state-of-the-industry benchmarks (Bohac 2013, Emmerich 2013). Cost targets have been normalized to a per-ft²-of-building-envelope basis (5-sided area index), consistent with current industry practice. Cost sensitivity is not linear because of the costs of sealing different leakage sources. The cost of sealing large, concentrated leaks (to reduce leakage from 1.38 to 1.24 CFM75/ft²) is not expected to change substantially from the cost metrics presented in Bohac's analysis (~$0.17/ft²), but the majority of costs will result from sealing more dispersed, costly leaks needed to achieve the final performance targets (0.25 CFM75/ft²).

Building Envelope High Priority R&D Topic: Highly Insulating Roofs for Commercial Buildings

Overview

Roof systems may contribute to up to 33% of building losses, depending on the building zone (Roof 2013). Table 2 shows that, in the commercial sector, roofs contributed to 0.88 and 0.05 quads of energy lost for space heating and cooling, respectively, in 2010. While the residential sector loses more energy to roofs than the commercial sector, R&D focus is on commercial sector roofs because typical residential homes have attics that can insulate effectively with existing technologies by adding thermal resistance between the roof and the conditioned space of the home.[46] However, because less energy is lost through roofs than through walls and infiltration in the commercial space, this is a secondary R&D priority relative to thermal insulation materials for walls and infiltration control. The R&D goal is to develop a roof system that exhibits a reduction in energy use equivalent to doubling the R-value of current ASHRAE values (90.1-2010) at an incremental cost increase of ≤$1/ft^2 ($100/100 ft^2) compared to standard roof technology. The R&D roadmap for moving this technology forward is shown in Table 33.

Technical Barriers and Challenges

Table 31. Technical Barriers and Challenges to the Development of Cost-Effective Highly Insulating Commercial Roofs

Topic/Barrier		Description
R&D Barriers	Novel materials to reduce roofing heat flux	Reducing heat flux by 50% will likely require exploiting new materials, such as nanomaterials, or novel arrangements of existing roofing materials.
	Sustainability of product to maintain performance goal	Roofs must maintain their flux properties over their service lives in order to achieve predicted energy savings.
	Chemical compatibility and moisture resistance	Any new roof system will need to maintain existing chemical and physical properties despite exposure to extreme temperature, moisture fluctuations, and other environmental factors.
	Rating and characterization at delivery temperature	Because roofs in different ASHRAE environmental zones require different performance requirements, it is important to identify the necessary capabilities at those conditions and the method by which those are identified.
Manufacturing and Scale-Up Barriers	Thermal bridging reduction	To achieve the performance goal for the overall roof system, new roof materials and roofing structures need to be designed to optimize temperature gradients through roof components and between the roof and the wall (Seaverson 2008)
	Compressive and tensile strength	Novel roof systems must not sacrifice basic mechanical requirements for building roofs.
	Benign (environmentally friendly) blowing agents and raw materials	Considerations in occupational safety must be a significant aspect in the design of advanced roof systems.
	In-situ characterization of performance (field demonstration)	Large area true-service life performance characterization will be important in order to validate the performance of the enhanced roof product.

[46] Typical commercial roofs are a mix between low-slope water impermeable materials (thermoplastic polyolefin, polyvinyl chloride, ethylene propylene diene monomer, bitumen, built-up roof membranes, spray foam, and metal panel) and steep-slope (metal panel, shingle, tile, and synthetic). Commercial roofs are typically more expensive than residential roofs because a low-slope roof must be water tight and must include a drainage system in the roof assembly to prevent water ponding on the roof. Current commercial roof technology costs are in the range of $5–$10/ft^2.

Market and Deployment Barriers

Table 32. Market and Deployment Barriers to the Adoption of Highly Insulating Commercial Roofs

Market/Deployment Barrier	Description
New Technology Adoption and Proof of Concept	Inherent resistance to using newly developed building materials in construction necessitates targeted training of installers and contractors on the benefits of utilizing the new systems as well as of sharing performance data from the proof of concept demonstrations. (Goldsberry 2013)

Table 33. Highly Insulating Roof R&D Technology Roadmap

Topic Description: A roof exhibiting energy use reduction that doubles ASHRAE 90.1-2010 R-values at an increased cost limited to ≤$1/ft^2 compared to standard roof technology.[46]

	Roadmap Action Plan Activities	Milestones
Near Term (<5 yrs)	• Survey existing and potential insulation materials for cost effective: ○ thermal conductivity ○ moisture tolerant performance • Develop simulation models to identify optimal material systems and roofing designs across various ASHRAE climate zones • Develop methodology to create and integrate low-flux roof systems	• Prototype hydrophobic roof for climate zone 6 (cold climates) with an R value equal to 45 (Standard 2013; ASHRAE 2013) • Prototype hydrophobic roof for climate zone 2 (hot climates) with an R value equal to 35 • Manufacturing processes demonstrated for roof areas >10 ft^2 with an increased cost <$10/ft^2 and a critical path determined to achieve final cost targets
Mid Term (6 – 9 yrs)	• Develop improved systems and methods for accurately evaluating the performance of new versus existing roofing materials • Perform failure mode examinations to ascertain system performance under service conditions and identify aspects for material optimization	• Simulation of roof material models' performance with accuracy within 10% of experimental results • Validation of developed roof material systems against ASHRAE 90.1-2010 standards to performance metrics at each climate zone, compared to existing roof systems • Small-scale field testing of a hydrophobic roof (>50ft^2) for climate zone 6 with an R value equal to 60 (50% reduction in heat flux compared to ASHRAE 90.1-2010) • Small-scale field testing of a hydrophobic roof (>50ft^2) for climate zone 2 with an R value equal to 50 (50% reduction in heat flux compared to ASHRAE 90.1-2010) • Demonstrate manufacturing process for >50ft^2 at an increased cost < $3/ft^2
Long Term (9 – 12 yrs)	• Conduct performance testing • Conduct acceleration testing and calibrate against weather/environment phenomena	• Field testing of a hydrophobic roof (>50ft^2) for climate zone 6 with an R value equal to 60 (50% reduction in heat flux compared to ASHRAE 90.1-2010) • Field testing of hydrophobic roof (>50ft^2) for climate zone 2 with an R value equal to 50 (50% reduction in heat flux compared to ASHRAE 90.1-2010) • Demonstrate the manufacturing process for >50ft^2 at an increased cost of < $1/ft^2

