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DRAFT Research and Development Opportunities Report for Windows

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Disclaimer

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List of Acronyms

BTO	Building Technologies Office
DOE	U.S. Department of Energy
ECM	energy conservation measure
EERE	Office of Energy Efficiency and Renewable Energy
EIA	U.S. Energy Information Administration
GEB	grid-interactive efficient building
HVAC	heating, ventilation, and air conditioning
IGU	insulated glass unit
ISO	independent system operator
LBNL	Lawrence Berkeley National Laboratory
MPC	model predictive control
NFRC	National Fenestration Rating Council
NIR	near-infrared
NREL	National Renewable Energy Laboratory
ORNL	Oak Ridge National Laboratory
PV	photovoltaic
R&D	research and development
SHGC	solar heat gain coefficient
TRL	technology readiness level
uPVC	unplasticized polyvinyl chloride
VIG	vacuum-insulated glazing

Executive Summary

Background

In 2019, buildings accounted for 39.2% of total U.S. primary energy use, with electricity use accounting for 71.1% of building primary energy use [1]. Much of this energy is used to maintain the indoor environment to be comfortable to building occupants. The building envelope consists of transparent and opaque elements that serve as a controllable barrier to help maintain the indoor environment regardless of external conditions. The envelope also allows the exchange of light, air, and other transfers with the external environment when it is beneficial for the building occupants. By leveraging desirable external environmental conditions (e.g., fresh air and natural light) and mitigating the influence of undesirable conditions (e.g., moisture, temperature swings, wind), the building envelope can reduce the need for space conditioning and electric light, and thus reduce energy use associated with lighting and heating, cooling, and ventilation equipment.

The U.S. Department of Energy (DOE) Building Technologies Office's (BTO's) Emerging Technologies program supports R&D for technologies, systems, and software tools that can contribute to reductions in building energy use. Emerging Technologies funding is distributed competitively through solicitations (e.g., Funding Opportunity Announcements and National Lab Calls, which in general are open to applications from industry, academia, national laboratories, and other entities) and other mechanisms.

This document focuses on R&D for windows and window system technologies and will provide guidance for BTO's investments in developing the next generation of high-performance, affordable, cost competitive windows, as well as integrated daylighting and shading technologies in partnership with industry and researchers. This document also addresses areas where DOE invests in software and design tools that translate sophisticated and complex physics into easy-to-use energy performance and optimization methods used by industry and other stakeholders for implementation.

Windows are responsible for about 10% of energy use in buildings and influence end uses that comprise 40% of building energy use (Figure ES-1). Energy use associated with windows varies widely between buildings depending on climate, building vintage, window and glazing characteristics, window/wall ratios, and other factors.

Although windows have a moderate direct energy impact, their biggest impact is on occupant comfort and on peak electricity and natural gas use. Comfort is a major concern in cold climates where poorly insulated windows create extreme radiant discomfort and generate cold drafts from air dropping across the surface of the glass (many consumers report that it feels as if the windows are open or have very large edge gaps). In hot summers, with static glass optical properties, occupants in perimeter zones may be thermally uncomfortable even with conventional blinds and shading installed. Providing consistent visual comfort can be a challenge in all climates throughout the year on any sunny day and for other bright sky conditions. The highly insulating and dynamic solar control core technological solutions can solve these problems in all residential and commercial buildings independent of climates, and have the potential to save more than 4 quads of energy by offsetting some lighting energy loads in addition to virtually all the window energy loads.

Opportunities and Challenges

Modern windows provide improved thermal performance, including reduced air leakage, but also offer enhanced amenities such as daylight, views to the outdoors, and natural ventilation. Optimizing the energy performance of windows requires taking into account heat conduction, convection, and radiation while also ensuring that aesthetic considerations are satisfied. Opportunities exist in improving window glazing, gas filling, vacuum insulation, insulating frames, and air infiltration/exfiltration. Furthermore, improvements to dynamic facades and glazing, fixed and operable attachments, and daylight redirection can significantly increase the value of window systems.

BTO's Windows Program has played a major role in the development and the high market adoption of low-emissivity glass and improved frame performance that has resulted in today's typical ENERGY STAR® windows being two to three times better performing than windows installed in the 1980s (Figure ES-2) [3]. The Windows Program also played a key role in the development of dynamic glazing and the highest thermally performing windows on the market, which offer dramatic improvements over ENERGY STAR windows with static solar control. However, further R&D is needed to achieve the next level of performance and affordability.

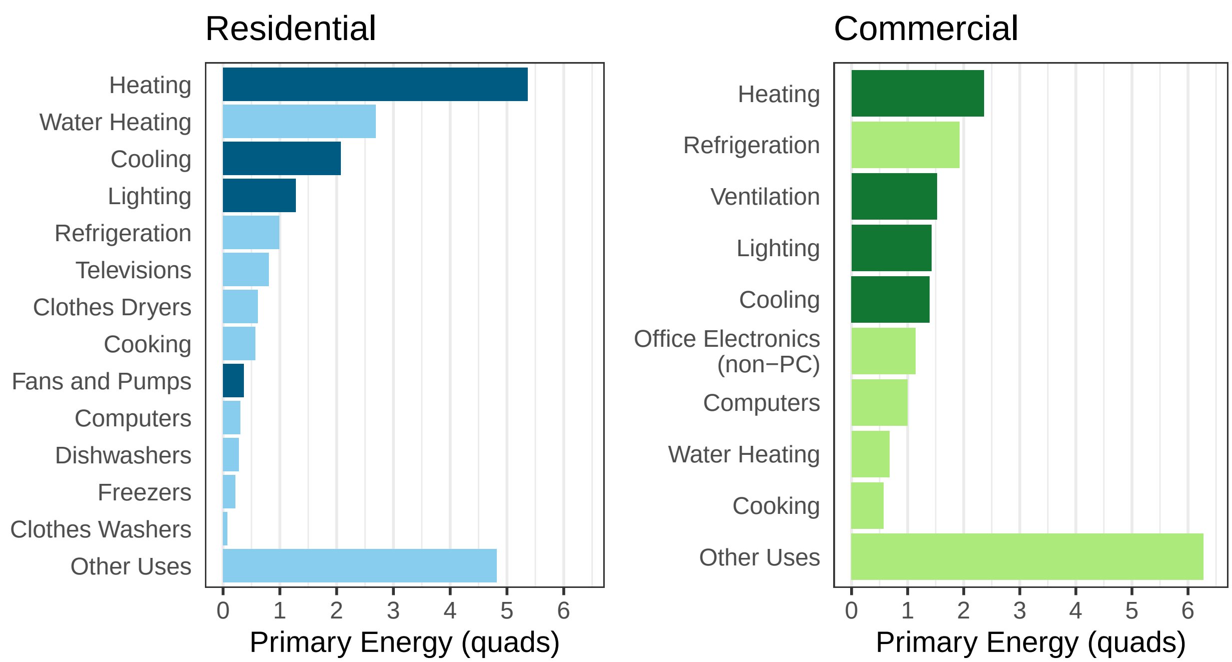

Figure ES-1. Windows affect end uses (highlighted with darker bars) that comprise about 40% of building energy use and lead directly to 10% of building energy use, corresponding to almost 4 quads of primary energy use (see Figure 3).
Data from the EIA 2018 Annual Energy Outlook [2].

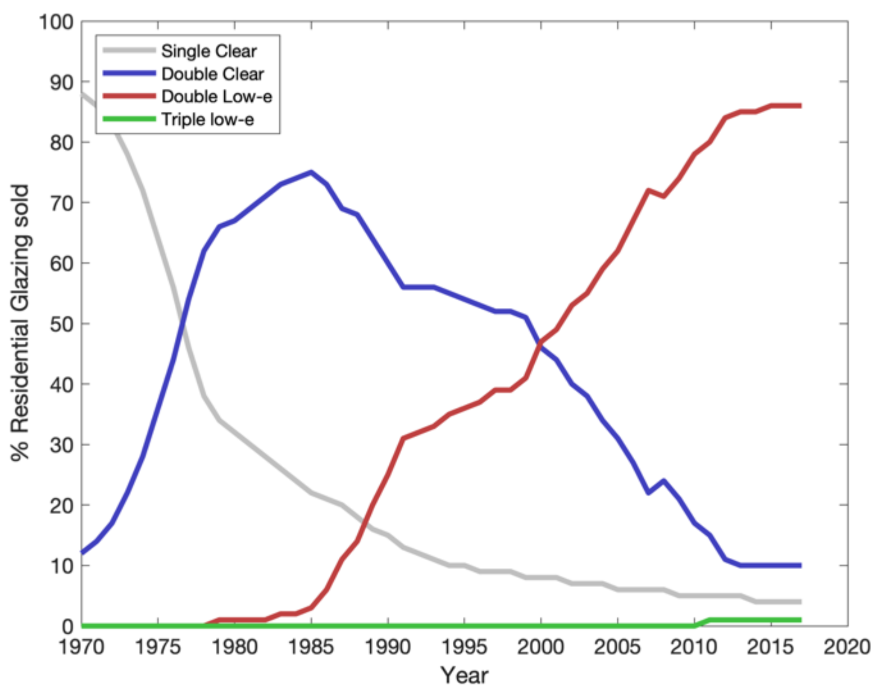

Figure ES-2. Market share by glazing type; triple pane is still 2%.
Figure from Selkowitz, Hart, and Curcija [4].

R&D is needed to enable next-generation windows that have the same thermal performance of most existing buildings' insulated walls,[1] while also harvesting passive heating contributions in winter and rejecting unwanted solar heat gain in summer. An R-10 window with dynamic glazing has the ability to be energy positive in many climates, thus resulting in buildings with less energy use than if they did not have any windows at all.

Additional opportunities exist for whole-building modeling software tools to better capture the energy and nonenergy impacts of window features, and to allow for outputs to be readily incorporated into building design workflow, as well as building operation. Today, the overwhelming majority of U.S. windows are designed using DOE/Lawrence Berkeley National Laboratory (LBNL) software tools that enable performance improvements to be assessed and incorporated with much less impact compared to the days of building costly prototypes.

Future Technology Development

R&D, including new material discovery, novel technological approaches, as well as applied engineering, is key to addressing many of the performance and cost challenges faced by industry to produce highly efficient affordable windows that can achieve mainstream market acceptance. These technologies are generally expected to offer significant energy savings compared to the current cost-effective technology, but they also have other energy and nonenergy benefits—reduced peak load, time-shifted envelope-related thermal loads to match distributed renewable generation availability, reduced glare, increased thermal comfort, and improved occupant satisfaction and productivity.

High-performance windows are crucial to achieving low-energy buildings. Modifications to the frame, advanced glazing packages, and subcomponents are essential to achieving window performance that can surpass ENERGY STAR performance by more than three times. These include advanced glazing (e.g., thin triple or vacuum-insulated glazing [VIG]), higher-performing inert gas fills (e.g., krypton), or replacing the fill with a transparent low-conductivity solid material and developing highly insulated window spacers and frames (Figure ES-3).

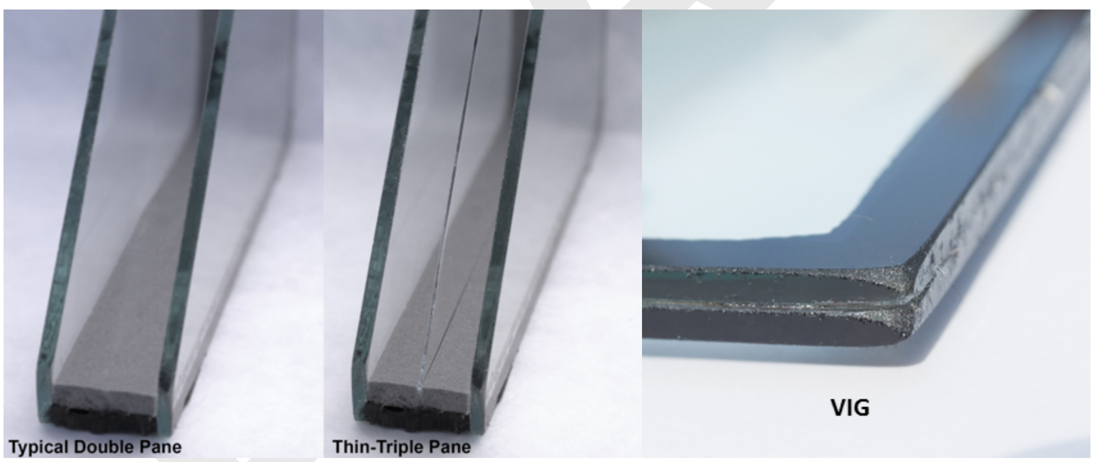

Figure ES-3. Thin-triple pane glazing requires production engineering and will fit in about 80% of existing frames; VIGs need extensive R&D to become affordable and practical.
Photos courtesy of LBNL.

For this document, modeling has helped establish price and performance targets for residential and commercial windows. Table ES-1 summarizes these targets, which were guided by an energy savings analysis that includes future energy prices, building replacement and new construction rates, window replacement rates, and projected baseline ("business-as-usual") improvements in window performance. The targets are based on energy savings estimates under a technical potential scenario, which assumes immediate national adoption of the specified high-performance windows and thus represents an upper bound on total energy savings potential.

This analysis used energy savings and the resulting utility bill savings with varying simple payback targets to determine market-acceptable price premiums for given window performance levels. The savings estimates from this

[1] Many walls have R-11 or R-13 cavity insulation, and with structural thermal shorts have only R-10 or lower performance.

analysis yield the following results: to be cost-effective in residential buildings, windows can have a total installed price premium of \$1.80/ft^2 window area for R-6 windows (assuming a 5-year payback period), ranging to a total installed price premium of \$5.60/ft^2 window area for R-13 windows (assuming a 10-year payback period). These varying cost-effectiveness thresholds, defined using simple payback, allow for a range of financing mechanisms for residential buildings to amortize the cost of window upgrades. For commercial buildings, total installed price premiums range from \$3.90/ft^2 window area to \$11.90/ft^2 window area for R-6 to R-10 windows assuming an acceptable payback range of 3 to 7 years, respectively.

The difference between residential and commercial window installed price premiums is a result of the lower performance of existing commercial windows compared to residential windows and the low rates of window performance upgrades in commercial buildings. The lower performance level of the existing window stock yields much larger per-building energy savings from upgrades in commercial buildings versus residential buildings (e.g., from R-2 to R-10 versus R-3 to R-13), thus yielding better cost-effectiveness at higher installed prices. These targets are based on stock-wide performance, including both new construction and existing buildings. In general, upgrading existing buildings with new high-performance windows yields much greater energy savings compared to newer construction. Accordingly, primary energy savings decrease between 2030 and 2050 because of the gradual replacement of some older buildings with new construction that, by default, meets or exceeds projected future building energy codes. As a result, these new buildings deliver less savings with a given upgrade (e.g., to R-6) than existing buildings.

Table ES-1. Whole-window performance and installed price premium targets are based on two cost-effective payback periods (5–10 years for residential and 3–7 years for commercial buildings) and the corresponding primary energy savings for the upper end of the performance range in 2030 and 2050.

Windows						
Building Sector	Performance		Installed Price Premium		Primary Energy Savings (quads)	
					2030	2050
Residential	6–13	R-value	1.8–5.6	\$/ft^2 window area	1.28	1.07
Commercial	6–10	R-value	3.9–11.9	\$/ft^2 window area	0.93	0.72

Dynamic facades and glazing with variable solar heat gain control characteristics in response to diurnal and seasonal changes in heating and cooling demand, occupancy, and available daylight can substantially lower energy use compared with static glazing. With the same target payback period as static high-performance windows, dynamic glazing with an operating range between 0.05 and 0.65 solar heat gain coefficient are \$2.90/ft^2 window area for residential buildings and \$14.60/ft^2 window area for commercial buildings by 2030. Longer investment periods would allow for higher price premiums, though those longer investment periods might only be feasible for some building owners. If all of these price and performance targets are successfully realized by 2030 and if the technologies are applied to the entire stock by 2050, annual U.S. primary energy savings would approach 4 quads, or more than 4% of total U.S. energy use.

Novel approaches that rely on low-cost, high-throughput production methods could reduce product costs and expand availability of dynamic glazing along with holistic building systems that can allow for longer investment scenarios. Self-powering systems (e.g., using photovoltaic [PV] cells) for automated attachments and dynamic glazing would reduce installation and construction complexity while also avoiding additional ongoing maintenance costs. Additionally, improved control methods such as model predictive control and adaptive models using sensor inputs, user feedback, or machine learning algorithms can be used to improve energy-efficiency performance and user satisfaction over the life of the installation (Figure ES-4).

Visible light redirection increases the usability of available natural light to illuminate interior spaces. The calculated installed price based on a technical potential scenario for light redirection systems, assuming 40% lighting energy savings, is \$13/ft^2 window area added into existing windows. Light redirection systems must be designed so that they avoid glare and thermal discomfort while still being aesthetically pleasing, and they usually require integration with sensor and controls to turn off electric lighting when not needed. Technologies that do not depend on sidelighting for visible light redirection have the potential to be effective for spaces with low or otherwise incompatible ceilings and for windowless interior space.

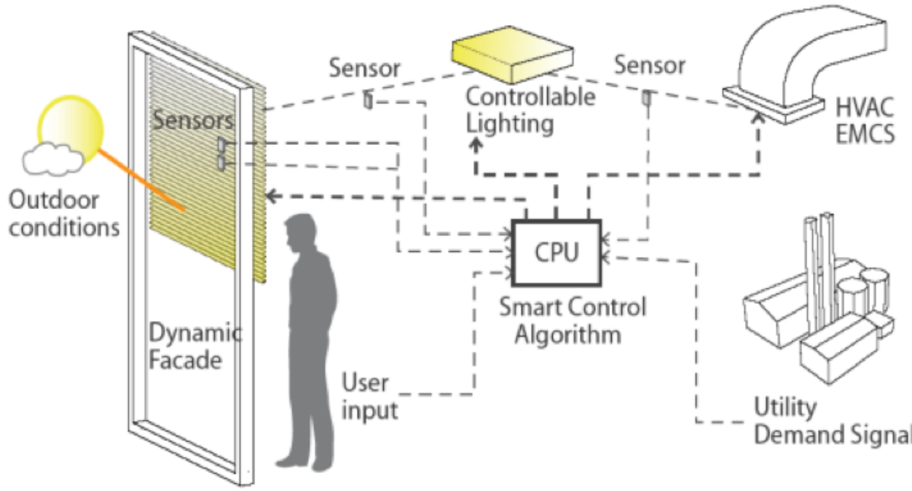

Figure ES-4. Dynamic window systems can be fully integrated with building energy management systems.
Figure courtesy of LBNL.

Integration

The integration of advanced windows and integrated window system technologies into a building can be improved by the consideration of holistic system-level strategies as well as incorporating technologies and business practices from other industries. Window and opaque envelope features that can deliver energy savings also affect building occupants and the operation of major building subsystems, including space conditioning, ventilation, and lighting.

In residential buildings, advanced windows can allow for the downsizing of mechanical equipment and eliminate the need to run ductwork to the perimeter, typically installed above or below windows. Improved comfort and reduced peak cooling are additional benefits of advanced windows with appropriate solar control, and dynamic solar control can also offer passive heating in winter. Replacement of older windows can be a challenge because of high cost, but during major renovation, integration with wall systems can allow for entire home renovation that may also lead to increased property values. Thus, whole-house integrated solutions may offer increased financial viability and affordability that can be justified based on financing at the time of purchase or refinancing for upgrade, where the energy savings are greater than the increased monthly expenditures. These approaches are consistent with BTO's new initiative on Advanced Building Construction Technologies and Practices (ABC),[2] which seeks automation in whole building design and renovation.

Commercial buildings also have significant opportunities for integration that help improve comfort and reduce heating, ventilating, and air-conditioning (HVAC) system capacities. A major benefit is the ability to harvest natural daylight through automated solar control, including dynamic glass and window shades. Integrated facade and electric lighting systems have been validated to save significant energy while reducing peak electricity loads by more than 30%. System-level approaches can be pursued during design for new construction, which offer the greatest financial benefit, but they also can play a key role in building renovation. For example, secondary glazing systems can be incorporated as an upgrade to existing buildings without disrupting occupants. Solutions today include low-e glass panels (i.e., storm windows), but in the future they could include dynamic and vacuum glazing. Such windows could dramatically improve the thermal and optical performance of large glass facades, and the avoided cost of full HVAC replacement can help offset window upgrade costs.

Energy used at different times and locations will vary in cost and impacts according to the fuel used, market structures, and technological constraints. For electricity, the increasing penetration of variable renewable energy generation suggests a long-term need for additional flexibility to facilitate balancing supply and demand. Active control of building electric loads could provide demand-side flexibility. BTO is developing a new strategy to elaborate the

[2]For more information, see: https://www.energy.gov/articles/doe-announces-335-million-energy-efficient-advanced-building-construction-technologies.

potential for buildings to provide grid services through demand flexibility, which complements BTO's continuing focus on energy savings [5]. Buildings that can automatically and dynamically adjust the timing of their energy in response to electric grid needs might also receive remuneration for their provision of beneficial grid services, and this could be an important value for window and shading with dynamic solar control.

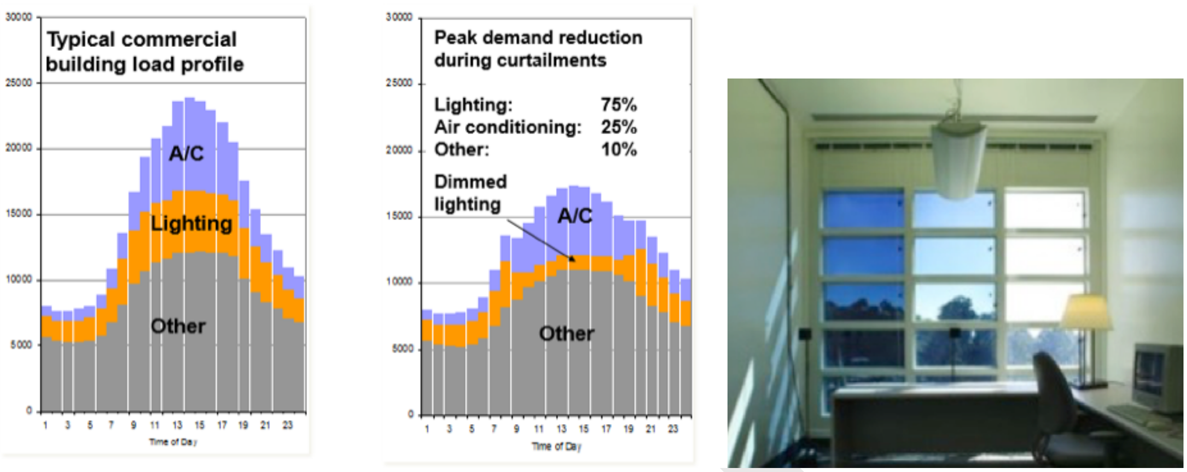

Figure ES-5. Dynamic glazings have been field validated and have shown significant potential in reducing peak electricity demand, reducing total annual energy use, and improving comfort.
Figure from Rubinstein and Kiliccote [6] and photo courtesy of LBNL, Test Facility 71T.

Implementation

To realize the energy savings potential of novel technologies developed for windows, these technologies must be brought to market by companies that can market, sell, distribute, and support them. Beyond window technology development, BTO conducts technical field validation of advanced windows in collaboration with industrial partners. DOE also supports technical analyses to enable stakeholders to pursue downstream market activities. The building construction and window industry in the United States is a mature market with significant inertia; fundamental changes take time. Prevailing construction and building retrofit market conditions and adjacent factors can create significant barriers to technology uptake. These barriers can be financial, knowledge-related, or implementation-related. Approaches to addressing these barriers can include a range of voluntary actions, marketing and information sharing strategies, and policy interventions by stakeholders as well as technical assistance to enable industry and other stakeholders. Although the market is slow to mature, past BTO window successes have matured and today's window industry is producing much higher-performing products because of this federal investment. Key market studies have estimated the economic value of the energy savings as a result of double pane low-e (e.g., ENERGY STAR) high market share to be $150 billion [7]. The potential for dramatic improvements in the future is likely with continued technical innovation.

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1 Introduction

1.1 Buildings and Their Contribution to U.S. Energy Use

Modern buildings require energy: to provide occupant comfort, operate appliances and devices, and illuminate interior and exterior spaces. The building services provided through energy use are central to the purposes that buildings serve in our society. In 2018, residential and commercial buildings in the United States used 20.4 and 18.3 quadrillion Btu (quads), or 20.6% and 18.5% of total U.S. primary energy use, respectively [2]. As shown in Figure 1, residential and commercial buildings together represent more domestic energy use than either the industrial or transportation sectors. On a primary energy basis, electricity comprises a majority of building energy use: 27.8 quads or 71.9% of all building energy use [2]. Direct natural gas use in buildings is limited to only a few end uses, such as heating, water heating, and cooking, but still represents 8.4 quads or 21.6% of primary energy use in buildings [2]. Other petroleum fuels and renewable generation[3] provide the remaining 6.5% (2.5 quads) [2].

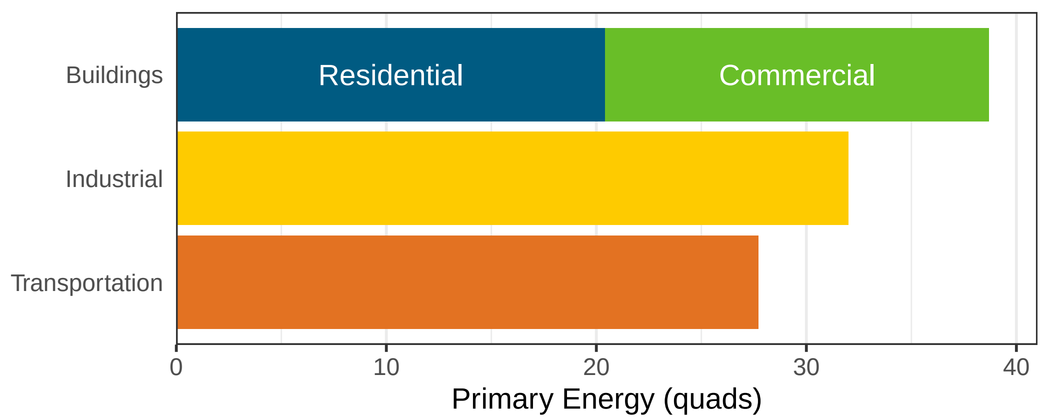

Figure 1. Residential and commercial buildings together are the largest single sector of U.S. primary energy use.
Data from the U.S. Energy Information Administration (EIA) 2018 Annual Energy Outlook [2].

The breakdown of energy use among building services and devices (i.e., end uses) for an individual building can vary widely depending on the building type or function, square footage (size), local climate, and many other factors. More generally, the division of U.S. buildings' energy use among end uses differs between residential and commercial buildings, as shown in Figure 2. For residential buildings, energy use is dominated by space conditioning—heating and cooling—comprising 7.8 quads, or 38% of total residential energy use [2]. Water heating (2.7 quads, 13%) and lighting (1.3 quads, 6.3%) are also significant contributors, and together with space conditioning, represent more than half of total residential energy use [2]. In commercial buildings, space conditioning and mechanical ventilation together remain the dominant end use (5.3 quads, 29%) [2]. Lighting is also a significant contributor to primary energy use that is relevant to windows, representing 1.4 quads or 7.8% of the total in commercial buildings [2].

1.2 Influence of Windows on Building Energy Use

Both transparent and opaque components of the building envelope protect building occupants from undesirable external environmental conditions. Some envelope elements can also be configured to take advantage of desirable external conditions by allowing visible light, infrared radiation, or air to pass through. Both strategies—leveraging desirable external environmental conditions and mitigating the influence of undesirable conditions—can reduce the need for space conditioning and electric lighting, and thus reduce energy use associated with lighting and heating, cooling, and ventilating equipment.

High-performance windows, such as those discussed in this report, have substantial potential to reduce energy use in buildings. Data in Figure 2 show that 34% of U.S. buildings' primary energy use is from space heating and cooling.

[3] Renewable generation in this context includes biomass, solar thermal, solar PV, and wind energy [2].

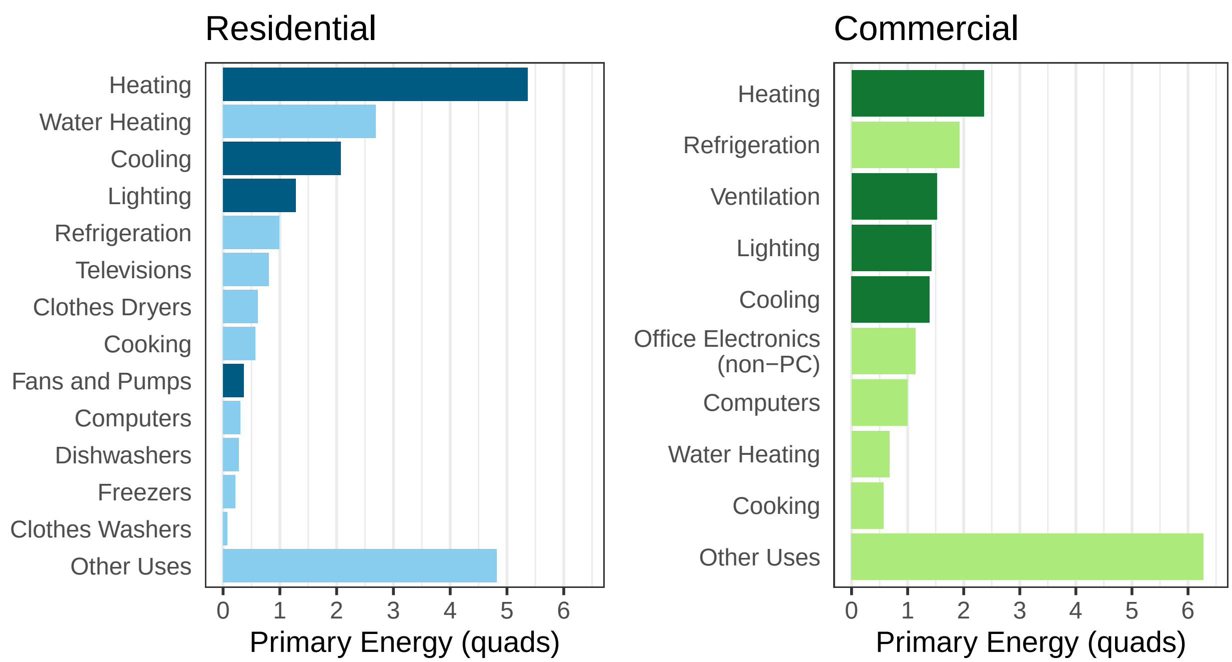

Figure 2. Apart from "other uses," heating is the largest single end-use contributor to total primary energy use in both residential and commercial buildings. When all space conditioning-related end uses—heating, cooling, fans and pumps, and ventilation—are taken together, they represent significantly more energy use than any other end use. These end uses (along with lighting, to a lesser degree), highlighted with darker bars, represent the energy use that can be reduced with performance improvements in windows. Data from the EIA 2018 Annual Energy Outlook [2].

Figure 3 shows the breakdown of that energy use by envelope component, both windows (through heat conduction and solar heat gain) and the opaque envelope.[4] The opaque envelope is represented by the major building elements where sensible heat transfer[5] occurs—the roof, walls, and foundation. Air and moisture flows that carry sensible and latent heat into or out of the building (denoted by "infiltration") pass primarily through interfaces between components, such as around window sashes and frames, between window frames and rough openings, between walls and the roof and foundation, and around miscellaneous penetrations through the opaque envelope (e.g., ducts and electrical outlets). Based on the data shown in Figure 3, for both residential and commercial buildings, the components that offer the greatest opportunity for energy savings (represent the largest contributors to energy use) are infiltration, walls, and conduction through windows. The data shown in Figure 3 represent U.S. totals, and the balance of energy use among envelope components varies by climate zone. For example, solar heat gain through windows reduces net HVAC energy use in heating-dominated climates, but not in cooling-dominated climates. These data do not include the potential lighting energy savings from the management of visible light available from windows or skylights to offset electric lighting needs ("daylighting").

Taken together, windows for new construction and for retrofits of existing buildings represent a substantial market in the United States, as shown in Table 1. Notably, in residential buildings, the retrofit market is already larger—by number of units sold—than the new construction market. Novel technologies that are appropriate for retrofits are therefore especially relevant to the current market. In commercial buildings, new construction dominates, but retrofits still comprise one-third of the total market. Technologies that can reduce the price of commercial building window retrofits or expand the nonenergy benefits of replacement windows might help increase the uptake of new

[4] These data do not account for the potential for daylighting to reduce lighting loads.
[5] "Sensible heat" denotes heat transfer that causes the temperature of the system to be increased or decreased. "Latent heat" denotes heat transfer that occurs without a change in temperature; it relates to the difference in how a 90°F day feels in Phoenix and Atlanta. In the context of the building envelope, this type of heat transfer is associated with the movement of water vapor (i.e., changes in humidity) through the opaque envelope.

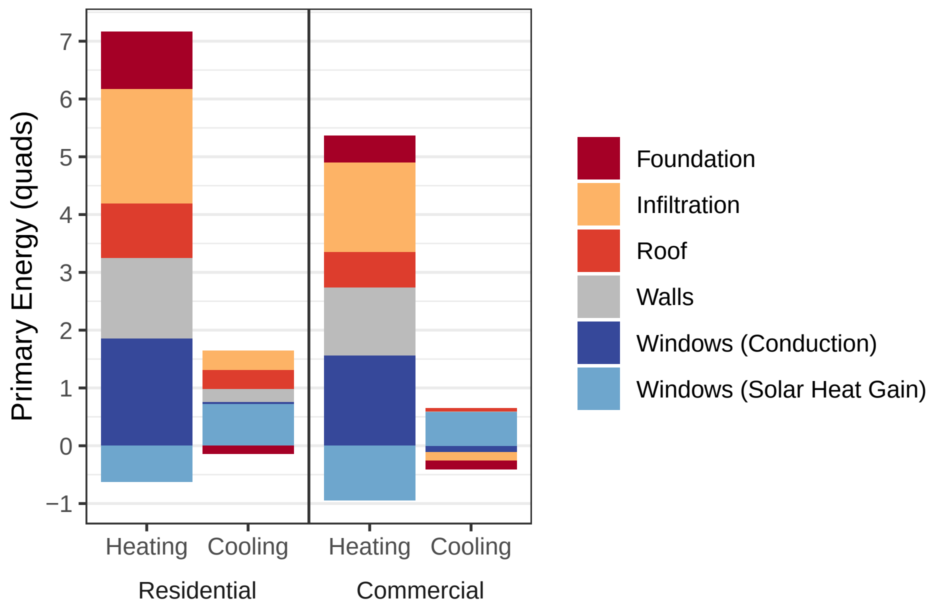

Figure 3. The breakdown of energy use by building envelope component in residential and commercial buildings during the heating and cooling seasons shows that the opaque envelope is the single largest contributor to envelope-related energy use, followed by infiltration (and exfiltration) and heat conduction through windows. Bars with negative values represent component contributions that reduce energy use (e.g., solar heat gain through windows in the heating season). Data from Scout [8].

Table 1. The breakdown of window sales by millions of units (residential) and million square feet (commercial) shows that although both sectors have some sales to existing buildings, the retrofit market share in commercial buildings lags significantly behind that of residential buildings. Data from the American Architectural Manufacturers Association [9].

	Residential (10^6 units)	Commercial (10^6 ft^2)
New Construction	21.4	306
Existing/Retrofit	27.6	152
Total	49.1	458

windows as part of commercial building retrofit projects. Of particular interest, 105 million square feet of the 458 million square feet of commercial windows delivered in 2016 were for curtain wall systems [9].

The composition of the building stock changes over time as new buildings are built and some old buildings are demolished, but the turnover rate (accounting for demolitions and new construction) of the U.S. building stock is relatively slow, particularly for residential buildings. Figure 4 shows the effect of building turnover rate on the prevalence of “existing” buildings (built before 2018) and “new” buildings (built in or after 2018); residential buildings are shown by housing unit and commercial buildings by available square footage. Because windows, air and water-resistive barriers, and insulation are built into the envelope at the time of construction, it is generally easiest to augment the energy performance of the envelope during initial construction.

Though it might be easiest to incorporate high-performance envelope components in new construction, the data in Figure 4 highlight the importance of developing envelope technologies that are also suitable for retrofit of existing buildings. By 2050, these data indicate that slightly more than half of the commercial square footage existing today will have been replaced, while only one-third of residential units will have been replaced, and in the interim period, existing buildings will dominate the building stock. Moreover, these data do not account for which buildings are

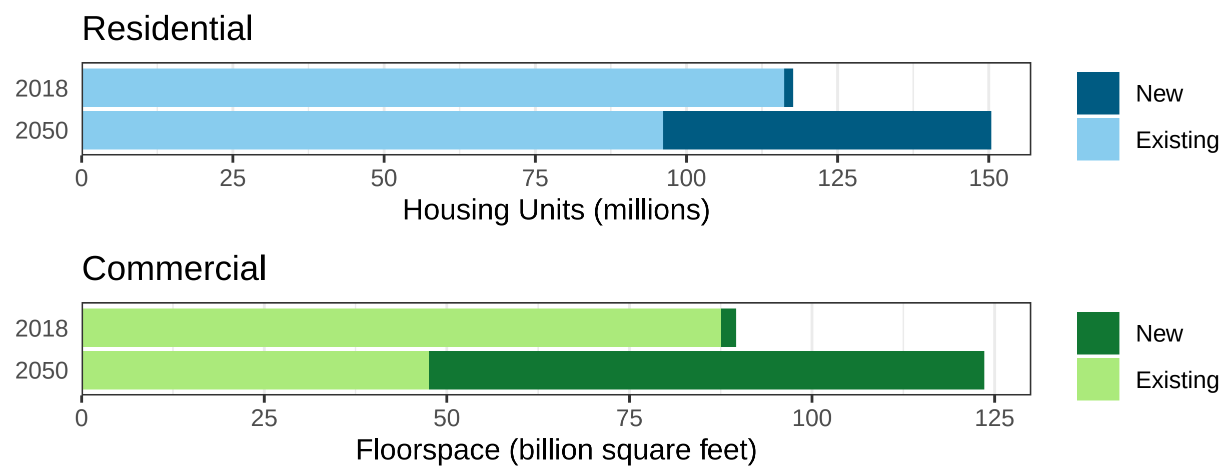

Figure 4. To maximize energy savings, new technologies must be suitable for retrofitting existing buildings, particularly in the residential sector, where by 2050, nearly two-thirds of the building stock will still be composed of "existing" buildings—those built before 2018. The remainder of the stock, represented as residential housing units and commercial square footage, will be buildings that were built after 2018. Commercial buildings turn over somewhat faster than residential buildings, but even then, in 2050, approximately 40% of square footage existing in 2018 will remain in the stock.
Data from the EIA 2018 Annual Energy Outlook [2].

Table 2. Windows/doors and roofs are replaced at rates comparable to HVAC systems, though with widely differing median project sizes. Siding projects can come with larger median expenditures, but are performed less frequently than other upgrades. Insulation projects are conducted somewhat more often, though both the number of projects and median expenditures lag other categories.
Data from U.S. Census Bureau [10].

	Number of Projects (10^6)	Median Expenditure
HVAC	5.2	$3,150
Insulation	1.8	$750
Windows/Doors	4.3	$1,500
Roofing	4.0	$5,500
Siding	1.1	$3,000

being replaced, so it is possible that the buildings being turned over are newer buildings and the data in Figure 4 underestimate the size of the existing stock.

While Figure 4 shows overall stock turnover, Table 2 shows the approximate number of retrofits of various envelope components in millions of owner-occupied housing units in 2015. These data show that some retrofits, particularly those that involve key critical structural or life safety components (e.g., roofs) are pursued more frequently, in spite of their high prices, than retrofits to insulation or siding that might be principally to improve aesthetics or thermal comfort. HVAC systems are shown as a cost and scale point of comparison to underscore that although HVAC systems must often be replaced because of major mechanical faults, other envelope components are also regularly replaced. The replacement of envelope components at a rate that approaches or even exceeds the total number of new housing units built each year suggests that there might be meaningful opportunities for package retrofits that simultaneously repair or replace a major envelope component and improve energy performance. Table 3 shows renovation data for commercial buildings in 2012. These data show similar relationships between upgrade rates for different envelope components, where roof replacements occur at rates comparable to HVAC system upgrades and replacements, while insulation upgrades lag behind.

Novel approaches discussed in this report have the potential to increase the retrofit rates or adoption of envelope energy performance upgrades for existing buildings by addressing the labor requirements (and concomitant price

Table 3. Among commercial buildings constructed before 2008, roof replacement occurred at a rate nearly comparable to HVAC system upgrade or replacement. Other envelope upgrades were less prevalent, led by windows and followed by insulation upgrades and other exterior wall renovations.
Data from EIA Commercial Buildings Energy Consumption Survey [12].

	Number of Buildings (10^6)	Percentage of Pre-2008 Buildings
HVAC	1.10	21.0%
Insulation	0.38	7.2%
Windows	0.56	10.7%
Roof	0.99	18.8%
Exterior Walls	0.19	3.7%

implications), disruption to building occupants, and other factors that currently limit the frequency of window replacements. Furthermore, in many cases window replacement is not an option, but window attachments such as low-emissivity—or "low-e"—energy panels (storm windows), cellular shades, low-e window films, and a large variety of shading products can be added to existing windows to improve performance. Recently, the U.S. Department of Energy (DOE) supported the formation of the Attachment Energy Rating Council, which has developed initial product ratings and is continuing to add more product categories [11].

1.3 DOE Building Technologies Office

Research supported by the Building Technologies Office (BTO) is focused on reducing energy intensity and cost for technologies across the buildings sector, while maintaining or enhancing occupant comfort, productivity, and product performance. In essence, a building must use energy more productively and efficiently, not only use less energy. Progress toward achieving this goal will make building energy costs more affordable—especially beneficial to U.S. families and businesses.

BTO's approach to improving energy productivity includes its grid-interactive efficient building (GEB)[6] strategy, which advances the role buildings can play in energy system operations and planning. This strategy includes both new and existing residential and commercial buildings, including their energy-consuming and labor-saving equipment. BTO's strategy will support greater affordability, resilience, environmental performance, reliability, and other goals, recognizing that:

- Building end uses can be dynamically managed to help meet grid needs and minimize electricity system costs, while meeting occupants' comfort and productivity requirements;
- Technologies like rooftop photovoltaics, electrochemical and thermal energy storage, combined heat and power, and other distributed energy resources (DERs) can be co-optimized with buildings to provide greater value and resiliency to both utility customers and the electricity system; and
- The value of energy efficiency, demand response, and other services provided by behind-the-meter DERs can vary by location, hour, season, and year.

Developing next-generation building technologies, including building materials, components, equipment, energy models, and systems, is critical to increasing energy productivity cost-effectively.

To achieve these objectives, BTO sponsors R&D efforts that target improving the largest energy uses within buildings (shown in Figure 2): lighting, space conditioning, water heating, appliances, and miscellaneous electric loads, as well as building envelopes. BTO's R&D support also includes systems-level initiatives, including developing algorithms for improved energy modeling and system controls required to better predict and manage energy-efficient equipment and whole-building energy usage, particularly to enable grid-responsive operations.

[6] A grid-interactive efficient building is an energy-efficient building that uses smart technologies and on-site distributed energy resources to provide flexibility while co-optimizing for energy cost, grid services, and occupant needs and preferences, in a continuous and integrated way. For more information, see the recent *Grid-interactive Efficient Buildings Technical Report Series*. The *Overview of Research Challenges and Gaps* report can be found at https://www1.eere.energy.gov/buildings/pdfs/75470.pdf and contains introductory information as well as links to the other four technical reports in the series.

BTO collaborates with industry, academia, and other leaders across the building sector to develop, validate, and verify solutions that help building owners and homeowners reduce energy use. Ultimately, design and decision tools developed with BTO support help building owners and operators apply efficient building operational practices and technologies through improved understanding of their costs and benefits, resulting in more cost-effective, comfortable, and healthy buildings.

Lastly, BTO works with industry, professional societies, trade groups, and nonprofits such as ASTM International and ASHRAE to develop and implement methods to evaluate and validate the energy performance of building components. BTO also evaluates changes to model building energy codes developed by ASHRAE and the International Code Council, which inform state and local building code processes.

1.4 BTO Emerging Technologies Program

The BTO Emerging Technologies program supports R&D for technologies, systems, and software tools that can contribute to improving energy efficiency and load flexibility. The Emerging Technologies program provides R&D support in five primary areas: solid-state lighting, HVAC and refrigeration (including water heating and appliances), sensors and controls, windows and envelope, and modeling and tools. The majority of Emerging Technologies funding is distributed competitively through solicitations (i.e., Funding Opportunity Announcements), which in general are open to applications from large industry, small businesses, academia, national laboratories, and other entities. BTO also invests in state-of-the-art capabilities at DOE national laboratories that support its mission; these facilities are available to the buildings R&D community for cooperative research, component evaluation, and product performance validation. The Lawrence Berkeley National Laboratory (LBNL) has been designated the core window energy performance laboratory and the National Renewable Energy Laboratory (NREL) has been designated as the enabling laboratory for window durability.

The Emerging Technologies program contributes to BTO's energy use intensity reduction objective by supporting the development of cost-effective, energy-efficient technologies. Broadly, to make significant progress toward the program objective, any next-generation window technologies must achieve widespread adoption. As a result, specific emphasis is placed on developing technologies that will have market-acceptable characteristics, including payback period and total installed price, aesthetics, durability, and sustained energy performance over the lifetime of the technology.

1.5 Organization and Purpose of this Report

This report focuses on R&D opportunities for energy-efficient window technologies. It is the result of collaboration with prominent researchers and leaders in the field and aims to provide strategic guidance for BTO's investments in developing the next generation of high-performance, cost-competitive windows.

The R&D opportunities identified in this report are predicated on an assessment of the need for improvements in the performance of windows. This assessment is included in Section 2, "Current Technologies—Opportunities and Challenges," and it provides the motivation for the fundamental and enabling research areas identified in Section 3, "Future Technology Development." Section 3 includes a discussion of the current state of research, future research opportunities, technology-specific performance metrics, and the associated national energy savings potential. Technical, manufacturing, and market risks are also noted briefly in Section 3. The final two sections address topics that are important to the successful market entry of the technologies in Section 3. Section 4, "Integration," addresses two opportunities to fully realize a broader value proposition for envelope technologies: the adoption of a systems-level approach to new building design and deep retrofit planning, and the application of envelope technologies to benefit electric grid operations. Section 5, "Implementation," examines the technology transfer landscape as it relates to moving technologies from early-stage R&D to market-ready, commercially available products. Section 5 discusses the roles of industry, academia, national laboratories, and other public- and private-sector entities alongside BTO, with a particular focus on accelerating the handoff of technology R&D from BTO to its private-sector partners.

This report is a reconsideration of the technology R&D opportunities, technical risks, and deployment barriers in the 2014 roadmap report [13]. Many of the technology R&D opportunities discussed in this report are also mentioned in the 2014 document. This report seeks to build on the earlier effort by broadening the discussion of technical needs and opportunities and moving that discussion forward to fully encapsulate the R&D technology directions detailed in Section 3. This report also goes beyond the 2014 report to address system-level impacts, load flexibility, grid interaction, and resilience.

This report does not provide an exhaustive presentation of all of the R&D opportunities related to windows. The research opportunities presented in this report are seen as the most promising and impactful as they relate to national energy savings, consumer benefits, technical risks, and other factors that might affect the suitability of these R&D opportunities for future investment. This report includes some discussion of manufacturing risks, market barriers, and other concerns not directly tied to R&D, but it does not include an extensive treatment of these factors, only so much as is needed to provide context for and a robust appraisal of the various research opportunities presented. Similarly, because the focus in this document is on R&D program strategy, regulatory programs and incentive or rebate design are beyond our scope.

By articulating opportunities of particular importance and potential energy use impact, and the barriers inhibiting their progress, this report may help 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.

Successful research, development, market entry, and widespread adoption of novel window technologies requires sustained, long-term, high-risk research investment. Collaboration between academia, national laboratories, government, and private industry is critical to achieving these objectives. This report is intended to be a resource to assist in this process, not just for BTO, but for the range of entities involved in the development and deployment of these technologies—state and local governments; utilities; academic, national laboratory, and private-sector researchers; international organizations; and others—and as such it will continue to be refined and updated as the market develops and as technology matures.