Benefits and Impacts

Factor	Impact	Description
New Buildings	High	Enhances envelope insulation and positively impacts active equipment
Retrofit Buildings	Medium	Limited impacts due to the high cost of roof retrofits, which results in a market size of highly insulating roofs for existing buildings that is only 10 TBtu higher than the market size of roofs for new buildings, despite the larger stock of existing buildings (Table 5).
Industry Competitiveness	High	Support domestic roofing technology manufactures and building contractors
Cost Reduction	Medium	The R&D performance target doubles energy performance with a modest increase in cost to ensure reasonable payback for consumers. Meeting the roadmap cost and performance targets will lower payback from approximately 19 years to 12 years.

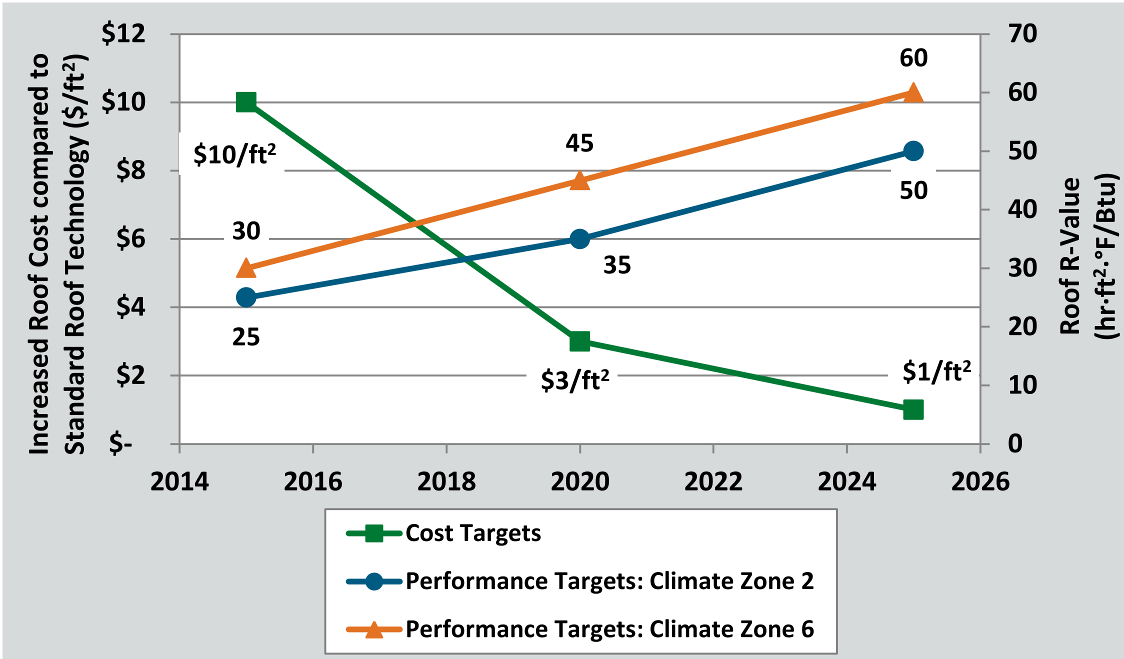

Figure 33. Highly insulating roof technology installed cost and performance targets[47, 48]

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[47] Baseline cost of increased roof insulation = $1/ft^2. Source: BTO Prioritization Tool, Measure 741. References of all Prioritization Tool measures are located in Appendix C.

[48] ASHRAE climate zones divide the United States into temperature-oriented climate zones. Climate zone 2 covers portions of the southern United States that typically experience hot temperatures, including parts of Florida, Texas, and Arizona. Climate zone 6 covers portions of the United States that typically experience cold temperatures, including parts of New York, Wisconsin, and Michigan. Climate zones are described and illustrated in more detail in volume 7.1 of DOE's Building America Best Practices Series, which can be found here: apps1.eere.energy.gov/buildings/publications/pdfs/building_america/ba_climateguide_7_1.pdf.

5. Crosscutting Drivers and Challenges

Overview

There are numerous market drivers beyond energy savings and cost effectiveness that facilitate rapid technology adoption of next-generation building energy efficiency technology. Similarly, there are many non-energy and non-cost factors that hinder the mass-market adoption of these technologies. Many of these market barriers cross-cut windows and building envelope technologies and can apply to both the residential and commercial sectors; others are more specific to the technology type and the sector. In order to promote mass-market adoption of next-generation, energy-efficient technologies, it is important to better understand the issues that would limit or accelerate mass-market adoption, addressing challenges in parallel to technology development. The main challenge areas include:

1) Identifying which technology areas would benefit most from reducing balance of system (BOS) costs and approaches to achieve BOS cost reductions.
2) Developing diagnostic technologies that will help make a business case for building energy upgrades and changes in building codes
3) Understanding methods for strengthening the business case for retrofits and developing appropriate and innovative business plans

Soft Costs

In residential and commercial buildings, soft costs, or BOS costs, include factors such as labor costs, ease of installation, transportation issues, wiring, wireless, etc. As discussed in detail in Chapter 4, in many cases, these factors dominate the installed cost. For example, the installed cost (materials + labor) of 3.5 inches of fiberglass batt insulation to an interior wall is estimated to cost $0.57/ft^2 (Kosny 2013). The labor portion of this cost is estimated to vary from $0.43/ft^2 to $0.47/ft^2 (Kosny 2013). For ENERGY STAR rated windows, installation cost varies, but is approximately 50% of the total installed cost (Checklist 2013). The BOS costs must be minimized to enable the adoption of next-generation, energy-efficient technologies. In order to reduce these costs, it is important to consider which technology areas within the windows and building envelope space (e.g., dynamic windows and façades) and similarly which applications (e.g., building retrofits vs. new construction) would benefit most from BOS cost reductions.