2 Current Technologies—Opportunities and Challenges

This section outlines the challenges of existing window technologies and the opportunities for R&D and novel technology development to address these challenges. These challenges include not only technology characteristics that directly affect energy use at the component level, such as thermal conductivity, but also factors that might influence total U.S. long-term energy savings potential by reducing or increasing technology adoption, such as installation price, quality control and repeatability, durability, and retrofit suitability, among others. This discussion of challenges, which is structured by technology area, provides the motivation for future technology R&D and outlines the potential impact that improvements in these technology areas could have on occupant comfort, durability, and building energy use. A summary of the major challenges and opportunities by opportunity area, corresponding to the subsections within this section, is given in Table 4. Section 3 describes the specific improvements to be made, novel technologies to be researched, and supporting tools to be developed to address these challenges.

Table 4. Each opportunity area in this section articulates specific opportunities and challenges faced by the current state-of-the-art that should be targeted through novel R&D activities, which are elaborated from these opportunities and challenges in Section 3.

Opportunity Areas	Opportunities and Challenges
Highly Insulating IGUs (Section 2.1)	• Low-cost, highly insulating interpane cavity filling materials • Lower-conductivity spacers • Thin and light (double-pane equivalent thickness and weight) IGU configurations that achieve higher R-value than existing double pane IGUs.
Highly Insulating Frames (Section 2.2)	• Reduced air infiltration/exfiltration • Novel materials for low thermal conductivity wood, metal frames • Novel frame geometries to reduce heat transfer.
Improved Light Control at the Facade (Section 2.3)	• Decoupling of solar control and visible light transmission • Lighting controls that account for available daylight • More flexible daylight redirection for interior spaces • Simplification of installation and commissioning • Facade system controls that can balance energy savings and occupant optical and thermal comfort.
Advanced Window Performance Characterization (Section 2.4)	• Integration of window simulation tools into existing computer aided design (CAD) software workflows • Novel methods to manage computational expense for daylighting simulations and controls operation • Integration of window and attachment performance into building information modeling tools to capture the full value of high-performance facades.

Windows comprise the transparent portion of the building envelope, and thus serve many of the same functions as the opaque envelope. Windows serve additional functions not shared with the opaque envelope: admitting daylight, views to the outdoors, natural ventilation, and solar heating that can offset heating energy requirements in cold weather. Windows often incorporate operable elements that facilitate the exchange of indoor and outdoor air. Windows also often have "attachments"—blinds, shades, awnings, or other interior- or exterior-mounted devices that can be used to dynamically moderate daylight, provide privacy, and reduce unwanted solar heat gain, resulting in improved comfort and reduced energy use. The adjustable features of windows and window attachments offer the potential for dynamic heat, air, and moisture exchange through the envelope; this ability to operate dynamically could provide GEB services if combined with appropriate sensors, controls, and actuation systems. Opportunities

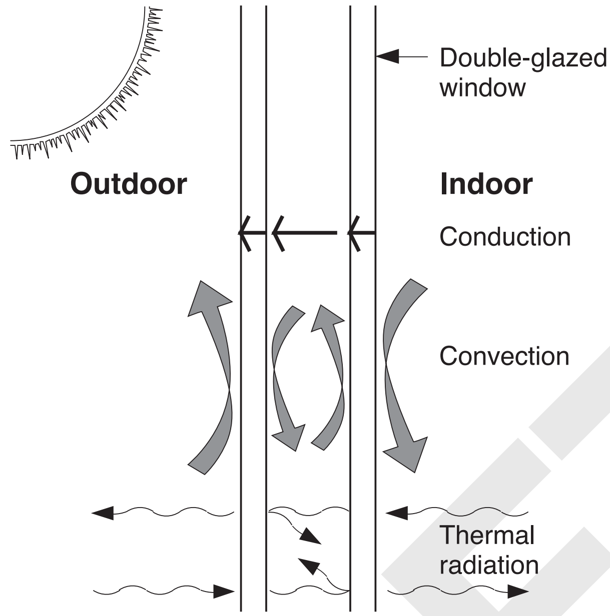

Figure 5. Heat transfer between the building interior and ambient exterior through the glazed portion of the window can occur through conduction, convection, and radiation. The extent of the heat transfer by each mode depends on weather conditions, interior temperature and air movement, and the design of the window itself. Heat transfer also occurs by all three modes through the frame as well (not shown), though the relative contributions of the modes will differ from the glazing. The total heat transfer per unit surface area through the frame will likely far exceed that of the glazing for a typical new window.
Figure courtesy of LBNL.

remain for both energy efficiency improvements in windows and window attachments, as well as improvements that can enable their GEB potential and expand that potential through further developments in both the dynamic elements themselves and the components that facilitate their automated operation.

Modern windows have undergone decades of refinement, which has dramatically improved energy performance compared to their single-pane ancestors (see the Enabling a Game Changer: Low-Emissivity Coatings success story [14]). In spite of these improvements, typical new windows still have R-values around R-3.5, while a well-insulated wall might be R-20 and a roof system R-50 or higher. The overall performance of a window system is a combination of the individual window components' performance. Although actual performance of the same window system can vary considerably depending on different building designs, installation quality, and environmental conditions, the window design usually represents a trade-off between cost and a range of desired performance attributes, including structural performance, thermal performance, solar heat gain, aesthetics, and others. Optimizing the energy performance of windows must take into account heat conduction, convection, and radiation while also ensuring that aesthetic considerations are satisfied—adequate visible light transmission, minimum spectral attenuation, low haze, and high clarity.

Figure 5 illustrates the effects of the various modes of heat transfer on the glazed portion of a window. Conductive heat losses occur through both the glazing and the frame of the window, but frame conductive losses contribute substantially more overall heat loss in multiple-pane windows. Heat conduction through the window frame and glazing is dissipated from the surface to the surroundings by convection and long-wave radiation, accelerating heat losses. Control of solar radiation through windows is also critical to their energy performance. Windows that permit appreciable solar heat gain in colder climates will generally help offset building heating loads, while the same windows in warmer climates will result in increased cooling loads relative to lower solar heat gain windows. In addition to the aforementioned simple heat transfer scenarios, the interfaces between different window components or materials can act as weak points for thermal energy transfer ("thermal bridges") if not designed properly. Figure 6 illustrates the dramatic impact on heat transfer, and ultimately on energy performance, that arises from thermal bridging in window frames. A holistic perspective must be taken when identifying opportunities for improving window systems for higher thermal performance while maintaining favorable aesthetics and comfort at reasonable cost.

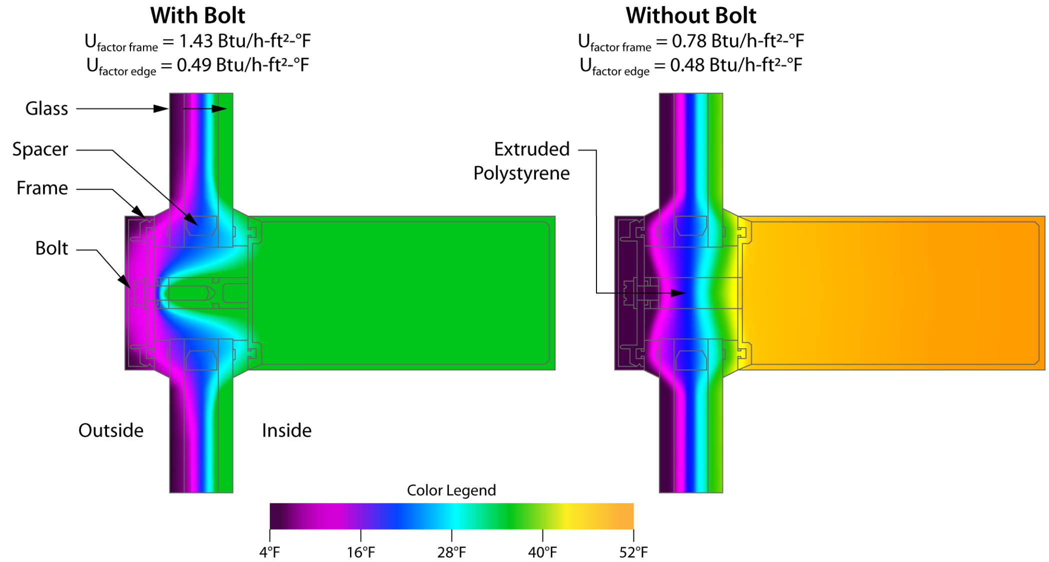

Figure 6. A simulation of heat transfer through a commercial window assembly shows the impact of thermal bridging. In the left panel, a bolt connecting an exterior frame component exposed to the cold outside air acts as a conduction pathway to the interior of the building, thus transferring warmth from the building to the exterior and making the adjacent interior surface cold. The right panel shows that when that fastener is replaced with an insulating component, heat in the building interior is retained better, which is indicated by the lighter color (higher temperature) on the interior side of the window compared to the left panel.
Figure created by Alfred Hicks, NREL.

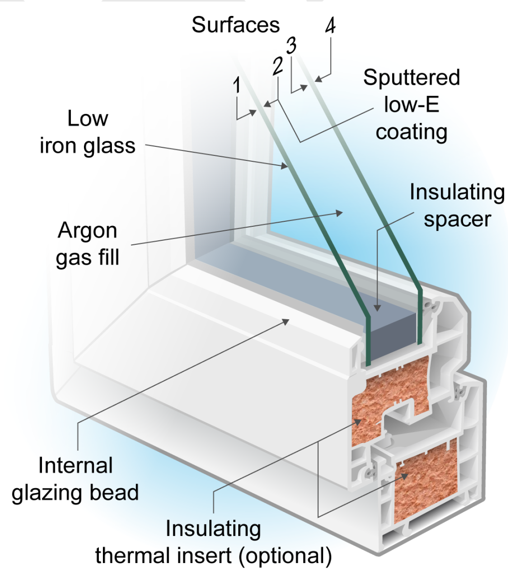

Figure 7. A typical residential "vinyl" (unplasticized polyvinyl chloride [uPVC]) frame window with a double-pane IGU has some voids and inserts in the frame profile to reduce thermal conductivity. The double-pane IGU, argon gas fill between the panes of glass, and warm-edge spacer all contribute to further reducing the thermal conductivity, measured as U-factor or R-value, of the assembled window.
Graphic created by Alfred Hicks, NREL.

The major components of a modern window are depicted in Figure 7. Typically, two or more glazings (glass panes) are combined and separated by spacers at the interface with the window frame that supports the glazings. Frames for residential windows employ a combination of plastics, metal (aluminum), wood, and thermally insulating materials, depending on the target market, whereas windows for commercial and high-rise residential buildings use aluminum because of its superior structural properties. Multiple glazing layers increase the thermal resistance of the window. Air occupies the interstitial space between glazings in simple multiglazed windows, but higher-performance windows are often filled with lower thermal conductivity gases, such as argon or krypton. A low-e coating is typically added to surface 3 for cold climates and surface 2 for hot climates. The low-e coating used in hot climates is typically spectrally selective, thus admitting more visible light for an equivalent solar heat reduction compared to standard low-e coatings. In colder climates, a low-e coating can also often be found on surface 4 (shown in Figure 7), which reflects ambient infrared heat back into the interior space. In warmer climates, window films/coatings can be applied to exterior glazing surfaces (surface 1) to block transmission of a portion of the heat from visible and near-infrared (NIR) light. Extensive reviews of the design of residential and commercial window systems can be found in Carmody et al. [15] and Carmody et al. [16], respectively.

Enabling a Game Changer: Low-Emissivity Coatings

Approximately 80% of residential and 50% of commercial windows sold today (98% of energy-efficient windows) incorporate low-emissivity ("low-e") coatings. DOE's 40-year continuous support of low-e windows has transformed the windows market and directly contributed to this technology's dominant status in the window industry globally. DOE investments, from initial R&D through modern ratings updates, have resulted in extensive cost savings within the building industry as well as among consumers. This technology, which involves microscopically thin coatings that allow visible light but block radiant and solar heat, now serves as a technology platform for further innovations related to coatings and glazing.

History

DOE funding to Lawrence Berkeley National Laboratory (LBNL) in the 1970s and 1980s jumpstarted the low-e R&D efforts, with the intent of understanding the mechanisms of window heat transfer, reducing heat losses, and paving the way for private industry to commercialize the process. This research led to additional funding for an LBNL partnership with a startup company that created the first commercial low-e glass in the 1980s. The demonstrated potential of this technology and the success of the startup partnership inspired major window and glass manufacturers to rapidly accelerate their own investment in low-e research, coating technology, and better window products.

As low-e sales grew in the 1980s and 1990s, DOE helped bolster public trust (and the trust of manufacturers and industry) in this technology's savings potential by funding facilities to produce performance data. Researchers disseminated those data to code officials, utilities, and research staff from window manufacturers, helping address concerns and build confidence. DOE also funded LBNL to adapt its window performance software tools to be used by the newly created National Fenestration Rating Council (NFRC). This allowed consumers access to an objective and certified resource to help them select windows, and NFRC ratings are now invaluable reference values for national and state codes and standards, as well as for successful programs like ENERGY STAR®. More than 80% of residential windows today are modeled using LBNL's simulation tools and certified with NFRC ratings.

Looking Forward

Continued DOE support allows for upgraded software tools and standardized labeling programs that meet the evolving needs of modern manufacturers, code officials, homebuilders, and the NFRC. Current efforts also make these technologies increasingly cost-effective and contribute to DOE's ultimate vision for windows—producing solutions that are energy positive and windows that perform even better than insulating walls. DOE's essential role in developing this technology helped turn low-e windows from a rarity a few decades ago into an integral part of the U.S. building industry today; this success sets the bar for future cutting-edge energy research.

2.1 Highly Insulating IGUs

Glazing systems represent a major opportunity to improve the thermal performance of windows because of their high area ratio in a window (typically 70%–80% of the window area is glazing). In the United States, typical high-performance windows today have double glazing with one or two low-e coatings (one facing the glazing cavity and the other facing the building interior) and 90%–95% argon gas fill. In residential applications, this configuration is equivalent to R-3 to R-4.5 windows, or U-factor of 0.22 to 0.33. Whole-window U-factor can be decreased further in the insulated glass unit (IGU) by increasing the number of panes or adding transparent thermally resistive films in between panes. However, each additional pane requires another spacer system, so the frame and sash will normally require redesign to ensure structural stability with the increases in thickness and weight from the added panes. Although using an intermediate suspended film adds negligible weight to a double-pane IGU, the cost of the suspended low-e film, complex fabrication process, and durability and reliability issues resulting from the tension applied to the suspended film have precluded widespread adoption. Figure 8 shows the rapid adoption of double-pane IGUs and low-e coatings in the U.S. residential market, contrasted with the limited adoption of triple-pane IGUs. As of 2016, triple-glazed windows represent less than 2% of all U.S. windows sold [4].

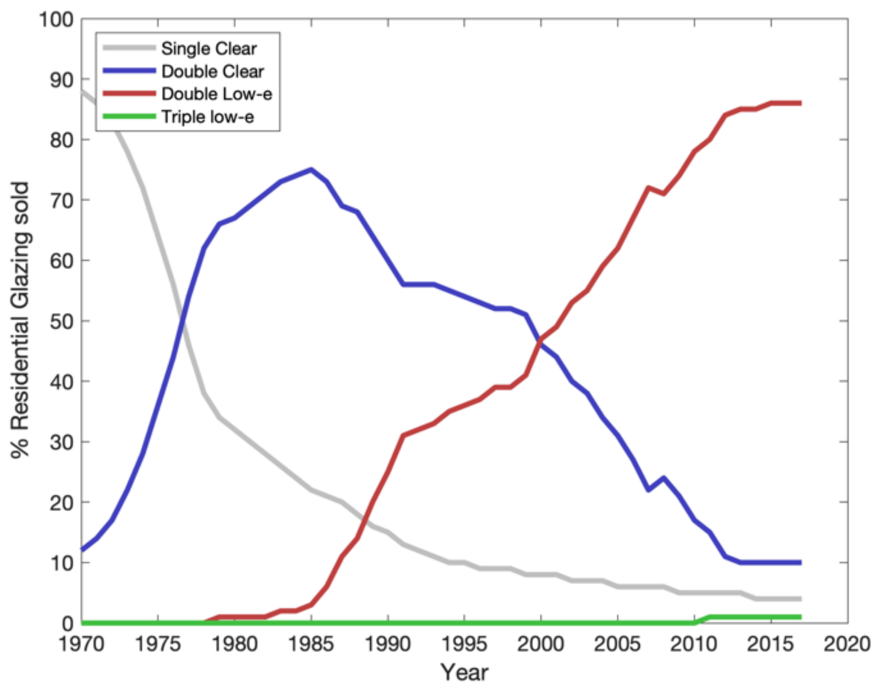

Figure 8. Residential glazing market share trends show that low-e coatings have seen rapid adoption since their introduction, while triple-pane IGUs have remained a small portion of the overall market. Commercial glazing shows similar relative trends in the adoption of low-e coatings and triple-pane glazing, but with lower overall adoption of both technologies.
Figure from Selkowitz, Hart, and Curcija [4].

Vacuum-insulated glazing (VIG) has the potential to yield superior thermal performance compared to multiple glazing IGUs, typically reaching center-of-glass thermal resistances of R-8 to R-12. However, VIGs continue to face challenges with respect to cost, durability, edge seal reliability, and the ability to easily fabricate windows in a wide range of sizes and shapes. Further research is needed to improve the reliability and resilience of VIG technology, reduce complexity of fabrication, improve edge sealing, and improve glass tempering to reduce distortion of the VIG under thermal stress.

Opportunities remain to improve the performance of existing IGU configurations as well. Low-e coatings are required for virtually all insulating windows, and most IGUs need gas fills in addition to low-e coatings to achieve the optimal thermal performance. Low-e coatings are mature technologies for use in protected IGU cavities and are available with a wide range of solar control and light transmission properties in addition to low emissivity. There is some remaining opportunity to improve the performance, durability, and cost of low-e coatings now used in the interior-room-facing surface (surface 4, as shown in Figure 7) and potential for expanding use to the exterior surface (surface 1). Argon is the preferred gas for filling sealed IGU cavities because of its low cost. The typical IGU gas-filling process in use today—two-probe filling—is simple, but wasteful because argon is plentiful and very low cost. The thinner cavities in triple-pane IGUs require a lower thermal conductivity gas, such as krypton, which is more expensive than argon. Higher-performance IGUs that require low thermal conductivity gases will therefore benefit from more efficient filling processes. Alternatively, fill materials besides noble gases might be able to be used in between panes, achieving a similar effect, potentially with superior insulating performance.

To prevent condensation on interior surfaces of windows, in addition to insulating glazing and frames, spacer systems need to be insulating as well. Insulating spacer systems increase the temperature of the glass's edges and immediate spacer area and are typically made out of polymer materials. These materials must have limited off-gassing, so that interior low-e surfaces are not fouled, and desiccants are also added to trap any moisture that can get past the spacer and between the panes. Spacers are subject to structural loads like the rest of the components in the window assembly; high structural loads, such as those imposed by the most stringent structural performance rating from the American Architectural Manufacturers Association—the Architectural Window rating—creates a particular challenge for relatively soft and flexible polymeric spacers. An opportunity exists for the development of spacer systems that can meet these strict structural standards with improved insulating properties.

2.2 High-Performance Frames

Window frames must satisfy many demands, such as hosting operating hardware, supporting the glazing system, and providing mounting infrastructure, which makes improving frame thermal performance especially challenging. Though the frame represents 15%–30% of the total window area, even the highest thermal performance frames lag behind the performance of highly insulating glazing. As such, the frame can often serve as a low thermal resistance pathway for heat conduction and subsequent convection away from the frame, significantly limiting the overall energy performance of the window system. Figure 9 illustrates quantitatively the impact of frame performance on high-performance windows; as IGU performance (U-factor) increases, the frame has an increasing impact on overall window U-factor. Windows with frames that comprise a greater share of the total window area are affected even more by a high U-factor frame. Poor frame thermal resistance also limits condensation resistance, which can lead to aesthetic, durability, and indoor air quality problems.

The current state-of-the-art in high-performance materials for residential window frames are various proprietary polymer matrix-fiber composites and unplasticized polyvinyl chloride (uPVC) frames with multiple frame cavities filled with insulating materials. Though these materials are relatively inexpensive and have adequate thermal resistance, alternative materials and assemblies with lower thermal conductivities or the incorporation of thermal breaks and alternative geometries could improve performance. Integration of these new frames into prevailing window frame depths and profile dimensions typical of the U.S. market—especially when also accommodating high-performance IGU thickness—represents a challenge that must be considered when developing new frame materials or configurations.

For commercial buildings, structural requirements almost universally require the use of aluminum alloys for window frames. Unfortunately, the thermal performance of aluminum is relatively poor; its thermal conductivity is three orders of magnitude higher than wood or uPVC. Thermal breaks are used to reduce conduction heat transfer when using aluminum as a frame material, though thermal break technology and adoption have progressed very slowly. Currently, two major thermal break designs dominate the U.S. market: pour-and-debridge polyurethane thermal breaks and crimped insulating bars. The thermal performance of thermal breaks can be further improved by increasing heat transfer path lengths and developing new frame materials with low thermal conductivity and high strength.

Air infiltration/exfiltration through interfaces between operable window elements can significantly increase cooling and heating loads. Though newer windows have significantly improved airtightness, there is still a difference between sliding operable windows and casement or awning-style operable windows. Seasonal changes may also impact the effectiveness or durability of seals. Air leakage tends to increase with age as seals wear and other window components change shape, thus the long-term performance of the seals remains a critical challenge. Methods that

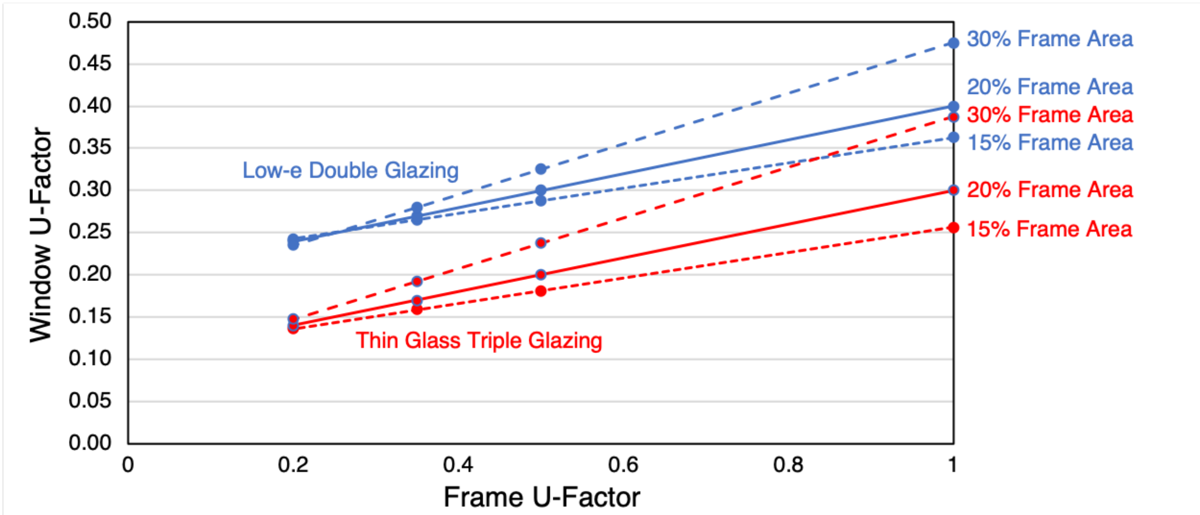

Figure 9. With either traditional low-e double glazing or advanced thin glass triple glazing, as the proportion of the frame contributing to total window area increases, the effect of frame U-factor on overall window U-factor increases (the slope of the line increases). Frame performance is even more important for windows where the frame comprises as greater share of the overall window area. As a result, continuing improvements in IGU performance underscore the need for improvements in frame performance.

can readily identify and products that can easily remediate deficient seals are needed. Incorporation of effective and durable sealing materials and strategies within window assemblies is critical to overall window performance.

2.3 Dynamic Facades and Daylighting

Sunlight and air can be selectively transmitted through windows to provide solar heating, cooling, and/or interior illumination. With their time-varying properties or configurations, dynamic glazing and other dynamic facade elements can strategically admit or reject solar heat gains and daylight through windows and skylights to reduce heating, cooling, and lighting energy use while improving occupant visual comfort. Dynamic facade components can employ control strategies that incorporate GEB benefits, which is discussed further in Section 4.2. Additionally, variation of solar intensity and its spectral composition, facilitated by daylighting, have been correlated with less-tangible indoor environmental quality and health benefits of building occupants (e.g., sleep-wake cycle regulation, circadian rhythm, seasonal affective disorder, sense of well-being) [17, 18], and with scholastic performance [19]. The applicable technologies and operational strategies required to obtain these benefits are a function of the latitude, climate, window size and orientation, as well as the type and vintage of the building. In general, improved quantitative understanding of the effects of these factors on the energy and nonenergy impacts of dynamic facades and daylighting is needed, as well as the trade-offs associated with using it in various building/occupant environments. This understanding would provide insight into the critical performance design points to ensure dynamic facade and daylighting systems are appropriately matched to the needs of specific buildings and that these systems are properly installed and operated.

2.3.1 Fixed and Operable Attachments

Window attachments comprise fixed and operable interior- and exterior-mounted devices and architectural features, such as blinds, shades, overhangs, and awnings, that can control direct sunlight (for thermal and visual comfort), reduce solar heat gain, improve thermal performance, and provide privacy. Most buildings have some form of attachment, typically indoors, and virtually all currently installed attachments are static or manually operated. Operable exterior shading attachments have the greatest potential for energy savings in both new construction and retrofits, but they have seen limited market adoption in the United States because of their higher installation prices, more difficult maintenance, and interference with facade aesthetics when compared to interior shading attachments. Between-pane static and operable shading systems can reduce maintenance costs, but have also seen limited application. Between-pane angular-selective shading systems, for example, have been used in atria, libraries, and museums to provide solar control, daylight, and view for sloped and vertical glazing.

Advances are needed to improve solar rejection (when needed) while maintaining daylight and views to the outdoors even when the shade is in place. Systems need to be aesthetically acceptable, durable, and require little to no maintenance. Shade materials that block glare from direct sun without eliminating useful daylight and view do not currently exist. These are of particularly critical need, because they can maintain the benefits of windows without compromising occupant visual comfort. Low-e indoor shade materials could reduce radiative heat transfer to nearby occupants, improving thermal comfort and potentially reducing the need for perimeter HVAC. Alternate options for actuating (e.g., nonmechanical, passive) and supplying power to operable components at lower cost with reduced installation effort are needed. Systems that enable solar and glare control without impeding airflow would complement windows used for natural ventilation or provision of outside air.

Automated shading systems have the potential to consistently deliver the energy and nonenergy comfort and productivity benefits that can come from window attachments when used most effectively. Fixed and manually operated attachments are lower cost and less complex than automated systems, but deliver reduced and less dependable energy savings [20, 21, 22]. For automated shading systems to achieve widespread adoption, precision actuation, robust cybersecurity, low power requirements, ease of installation, and minimal maintenance are needed. Technology solutions that address the higher installation costs and initial configuration complexity of automated systems are now commercially available, including self-contained power supplies and wireless internet-protocol-based control connectivity.

Cybersecurity and standardization issues are being addressed by the building controls industry. User or facility control of shading systems via mobile app interfaces has increased the transparency of automated system operation and facilitated troubleshooting in residential and small commercial applications. A critical shortcoming, however, is the general lack of knowledge on how best to control attachments for energy savings, occupant thermal and visual comfort, and user satisfaction. Automated systems can also provide GEB benefits by configuring attachment components to affect the timing of HVAC and lighting energy requirements in a manner that is complementary to electric grid operational needs, but how to control automated systems for GEB benefits remains unknown. Currently, commercialized control systems use building simulations to design rule-based controls for large-scale applications; to accommodate the continuing changes in utility operations and electricity markets in response to evolving demand- and supply-side conditions, more flexible approaches to controls design are needed.

2.3.2 Daylight Redirection

Electric lighting savings from daylight is typically limited to the area immediately adjacent to the window—about 1.0–1.5 times the ceiling height—because of the nature of diffuse daylight sources and because shades are typically lowered to reduce glare when direct sun is present. Sunlight has sufficient intensity to provide adequate lighting 30–40 feet from the windows, but the control and distribution of that light remains a challenge. Some static products exist to redirect daylight and sunlight deeper into spaces, but none have managed to achieve significant market penetration because of aesthetics, cost, and inadequate performance. Rooftop skylights are effective at daylighting the top floor of buildings, but light shafts that bring daylight down one or more floors below the top floor have not achieved significant market impact because of cost, complexity, and the disruption to existing building envelopes.

Technological innovations are needed that bring daylight deeper into the building (15–40 feet from the window or across the core zone on floors below the top floor) without glare and thermal discomfort and without increasing the cooling load in the building. Integration of daylighting redirection devices with active lighting control systems to achieve desired illumination levels amid variation in daylight intensity and patterns of distribution remains a challenge. It is also necessary to avoid downward, specular transmission of intense sunlight, spectral attenuation of daylight, chromatic dispersion (rainbow patterns of light), excessive light absorption, or other undesirable variations in the light, as can happen with certain light guides.

2.3.3 Dynamic Glazing

Switchable or dynamic glazings include technologies that can modulate light transmission, reflection, and/or absorption properties (in specific wavelength ranges) and thermal properties (e.g., thermal mass, thermal insulation).

Various actively modulated and passively responsive glazings have been developed at least at the laboratory scale, including electrochromic, thermochromic, and photochromic devices. Electrochromic glazings that actively modulate visible light and NIR transmission have been introduced to the market over the past decade and have achieved a modest level of adoption in high-end, niche markets (see the Dynamic Windows success story). However, market adoption has been slow because of concerns about color, switching speed, durability, inadequate automated control, and cost. Uniform facade appearance, desired by some in the architecture and real estate industries, can limit control options and long-term energy savings. Slow switching speeds (10–30 minutes) sometimes lead to the installation of supplemental shades to satisfy occupant comfort, which eliminates the aesthetic benefits and potential cost savings from eschewing interior shades. For commercialized formulations, durability concerns have been partially addressed with the development of ASTM 2141, which defines accelerated aging methods for dynamic glazing. Beyond these existing concerns, novel chromogenic formulations with the ability to independently attenuate visible and NIR light would allow greater control over the daylighting and solar heat gain trade-off. This feature would be particularly beneficial in commercial buildings with high internal loads where electrochromic windows otherwise remain in a switched (darkened) state in the winter months. High-performing laboratory-scale electrochromic devices have been developed toward that end [23], but achieving highly replicable, large-scale, and inexpensive manufacturing remains a challenge, alongside outstanding technical concerns related to coloration, switching time, and, in some cases, long-term durability.

2.3.4 Dynamic Facades

Dynamic facades combine multiple static and active transparent facade elements, such as fixed and operable attachments, dynamic glazing, and daylighting systems, with the aim of operating those elements in concert to minimize energy use associated with the facade. Dynamic facades also simultaneously address comfort, indoor environmental quality, and occupant performance objectives. Real-time control of the operable facade elements in response to detected time-varying external (e.g., weather, energy demand) and internal (e.g., occupancy, task) conditions could lead to significantly lower energy use compared to manual operation.

Dynamic facades have seen limited market adoption to date because of various technical and market-related issues: price, real and perceived complexity, concerns regarding technology lifespan, and occupant dissatisfaction with automated controls. Although individual components that might comprise a dynamic facade system have seen improvements, simple plug-and-play operation and coordinated control across multiple facade elements have proved elusive. Thus far, controls have been limited primarily to maximizing zonal performance using scheduled control or heuristic logic. Control algorithms are becoming increasingly sophisticated, where building energy simulations are used to enhance rule-based control logic, but this approach is not yet widely adopted. More often, controls are set conservatively and tuned over time to minimize complaints. As with individual automated facade elements, dynamic facades have the potential to offer GEB benefits, though additional research is needed to determine the GEB potential of the elements of dynamic facades, both independently and when operated in a coordinated manner.

Maximizing energy savings requires not just control ability but optimal control strategies that integrate all available dynamic facade elements. These control algorithms should be able to offer an optimal balance of energy savings and occupant comfort and satisfaction given a range of available dynamic facade components and adapt to later changes in what components are available. The proprietary nature of the building automation systems on which these technologies depend can create concerns regarding vendor lock-in and resulting high long-term system operation and maintenance costs, particularly in commercial buildings, where the systems can be very capital intensive. Control solutions that employ open-source interfaces or building-block-style models could provide solutions that enable long-term energy savings and reduce adoption risks for consumers.

2.4 Characterization of Window System Performance and Benefits

There are three primary applications of window and attachment component system modeling software tools: (1) supporting R&D of novel components and materials; (2) enabling architects, engineers, and designers to understand the energy, cost, and ancillary impacts of commercially available products; and (3) underpinning rating and labeling programs that provide building owners with quantitative assessments of the energy performance of commercially available products. Window and attachment software tools and databases currently maintained with DOE support include THERM, WINDOW, OPTICS, Radiance, the International Glazing Database, and the Complex Glazing

How DOE Accelerated the Development of Dynamic Windows

Advancements in energy-efficient windows over the past 40 years have been exceptional, but they represent only a fraction of the energy savings potential of windows. If rejection or admission of solar heat gains and daylight are appropriately timed—based on season, cloud cover, occupancy, or HVAC system operation—then heating, cooling, and lighting energy use at the perimeter zone can be reduced even further. Dynamic glazing enables such control through the glazing's active modulation of solar control properties.

History

Starting in the 1970s and continuing today, much of the key work to bring this technology to market has been conducted at the national laboratories—primarily at LBNL and NREL—with support from DOE (Office of Energy Efficiency and Renewable Energy [EERE]). This work has included developing switchable chromogenic coatings, tuning material properties, and improving longevity under extreme conditions. In scaling up these technologies from coupon-size prototypes to large-area windows produced by high-volume manufacturing, LBNL and NREL have helped a wide variety of early-stage companies commercialize them. This R&D was guided by performance specifications developed by national laboratories, indicating what material properties were needed to reduce energy use, minimize discomfort, enhance outdoor views, and meet owner and occupant requirements. National laboratories assumed a critical role during the development phase of dynamic windows by conducting field testing and durability and failure analysis, as well as defining laboratory protocols to characterize material properties and incorporating them into simulation tools. These activities supported decision-making for further industry R&D investment, helped define the value proposition for consumers, and demonstrated the energy-efficient performance of commercially available switchable windows under long-term occupied conditions. This in turn has enabled the development of codes and standards that support the specification of dynamic glazing products by the buildings industry.

Looking Forward

Through EERE, DOE has supported a diverse group of companies to forward their technologies—including industry leaders View, Sage Electrochromics, and Pleotint—both through direct funding and indirectly through national laboratory partners. The early work funded by EERE has now led to more than $2 billion in private sector funding to support commercialization, and large-scale product installations are currently underway. Today, research continues to produce innovative switchable coatings that switch faster and over a broader range, provide independent control of daylight and solar control, and can be manufactured at a fraction of the cost of previous devices.

Figure 10. Dynamic glazing can be adjusted to a range of levels to manage occupant thermal and optical comfort while maintaining views to the outdoors.
Photos courtesy of View Inc.

Database. These products are used by manufacturers to design window products; by the U.S. Environmental Protection Agency, the National Fenestration Rating Council (NFRC), and the Attachment Energy Rating Council to rate windows and attachment products; and by architects and engineers to design high-performance building envelopes (see the Window Software Tools success story). Future development of software, modeling tools, and databases that support the evaluation of the energy performance and adjacent nonenergy benefits of windows, attachments, and daylighting systems should lower barriers to their use by providing well-documented, open-source, platform-agnostic data and modeling results that can be readily integrated into existing commercial and open-source software workflows employed by manufacturers and building designers.

Advanced simulation software tools could enable the window industry to further accelerate iterative product design and development. For manufacturers, relying on software for characterization helps them to understand how to improve the benefits of their products and provides them the ability to rate and label products for more effective marketing and code compliance. Typically, manufacturers start their design process using computer-aided design software—accurate window modeling software tools also enable manufacturers to do some product design virtually, avoiding the time and expense associated with iteratively manufacturing and testing prototypes. Though existing modeling and simulation tools are widely used, they often do not seamlessly integrate into users' existing (commercial and noncommercial) software workflows, but rather are used as standalone applications. With this disjointed workflow, data exchange is cumbersome. Moreover, the inputs and outputs of these tools might not be well matched to the inputs and outputs of other software tools employed in the design, evaluation, or labeling process. In addition, the energy and nonenergy impacts of some window features and design requirements are not well represented in existing window modeling tools. Often, product performance requirements have conflicting energy and nonenergy effects. For example, the structural requirements of blast-resistant windows typically yield degraded thermal performance, while laminated glazing provides improvements in both blast and acoustic performance. Capturing these various trade-offs entirely within the virtual windows design workflow used by manufacturers can facilitate increased energy performance by incorporating energy performance in-line with the evaluation of nonenergy window features that are critical to meeting customer requirements.

Daylighting and solar control technologies and glare control methods present an entirely different modeling challenge because the distribution of direct sunlight should be represented accurately to determine their effectiveness in managing glare and thermal discomfort and providing adequate daylighting. Accurately representing the angle-dependent, solar-optical properties of facade elements that affect the intensity and distribution of solar radiation and daylight is thus critical not only to the commercialization of novel daylighting and shading facade materials, but also to facilitate the integration of both novel and currently available technologies into facade designs and provide label-based information to help consumers select appropriate products. For glare modeling, generating high-resolution light ray tracing images requires significant computational expense and yields large data files. Trade-offs between accuracy and calculation speed need to be characterized so that industry can make informed decisions on which simulation methods to use. Simpler methods and performance indices may suffice for early design. For novel products, more detailed and accurate simulations can avoid investment in a technology that looks promising in early stages but can be shown to not be market acceptable based on detailed characterization and modeling. These data therefore cannot be readily incorporated into a design workflow, and the impact of design changes to a daylighting system and supporting controls cannot be evaluated without additional time-consuming simulations.

With regard to building design and construction, architects, engineers, and construction teams, accurately representing the building energy performance impacts of windows, attachments, and daylighting systems is critically important to demonstrating their value and thus retaining high-performance windows and other facade systems in project designs. In addition, building design and construction software workflows need to convey critical construction details to installers. For dynamic facade components and daylighting systems, transitioning from the original design to operation when integrated into a control system is not seamless. Minimizing energy use while controlling glare, maintaining adequate views to the outside, and managing illumination levels often proves challenging, and significant remediation from the original design can be required from the building operations team because of changes during construction or inadequacies in the control configuration. Designers need assistance in their existing software workflows to ensure that the specification and placement of the sensors and configuration of the control system will be sufficient to achieve the intended control objectives and that factors that might result in deactivation of the system (e.g., inadequate glare control) are addressed.

Window Software Tools: Supporting Efficient Next-Generation Window Technologies

Software tools developed by DOE and LBNL enable users to make informed, data-driven decisions as they develop the next generation of energy-efficient window technologies, spurring energy savings and comfort improvements worldwide.

LBNL's window software tool suite enables manufacturers, engineers, professional simulators, architects, researchers, and members of academia to perform their own energy efficiency analyses on windows and building envelopes. They help users design and rate next-generation window products and evaluate the impact of windows on building energy consumption. Some tools supplement basic material characterization, such as the OPTICS software that is used to calculate optical properties of glazing materials. Others, such as WINDOW and THERM, enable users to model thermal and optical performance of windows, shading, and opaque building assemblies. Still others, such as COMFEN and RESFEN, enable users to analyze the energy impacts of various windows and facade elements on the energy balance of buildings exposed to a variety of climates.

History

These tools are well respected in the industry. Since 1992, they have been used to rate and certify window and facade products. In fact, every NFRC window rating label for windows sold in the United States includes performance indicators that were calculated by OPTICS, THERM, and WINDOW. They also are used globally, often for certification of fenestration products. Annually, the tools get more than 50,000 unique downloads and more than 1 million program starts.

Looking Forward

The recent version 7.7 of WINDOW and THERM includes sophisticated methods to calculate the performance of complex window systems and highly insulating and solar control windows and window attachment products. As window technologies advance, LBNL will continue to expand its suite of window software tools to support the next generation of efficient window technologies.

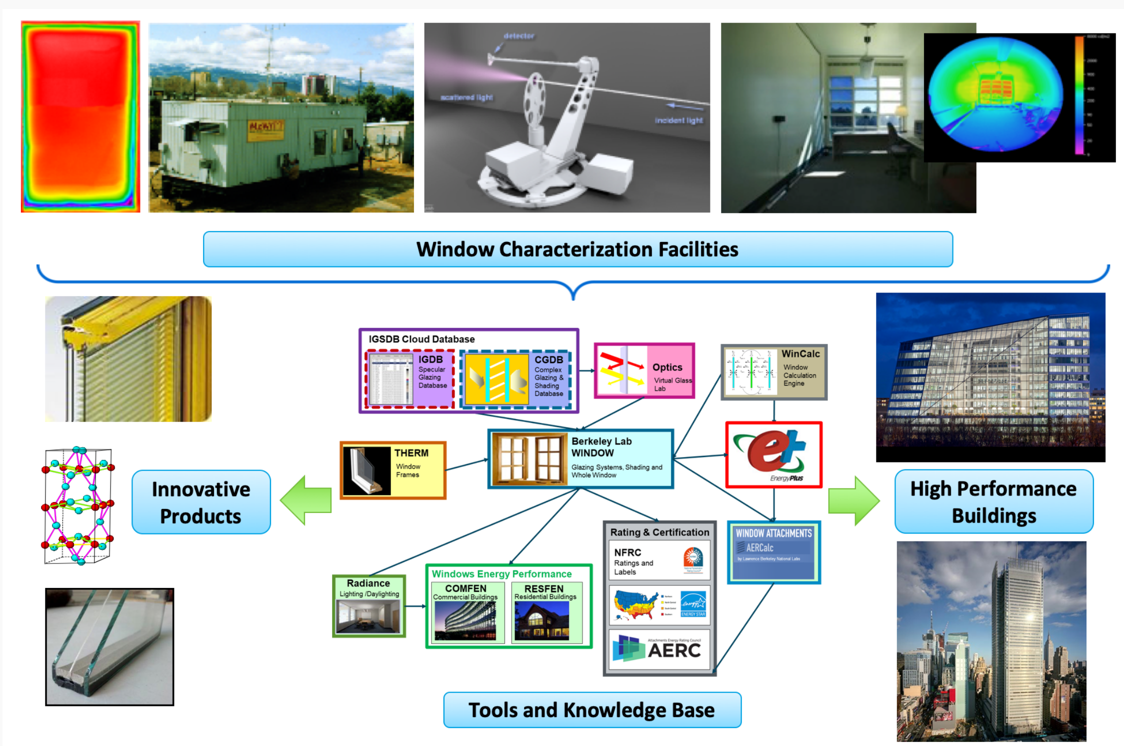

Figure 11. Window technologies workflow from early research to advanced products.
Figure courtesy of LBNL.

2.5 Cross-Cutting Barrier: Envelope Retrofit Adoption

Although equipment in buildings—such as heating and cooling systems, water heaters, and light bulbs and fixtures—is often replaced because of increasing maintenance costs or outright failures, the same does not hold true for windows and other building envelope components. The degradation of these components, including windows, is often gradual and can typically be masked by additional heating and cooling. Given the relatively recent advent of high-performance building envelopes, people are likely accustomed to poorly insulated, leaky facades and windows and might perceive those conditions as typical or characteristic of best-available envelope performance.

Tables 2 and 3 show that windows and other envelope components in existing buildings are rarely upgraded to reduce energy use, remedy performance problems or defects, or to improve aesthetics in spite of their significant contribution to building energy use. Residential windows are an exception, because they offer aesthetic and functional improvements that are appealing to homeowners and as of today are relatively easy to install, compared to most envelope upgrades that offer energy savings.

The cost of envelope retrofits is directly related to the disruption to building occupants and the scale and complexity of teardown and reconstruction of an entire building envelope. These factors contribute to the significant on-site labor effort that can be required to complete an envelope retrofit project, and thus the overall project cost. While manufacturing and on-site installation labor costs do contribute to the overall project cost for window replacements, other manufacturing costs are also significant contributors [24]. With window replacements, as with the opaque envelope, interface detail work performed during installation is critical to the energy performance and durability of the installed window and the surrounding envelope.

There are some envelope upgrades that are performed more frequently than others, such as window and siding replacements, blown-in ceiling insulation, and drill-and-fill wall cavity insulation. Table 2 shows the frequency of these retrofits by category. In general, these retrofits share the characteristic that they require minimal on-site labor effort. For the insulation retrofits in particular, there are also task-specific off-the-shelf tools that installers can use to simplify and expedite the job. Conversely, window and siding replacements provide an aesthetic upgrade, in addition to improving energy efficiency (in the case of insulated siding retrofits). Additional value streams beyond energy savings, such as aesthetics, ease-of-use, or comfort, can help increase adoption. In particular, value streams that are readily observable, such as aesthetics or convenience features, can help broaden the appeal of envelope retrofits that also increase energy efficiency.

As shown in Figure 4, existing buildings will dominate the building stock in the coming decades, and thus novel envelope technologies have the greatest potential for energy savings if they are suitable for retrofitting existing buildings. To maximize their potential applicability for retrofit applications, envelope technologies should:

- Minimize on-site labor requirements
- Minimize disruption to building occupants
- Reduce and/or simplify interface detail work
- Offer fault-tolerant installation
- Deliver additional benefits beyond energy savings.

Many of these features would also be beneficial in new construction, thus envelope technologies under development need not incorporate these features exclusively for the retrofit market.

3 Future Technology Development

This section builds upon the extant challenges described in Section 2 by articulating the characteristics required of any future technologies developed to address those challenges and identifying specific technologies or technology development pathways to target those challenges. These technologies are generally expected to offer significant energy savings compared to the current cost-effective technology. In addition, they might offer other energy and nonenergy benefits: reduced peak load, time-shifted envelope-related thermal loads to match distributed renewable generation availability, reduced glare, increased thermal comfort, or improved occupant satisfaction and productivity. These benefits can broaden the value proposition for these novel technologies and thus help drive both early industry R&D off take (see Section 5.1) and accelerate adoption (see Section 5.2). In addition, this section discusses future developments in supporting opaque envelope and window component and system modeling technologies, as well as how these supporting modeling tools and capabilities can be used to accelerate adoption, improve construction quality, and ensure that dynamic systems are configured as intended to maximize energy savings and nonenergy objectives.

This discussion is organized into subsections by technology based on capability, functionality, or common material or other technical characteristics. Each subsection: (1) describes the critical quantitative and qualitative characteristics for the technology to be acceptable to architects and engineers, building trades, and building owners and occupants; (2) reviews the state of the relevant literature; (3) specifies total installed price and energy performance-related metrics, future price and performance targets, and the corresponding U.S. energy savings if those targets are achieved; and (4) outlines future work to address shortcomings in the current state-of-the-art and thus achieve the energy performance, total installed price, and nonenergy performance characteristics ("critical characteristics") needed to be market acceptable and encourage widespread adoption.

For windows, there are a range of opportunities to improve upon the current state-of-the-art with respect to total installed price, energy performance, and nonenergy characteristics that can influence technology adoption and total U.S. energy savings. These opportunities include:

- Reducing infiltration through window frames (especially for windows with sliding sashes)
- Reducing the thermal conductivity of the window frame and IGU
- Enabling improvements in the design, configuration, installation, commissioning, and operation of the sensors and control systems for dynamic facade components and systems of components
- Developing self-powered systems for dynamic and automated facade elements as well as dynamic glazing that can independently control visible and near-IR transmission at much lower prices through improvements in materials and the compatibility of those materials with high-volume throughput manufacturing methods.

This section articulates potential technology R&D opportunities that address these challenges with the current state-of-the-art, as articulated in Section 2.