BOS costs are particularly important for the retrofit market. Walls, roofs, and windows make up the structure of the building. They vary widely from building to building, and as a result, retrofits must be done on a case-by-case basis. This leads to long construction times, high labor costs, and energy-efficiency improvements that are poorly suited to the building and have negative impacts on building performance metrics, such as the indoor air-quality or moisture control.

BOS costs dominate the total installed costs for many sealing and insulation technologies. Possible approaches to reducing these costs include low-cost advanced thermal insulation with reduced thickness to enable quick interior retrofits that do not require construction tasks, such as rearranging outlets and re-adjusting pipes; combining exterior continuous insulation with siding or roofing products; and producing an airtight and watertight envelope with automated sealing verification.

Dynamic façades, including dynamic windows, attachments, films, and glazing, are one area where reductions in soft costs would reduce a substantial portion of the total installed cost. These dynamic window technologies that are self-contained, easy to install, and autonomous with wireless communications and powering and a reduced footprint, could be installed without changing the methods currently used by practitioners. Conversely, if the installation method is more complicated than current methods, market adoption of dynamic facades would be diminished, despite the merits of the technology. Common communication standards and interception protocols for dynamic windows would also help to reduce soft costs and encourage interoperability. Other approaches specific to achieving reduced soft costs for dynamic windows include reducing sensor costs and the cost of a warranty in the window's base cost.

Designing and manufacturing insulation products, walls, roofs, and windows that are simple and quick to install would help to reduce the labor costs. This could be done by developing systems that either come complete as a kit, easily snap into place, or are pre-cut for quick installation. Modular, pre-fabricated assemblies, components, and envelope or window sections would involve less installation and commissioning costs while promoting higher-performance systems. Similarly, access to the insulation space needs to be less intrusive, allowing for quick optimization opportunities at convenient times. An alternative approach to reducing soft costs would be to standardize installer workforce training through the development of uniform best practices, with trainings offered at community colleges across the country. This training could be focused on the installation, operation, and/or maintenance of specific systems or devoted to specific topics, such as weatherization. Other methods to reduce soft costs could come from improvements in logistical, non-technology areas. This would include improving project initiative methods to prevent delays and higher costs; improving marketing and community-based efforts; and focusing on reducing product weight, handling, and shipping, and using local or distributed shipping approaches. The development of regional centers could allow for more accessible information solutions on a local, rather than federal level.

Building Diagnostics

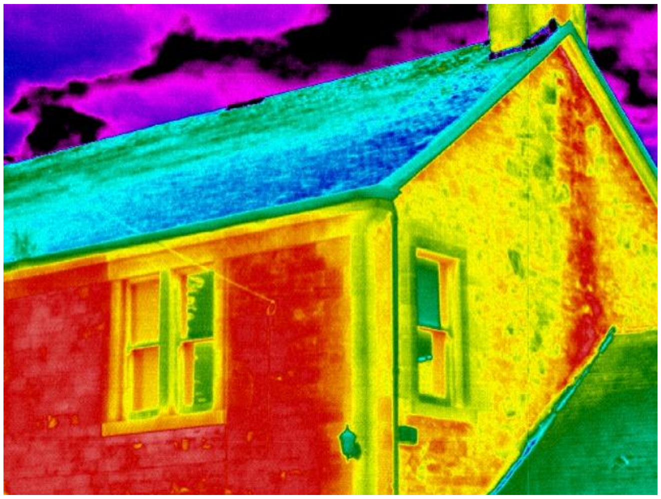

Figure 34. Infrared image of a residential home, showing parts of building with high energy losses (red)

Existing buildings offer great potential for energy savings from the implementation of energy efficiency building retrofits. Table 4 in Chapter 2 shows that in 2010, 1.193 million new buildings were constructed in the United States compared to 82.7 million existing buildings. Similarly, in 2035, 1.114 million are projected to be built compared to 104.85 million existing buildings. This data clearly shows that the market, and therefore the energy savings opportunity, for retrofitting existing buildings is far greater than for constructing new buildings. Additionally, new buildings generally have better energy performance than existing buildings due to improving codes and energy-efficiency performance degradation over time. A lack of awareness of these energy saving opportunities often leads to inaction, even when it is simple and cost-effective to perform retrofits. A more convincing business case for retrofits can be made with improved building diagnostic and measurement technologies, such as improved sensors and new modeling methods, as well as more effective methods to disseminate this critical information to residential and commercial building owners and code officials. Existing diagnostic technologies, such as IR cameras and blower door tests, are not broadly utilized to inform consumers about the energy savings potential in wide-scale building retrofits. For example, IR camera images of buildings can be a persuasive method to visually show areas of high building losses and identify the highest-priority retrofit projects. However, consumers are often unaware of what their building thermal image may look like, and unaware of energy savings opportunities. One method to address this issue is to develop an informational website, such as something similar to Google Street View, that allows consumers to see their home's existing thermal image and compare it to an image showing the results of different improvements or retrofits (as well as the resulting annual energy cost savings that would result) (LaMonica 2013). Alternatively, a low-cost (i.e., <$100) infrared camera that can quickly and accurately scan buildings and is easily available to consumers or contractors would also help to raise awareness of the savings available from building retrofits. Moreover, in large commercial buildings, there is no available technology to identify infiltration, and as a result it is omitted from the codes and standards for commercial buildings.