Price and Performance Target Development

Total installed price and technology performance targets are specified for each technology area. This helps define the potential opportunity offered by substantial energy performance improvements and to suggest needed reductions in installed price for state-of-the-art high-performance windows to be cost-effective for a majority of the market. The price and performance targets were established using Scout, a model that estimates the energy use and cost impacts of the adoption of efficient technologies in residential and commercial buildings. Scout accounts for building and equipment stocks and flows out to 2050. Energy use reductions for a given technology estimated using Scout are based on the difference in performance—R-value in the case of highly insulating windows, for example—between the incumbent or "business as usual" and the more efficient technology. These energy savings are then converted to utility bill savings based on average retail energy prices. Annual utility bill savings can then be used with a desired or "acceptable" simple payback period to determine a target total installed price for the performance level specified.

The configuration of Scout influences the price and performance targets. For all of the targets in this report, a "technical potential" scenario that excludes competition between technologies is used in Scout. The technical potential scenario assumes immediate and universal national adoption of the technology being considered, and excluding competition ensures that for any given technology, none of its energy savings potential is diminished because of parallel adoption of other efficient technologies. These assumptions maximize the energy savings potential for a technology, thus increasing the total installed price target. The performance and associated price targets are based on a range of assumptions in Scout that represent climate zone or national stock-wide average characteristics, including retail energy prices, window-wall ratios, building facade areas, existing window performance, and other factors. As a result, these targets represent performance and acceptable installed price for an average building in the United States; individual buildings vary enormously, thus building-specific "acceptable" total installed prices for a given performance level might be much higher or lower than these targets. Further information about Scout and how it was used to develop the targets in this report is provided in Appendix A.

3.1 High-Performance Windows

Windows must provide thermal separation between the conditioned space within a building and the external environment and withstand wind-driven dynamic structural loads just like the opaque portion of the envelope, while also providing daylight and views to the outdoors. Energy use associated with windows is dominated by conduction through the IGU and frame. Although windows have seen meaningful improvements that reduce conduction losses over the past several decades [3, 25], many opportunities remain for further improvements in IGUs and frame materials. These changes can reduce energy use and improve occupant thermal comfort. In new construction or deep retrofits, especially in commercial buildings where window-wall ratios can be quite high, these improvements have the potential to offset requirements for perimeter zone HVAC, which can thus offset some or all of the cost of more advanced window systems.

Most windows today share common features to reduce thermal conductivity—a double-pane IGU, one or more low-e coatings, and a thermally improved frame. Many double-pane IGUs also replace the air between the glass with argon gas for a small bump in insulating performance by reducing convection in the IGU cavity. Further improving the energy performance of the typical IGU usually involves adding another pane of glass to the IGU—moving to a triple-pane IGU—and switching to krypton gas. Triple-pane IGUs add weight and thickness, which requires a thicker, heavier, more robust frame to support the added weight from the IGU, which dramatically increases cost. Additional improvements in thermal performance require adding yet more glazing layers to the IGU, or switching to VIG, which is discussed further in Section 3.1.1. Modifications to the frame to improve thermal performance generally involve adding thermal breaks—inserting material with very low thermal conductivity between the exterior and interior portions of the frame to inhibit heat transfer. There might be many further opportunities to improve frame thermal performance through the development of novel materials, which are elaborated in Section 3.1.2.[7]

Technology Area Targets

The installed price premium and performance target ranges for windows in 2030 are given in Table 5. The performance targets are for whole-window average R-value, not center-of-glass. Installed price premiums for each performance level are based on utility bill savings derived from energy savings for that performance level and a selected payback period to establish cost-effectiveness. These savings estimates lead to total installed price premiums for residential buildings ranging from $1.80/ft^2 window area for R-6 windows (assuming a 5-year payback period) to $5.60/ft^2 for R-13 windows (assuming a 10-year payback period). These varying cost-effectiveness thresholds, defined using simple payback, allow for a range of financing mechanisms for residential buildings to amortize the cost of window upgrades. For commercial buildings, total installed price premiums range from $3.90/ft^2 window area to $11.90/ft^2 window area for R-6 to R-10 windows, assuming an acceptable payback range of 3 to 7 years, respectively. Price premiums are calculated by subtracting the total installed price for the performance level or technology specified from the total installed price for the incumbent. Baseline prices are $48.40/ft^2 for residential buildings and $56.20/ft^2 for commercial buildings. Shorter payback periods were used to develop the targets for commercial buildings given that commercial building owners and tenants might evaluate payback or return on investment across a wide range of potential deployments of capital resources, and investments in building energy efficiency must compete against these investments for the limited capital available. A survey of U.S. companies found that the median required payback period for energy efficiency technologies is 3–4 years, and the vast majority of respondents requiring payback periods of 6 years or less [26]. Publicly traded companies require even shorter payback periods, with a median response of 2–3 years [26]. The difference in price premiums for residential and commercial buildings are a

[7] See the additional discussion in the Highest Thermal Performance Commercial Window success story.

Table 5. Whole-window performance and installed price premium targets are identified for 2030, along with the corresponding technical potential primary energy savings in 2030 and 2050 for the upper end of the performance range. The price premiums are on top of baseline prices, which are detailed in Appendix A.

Windows						
Building Sector	Performance		Installed Price Premium		Primary Energy Savings (quads)	
					2030	2050
Residential	6–13	R-value	1.8–5.6	$/ft^2 window area	1.28	1.07
Commercial	6–10	R-value	3.9–11.9	$/ft^2 window area	0.93	0.72

result of the difference in baseline window performance. The baseline performance of commercial buildings is modeled as approximately R-2, while the baseline for residential buildings is approximately R-3. As a result, per-building energy savings are higher in commercial buildings, thus supporting higher installed prices. Further details regarding Scout and the assumptions that influence these results are provided in Appendix A.

The whole-window performance levels in Table 5 could be achieved through improvements to the frame, IGU, or likely a combination of both, but do not explicitly assume specific performance contributions from any particular element of the window assembly. If the performance levels in Table 5 are achieved, the primary energy use associated with windows will be reduced by 70% in residential buildings and by 90% in commercial buildings in 2050, respectively, compared to the baseline. This enormous energy savings opportunity underlines the importance of a holistic, systems-level approach to specifying building upgrades to maximize the potential value of window performance upgrades, as discussed in Section 4.1. Figure 12 shows the installed price premiums for a range of R-values and payback periods. All of these prices include marginal fully burdened installation labor and all other material and supply chain costs besides the window itself; strategies that reduce these ancillary costs allow for added costs for the technologies that improve window performance.

3.1.1 High-Performance Glazing

There are a range of approaches to improving the energy performance of existing IGUs, particularly to achieve performance that exceeds double-pane IGUs without the weight penalty of adding a third pane of glass. These approaches generally focus on minimizing heat transfer between the panes in the IGU, particularly by controlling convection by removing the air between the panes or replacing the air between the panes with another material.

Triple-pane IGUs have a lower U-factor (higher R-value) than double-pane IGUs. Although effective at reducing heat transfer, the additional glazing layer and second spacer in a triple-pane IGU add significant weight and thickness to the finished IGU, which affects the frame as well. Alternative approaches that create two chambers in the IGU—comparable to a triple-pane IGU but without the weight and thickness penalty associated with an additional glazing layer and spacer—would yield an IGU suitable for a much wider range of retrofit applications. The weight of a triple-pane IGU could be reduced by employing thin glass for the intermediate pane in the IGU. Recent improvements in thin glass technology, sparked by the demand for display systems such as large TVs and smartphones, have resulted in dramatic cost reductions such that submillimeter-thick glass is comparable in cost to standard double-strength glass. A traditional two spacer system could be used between each pair of glass panes, or a single combined spacer that suspends the center glass could be developed, though any spacer system developed for this window configuration should be compatible with or amenable to integration with automated IGU manufacturing systems. A thin glass triple-glazing system would more than double the thermal insulating value of a window, from a nominal U-factor of 0.3 (R-3) to 0.14–0.15 (R-7).

VIG reduces heat transfer by eliminating the air in the space between the two panes of glass in an IGU. Although VIGs are simple in concept, they have proved extraordinarily difficult to mass produce with a method that yields market-acceptable unit prices. Creating a vacuum between the panes of glass causes the panes to be drawn together, which would create a thermal short circuit from the outer to the inner panes if they touched. A supporting structure, often small “pillars,” must be added to separate the panes. This support structure creates small thermal bridges (pathways for conduction) between the inner and outer panes and stress concentrations in the glass, which can crack the glass. Support structures that minimize thermal bridging and stress concentrations would improve energy performance and long-term durability. The two panes of glass must be joined at the perimeter with a continuous

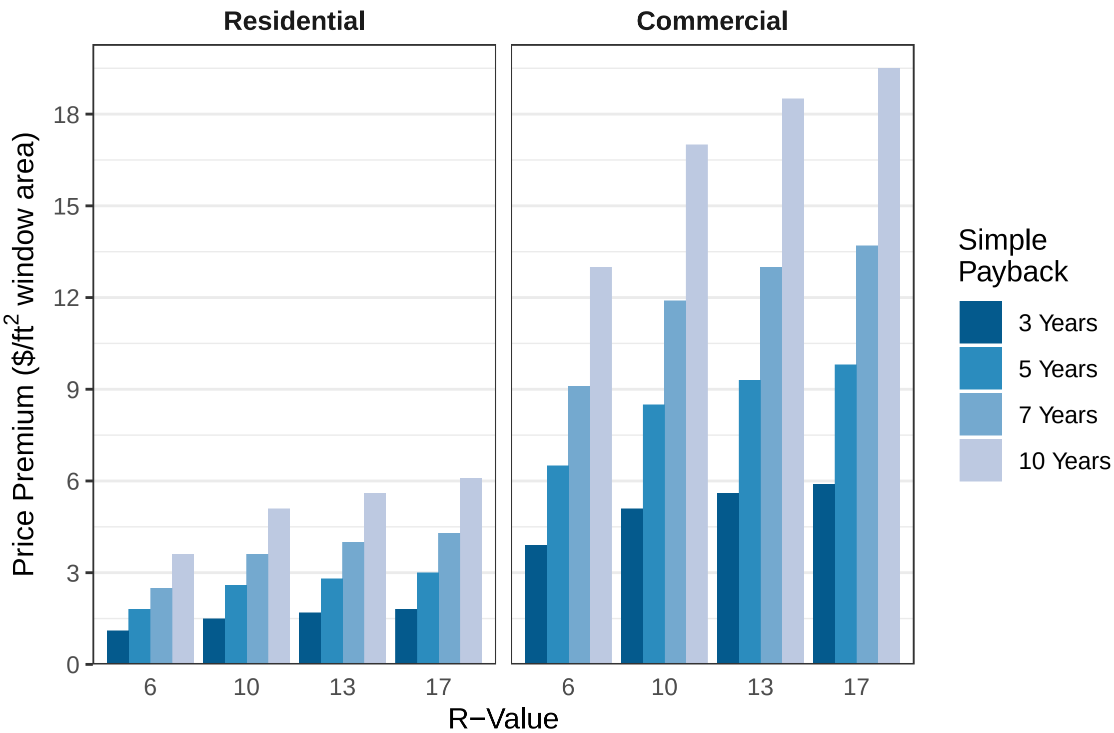

Figure 12. Price premiums for multiple whole-window R-values are shown for residential and commercial buildings. The lower R-value of windows typically installed in commercial buildings compared to residential buildings leads to greater energy savings in commercial buildings and thus substantially higher price premiums for equivalent payback periods.

seal that can maintain a vacuum. The typical approach uses a glass frit, which creates a strong and rigid seal. When there are large temperature differences between the interior and exterior glass, differences in thermal expansion can cause a rigid joint to fail; more flexible joining methods (e.g., polymeric edge seals) have so far been inadequate for maintaining a vacuum. The high temperatures required to bond the frit to the glass can also affect tempering and damage low-e coatings. Alternative bonding materials are needed; these materials should be able to maintain a vacuum of less than 0.1 Pa (for a between-pane spacing of approximately 200 μm) with limited degradation for the life of the window, form a seal at temperatures below 180°C, and ideally, have low thermal conductivity.

Replacing the air or fill gas (e.g., argon, krypton) between the panes in an IGU with a solid material switches the dominant mode of heat transfer between the panes from convection (of the trapped gas) to conduction through the interpane material. For this approach to improve performance and yield an acceptable IGU, the material must be transparent, low haze, very low thermal conductivity, and stable under the conditions in the interpane space in an IGU. Aerogels might be a suitable material for this application, but several key technical challenges must be addressed. The aerogel must be produced using an approach that is scalable and compatible with continuous (nonbatch) manufacturing methods, compatible with existing glass coatings, and amenable to the glass handling and IGU assembly methods typically employed for IGU and window manufacturing (or compatible with alternative aerogel formation/deposition and IGU assembly approaches that have low capital costs). The aerogel itself must also be hydrophobic or otherwise modified to prevent pore collapse at the edges of the IGU if the edge seal fails and water vapor enters the IGU, and should not expand, sag, or compress over the lifetime of a typical IGU (>20 years).

3.1.2 Highly Insulating Window Frames

Though there have been improvements in the insulating performance of window frames, these improvements have been relatively modest compared to improvements in both the performance of IGUs and the typical performance of the opaque envelope. Window frame materials vary by application area—commercial buildings generally use

Highest Thermal Performance Commercial Window

Arconic was competitively awarded a cooperative agreement from BTO to pursue a high-performance commercial window. The OptiQ window system was designed and commercialized, and it incorporates a high thermal resistance thermal break in an aluminum frame that passes high structural requirements (80 lbs/ft^2 design pressure). OptiQ windows achieve a whole-window NFRC U-factor rating of 0.17 BTU/hr-ft^2 F (almost R-6).

Arconic won a subsequent competitively awarded cooperative agreement to further improve the most efficient high structural requirement window on the market, its OptiQ system. The new approach developed an even higher thermal resistant thermal break system that was bonded to the aluminum structural members. A fixed window prototype was tested in accordance with standard NFRC and American Architectural Manufacturers Association standards, and it achieved a frame thermal improvement of 20%. When combined with a typical triple-pane glazing package with two low-e surfaces, it achieved a U-factor of 0.14 BTU/hr-ft^2 F (R-7).

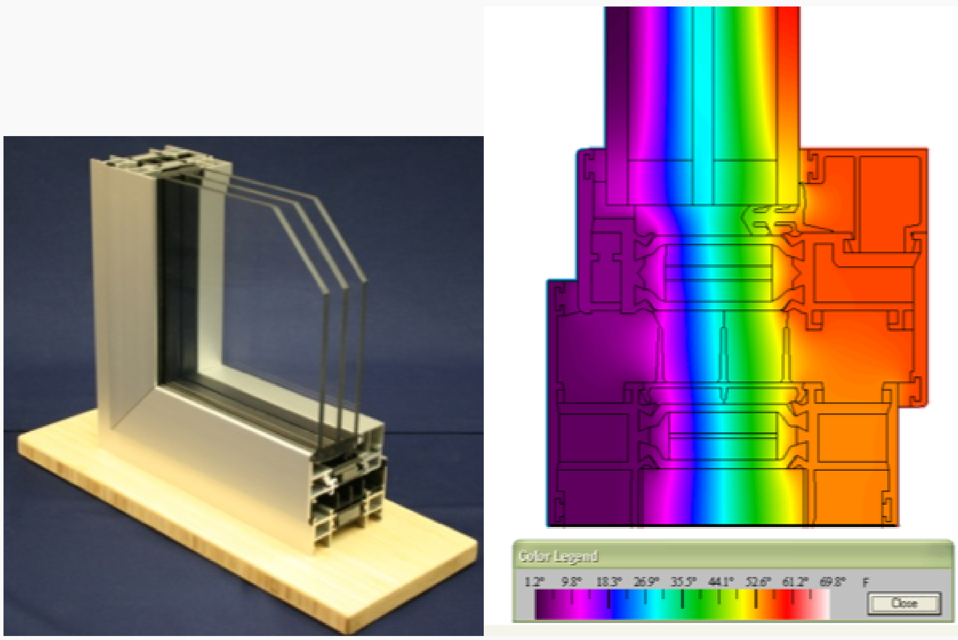

Figure 13. Arconic OptiQ commercialized high structural and thermal performance window with thermal plot.
Figures from Kumar [27].

aluminum frame windows and curtain walls, whereas residential (and some low-rise commercial) buildings can have windows with wood, fiber-reinforced plastic, or uPVC frames. The methods and materials that can improve the insulating performance of window frames vary depending on the primary window frame material. Frames constitute 5%–35% of the overall window area, and in the latter case, they limit the overall window R-value. Typical window frames currently range from R-1 to R-3, and even when combined with an IGU rated with an infinitely high R-value, the overall R-value of the window could not exceed R-9 [4]. Highly insulating window frames are therefore critical to improving the overall performance and energy savings potential of windows. In spite of this need, research to develop novel window frame materials and assemblies to reduce heat transfer has been limited to high-structural-performance aluminum framing (see the Highest Thermal Performance Commercial Window success story [27]).

Aluminum, fiber-reinforced plastic, and uPVC frames, as illustrated in Figure 7, are a mix of solid structural elements and voids that reduce thermal conductivity and weight. As a result, viable approaches to improving thermal performance for these frames, compared to the current state-of-the-art, involve reducing the thermal conductivity of the structural elements and minimizing convection and radiation heat transfer within the voids. Approaches that rely on frame designs and materials that are compatible with existing manufacturing methods and tooling are likely

Table 6. Critical Characteristics for High-Performance Windows (IGUs and Frames)

Critical Characteristics
• IGU thicknesses should be comparable to double-pane IGUs—0.6–0.75 inches (residential) and 0.85–1 inches (commercial)—such that they can be accommodated in existing frames manufactured for double-pane IGUs • IGU weight should be similar to double-pane IGUs, approximately 3 lb/ft^2 window area and 6 lb/ft^2 window area for residential and commercial windows, respectively • Durability (for all components) should be equivalent or superior to existing windows; multiple ASTM and American Architectural Manufacturers Association durability standards apply to various window components and complete windows • Novel IGU and frame components should have a pathway to compatibility with current typical manufacturing methods (e.g., automated IGU assembly).

to deliver energy savings with the lowest possible incremental cost impacts. Novel window frame materials—such as insulating structural foams or other materials with especially low thermal conductivity that can also meet the structural performance requirements for windows—also have significant energy savings potential, but must employ low-cost feedstocks and mature or readily scaled novel manufacturing methods.

Aluminum frames are produced as individual frame elements ("lineals") that are assembled into a system that typically combines exterior and interior aluminum elements with a thermal break, and then cut to length for each window. Because the frames start out as individual metal and polymer sections, to reduce radiation heat transfer, the metal pieces could be treated with a low-e coating when the surface finish (e.g., painted, anodized) is applied. Conduction heat transfer can be reduced by lengthening the thermal break or reducing the thermal conductivity of the thermal break or the aluminum itself. BTO has supported recent work to develop a novel polymer foam thermal break [27]. Approaches that modify aluminum to reduce its thermal conductivity must maintain its structural properties for the resulting windows to meet structural performance requirements.

The thermal performance of fiber-reinforced plastic and uPVC frames could be improved through modifications to both the material itself and the frame assembly. Fiber-reinforced plastic and uPVC frames are manufactured using forming methods that result in a complete cross-section for the entire frame. To control radiation heat transfer by reducing emissivity, either the uPVC or resin must be modified to reduce its emissivity, or a liquid-applied coating could be used. Reducing thermal conductivity could also be achieved through alternative materials compatible with the extrusion and pultrusion methods used for uPVC and fiber-reinforced plastic frames, respectively, or materials that modify existing uPVC or fiber-reinforced plastic formulations to inhibit conduction. As with any effort to modify the conductivity of aluminum, materials that reduce the thermal conductivity of uPVC or fiber-reinforced plastic must have comparable strength to satisfy window structural requirements.

Frames made from wood typically use solid wood with no thermal break. Because the frame cross-section is an uninterrupted solid or multiple solid pieces butted together (in the case of operable windows), improving thermal performance requires modifying the properties of the solid or adding a thermal break. Solid wood frame windows are a particularly lucrative market for residential window manufacturers; thus, the absence of approaches to improve thermal performance is a significant barrier to improvements in window R-value voluntary specifications for the entire industry. Modifying wood to extend its life has been widely investigated, and various methods have been adopted for centuries. Superficially, similar approaches might be employed to modify the thermal conductivity of wood used for window frame applications. (Notably, similar modifications might also be possible for wood used for building framing to reduce wall thermal conductivity.) Although thermal breaks are common in aluminum frames to reduce overall thermal conductivity, they have not been widely applied to wood frames. While the polyamide thermal breaks used in aluminum-frame windows are likely not the right geometry for use with wood joining methods, low thermal conductivity materials could be used to develop thermal breaks with appropriate geometries for compatibility with wood-joining techniques. Alternately, structural foams could be bonded to wood frame elements using an approach similar to that developed by Arconic for commercial windows.

Table 7 summarizes the future research opportunities for IGUs and window frames discussed in this section. These opportunities for the individual technology focus areas suggest broad R&D activities that can move window price

Table 7. Future Research Opportunities Related to IGUs and Window Frames

Future Research Opportunities		
Technology	Objectives[a]	R&D Activity
Thin Highly Insulating IGUs	Reduce weight Reduce thickness Reduce thermal conductivity[b]	Design triple-pane IGU with thin center lite to minimize heat transfer and manufacturing cost
	Improve durability Reduce thickness	Design spacers for triple-pane IGU with only two leakage paths (“suspended” center lite)
	Reduce manufacturing cost[b] Improve durability	Develop thin triple-pane IGU configuration(s) that are compatible with automated IGU assembly systems
VIGs	Reduce thermal conductivity[b] Improve durability Reduce manufacturing cost[b]	Develop mechanical pillars for VIGs, including materials, method of installation, and avoidance of fatigue cracking
		Optimization of glass strength, support geometry, support material and spacing
		Develop durable edge sealing materials that reduce mechanical stresses under thermal cycling
		Investigate low-temperature seal bonding and curing methods
Frames (all)	Reduce heat transfer[b]	Develop surface coatings or material additives
Frames (aluminum)	Reduce thermal conductivity[b]	Develop novel thermal break materials or frame designs to reduce thermal conductivity
Frames (wood)	Reduce thermal conductivity[b]	Design novel cross-sections that maintain strength and are compatible with existing fabrication processes

[a] Objectives are detailed further in Table 6.
[b] Cost and performance levels must be sufficient to achieve the overall price and performance targets for this technology area, which are given in Table 5.

and performance in the direction of the targets articulated in Table 5. Table 6 articulates additional characteristics that are not necessarily needed to achieve the price and performance targets in Table 5, but that are important to consider when developing materials and components such that those R&D efforts yield windows that meet or exceed industry standards and customer expectations of performance and durability, and maximize their potential path to commercialization.

3.2 Dynamic Facades and Glazing

In buildings in heating-dominated climates, the heating energy use reductions from solar heat gain through windows in the winter months can be substantial, as shown in Figure 3. Conversely, in climates with significant cooling seasons, solar heat gain exacts a significant cooling energy use penalty. As a result, windows with static solar heat gain coefficients (SHGCs) represent a climate-zone-specific compromise between reductions in heating energy use and increases in cooling energy use. Although the introduction of low-e coatings and higher R-value glazing has benefited cooling-dominated climates, these technologies have also substantially reduced beneficial passive solar heat gain in heating-dominated climates. These trade-offs are shown in Figure 3 as the energy use contribution from solar heat gain appears below zero in the heating season and above zero in the cooling season. Conversely, dynamic glazing and facade systems, which have variable solar heat gain control characteristics, can substantially lower energy use compared to static glazings. Dynamic glazings and shading systems enable real-time management of window configuration in response to diurnal and seasonal changes in heating and cooling demand, occupancy, and available daylight. As detailed in Section 4.2, dynamic facades can also be used to provide grid benefits by enabling changes in the timing of heating, cooling, and lighting loads and thus influencing electric load shape, peak demand, and demand-side ramp rates.

There are currently available dynamic glazing and automated window attachments that can improve energy performance compared to traditional glazing with fixed SHGC and Tvis. Electrochromic and thermochromic dynamic glazing systems are available primarily for commercial buildings, but limited availability coupled with high product and installation costs have curtailed demand. Automated window attachments can offer adjustable control over daylighting and/or solar heat gain, but bringing power to the attachment system again increases installation costs compared to nonautomated systems, although self-powered and battery powered options are now entering the market. For both dynamic glazing and automated attachments, control system design also poses a key challenge. Significant effort can be required to configure coordinated controls of multiple automated systems to achieve energy savings, peak demand reduction, and occupant comfort objectives.

Technology Area Targets

Table 8 gives the targets for installed price premium and performance for dynamic windows and automated attachment systems with equivalent solar heat gain control functionality. These targets are set for technologies entering the market in 2030 and are based on a 5-year simple payback target. The primary energy savings associated with the indicated performance level include only heating and cooling energy savings; potential lighting energy savings derived from additional daylighting as a result of shades and glazing being optimally adjusted throughout the day are excluded. Primary energy savings increase for dynamic windows and other dynamic solar control technologies between 2030 and 2050 because the baseline window is assumed to have a static SHGC. New construction thus does not yield substantial improvements over the existing stock, and as the stock grows in the future, the energy savings potential of dynamic glazing and shading systems grows as well.

Table 8. Dynamic window and facade performance and installed price premium targets for 2030, as well as corresponding primary energy savings potential in 2030 and 2050. These targets apply to any dynamic window technology or other technology that provides an equivalent solar heat gain attenuation range and are inclusive of any additional nonglazing installation costs (e.g., electrical connections or site-specific controls configuration). These price premiums should be added to baseline window prices when evaluating the competitiveness of new dynamic windows or equivalent technologies.

Dynamic Windows						
Building Sector	Performance		Installed Price Premium		Primary Energy Savings (quads)	
					2030	2050
Residential	0.05/0.65	SHGC (active/ inactive)	2.9	$/ft^2 window area	1.35	1.50
Commercial			14.6	$/ft^2 window area	1.56	1.64

Price premiums for several combinations of performance levels and payback periods are shown in Figure 14 to illustrate the range of possible market-acceptable installed price premiums depending on the performance of a given technology and the financial requirements of a particular building owner. These price premiums should be added to the baseline prices given in Appendix A when comparing prices with other high-performance window technologies. Although the installed prices in Table 8 are required to achieve a 5-year payback at the target performance level, market-acceptable payback based on energy cost savings is not the exclusive determinant of widespread adoption for dynamic glazing and shading technologies. Instead, the parameters in the critical characteristics table define additional features, functionality, or characteristics that these technologies should seek to incorporate to broaden their potential value proposition and satisfy prospective customer expectations. Moreover, Figure 19 illustrates the potential for dynamic glazing to deliver electric load reductions during peak periods, which could provide additional utility bill savings for building owners. Figure 14 shows that commercial buildings offer a particularly significant opportunity for energy savings, which is reflected in the substantially higher installed price premiums for all payback periods when compared to residential buildings.

3.2.1 Reducing Manufacturing Costs

Dynamic glazing is typically manufactured using high-cost and often low-throughput methods, which negatively impacts product availability and pricing. Novel approaches that rely on low-cost, high-throughput production methods could reduce product costs and expand availability, though new electrochromic processing methods must also produce adequate performance and durability characteristics as compared to incumbent technologies. In addition,

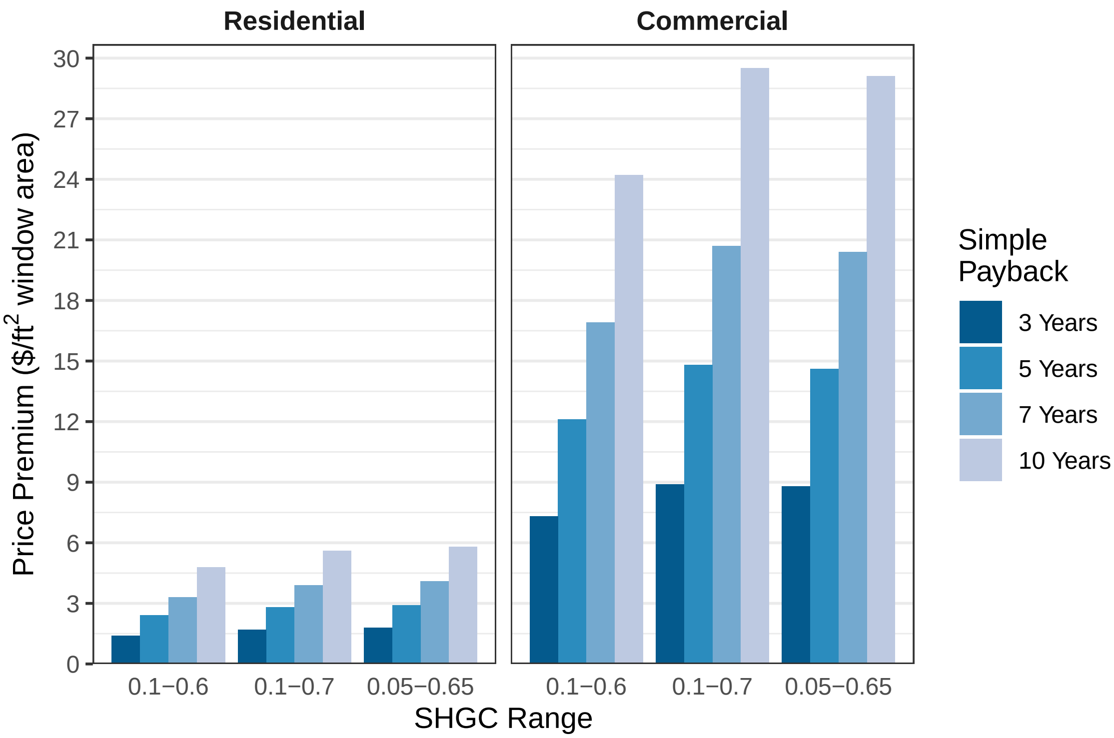

Figure 14. In general, larger differences between minimum and maximum SHGC yield greater energy savings and thus larger acceptable price premiums for a given payback period, though the specific SHGC range that maximizes energy savings might vary somewhat between buildings. Total installed prices should be used when evaluating the cost-competitiveness of novel dynamic window technologies.

these new approaches must not rely on formulations with expensive materials, precursors, catalysts, or intermediate processing steps, as these might significantly reduce or even offset the product cost improvements gained from the substitution of a lower-cost, higher-throughput manufacturing method.

Transition metal oxides represent the current state-of-the-art in electrochromic glazing, generally relying on a tungsten-based formulation produced using a physical vapor deposition method [28]. More recently, plasmonic electrochromism has been found in nanostructured transparent conducting oxides such as tin-doped indium oxide [29] as well as aluminum-doped zinc oxide nanocrystalline films [30]. The underlying mechanism should also apply to tungsten oxides as well [29], but it has not been demonstrated empirically. Electrochromic polymers can be fabricated from abundant materials using low-cost methods [28] including roll-to-roll deposition on flexible substrates [31], but they face other significant barriers for building energy efficiency applications, including adequate cycling durability[8] (adequate control of irreversible reactions), high transparency in the clear state, as well as potential switching in the NIR or visible and NIR ranges [28, 32]. If future work can address these challenges, polymer electrochromic materials might offer an additional low-cost alternative to novel high-performance and lower-cost metal oxide formulations.

In general, novel approaches likely maximize cost savings potential by being compatible with current glass coating and IGU manufacturing processes. These requirements include production rates and processing conditions, so these methods can then transfer readily to existing float glass production facilities that are already part of the window supply chain. Ideally, a solution that can allow fabrication of dynamic windows to be broadly placed throughout present manufacturing channels will have the highest probability of reducing cost and accelerating diffusion into the market. Present electrochromic windows are produced at dedicated sites, whereas some thermochromic technologies

[8] Durability is evaluated for dynamic glazing with ASTM 2141, which requires enduring high temperature, high ultraviolet exposure, and 50,000 device cycles, concurrently.

have been integrated into products already in use in established manufacturing facilities. These thermochromic technologies are beginning to diffuse more rapidly through these manufacturing channels, which should accelerate adoption. A similar model for electrochromic windows would be highly desirable.

3.2.2 Increasing the Selectivity of Wavelength Attenuation

Current state-of-the-art dynamic glazing technologies attenuate both visible and NIR wavelengths. Decoupling switching in the visible and NIR ranges would enable independent control of glare (tinting) while admitting some solar heat gains (NIR switching) in the winter, or restricting some solar heat gains and allowing in daylight in the summer, particularly for buildings that are occupied during daylight hours [33]. Ideally these systems would have a wide operating range for SHGC (0.01–0.7) and Tvis (0.0–0.6). In cooling-dominated climates, decoupled NIR switching is not especially valuable, but in climate zones with large seasonal temperature swings, fully decoupled Tvis and solar heat gain control is valuable [33]. Nanocrystalline transparent conducting oxide films, particularly tin-doped indium oxide and aluminum-doped zinc oxide, have been demonstrated to have electrochromic properties with NIR-only switching [28, 30]. These materials show fast response times, and aluminum-doped zinc oxide has also shown good cycling durability [30]. As noted in Section 3.2.1, additional work is needed to identify viable low-cost manufacturing methods for these materials that achieves the required nanostructure. To get visible light control with these materials, a separate automated attachment system or glazing layer that switches in the visible wavelengths (e.g., suspended particle device glazing) would be required. In the future, if similar low-cost processing methods can be developed for chemistries that show switching in the visible or NIR spectra, a sandwich system with separate visible- and NIR-controlling electrochromic layers might be viable. Thermochromic glazing with NIR control has been demonstrated at the lab scale using vanadium dioxide nanoparticles ($<$50 nm). In addition, recent work has demonstrated semi-uncoupled control of visible and NIR wavelengths in a single electrochromic coating, where at low voltages, switching is primarily in the NIR range; as voltage is increased, switching begins to occur strongly in both the NIR and visible ranges [34]. The study by DeForest et al. [33] shows that semi-uncoupled electrochromic systems deliver greater total energy savings across the United States compared to NIR-only or coupled visible and NIR switching systems, which are better suited to northern and southern climates, respectively. More generally, features such as fully uncoupled NIR and visible wavelength switching, privacy control (fully opaque or Tvis = 0), and the ability to separately control sections of a single chromogenic pane might not yield increased energy savings, but would improve occupant comfort and broaden the value proposition for dynamic glazing systems.

3.2.3 Self-Powered Systems

Automated attachment and electrochromic glazing systems face additional challenges with respect to installation effort, commissioning, and cost. In general, installation of these systems requires two trades to visit the site, one to install the hardware itself and one for the electrical connection. Battery-operated dynamic technologies eliminate the need for additional electrical work, but require regular battery maintenance. Systems that have an integrated power system would reduce installation and construction complexity while also avoiding additional ongoing maintenance costs. These systems can use small photovoltaic (PV) cells surface-mounted to the frame or on protruding structures anchored to the frame or attachment system (if externally mounted) to provide electricity for state-change operations [33]. However, with the conversion efficiency of mainstream low-cost PV, self-powered systems with surface-mounted PV would need to be especially efficient. For future electrochromic systems that can provide complete privacy (fully opaque or Tvis = 0), particularly for residential applications, energy storage will also need to be integrated into the frame assembly to power the system at night. Any storage and PV system will require careful sizing to ensure continuous operation during extended periods of low solar radiation. Finally, for these systems to have long-term durability, attention should be devoted to design for reparability, as minor electrical faults in the glazing or attachment power system should not create a requirement for major facade disassembly or reconstruction. Thermochromic glazing can deliver dynamic operation without requiring power, but thermochromic materials face many unique challenges, which are addressed by Lee et al. [35].

For self-powered systems, or even to generate surplus electricity, PV can be integrated into the IGU with novel approaches. The most expensive components of PV panels are the glass and the transparent conductors (tantamount to low-e layers) that already compose IGUs [36]. However, durability, integration, and efficiency remain challenging and are the focus of current research efforts. There are two main types of static PV glazing: transparent [37] and semitransparent [38]. Transparent designs convert only nonvisible solar energy (ultraviolet and infrared) to maintain maximum Tvis. However, the power conversion efficiency—the ratio of electrical power out to solar power in—has never experimentally exceeded 5.1% [37], though the theoretical maximum is 20.5%. The ultraviolet portion of the spectrum makes up only a small fraction of the solar spectrum, yielding a maximum theoretical power conversion efficiency of 2.5%. Though ultraviolet PV glazing has been demonstrated to power an integrated electrochromic device [39], it is not appropriate for large-scale electricity generation.

Because of limited power conversion efficiency in transparent designs, most IGU-integrated designs are semitransparent, relying on the visible portion of the spectrum but only absorbing a fraction of the incident visible light. The amount of light absorbed and converted to electricity is limited by the need to maintain adequate Tvis. Current semitransparent PV designs thus suffer from the fundamental trade-off between power conversion efficiency and Tvis. The advent of switchable PV windows [40, 41], a third type of window PV technology, circumvents this fundamental trade-off by switching from a visibly transparent state (high Tvis) to a darkened state (low Tvis) in a manner similar to thermochromic glazing. Dynamic PV glazing allows for increased power conversion efficiency in the colored state without sacrificing Tvis during off hours. The technology uniquely combines higher power conversion efficiency PV with the energy-saving benefits of dynamic glazing in a single system. Dynamic PV glazing is still in its early stages, and durability and switching temperature must be optimized before commercialization of switchable designs will be realized. If these PV systems generate additional electricity, it could be used in an independent DC power system to operate other dynamic facade components, or if significant additional generation is expected, the additional installation cost required to integrate the glazing PV into the building electrical system should be offset by the value of the electricity generated.

3.2.4 Improving Dynamic Facade Component Sensors, Controls, and System Integration

Automatic control of dynamic facade components requires a complex balance between solar control and daylighting to maximize energy savings and occupant comfort. Currently available automated controls combine heuristic rules and setpoint schedules that require considerable configuration effort for each new installation. Control methods from other industries are being investigated for application in the building sector to address this complex optimization problem. Model predictive controls (MPCs) can use thermal and daylighting models of dynamic glazing and models of room thermal response; HVAC, lighting, and thermal energy storage parameters; and occupant preferences to produce optimal control based on forecast performance over a specified time horizon (e.g., 24 hours). For GEB objectives, electricity prices and distributed energy resource forecasts can be combined with dynamic facade control algorithms to minimize utility costs [42], but work remains to develop the required models and algorithms for grid-coordinated operation. Fundamental work has been conducted to build open-source models for dynamic glazing and the workflow to enable routine implementation of MPCs [43, 44, 45, 46]. Control can be achieved autonomously without real-time data exchange or integration with HVAC and lighting systems. Adaptive models using sensor inputs, user feedback, or machine learning algorithms can be used to improve energy efficiency performance and user satisfaction over the life of the installation.

These dynamic glazing and automated attachment systems face additional challenges with respect to the costs to integrate them into centralized building management or control systems. In both residential and commercial building applications, significant advancements are needed to facilitate straight-forward, reliable, low-effort system integration for dynamic facade components. When these components are installed, the labor effort required to configure them for coordinated operation should be minimized. Needed improvements include networking and communication protocols, sensor node naming conventions, sensor integration, data exchange, and hierarchy of control. Once operating, improved monitoring, state verification, and automated fault detection and diagnosis tools are needed to ensure that the facade systems are operating as designed. As an alternative to automated control of dynamic facade components, existing manual facade elements could be operated by building occupants in a manner that reduces energy use. The development of control strategies for manual facade operation would then enable software or hardware systems (e.g., push notifications to mobile phones) that prompt building occupants to adjust manual facade components—lower or raise shades, open or close windows. Such solutions might be more cost-effective than fully automated systems, especially in existing buildings. Once these systems are developed, research should also be conducted to empirically validate predicted energy savings based on occupants' deviation from prompted operation (e.g., windows left open, shades remaining closed).

Automated dynamic glazing and facade control systems and their supporting hardware must also be developed with attention to cybersecurity considerations, because these devices are likely to be left in near-default configurations once installed and initially commissioned, potentially with limited active effort to install updates and patches or conduct other cybersecurity-related maintenance. In the future, these systems might represent a large number of network-connected devices, which would present an appealing target for use in attacks on other systems [47], as well as an opportunity to cause widespread disruption to building operations.

Table 10 summarizes the future research opportunities for dynamic glazing and dynamic facades discussed in this section. These opportunities suggest broad R&D activities that can move product price and performance in the direction of the targets articulated in Table 8. Table 9 articulates additional characteristics that are not necessarily needed to achieve the price and performance targets in Table 8, but that are important to consider when developing materials and components such that those R&D efforts yield dynamic glazing and facade systems that meet or exceed industry standards and customer expectations of durability, and maximize occupant acceptance of and comfort and productivity benefits from these systems.

Table 9. These critical characteristics define the additional performance or functionality needed from dynamic glazing, not necessarily for energy savings, but to yield glazing that is appealing to architects and accepted by building occupants.

Critical Characteristics (Dynamic Glazing)
• Broad dynamic range for Tsol and Tvis (e.g., 60:1 between minimum and maximum tint states) • For adequate glare control, switching time to Tvis <0.03 or fully opaque/translucent state of <3 min for a large window (e.g., 1.5 x 2.75 m) at operating temperatures of -20–80°C • Ke (Tvis/SHGC) >2 in both the inactive and switched (blocking) states • Low power for switching and maintaining the switched state (<3 W/m^2) with low voltage power supply (3–5 V DC) • Neutral color (e.g., clear, gray) in both the inactive and switched (blocking) states • Continuous tinting or multiple intermediate tint states.

Table 10. Future Research Opportunities Related to Dynamic Glazing and Facades

Future Research Opportunities		
Technology	Objectives[a]	R&D Activity
Dynamic Glazing	Reduce total installed price[b]	Develop novel materials compatible with fabrication methods suited to existing float glass production processes
	Increase energy savings potential[b]	Investigate novel materials that can independently attenuate visible or NIR wavelengths
	Broaden value proposition	Develop PV materials with properties complementary to dynamic glazing
Dynamic Facades	Reduce total installed price[b]	Achieve fully encapsulated, self-powered systems
	Reduce total installed price[b] Increase energy savings potential[b]	Develop simplified sensor and control architectures that optimize energy savings and occupant comfort
	Broaden value proposition	Develop novel control methods for grid-integrated operation
		Investigate required communications and data exchange protocols to support grid-integrated operation

[a] Objectives are detailed further in Table 9.
[b] This objective is not addressed directly in Table 9, but cost and performance levels must be sufficient to achieve the overall price and performance targets for this technology area, given in Table 8.

3.3 Visible Light Redirection

Visible light redirection or "daylighting" systems increase the usability of available natural light to illuminate interior spaces. Commercialized daylighting systems include interior and exterior light shelves, louvers, and films adhered to the glass itself. These systems typically apply to clerestory windows or the upper part of the main windows, while the remaining window area is unimpeded to maintain exterior views. Visible light redirection systems also include technologies that capture light at the roof or facade and redirect it to interior spaces that do not have windows. When these technologies are combined with lighting sensors and controls and, ideally, with dimmable lamps or luminaires, they can significantly reduce the lighting energy use in some types of commercial buildings by substantially increasing the floor area with adequate illumination from available daylight alone. Moreover, daylighting has been cited as a mechanism to improve health and productivity [18, 48, 49], and labor costs far exceed typical energy costs for most organizations [50].[9]

Technology Area Targets

The performance and installed price targets for visible light redirection and daylighting systems that can reduce lighting energy use available in 2030 are given in Table 11, along with technical potential primary energy savings for these technologies at the indicated performance level in 2030 and 2050. The target installed price assumes a 5-year simple payback; for payback periods ranging from 3 to 10 years, installed prices for visible light redirection systems range from \$11.90 to \$15.60/ft^2 window area. The installed price does not include any window costs, because it is assumed that the daylighting system is added onto existing windows.

The installed price in Table 11 also assumes that the daylighting system covers the entire surface area of all windows. If the system applies to only a fraction of the window area or only some of the windows in a building, the installed price per unit daylighting system area would increase accordingly, so long as the indicated performance level is achieved. For example, if the system can achieve 40% lighting energy savings covering only the top third of all the windows in a building, the corresponding total installed price could be \$39/ft^2 area. The installed price target includes any required sensors and control systems, as well as installation and commissioning of those systems, to achieve the indicated performance level consistently for the entire operating lifetime of the system. The installed price target does not include cost savings derived from longer lamp lifetimes associated with reductions in annual lamp operating hours, though the already long lifetimes of solid-state lighting likely reduces the net present value of the avoided lighting costs. Other nonenergy cost savings—such as potential health or productivity benefits—are not factored into the installed price target, though they might be substantially greater than the energy cost savings alone [50]. The indicated energy savings and corresponding energy cost savings embedded in the total installed price do not implicitly require any particular floor plate depth; a 40-foot floor plate is a reasonable target for visible light redirection, though technologies that rely on mechanisms not influenced by floor plate depth need not adhere to this guideline.

Table 11. This table includes installed price and performance targets for visible light redirection technologies available in 2030, as well as technical potential primary energy savings in 2030 and 2050. Energy savings and performance objectives for these technologies are based on lighting energy use reductions.

Visible Light Redirection/Daylighting						
Building Sector	Performance		Installed Price		Primary Energy Savings (quads)	
					2030	2050
Commercial	40%	Lighting Energy Savings	13	\$/ft^2 window area	0.26	0.17

Visible light redirection devices intended to reduce lighting energy use in buildings have been explored for many decades [48], but they have found limited commercial adoption because of several challenges related to both the technologies themselves and the supporting infrastructure required to realize consistent lighting energy savings. Light redirection systems installed in pilot projects have demonstrated significant lighting energy savings [52], but designers and building operators have found it difficult to replicate these savings. Correctly designing and commissioning the lighting control system to deliver expected lighting energy savings and operate in a manner that is

[9] Notably, the most direct study of the implications of daylight on individual cognitive performance or productivity focused on students in a classroom setting [51].

acceptable to building occupants is not trivial. The difficulty of achieving the expected energy savings and thus realizing any potential operational cost savings limits the acceptability of the additional design, equipment, and installation costs of these systems. There might be software-based workflows that can facilitate appropriate system design and commissioning to address these post-commissioning performance challenges while reducing design effort and associated costs.

With respect to visible light redirection devices themselves, glare and aesthetics are persistent challenges. Systems that allow transmission of downward sunlight cause glare and thermal discomfort. Installing a secondary shade to prevent discomfort reduces the efficiency of the daylight redirecting device. Moreover, the patterns of redirected sunlight can be nonuniform and produce high contrasts of bright sunlight and shadowed areas on the ceiling and walls. Some lighting designers and building occupants find that this nonuniformity detracts from the overall design and are therefore reluctant to employ daylight redirection technologies. For retrofit applications, sidelighting redirection technologies might not perform well because of low ceiling heights, inappropriate ceiling surfaces for light reflection (e.g., extensive exposed mechanical systems), existing blinds that block the light redirection system when closed, and inadequate control system infrastructure to support appropriately configured lighting controls [52]. Interior walls can also limit or eliminate daylighting potential in office settings with extensive perimeter offices. Understanding the energy savings contributions from these complementary design choices could lead to overall improvements in light redirection system design and implementation.

Technologies that do not depend on sidelighting for visible light redirection have the potential to be effective for spaces with low or otherwise incompatible ceilings and for windowless interior spaces. These capabilities are critical to maximizing the lighting energy savings potential from utilizing available ambient light, particularly for retrofit applications where these building characteristics are not easily changed. These technologies should be developed to minimize the number and size of roof or facade penetrations, maximize visible light transmission, minimize heat transmission, and minimize total installed prices. The cost of any light transmission conduits should also be extremely low per unit length, and light decay in the conduits should be minimized to allow for long and indirectly routed runs. Systems should perform well with both direct and diffuse solar radiation to maximize lighting energy savings. Light concentrators that use fiber optic conduits generally do not have sufficiently low prices for the daylight provided; alternative approaches that leverage findings from solar PV research, digital projection technologies, and other research areas might be fruitful.

Table 13 summarizes the future research opportunities for daylighting and visible light redirection systems discussed in this section. These opportunities suggest broad R&D activities that can move product price and performance in the direction of the targets articulated in Table 11. Table 12 articulates additional characteristics that are not necessarily needed to achieve the price and performance targets in Table 11, but that are important to consider when developing materials and components such that those R&D efforts yield daylighting and visible light redirection systems that meet or exceed industry standards and customer expectations of durability, and maximize occupant acceptance of and comfort and productivity benefits from these systems.