The development of real-time displays that show whole building energy use status and identify how little or how much energy is being lost through windows or envelopes through infiltration is another method to help build the business case for building retrofits, as well as promote a culture of energy efficiency in daily building use. Placing similar displays in public spaces in both commercial and residential buildings would likely encourage awareness among building occupants, who are not directly responsible for the payment of building energy bills. The ability of these self-diagnostic building displays to show accurate, real-time data is contingent on the development of low-cost, automated, and non-intrusive sensor technologies. Sensors will be able to detect failures or problems before or immediately after they occur, allowing consumers to understand acceptable rates of air leakage and to alert consumers to immediately take action if problem areas emerge. Sensors and controls can also be embedded in components during the manufacturing process so they can provide immediate automated sensing of building aspects, such as lighting and shade control or measuring in-situ thermal performance. Widespread adoption of sensors in building components is contingent on these low-cost sensors being developed.

Other related strategies can help consumers be more aware of energy consumption issues within buildings. Simple and tactile sensor technologies can be sold directly to the consumer for placement in and around buildings. Currently available sensor technologies will need to be easier and more inexpensive to integrate with lighting, air filtration, and other systems. Specifically, sensor technologies that can measure properties such as air leakage, temperature, and moisture within the building envelope should be developed so that energy efficiency, energy consumption, and IAQ can be easily monitored. IAQ sensors and diagnostics that can provide feedback to building occupants and managers can help maintain optimal air quality and remove any chemical pollutants as soon as they are detected. Another specific example is the need for an SHGC sensor for windows that has both interior and exterior components. With the development of these sensor technologies, it is important to also develop the appropriate software tools to manage the large amounts of resulting data and give consumers appropriate action recommendations to achieve cost-effective energy savings.

These building self-diagnostic technologies will be able to identify areas of high energy losses and recommend actions to save energy. It is also important to develop complementary modeling software and control logic to compare the costs and expected energy savings of different retrofit options, including the complete replacement of technologies with energy-efficient upgrades, as well as identifying how space can be optimized after retrofits are completed (Selkowitz 2013). A public database, which could be accessed via smart phones, could also provide a range of retrofit options based on orientation, geography, and the base system used. Other tools that are currently needed include an occupant comfort feedback and sensing tool, as well as imaging technology that can probe the sub-wall surface. For testing, there is a lack of portable testing kits for homeowners to identify existing problems with windows, as well as a standardized field-testing protocol for window retrofits. Software or tools that provide field-verified guidance or performance verification during the construction stage is an example of another need.

The creation of smarter building components, which is even further down the development pathway, such as walls, roofs, and windows composed of self-sensing materials could enable the self-regulation of attributes such as thermal flow, light, and humidity, in addition to the self-diagnosis of any fluctuations in any of the self-regulated building properties. Research in this field is still in the very early stages (He 2012), but the use of these types of smart materials would result in increased energy savings, as well as reduced soft costs for building component installation and maintenance.

Technology Deployment Strategies

Because achieving targeted energy consumption reductions through commercial and residential building envelopes requires the adoption of next-generation energy efficiency technologies, it is important to consider and understand the market drivers that can enable or hinder their mass-market adoption. Enabling market drivers must be identified in parallel with the development of next-generation technologies in order to foster mass-market adoption and reduce their time to market. The extent to which specific drivers should be considered during technology development and what, if any, price premiums they could command in the market will likely vary by market and technology.

Aesthetics

In the residential buildings sector, aesthetics is a top market driver and the driver for which consumers are most likely willing to pay the greatest price premiums. Also, aesthetics are especially important for windows, as they play a large role in the aesthetics of buildings. For the commercial sector, providing a range of available colors for dynamic windows will allow the architect to have more design control. Other examples of improvements that can enable mass-market energy efficiency technology adoption include the visual aesthetics of static glazing, cool roofs and walls that will remain clean, and aesthetically pleasing or dark-colored cool roofs and walls.

Simulation Tools

Researchers, manufacturers, building designers and operators rely on accurate simulation tools to understand, promote and develop new energy efficient technologies. DOE supports the development of modeling tools that simulate the thermal and/or optical performance of individual building components, such as a window or a wall, as well as integrated façade systems. These tools are used to aid in the development of more efficient products by saving time and money for product design and development. These tools also feed into EnergyPlus, a DOE-supported whole building simulation program, as illustrated with the windows and daylighting tools shown in Figure 35. EnergyPlus allows for the optimization of building design and operation to minimize energy use and peak demand as well as thermal and visual comfort. Tools have a substantial base of regular users and must be constantly improved and upgraded to reflect technology advances and to meet the evolving needs of end-users.

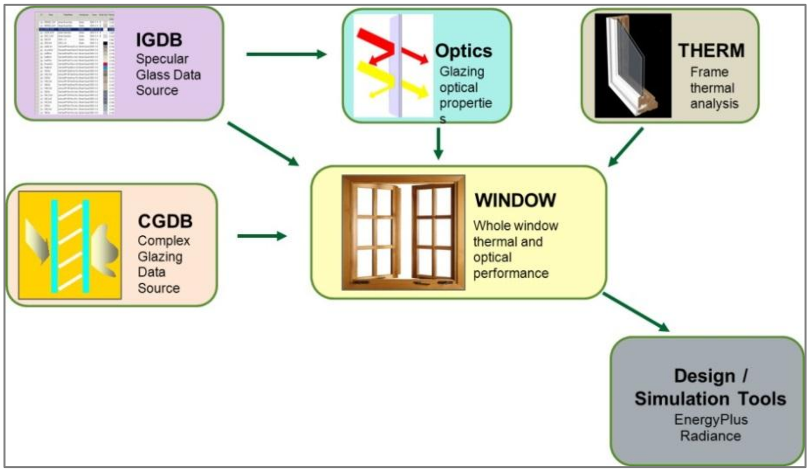

Figure 35. Selection of currently available windows and daylighting simulation tools, including the Complex Glazing Database (CGDB), EnergyPlus, International Glazing Database (IGDB), Optics, Two-Dimensional Building Heat-Transfer Modeling (THERM), Radiance and WINDOW. These tools and others are available for download at windows.lbl.gov/software/.

Role of Architect/Contractor

Architects and contractors are more indirectly involved during the development of energy-efficient technology, but can play an important role in the mass-market adoption of these technologies. There are both quantitative and qualitative aspects (e.g., human behavior and style trends) that the architect or contractor has to consider. As such, closer communications between architects and vendors or trade groups may help foster wider adoption of the technologies. With new technologies, there is more risk for the contractor compared to the architect, so it is necessary to convince the contractor/owner to take that risk. New products need to be able to fit seamlessly with an architect's design tools; the development of a rating system would better help architects understand the benefits or risks of specific new technologies. Finally, developing or offering training in building science for the architect or contractor would also be beneficial to the goal of driving the use of new energy-efficient technologies.

Acoustics and Soundproofing

In commercial buildings, acoustics and soundproofing can be considered a driver for the airtight construction of both windows and walls. Improvements in soundproofing could drive the adoption of multi-pane windows and encourage the development of thinner and more visually appealing products. When compared to other residential building market drivers, soundproofing was considered to be less important.

Thermal Comfort

The thermal comfort of building occupants is another key driver for the residential and commercial sectors and one of the largest drivers for change. Improved thermal comfort can be used as a selling point for technologies. When considering building technology solutions that result in greater thermal comfort, it is important to also focus on solutions that will reduce energy use rather than increase it. New technologies and methods to consider include composite thermal comfort models that are easy to use and being able to better understand human perception and personalized comfort.

Regulations and Codes

Building regulations and codes drive the market for energy efficiency technologies, especially for commercial buildings. In general, it takes a significant amount of time for codes to change; even though they are essential, they can cause challenges for energy-efficient technology development and adoption. Identifying code discrepancies that are barriers to new technologies and imposing rate structures that are energy based with end-use ceilings could increase the rate of adoption of next-generation technologies.

Payback/Return on Investment

Payback/return on investment is an important market driver for both the commercial and residential sectors. Specific areas where payback times should be focused on include façades and retrofits for existing buildings. For example, when retrofitting existing buildings, improving the comfort, acoustics, and heating would improve the quality of life for building occupants and could also be reflected in rental rates, allowing for additional selling points and quicker paybacks.

APPENDIX A: R&D ROADMAP WORKSHOP PARTICIPANTS

April 5, 2013 – Washington, DC

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Appendix B: Acronyms and Abbreviations

ACH50	Air changes per hour at 50 Pascals
ASHRAE	American Society of Heating, Refrigerating and Air Conditioning Engineers
BOS	balance of system
BTO	Building Technologies Office
Btu	British thermal unit
C	commercial
CFM75	Cubic feet per minute at 75 Pascals
DOE	U.S. Department of Energy
EIFS	Exterior Installation Finishing System
ET	Emerging Technologies
ft^2	square foot
HVAC	heating, ventilation, and air conditioning
IAQ	indoor air quality
IGU	insulated glass unit
IR	infrared
LBNL	Lawrence Berkeley National Laboratory
low-E	low-emissivity
PCE	power conversion efficiency
PV	photovoltaic
quads	quadrillion Btu
R	residential
R&D	research and development
SHGC	solar heat gain coefficient
TBtu	trillion Btu
TCO	transparent conductive oxide
VIG	vacuum insulated glass
VIP	vacuum insulated panel
V_T	visible transmittance

APPENDIX C: PRIORITIZATION TOOL RESULTS

BTO has used the Prioritization Tool to analyze a wide range of windows and building envelope technologies. The results for the technologies at development level[49] 3, 2, or 1 that are most relevant to the roadmap R&D targets are summarized in Table 34 and Table 35, and shown graphically in Figure 8, Figure 9, Figure 10, and Figure 11. The applicable buildings market segment, residential (R) and/or commercial (C) is shown in the technology description column. The PT results assume current costs of installed measures at the time of significant market adoption, as described in more detail in (Farese 2012b).

Table 34. Prioritization Tool Analysis Results for Select Windows Technologies at Development Levels 1, 2, or 3

Window Technologies						
Technology Description	Market Size[50] (TBtu)	Technical Potential[51], 2030 (TBtu)	Unstaged Max Adoption Potential[52], 2030 (TBtu)	Staged Max Adoption Potential[53], 2030 (TBtu)	Payback in 2030 (years)	Prioritization Tool Measure Number
Highest Priority: Highly Insulating Windows						
R-10 windows (R)	1,589	1,409	969	760	12	421
R-10 windows (C)	839	599	263	N/A	66	422
Dynamic Window Technologies						
Window attachments (R)[54]	1,380	530	530	528	3	575
Window attachments (C)[54]	842	461	122	122	2	576
Dynamic windows, existing buildings (R)	1,961	1,010	571	164	26	401
Dynamic windows, new buildings (R)	532	212	138	36	33	400
Dynamic windows, existing buildings (C)	947	416	73	31	61	402
Dynamic windows, new buildings (C)	911	308	215	92	57	399
Visible Light Redirection Technologies						
Daylighting (50-ft. floor plate)	682	345	168	126	10	816