Table 12. Critical Characteristics of Daylighting and Visible Light Redirection Technologies

Critical Characteristics
• Maintain instantaneous daylight glare probability < 0.35 • Redirect no direct solar radiation toward occupants' viewing positions • Provide spatial daylight autonomy $sDA_{300,50} \geq 55\%$ and $sDA_{300,20} \geq 80\%$ throughout a generic 40-foot floor plate without partitions and with daylight from only one side • Need minimal additional installation requirements relative to typical window products (e.g., blinds, films) • Need no additional maintenance requirements relative to typical window products • Demonstrate power consumption <1 W/m^2 clerestory window area at low voltage (3–5 V DC); self-powered or passive operation preferred • Establish compatibility with existing manual or automated shading systems.

Table 13. Future Research Opportunities Related to Daylighting and Visible Light Redirection Systems

Future Research Opportunities		
Technology	Objectives[a]	R&D Activity
Visible Light Redirection	Increase energy savings potential[b] Reduce total installed price[b]	Develop software to simplify design for lighting savings and occupant comfort while simplifying commissioning
	Increase energy savings potential[b] Increase size of applicable market	Develop software for sensor configuration to ensure adequate glare control
		Develop technologies that redirect light to interior spaces or otherwise do not require sidelighting
	Increase size of applicable market	Investigate novel light redirection materials with greater control over directional distribution of light

[a] Objectives are detailed further in Table 12.

[b] This objective is not addressed directly in Table 12, but cost and performance levels must be sufficient to achieve the overall price and performance targets for this technology area, given in Table 11.

3.4 Systems-Level Performance Evaluation and Characterization of Windows

The modeling tools, window evaluation facilities, and technical capabilities developed by DOE for the windows industry have had a pivotal role in the R&D, design, and manufacturing of high-performance windows, as well as their rating and certification. Looking forward, the impact of these tools, infrastructure, and expertise can be expanded by developing capabilities that enable systems-level assessment of window technologies. As discussed in Section 4.1, a systems-level approach to new construction and retrofit project planning and execution has the potential to help architects and engineers recognize the benefits of specifying a high-performance envelope. In addition, modifications to modeling and simulation tools could facilitate assessment of GEB performance for dynamic facades, including determining the GEB potential for an individual building and integrating GEB value into the overall assessment of the envelope with other building systems when specifying a project. Together, adding these types of capabilities to modeling tools will enable them to support many of the activities described in Section 4, which are specifically intended to broaden the value proposition of the novel technologies described in this section and help accelerate their market adoption.

4 Integration

Beyond developing novel window materials and systems as well as supporting tools and infrastructure, other actions can help broaden the related value proposition. Identifying, quantifying, and articulating the additional value streams or benefits associated with windows can help accelerate their adoption. Tweaking traditional approaches to building project procurement, design, and construction can help fully value the building end uses served with implementing a high-performance building envelope, improving occupant comfort, increasing usable floor space, and reducing HVAC system costs. Building envelope components with dynamic or time-varying properties could enable the provision of electric grid services, which could lead to direct remuneration or be used as part of a strategy for increasing the value of variable renewable energy generation. In addition to expanding the value proposition of building envelope materials and systems themselves, incorporating technologies, manufacturing methods, and engineering and business practices from other industries could represent innovations in the buildings industry that can be employed to improve performance or reduce total installed prices. In the buildings industry, these innovations could improve repeatability or precision in manufacturing or installation; reduce inventory, customer acquisition, or installation labor costs; or enable cheaper, simpler, site-specific customization for high-performance building envelope retrofits.

4.1 Systems-Level Approach

4.1.1 Building Construction and Retrofit with a Systems-Level Approach

Window features that can deliver energy savings also affect building occupants and the operation of major building subsystems, including space conditioning, ventilation, and lighting. Taking a whole-building systems-level approach ensures that the interdependencies of these major building subsystems are reflected throughout a building's development—from design to occupancy—to ensure that trade-offs in capital cost, operating cost, and other nonfinancial criteria are accurately accounted for in the specification of these systems to achieve the desired indoor environment. This approach should also capture differences in equipment and envelope component lifetimes in the operating costs. Using a systems-level approach could improve the adoption of energy-efficient envelope components and assemblies by showing early in the construction process the various impacts—cost and otherwise—of meeting building indoor environment targets with, for example, a code-minimum envelope and a large space conditioning system (heating, cooling, and ventilation) compared to a high-performance envelope and a smaller space conditioning system. Although the climate conditions in the United States make it more difficult than in Europe to completely eliminate space conditioning equipment by specifying a high-performance envelope [53], such an envelope can still offer substantial co-benefits for building owners, tenants, and individual occupants by better managing factors that influence occupant comfort. As noted by Gladden [50], labor costs dwarf typical utility costs in commercial buildings, so even small or uncertain improvements in employee productivity from improved thermal comfort, adequate outdoor views, and access to natural light might offset high-performance envelope component costs.

Software tools that can clarify the value proposition and trade-offs in the specification of the building envelope and related building systems during the design phase can help communicate the value of high-performance envelopes to decision makers. These tools should be able to highlight these trade-offs at a glance. Ideally, these tools could incorporate both quantitative factors (such as capital and operating costs) as well as semiquantitative or qualitative factors (such as construction budget and schedule risk as well as occupant comfort and productivity). These tools must fit into the existing workflows of architects, designers, and engineers such that the effort for them to obtain these systems-level insights is extremely low, and indeed, adds value to their workflow and provides insights that they can translate into value metrics for their clients. Critically, the software tools that are appropriate for the workflows employed by large firms for high-value, high-profile projects might be substantially different from the tools that are appropriate for smaller organizations that do not have the labor or overhead (i.e., room in their budget) to devote significant time to learning or using them. In these cases, tools that require less intervention or manual tuning to provide actionable insights—or even decision support tools that involve only simplified trade-off calculations—might be appropriate.

Incorporating a systems-level approach into business processes for new construction and retrofit of existing buildings, particularly in the commercial sector, can accelerate adoption of high-performance windows. For new commercial buildings, in the current typical practice, energy-efficient features are often considered relatively late in the design process, which adds significant cost and risk to incorporating those features [54]. Energy efficiency objectives should be incorporated early in the project life cycle to minimize capital cost; using a holistic, systems-level design approach, these objectives can be met using an optimal combination of high-performance envelope technologies and upgrades to other building subsystems to maximize operating cost savings and other cost-adjacent factors such as employee productivity. In existing buildings, a similar focus on energy efficiency at the outset of retrofit projects can help ensure that energy efficiency is incorporated into buildings with the lowest possible capital cost and schedule risk, while ensuring that the value proposition provided by energy-efficient envelope technologies and other components are integral to the retrofit design. In general, performance-based procurement—where performance requirements, including energy performance, are determined upfront and incorporated into the request for proposals and contract selection process—can achieve the objective of incorporating energy efficiency early in the design-build process, though there might be other strategies that achieve similar results but might be easier for some organizations to adopt [55]. Utilities can also use their incentive programs to promote the use of performance-based procurement by incorporating performance-based criteria into their programs, thus signaling to building owners that those criteria are central to receiving incentive funds [55]. Using this kind of incentive program structure also opens a performance-based pathway that encourages a systems-level approach to achieving utility program goals. These performance-based programs should also require post-occupancy measurement and verification, though different levels of measurement and verification will be appropriate depending on the size of the building and the value of the incentives offered.

4.1.2 Incorporating New Technologies Into Construction

Although drop-in replacement window components and systems might offer the most obvious route to commercialization, because they simply improve upon the performance of the current typical or state-of-the-art product, technologies and approaches that rethink the configuration of and methods for fabricating and installing the envelope assembly might offer more substantial energy savings. New retrofit methods can leverage a systems-level approach to increasing nonenergy benefits as well, improving occupant comfort, health, well-being, and productivity. Using novel approaches to assemblies or combinations of multiple components might reduce production costs, improve performance, and reduce errors by, for example, completing assembly in a controlled factory environment. Combining multiple control layers for air, moisture, and heat—as well as structural functions into fewer layers and components—could reduce complexity in factory and on-site construction, thus reducing cost and potentially improving performance, or providing an additional benefit that could justify incorporating a high-performance technology that is not otherwise required. Rethinking approaches for assemblies to simplify effort and improve flexibility or adaptability could be particularly beneficial for retrofit applications, which tend to require a high degree of customization because of the enormous variation in existing buildings; these variations add significant cost, quality, and performance challenges to retrofit projects, all of which inhibit envelope retrofit adoption.

Tools, materials, components, and platforms developed for other applications might be able to be directly applied to windows components or might offer insights into how challenges specific to envelope construction can be addressed with new approaches. BTO's Advanced Building Construction (ABC) initiative takes this approach to developing technologies and methods that improve the cost and scalability of deep energy retrofits [56]. For example, a wide range of advanced manufacturing methods might be relevant to buildings, including advanced robotics, automation, and lean production methods. Manufacturing methods that reduce the complexity and cost of customization could be particularly relevant for retrofits because of the wide variation in facade configurations between buildings. Additive manufacturing (i.e., 3D printing) is a method well suited to customization for project-specific parts, unique geometries that are difficult to fabricate using traditional manufacturing methods, and components or molds that do not need to be replicated many times. Additive manufacturing for buildings-related applications is often first thought to be a method for the direct deposition of material to build up whole envelopes, as in Oak Ridge National Laboratory's (ORNL's) Additive Manufacturing Integrated Energy demonstration [57]; however, additive manufacturing might have greater impact in envelope component applications, such as forms for precast concrete facade sections, as shown in Figure 15. These forms can increase the quality of facade sections [58], which could contribute to reducing infiltration for finished facades, both in retrofits and new construction. Printed molds might also enable more complex form geometries, which could provide more effective passive shading to reduce solar heat gain through windows and increase the appeal of facade retrofits. Direct deposition of novel materials that incorporate multiple functionalities, such as low-thermal conductivity structural materials that also manage air and moisture transport, could help justify the additional cost of additive manufacturing compared to traditional on-site construction methods, while also offering substantially higher dimensional precision than those methods. The continued advancement of computer vision hardware and image processing algorithms for manufacturing and various software applications could be applied to data collection for retrofits by simplifying dimensioning for retrofit parts. Image processing combined with additively manufactured inserts, for example, could be used in place of shims to quickly position windows in rough openings for installation while also providing a snug, potentially airtight fit. Printable materials with appropriate coefficients of thermal expansion will be needed for compatibility with typical window frames and structural framing materials. There are likely many additional areas where computer vision, image processing, or additive manufacturing can be used, particularly for envelope retrofits where building-specific customization adds substantial cost and risk. Further work is needed to identify envelope energy savings opportunities that are feasible with currently available products and to identify areas where novel materials, software tools, or printing capabilities would facilitate additional energy efficiency improvements for building envelopes.

Figure 15. Additive manufacturing has been demonstrated successfully for precast concrete forms of building facades. Avenues to employ advanced manufacturing techniques, such as additive manufacturing, for energy-efficient window-to-facade integration merit additional investigation.
Photos courtesy of ORNL.

In addition to image processing, other software and computational methods used in other industries could enable component, subsystem, and whole-building designs that improve energy efficiency. At the component level, topology optimization could be applied to some window components [59]. In general, topology optimization describes a method used to identify the optimal geometry for a structural component subject to specific loads while minimizing weight and/or the material required. Topology optimization could be used to optimize the geometry of window frame and curtain wall components to reduce thermal transport while meeting structural requirements, such as in the work of Lee et al. [60] applying topology optimization for curtain wall mullions. For whole-building and subsystem design, artificial intelligence, including machine learning, might find applications. Although machine learning can be extremely expensive to apply to any single project, high-volume decisions or design actions that are relatively repetitive but require extensive labor effort could be initial areas where machine learning might offer cost reduction opportunities. For example, machine learning might be appropriate in providing actionable design decision guidance, particularly with respect to incorporating a systems-level approach into design workflows. Machine learning could be used to automatically investigate alternative envelope design approaches to improve efficiency and performance while simultaneously meeting other envelope performance and system cost requirements. These capabilities would be particularly valuable for smaller firms that traditionally do not have adequate staff resources to investigate many potential design alternatives for each project. Throughout the project design process, there might be similar opportunities to increase the adoption of energy-efficient envelope components and designs using artificial intelligence methods. Applications of artificial intelligence in building design and construction are currently being explored, though not generally with the aim of increasing envelope performance or building energy efficiency more generally; further work is needed to identify these specific opportunities and evaluate their feasibility.

4.2 Grid-interactive Efficient Buildings

In line with BTO's focus on energy efficiency, goals for window technologies have historically included aggregate metrics such as national energy savings, reducing end-use intensity, and driving down prices. A limitation of these energy savings metrics is that they do not distinguish the varying value of energy; energy used at different times and locations will vary in cost and impacts according to the fuel used, market structures, and technological constraints. These differences are particularly pronounced in the electricity system, where supply must balance demand instantaneously at every moment in time. In order to better address the varying value of electricity demand reductions across time and space, BTO is developing a new strategy for GEBs, which complements the office's continuing focus on energy efficiency. The GEB strategy includes both connected and controllable technologies that might reduce electricity use at times when energy is more costly or impactful, as well nonconnected technologies that increase the capacity of the building to alter operations.

To help inform the building research community, BTO has published a series of technical reports that discuss its GEB strategy and evaluate opportunities for GEBs [5, 61, 62, 63, 64]. The *Overview of Research Challenges and Gaps* report [5] serves as an introduction to these technical reports and is intended to provide background on core concepts related to GEBs. It addresses how flexible building loads can be integrated and controlled to benefit consumers, the electric grid, and society more broadly. The *Windows and Opaque Envelope* GEB report details the technology opportunities and R&D opportunities specifically relevant to providing demand-side flexibility with windows and opaque envelope technologies [61].

Complementing this GEB report, the following subsections discuss: (1) the mechanisms by which buildings can provide demand flexibility that is beneficial to the electric grid, (2) the relevance of passive and active window technologies to electric grid operations, and (3) the specific window technologies that can deliver passive benefits or active responses to control signals to meet forecast or real-time electric grid operational needs.

4.2.1 Grid Services and Dynamic Building Operations

High-performance windows, particularly as part of a high-performance building envelope, are a key enabler for other end uses to provide grid services. In addition, dynamic glazing and facades have the potential to facilitate expanded grid service provision from heating, cooling, and lighting systems. The need for demand flexibility from buildings depends on the market and grid conditions at any given time. Requests for flexible operation could be on only a few days per year (e.g., reliability-based demand response), or on a daily, hourly, or even continuous basis. Typical grid services can be delivered by buildings via four different mechanisms: efficiency, load shedding, load shifting, and load modulation (i.e., frequency regulation or voltage support). The ability of window and facade technologies to deliver these services hinges on the existence of the necessary communications infrastructure to connect utilities directly to the end-use loads or the transparent facade's device-specific or whole-building energy control systems.

Energy efficiency and demand response are the most mature and established demand flexibility programs for buildings. In addition to overall energy savings, efficiency plays an important role in supporting grid reliability by decreasing peak demand and easing strain on the transmission and distribution system. Demand response is the main form of demand flexibility used today, though it is fairly limited in scope. The majority of demand response programs are generally focused on reducing peak demand through shedding or shifting—through direct load control (by utilities/demand aggregators) or behavioral load control programs in which utility customers make a decision to reduce their load in response to price signals.

The performance of both current demand response programs and demand flexibility from buildings more generally is heavily dependent on the heating and cooling loads of the building, and thus, the energy performance of the transparent facade. Currently, the vast majority of demand response in residential and commercial buildings is thermostat or air-conditioner compressor control—when the utility alters an indoor setpoint or reduces air-conditioner compressor cycling, the action has implications on the thermal comfort of the occupants. Buildings with high-performance windows and opaque envelopes have more capacity to provide demand flexibility while maintaining occupant comfort. With more advanced controls to enable more sophisticated grid service provision, not only will these passive window and opaque envelope measures contribute to comfort and demand response capacity, but dynamic windows and opaque envelope technologies that alter daylighting, solar heat gain, and opaque envelope thermal resistance in real time can be actively managed to co-optimize occupant comfort and productivity with grid service provision and corresponding remuneration.

Beyond demand response, building envelope technologies are able to engage directly in electricity capacity markets. Two independent system operators (ISOs) that operate electricity capacity markets allow the bidding of energy efficiency measures into their market, including building shell upgrades such as improved insulation [65]. Capacity markets exist in some but not all deregulated electricity markets as a contingency, so that grid operators can ensure that sufficient electrical generation capacity exists. For both ISO-NE and PJM, capacity resources bid 3 years in advance and can be either demand-side resources or electricity generators. In ISO-NE's auction for 2016, 4.25% of the total capacity market was energy efficiency, and another 3.3% of the capacity market was composed of demand response and distributed generation. In PJM's 2016–2017 auction, energy efficiency was a much smaller contribution, comprising 0.64% of the capacity, with other demand-side resources comprising another 7.3% of the capacity market. Although the study reporting on these capacity market advancements [65] did not provide a breakdown of the specific energy efficiency measures bid into the markets, it is likely that most of the demand response and a portion of the energy efficiency markets are dependent upon windows and envelope upgrades. During an internal ISO-NE audit of energy efficiency capacity performance, energy efficiency savings were found to be much more reliable than any other capacity market product, providing 120% of what was bid in summer months (and even more in winter months). Demand response resources came in second with 95.3% availability of the total bid. By contrast, supply-side generation is assumed to have 94.1% availability and peaking plants 80% availability [65]. With several years of participation in electricity markets, system operators are gaining confidence that energy efficiency and demand response resources are real and reliable for capacity markets. Because building envelope components can potentially bid as energy efficiency resources as well as enhance demand response capabilities when coupled with advanced HVAC control, remuneration from electricity markets provides an additional quantifiable value for transparent facade retrofits.

4.2.2 Co-Benefit of High-Performance Windows: Energy Resilience

Energy resilience describes the ability of building systems to predict and prepare for, withstand, recover rapidly from, and adapt to adverse events that affect the delivery of energy-based services such as heating, cooling, lighting, refrigeration and other energy end uses. High-performance windows generally reduce heating and cooling energy use, and thus increase the time from when an interruption occurs to when the building becomes uninhabitable because of temperature conditions. Figures 16 and 17 illustrate the effect of a high-performance building envelope (higher insulation, lower air infiltration, and improved windows) on occupant protection following a utility service interruption in the winter and summer, respectively. In the winter, increased envelope performance beneficially increases indoor temperatures and reduces temperature variations compared to a typical building, maintaining a temperature difference of up to 30°F. During a summer interruption, a high-performance envelope again reduces temperature variations, which reduces peak temperatures compared to a typical building, but peak outdoor temperatures are generally lower than peak indoor temperatures in all four building envelope cases considered. These results show that the impacts of static high-performance building envelopes on resilience can vary by climate zone and season. Energy efficiency and load flexibility can impact building energy resilience in both complementary and conflicting ways. As such, the interactions between efficiency, flexibility, and energy resilience must be considered holistically.

4.2.3 GEB-Relevant Window Technologies

Windows and attachments are crucial to increasing building capacity to shed or shift load. All transparent facade technologies that improve energy performance also have the potential to improve demand flexibility. In addition to passive and nonautomated technologies, dynamic window and facade technologies can actively change thermal capacitance or other heat transfer characteristics specifically in response to grid needs. Some of these technologies are already on the market and some are laboratory scale, but both passive and active window technologies can help manage thermal and lighting conditions in buildings to provide demand flexibility. In this section, currently commercialized and novel window technologies are reviewed with regard to how they might enable demand flexibility from buildings.

Passive High-Performance Window Technologies

In general, high-performance transparent facade technologies that effectively manage heat transfer through high thermal resistance, effective air sealing, and appropriate solar heat gain control for the climate will reduce energy use. Technologies with these characteristics will also reduce peak electricity demand, because these peak periods are typically driven by thermal loads. This peak-period demand reduction capability does not require dynamic or time-varying operation and is an inherent feature of correctly installed high-performance transparent facades. Technologies that lower the thermal load of the building include external devices for shading the building, internal

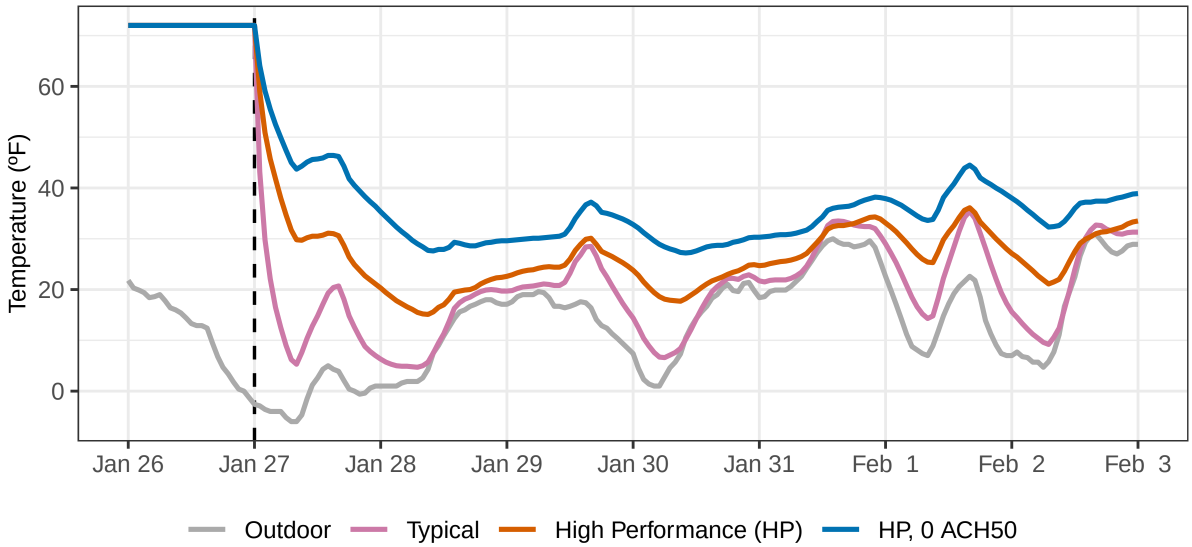

Figure 16. Indoor temperature trends compared to the ambient temperature for a single-family detached home with varying building envelope performance levels following a utility service outage modeled on January 27. As envelope performance increases, interior temperatures remain higher and more stable, even several days after service ceases. Figure derived from ORNL analysis [61].

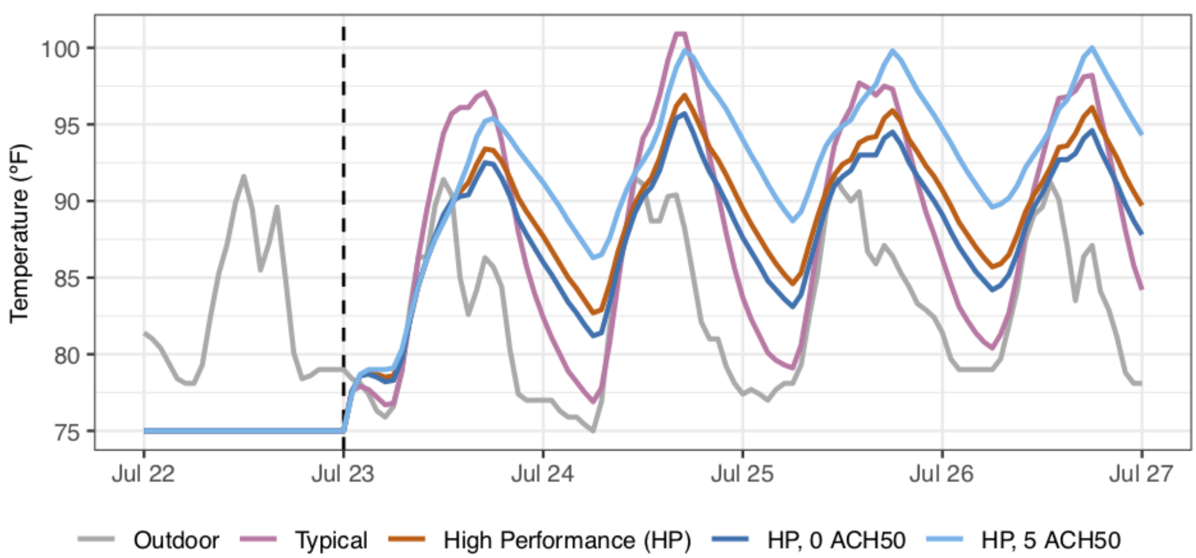

Figure 17. Indoor temperature trends compared to the ambient temperature for a single-family detached home with varying building envelope performance levels following a utility service outage modeled on July 23. As envelope performance increases, interior temperatures become somewhat more stable and peak temperatures are reduced, but minimum temperatures increase, because the building is less coupled with ambient temperature trends—both unfavorable and favorable. Figure derived from ORNL analysis [61].

devices that block solar heat gain through windows, window coatings that reflect solar energy, and other envelope measures [66].