[49] Level 1 is defined as early stage R&D (i.e., lab bench scale, beyond basic science), level 2 is defined as late stage R&D (cost reduction and performance improvements still needed, but technology may be available to early adopters), and level 3 is defined as early deployment (energy savings are not yet proven in a whole building context).
[50] Market Size represents the energy consumption associated with a building component (e.g., windows), within a particular buildings market segment (e.g., commercial, residential, new or existing buildings).
[51] Technical Potential assumes existing stock is immediately replaced with the new measure. The technical potential represents the theoretical maximum energy savings available if the technology is implemented in the U.S. buildings sector (free of practical constraints such as financing and deployment considerations).
[52] Unstaged Maximum Adoption Potential (TBtu) assumes a 'stock and flow' model accounting for unit replacement, elimination or addition. The unstaged maximum adoption potential represents the energy savings that would result if the technology is deployed only for all end-of-life replacements and new purchases.
[53] Staged Maximum Adoption Potential (TBtu) assumes that measures with the lowest cost of conserved energy are the first to capture their share of the market to avoid double counting. The staged maximum adoption potential represents the energy savings that would result if the technology is deployed only for all end-of-life replacements and new purchases, and does not include savings that result from other technologies with a lower cost of conserved energy.
[54] Energy-efficient window attachment products, such as low-E storm windows, cellular shades and low-E window films, do exist in the market. But these products have limited market penetration and are in need of market-driving initiatives to accelerate adoption.

Table 35. Prioritization Tool Analysis Results for Select Building Envelope Technologies at Development Levels 1, 2, or 3

Envelope Technologies						
Technology Description	Market Size[50] (TBtu)	Technical Potential[51], 2030 (TBtu)	Unstaged Max Adoption Potential[52], 2030 (TBtu)	Staged Max Adoption Potential[53], 2030 (TBtu)	Payback in 2030 (years)	Prioritization Tool Measure Number
Thermal Insulation Materials						
R-6 sheathing with sealing (R)	1,550	738	738	725	4.2	659
Sheathing with siding, no insulation (R)	620	111	111	52	27	658
Sheathing to exterior installation finishing system (EIFS) upgrade (R)	941	496	496	101	>100	660
EIFS with sealing (R)	1,163	791	791	217	71	657
EIFS R-30 walls (C)	857	547	336	64	25	592
R-30 walls, existing homes (R)	941	785	785	160	>100	591
R-30 walls, new homes (R)	443	277	259	0	5.8	590
VIPs in walls, existing buildings (R)	1,609	1,098	584	55	>100	667
VIPs in walls, existing buildings (C)	855	575	353	0	61	668
VIPs in walls, new buildings (C)	418	215	215	0	>100	808
R-10 slab edge in existing homes (R)	277	213	100	50	12	661
Air-Sealing System Technologies						
Building wrap (C)	479	289	278	80	18	427
Building wrap (infiltration reduction of 40% in 47% of drafty homes) (R)	1,767	706	706	653	6.8	391
Air-sealing systems (infiltration reduction of 10% in commercial buildings (C)	982	44	44	0	5.9	834
Commercial Roofing Technologies						
Increase roof insulation, new buildings (C)	257	129	129	44	19	741
Increase roof insulation, existing buildings (C)	267	90	90	53	4.6	746
Cool Roofs, 0.75 SR, only hottest two U.S. climate zones (C)	1,291	100	100	55	1.9	381

Table 36. Sources and Notes for Prioritization Tool Energy Efficiency Measures

Prioritization Tool Measure Number	Source(s) used for Measure	Relevant Notes
Window Technologies		
399	Lee, E.S., Yazdanian, M. & Selkowitz, S.E. The Energy-Savings Potential of Electrochromic Windows in the US Commercial Buildings Sector. Building 1-42 (2004). Cost: Personal communication - manufacturers and experts Other Supporting Sources: Arasteh, D.; Selkowitz, S.; Apte, J.; "Zero Energy Windows"; 2006 ACEEE Summer Study on Energy Efficiency in Buildings	BTP Tool: Impact from Lee paper scaled to full market Appendix B: ~95 TBTUs savings at 40% market penetration
400	Program Primary Source: Arasteh, D.; Selkowitz, S.; Apte, J.; "Zero Energy Windows"; 2006 ACEEE Summer Study on Energy Efficiency in Buildings Other Supporting Sources: Lee, E.S., Yazdanian, M. & Selkowitz, S.E. The Energy-Savings Potential of Electrochromic Windows in the US Commercial Buildings Sector. Building 1-42 (2004). Cost: Personal communication - manufacturers and experts	BTP Tool: Includes system benefits as cost reduction (i.e., blinds, HVAC) Appendix B: Table 4; adjusted for new building codes
401	Program Primary Source: Arasteh, D.; Selkowitz, S.; Apte, J.; "Zero Energy Windows"; 2006 ACEEE Summer Study on Energy Efficiency in Buildings Other Supporting Sources: Lee, E.S., Yazdanian, M. & Selkowitz, S.E. The Energy-Savings Potential of Electrochromic Windows in the US Commercial Buildings Sector. Building 1-42 (2004). Cost: Personal communication - manufacturers and experts	BTP Tool: Does not include system benefits Appendix B: Table 4; baseline updated to 2010 stock
402	Program Primary Source: Lee, E.S., Yazdanian, M. & Selkowitz, S.E. The Energy-Savings Potential of Electrochromic Windows in the US Commercial Buildings Sector. Building 1-42 (2004). Cost: Personal communication - manufacturers and experts Other Supporting Sources: Arasteh, D.; Selkowitz, S.; Apte, J.; "Zero Energy Windows"; 2006 ACEEE Summer Study on Energy Efficiency in Buildings	BTP Tool: Does not include system benefits Appendix B: ~95 TBTUs savings at 40% market penetration
421	Southwall, Alpeninc, PNNL Lost Opportunities Primary Source: 6. Apte, J. & Arasteh, D. Window-Related Energy Consumption in the US Residential and Commercial Building Stock. Buildings 1-38 (Berkeley, CA, 2006). Personal communication: various window experts Other Supporting Sources: Arasteh, Dariush; Selkowitz, Steve; Apte, Josh; LaFrance, Marc. Energy Impacts of Today' s Window Stock	BTP Tool: Does not include system benefits Appendix B: See tables 4 and 7 for use and savings Calculated from first principles; costs from NREL bottom-up VIG build
422		
575	DOE-EPA Attachmentsindustry presentation; solar-components.com/comfortex.htm Primary Source: Savings: first principles calculation from R- and SHGC- impacts of product Price: Comfortex. Manufacturer & expert interviews Other Supporting Sources: Kotey, N.A., Wright, J.L., Barnaby, C.S., Collins, M.R., "Solar Gain Through Windows with Shading Devices: Simulation versus Measurement," ASHRAE Transactions, Vol. 115, Pt. 2, (2009)	Appendix B: Savings: adding R-value of 1.75 and reducing SHGC to 0.35 Price: Comfortex current prices compressed 1/3rd to represent learning curve
576		Appendix B: Savings: adding R-value of 1.75 and reducing SHGC to 0.35 Price: Comfortex current prices compressed 1/3rd to represent learning curve Market: assumes 50% of windows benefit from attachments
651	Selkowitz, first principles Primary Source: Huang, J. Computer Simulation Analysis of the Energy Impact of Window Films In Existing Houses Selkowitz, S. Personal communication	BTP Tool: Savings only for single pain radiation Appendix B: Tables 12-16 used to generate estimate of population average Simplified to SHGF and used vs. existing baseline Improving SHGF from 0.74 to 0.30 on windows incurring the greatest load
652	Selkowitz, first principles Primary Source: Huang, J. Computer Simulation Analysis of the Energy Impact of Window Films In Existing Houses Selkowitx, S. Personal communication	BTP Tool: Savings only for single pain radiation Appendix B: Tables 12-16 used to generate estimate of population average Simplified to SHGF and used vs. existing baseline Improving SHGF from 0.74 to 0.30 on windows incurring the greatest load
816	Program	Cost calculations: $8/ 1 sqft of window * sqft of window/sqft of floor (0.36) * sqft of floor/ fluorescent lamp (1/0.024). Window to floor ratio: 0.4 * 0.9(space filled by glass) = 0.36; 0.024 lamps/sqft (LMC 2010, NCI: 811 xcl file calc.)

Prioritization Tool Measure Number	Source(s) used for Measure	Relevant Notes
Building Envelope Technologies		
381	eetd.lbl.gov/EA/Reports/40673/, roofcalc.com (broken); Energy Efficiency (2010) 3:53–109; fseer.com/DuroLastFacts.aspx; NEW SOURCE: coolrooftoolkit.org/wp-content/uploads/2012/07/CEC-Non-Res-Cool-Roof-Cost-summary.pdf Primary Source: Konopacki, S., Akbari, H., Pomerantz, M., Gabersek, S. & Gartland, L. Cooling Energy Savings of Light-Colored Roofs for Residential and Commercial Buildings in 11 U.S. Metropolitan Areas. 117 (1997).	BTP Tool: See added sheet at end Appendix B: Supporting calculations in tool
391	Savings and cost is based on RS Mean 2010 data. Other documents: DOE's BTP's Air Sealing Report 2010. Cost: pg. 18 (leaky house - max cost) apps1.eere.energy.gov/buildings/publications/pdfs/building_america/ba_airsealing_report.pdf. NREL measure database. Savings: energystar.gov/index.cfm?c=home_sealing.hm_improvement_methodology	BTP Tool: DQ 0: Experts agree 50% savings is most reflective of typical benefit and cost
427	NREL 46100 building research Primary Source: Elaine Hale, Matthew Leach, Adam Hirsch, and Paul Torcellini, "General Merchandise 50% Energy Savings Technical Support Document"; NREL/TP-550-46100 September 2009	BTP Tool: Peer Review Note: There are some possible ways to drive cost to $3.40/SF. Appendix B: The air barrier is assumed to reduce the envelope infiltration from 0.038 to 0.015 ACH… The cost of the air barrier is estimated at $1.40/ft2 of exterior wall area. MTG2: A few market barriers present.
590	Building Science, research report 0903, LaFrance Primary Source: Straube, J. and Smegal, J.; Building America Special Research Project: High-R Walls Case Study Analysis; Building Science Corporation 2009 (updated 2011)	Appendix B: Costs calculated from manufacturer quotes; savings calculated from first principles
591	Building Science, research report 0903, LaFrance Primary Source: Straube, J. and Smegal, J.; Building America Special Research Project: High-R Walls Case Study Analysis; Building Science Corporation 2009 (updated 2011)	Appendix B: Costs calculated from manufacturer quotes; savings calculated from first principles
592	Building Science, research report 0903, LaFrance and LBNL "Overview of US Building Stock", http://eetd.lbl.gov/ie/pdf/LBNL-43640.pdf	No notes
657	Jan Kośny, Nitin Shukla, and Ali Fallahi	BTP Tool: Savings is weighted average of walls and infiltration Appendix B: Costs calculated from manufacturer quotes; savings calculated from first principles
658	Building Science, research report 0903, LaFrance Primary Source: Straube, J. and Smegal, J.; Building America Special Research Project: High-R Walls Case Study Analysis; Building Science Corporation 2009 (updated 2011)	No notes
659	Building Science, research report 0903, LaFrance Primary Source: Straube, J. and Smegal, J.; Building America Special Research Project: High-R Walls Case Study Analysis; Building Science Corporation 2009 (updated 2011)	BTP Tool: Savings is weighted average of walls and infiltration Appendix B: Costs calculated from manufacturer quotes; savings calculated from first principles
660	Building Science, research report 0903, LaFrance Primary Source: Straube, J. and Smegal, J.; Building America Special Research Project: High-R Walls Case Study Analysis; Building Science Corporation 2009 (updated 2011)	No notes
661	Kanasas: buildersguide.pdf; slab insulation technology factsheet.pdf Primary Source: "A Builder's Guide to Residential Foundation Insulation" King, J.; Meyer, G Other Supporting Sources: FEMP Technology Fact Sheet: Slab Insulation", Southface Energy Institute, Oak Ridge National Laboratory	Appendix B: Supporting calculations in tool take savings calculated from Kansas climate zones then scaled nationally
667	Cost and Performance Data: Kosny, Jan. et al. Cold Climate Building Enclosure Solutions. 2013. Figure 3 & Table 1, nrel.gov/docs/fy13osti/55875.pdf	Target R value of 35; punctured VIP area would be reduced to R22
668	Cost and Performance Data: Kosny, Jan. et al. Cold Climate Building Enclosure Solutions. 2013. Figure 3 & Table 1, nrel.gov/docs/fy13osti/55875.pdf	Cost from Table 1 of nrel.gov/docs/fy13osti/55875.pdf
741	50% Grocery Store TSD (nrel.gov/docs/fy09osti/46101.pdf), 50% Large Office TSD (nrel.gov/docs/fy10osti/49213.pdf), 50% Medium Box Retail (nrel.gov/docs/fy08osti/42828.pdf) Primary Source: Leech, M. et. al.; "Grocery Store 50% Energy Savings Technical Support Document", National Renewable Energy Laboratory (2009) Leech, M. et. al.; "Technical Support Document: Strategies for 50% Energy Savings in Large Office Buildings", National Renewable Energy Laboratory (2010) Hale E. et. al.; "Technical Support Document: Development of the Advanced Energy Design Guide for Medium Box Retail—50% Energy Savings", National Renewable Energy Laboratory (2008)	BTP Tool: Based on upgrade from R-15 to R-30 c.i., cost is average of all 3 TSDs Appendix B: Costs and performance drawn from upgrading ASHRAE code roof insulation to most cost effective point from indicated source R-15 to R-30 upgrade, $0.88/sqft average cost

746	AERG for K-12 Schools (unpublished) Primary Source: NREL. 2011. Advanced Energy Retrofit Guide for K-12 Schools (Draft). EERE Report DOE/GO-102011-3467. Project Lead: Robert Hendron	BTP Tool: Assumes roof replacement is needed. Not close to cost-effective if roof is relatively new. Cost based on removing old roof assembly and replacing insulation with 6-in EPS (R-24). Appendix B: $108,2915 total cost, $59,858 incremental cost for replacing insulating sheathing with R-24 for 210,800 ft2 school in Chicago, Assumes roof is being replaced anyway. Energy savings based on increasing R-14 to R-24 EPS.
808	Cost and Performance Data: Kosny, Jan. et al. Cold Climate Building Enclosure Solutions. 2013. Figure 3 & Table 1, nrel.gov/docs/fy13osti/55875.pdf	Cost from Table 1 of nrel.gov/docs/fy13osti/55875.pdf ; RS means for cost of existing insulation (including installation). Costs for residential and commercial applications are assumed to be the same. (Data saved in supplemental documentation.)
834	Bohac, D. et al. (2013). Leakage Reductions for Large Building Air Sealing and HVAC System Pressure Effects. Minneapolis, MN: Center for Energy and Environment. Accessed July 17, 2013: mncee.org/getattachment/3fb02fdf-6654-4276-b1a2-1294574f482a/ Emmerich, Steve; Persily, Andrew. (2013). "Analysis of the NIST Commercial and Institutional Building Envelope Leakage Database." Accessed November 7, 2013: nist.gov/customcf/get_pdf.cfm?pub_id=913709	As in the Bohac et al paper, this analysis uses a 1.38 CFM75/ft^2 stock average. A cost of \$0.5/ft^2 of floor space is assumed rather than the average cost in the Bohac et al paper (\$0.17/ft^2), which is considered to be limited to "cold climates." In addition, the cost of the ~10% air tightness improvement in the Bohac paper is expected to be less than the cost of a much more substantial reduction in air leakage to the target of 0.25 CFM75/ft^2.
856	NREL measure database; eia.gov/consumption/residential/data/2009/xls/HC10.9%20Average%20Square%20Footage%20of%20U.S.%20Homes.xlsx Primary Source: Savings: first principles (i.e. ,50% target) Cost: NREL retrofit measure database for this performance level	BTP Tool: The average New US homes are 2400 sqft (census.gov/const/C25Ann/sftotalmedavgsqft.pdf); but the average stock is 1971 sqft (Table HC10.9 Average Square Footage of U.S. Homes, By Housing Characteristics, 2009 you can find at eia.gov/consumption/residential/data/2009/xls/HC10.9%20Average%20Square%20Footage%20of%20U.S.%20Homes.xlsx).

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