Several studies have estimated the impact of building envelope improvements on peak electricity demand. Two simulations in Hong Kong, a hot and humid climate, estimate energy savings at the annual peak between 37% and 47% from passive envelope measures [67, 68]. In a study in Greece, external awnings shading the building were found to reduce the cooling load of the building by 30% [69]. The effect of a high-performance opaque envelope on summer electricity demand was recently quantified by researchers at ORNL using a building physics simulation of two different single-family detached homes.[10] The "typical" building had equipment upgraded to the 2012 International Energy Conservation Code, but with duct leakage and an envelope and windows representative of typical existing homes. The "high-performance" building had similar equipment, reduced duct leakage compared to the "typical" home, and better-than-code envelope and windows. Average cooling season (June 12–September 17) electricity demand results for two International Energy Conservation Code climate zones are illustrated in Figure 18. These results show that demand is similar during the early morning hours for both the typical and high-performance homes, but throughout the peak period, increased insulation and improved solar control reduces electricity demand dramatically. Average cooling season peak period (12–6 p.m.) energy use reductions observed across modeled climate zones[11] ranged from 20% to 47%, with the largest peak reductions in hotter climate zones.

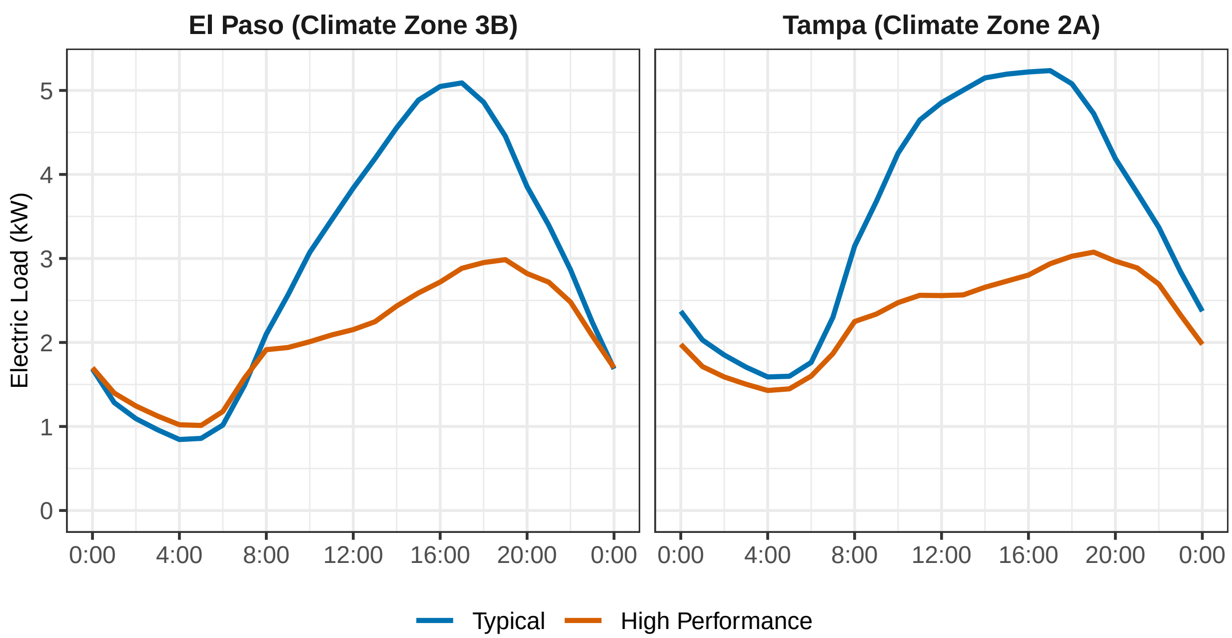

Figure 18. Simulation of a residential single-family detached home with varying levels of insulation reveals that improved windows (and increased insulation) from current typical existing building performance to slightly above current code levels yields dramatic reductions in electricity demand throughout the peak period during the cooling season.
Figure derived from ORNL analysis [61].

Active, Dynamic Window Technologies

Dynamic transparent facade technologies have the potential to provide additional demand flexibility beyond currently available static windows and fixed or manually operated window attachments. In addition, these dynamic technologies can actively manage occupant thermal comfort, daylighting, and optical comfort (glare) by modulating solar heat gain and admission of light. Active, dynamic window technologies can generally be divided into dynamic glazing and automated attachments.

[10] This ORNL research was conducted for the purposes of this report, and the results are not currently published elsewhere.
[11] The analysis included single-family detached homes simulated in all major International Energy Conservation Code climate zones.

Dynamic Glazing

Dynamic glazing refers to a suite of window technologies that can change the transmittance of visible light, solar heat gain, or both. Section 3.2 discusses these technologies in detail; this section highlights some of the most promising technologies in the context of demand flexibility. The most technologically mature of available dynamic glazing formulations are electrochromic windows, which change transmittance properties when a voltage is applied. This reversible switching is achieved through the movement of either protons or lithium ions through an ion-conducting layer, often tungsten oxide [70].

There are currently several major manufacturers of electrochromic glass on the market, but there are some barriers that have thus far prevented widespread adoption. Cost is primary among these, with commercially available electrochromic windows retailing for \$500–\$1,000/m^2 compared to conventional window prices of approximately \$115/m^2 [71]. Other concerns include the relatively long time period necessary to switch window tint level (5–12 minutes [72]) and the fact that most electrochromic windows do not independently modulate infrared and visible light, so a window switched to minimize solar heat gain will also reduce available daylight from the window. This might be less desirable for occupants who value daylight, but more importantly, this can have implications for lighting electricity demand, because indoor lighting levels might have to be increased if daylight is reduced. PV glazing that combines power generation with dynamic solar control has the potential to reduce peak demand by reducing cooling requirements while simultaneously generating electricity during peak hours [40]. It should also be noted that electrochromic windows are not generally designed to facilitate demand flexibility or maximize energy savings; often building owners purchase electrochromic windows to avoid attached shades and maximize views to the outdoors.

In simulation results, electrochromic windows have been shown to reduce peak cooling electricity demand between 5 and 7 W/m^2 in 10 North American cities, compared to static solar heat gain control glazing [73], and another simulation showed that electrochromic glazing can reduce solar radiation gains up to 88.9% compared to code-minimum glazing [74]. A separate laboratory experiment similarly found that electrochromic windows could save energy in cooling-dominated climates, with savings between 6 and 30 kWh/ft^2 [75]. Peak cooling loads in a full-scale testbed were reduced 25%–58%, with electrochromic windows compared to spectrally selective low-e windows [76]. Figure 19 shows simulation results considering the peak summer day in California in 1999; these results show that reductions in lighting and cooling system energy use (potentially enabled with dynamic glazing) can yield substantial reductions in peak electricity demand. In the example illustrated, peak demand is reduced by 7 GW, or approximately 30%.

Several other dynamic glazing technologies exist beyond electrochromics. One example is liquid crystal switching, which can be thermally, optically, or electrically activated and switched in milliseconds [77]. Another promising new technology is the electrodeposition of metals in from a solution of aqueous electrolytes, which is quick and reversible. Limitations include a narrow temperature band in which the technology operates and the difficulty of evenly dispersing the metals [78, 79]. Phase change materials store large amounts of energy in the transition between states, and a paraffin wax phase-change-material layer between glass panels has been proposed as a way of absorbing solar heat gain as latent energy. Phase-change-material applications might be limited in windows because they are nominally opaque and only transparent after periods of heat gain (e.g., mid-day) and have large volumetric changes during the phase transition (up to 10%) [80]. Gasochromic windows quickly change optical properties in the presence of oxygen, which is pumped in between layers of glass, and simulation shows they might reduce HVAC loads up to 25%–35% compared to single-pane glass [81], but they represent a risk for hydrogen explosion and need to be continually monitored [82]. Recently, pneumatically activated light modulation has been tested, which change properties in a window layer in response to pressure, but it is unclear whether this impacts only the visible light spectrum or also solar heat gain [83]. Ghosh and Norton [84] provide a comprehensive overview of existing glazing technologies and their thermal and optical properties.

Automated Attachments

Similar to static attachments, automated attachments seek to shield segments of the building shell from direct solar radiation. They utilize sensors, controls, and small motors to enable adjusting the position of the attachments in response to internal and external light conditions and occupant requests. Automated attachments can provide demand flexibility by adjusting thermal energy demand via solar heat gain to reduce electric heating and cooling needs [85].

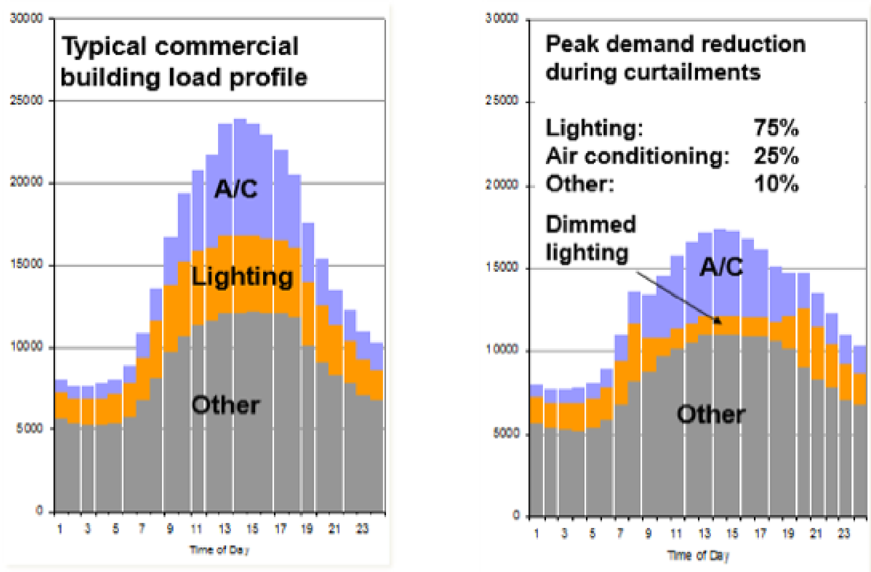

Figure 19. A simulation of electricity demand from the commercial building sector on the peak summer day in California shows that dimming lights and reducing cooling energy demand could reduce peak demand by approximately 30%.
Figure from Rubinstein and Kiliccote [6].

Automated attachments can be internal to the building (e.g., roller blinds) or mounted on the facade. Predictive control of automated attachments has some advantages over predictive thermal control, because the performance of the former is dependent on the known trajectory of the sun, especially for window attachments. The attachment positioning could then be altered to minimize solar heat gain to reduce cooling (perhaps at the expense of daylighting) as needed during a period of high demand. Kunwar et al. [86] provide an overview of existing automated shading techniques. Studies to date have found that window attachments can reduce cooling needs by 16%–30%, but this is highly dependent upon the climate zone and the control strategy [85, 87, 88, 89].

Control Strategies

A range of control strategies, including classical control hierarchies, could facilitate load shifting or shedding using active, dynamic transparent facade components. Classical control strategies include having a schedule of setpoints, perhaps altering comfort ranges during peak electricity rates. Another classical control strategy would be to allow the building's internal temperature to float within an acceptable range of thermal comfort.

Moving beyond classical controls, a range of new data-driven algorithms use machine learning techniques such as reinforcement learning to alter building control strategies. Figure 20 illustrates a possible sensor suite and control system architecture for coordinated operation of HVAC, lighting, and dynamic facade technologies in a building. MPC is the subject of active research, having origins outside the building sector. For MPC, a model forecasts the behavior of the building then provides an optimal sequence of events to maximize building performance. Although MPC is becoming increasingly popular and has been shown to be up to 25% more efficient than simple night setback when used with HVAC controls, it is still expensive and complex to implement [90]. Fundamental work has been conducted to explore the additional demand flexibility enabled with MPC with dynamic facades and precooling strategies with thermal mass [42].

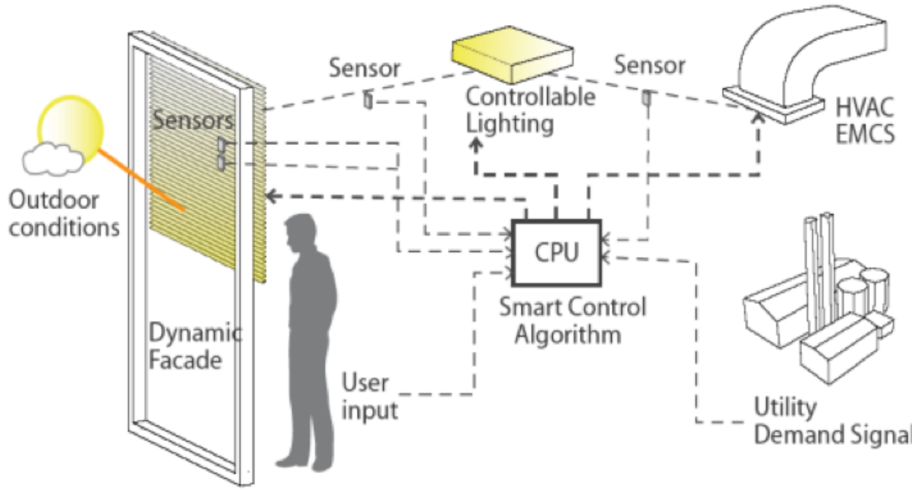

Figure 20. Demand flexibility enabled by dynamic transparent facade technologies is substantially increased with coordinated control of HVAC, lighting, and dynamic facade systems, especially when implemented with predictive controls.
Figure courtesy of LBNL.

5 Implementation

To realize the energy savings potential of novel technologies developed for windows, these technologies must be brought to market by companies that can market, sell, distribute, and support them. For technologies that involve fundamental changes in design or construction practices, even if those changes ultimately reduce labor effort, complexity, or total installed price, significant effort might be required to bring these changes to market. Technologies that can be used as drop-in replacements for existing components, materials, or systems might have a lower barrier to market entry because they fit in an existing market segment, but these technologies must still be taken from mid-stage development to a commercial product by resolving technical risks related to volume production, developing an appropriate go-to-market strategy, and investing in adequate marketing, sales, and distribution channels to reach the targeted market(s).

In general, DOE and BTO seek to invest in technologies that are early in their development and present technical or other risks that might preclude early private-sector investment but have the potential to transition, as early as possible, to private-sector R&D funds and ultimately to commercialization by a private-sector entity. To that end, BTO seeks to lower barriers to and accelerate the timing of private sector investment, commercialization, and scale-up. There are two primary types of barriers to BTO's R&D transition and long-term energy savings objectives—technology development and commercialization barriers as well as market adoption barriers. Technology development and commercialization barriers can include access to appropriate technology testing, validation, and demonstration capabilities; the cost and structure of capital as well as access to capital; expertise in manufacturing, particularly when new techniques must be developed; and an adequate understanding of building industry and customer needs, willingness to pay, and appropriate sales channels. Market adoption barriers for novel, high-performance windows and opaque envelope technologies include building owners' access to capital and awareness of novel technologies, market valuation of envelope upgrades and ease of capital recovery, confidence in energy savings estimates for envelope upgrades, and building construction industry practices that affect prices and installation quality. Many of these barriers are outside of BTO's purview, but might affect buildings technology adoption regardless. These barriers are collectively synergistic, because factors that act to inhibit market adoption of novel energy efficiency technologies create an environment in which original equipment manufacturers are reluctant to pursue development of those novel technologies for fear that they will not be able to recover their costs through revenue from product sales because of lack of market demand.

5.1 Technology Development Pathway

To achieve energy savings in residential and commercial buildings from novel window component and system R&D, early-stage, high-risk projects must transition to private-sector R&D and ultimately to commercialization. R&D projects funded by BTO are structured to promote private-sector transitions as early as possible. In general, private-sector capital for R&D competes with other potential uses of that capital that can deliver shareholder value. Long-term potential market impact derived from R&D successes presents investment risk, thus the overall risk profile of any R&D project (as well as the risk presented by projects within a BTO subprogram research portfolio) should be minimized aggressively as early as is practicable. Projects should be designed particularly to reduce schedule and labor effort (time to market) and technical risks. Ideally, upon project completion or final investment from BTO, the remaining effort primarily involves scaling well-understood and well-characterized materials and underlying phenomena. Material synthesis and product form factors should be compatible with existing traditional manufacturing methods as much as is practicable—ideally relying on methods that have relatively low initial capital costs, which will reduce the total capital exposure (before first sale) for a private-sector entity. BTO-funded work might still involve some investigation of manufacturing methods or scale-up, where again the focus is on novel processes or practices, particularly where they have the potential to reduce the capital or operating costs of volume manufacturing. Supporting systems (e.g., software; APIs, protocols and standards; modeling) can also be critical areas for BTO investment when they enable R&D, manufacturing, or adoption of novel windows. Regardless of the scope, projects incorporate industry engagement as much as is practicable to ensure private-sector relevance upon completion. This work might include input from product manufacturers as well as other building industry entities (e.g., component manufacturers, vendors and sales channel partners, architects, contractors, and installers). In some cases, input from these other entities might have greater impact on R&D project relevance than direct input from potential manufacturers. Input from these entities should flesh out the value proposition of the eventual functionalities or capabilities offered by a project to build the case for private-sector offtake.

Researchers can leverage existing resources and industry knowledge to accelerate private-sector offtake of R&D efforts. Figure 21 illustrates the technology commercialization process; throughout this process, researchers can pursue actions to accelerate the transition to the private sector. For university and national lab researchers, institutional technology transfer offices or teams might offer resources for collaborating with industry or pursuing a spin-off as a new venture. These offices might also be able to connect researchers with nontraditional sources of capital to support R&D that can further de-risk technologies, amplifying federal investment and improving suitability for offtake by manufacturers. Researchers should investigate building industry pain points related to the envelope and seek to align their projects to strategies that can address those points. Researchers should also explore established sales channels and typical market dynamics for their targeted application areas such that they understand the value proposition of existing products and other product attributes that might be valued by customers and channel partners.

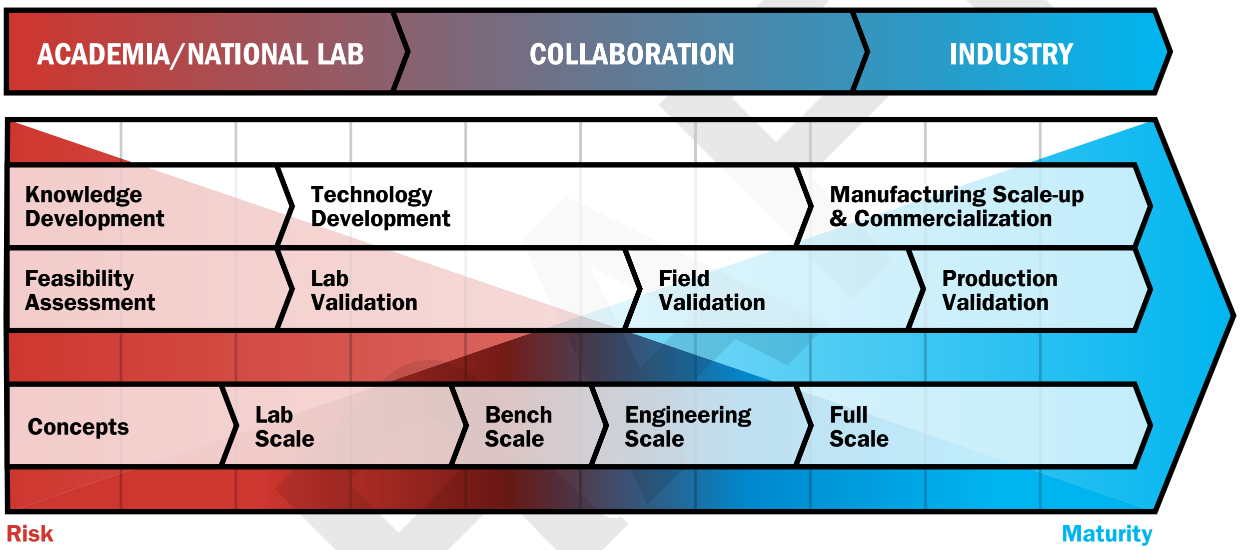

Figure 21. Commercialization process driven from early-stage research.
Figure adapted from DOE TRL Guide [91] by Christopher Schwing, NREL.

The building construction and products industry in the United States is a mature market that has been slow to change and adopt new practices and materials. Productivity in the buildings sector relative to construction and labor requirements has remained persistently low, even as other industries have dramatically increased their productivity in the past few decades [92, 93]. However, with regard to energy efficiency, the buildings sector has been much more productive, with energy intensity decreasing significantly over the same period. Building construction sector R&D investment hovers around 0.5% of the total market [92], which lags behind typical investment rates in most other sectors, particularly those with high levels of innovation [92]. Even with increased federal R&D investment in building technologies in recent years, broader industry investment has remained low [92, 94]. Given these conditions, business model or business practice innovation—possibly in concert with the deployment of novel technology developments—might have a larger effect on market transformation than from the development of novel technologies alone. In the solar PV market, novel financing models have enabled broader access to distributed rooftop solar, which when coupled with component and business practice innovations, significantly reduces the total installed price of distributed solar PV systems. Replicating this success might not be as readily achieved for window improvements or upgrades, because these changes—even those that have an aesthetic element or innovative technology—are perceived as incremental [95]. However, in general, the buildings industry presents significant low-hanging fruit with respect to driving novel technology adoption through system and business process and practice innovation.

5.2 Facilitating Technology Adoption with Market Transformation Partners

Once high-performance, energy-efficient window technologies are made commercially available, they must generally achieve volume market penetration to create sufficient production requirements to minimize production costs and maximize profitability. Prevailing construction and building retrofit market conditions and adjacent factors can create significant barriers to technology uptake. These barriers can be financial (e.g., adequate access to capital, appropriate financing mechanisms), knowledge-related (e.g., awareness of correct installation practices for novel technologies among contractors and installers), or implementation-related (e.g., the extended disruptiveness of many envelope upgrades). These barriers can be reduced or circumvented through a range of voluntary actions, marketing and information sharing strategies, and policy interventions, including many initiatives that are currently being explored or tested.

Product prices, available financing mechanisms and their costs, and an absence of appropriate market valuation for energy efficiency upgrades all present financial barriers to the adoption of high-performance window technologies. Similar to most new technologies, new energy-efficient windows are likely to have high prices at market introduction. The high capital costs of these technologies might limit demand and thus hinder the business justification for manufacturing at scale, which is typically needed to reduce unit costs and thus the price faced by consumers. For all building types, market valuation typically does not reflect energy-efficiency-related upgrades. The appraisal process generally does not capture energy performance or efficiency upgrades, which has a downstream effect on building valuation and therefore mortgage lending and capital recovery from upgrades [96, 97]. There is, however, an opportunity to revitalize home and building facades that could improve curb appeal and result in real increases in market value. Capturing these benefits for a given building would likely involve a major renovation that incorporates system-level perspectives, including full envelope and window upgrades and integration, along with potential downsizing of mechanical equipment, which could offer economic benefits [98].

Today, these connections to real estate market value improvement have not been established. On top of the limited valuation of these upgrades, in the residential sector, consumers face comparatively high interest rates for energy efficiency improvement loans [95]. Consumers might be unable or unwilling to take on moderate-interest debt to finance energy efficiency upgrades, particularly because they are often dubious about the true energy savings potential of upgrades. Consumers might also be unsure whether they can expect to be net cash positive, especially following upgrades that are pitched to them by companies with a vested interest in earning their business [95, 99]. In spite of these financing challenges, residential [95] and commercial [96] properties with higher energy performance have lower default rates. Though these data show that energy performance can reduce risks for private capital, accounting for these efficiency upgrades does not appear to be widespread among lenders.

Even if building owners and building construction industry members become aware of novel, high-performance windows and opaque envelope integrated solutions, and if they have access to appropriate and acceptable mechanisms for financing potential envelope upgrades, there still remain additional practical barriers to the implementation of these novel window/wall integrated assemblies. Because of the complexity and assembled-on-site nature of the opaque envelope, in particular, component manufacturers generally do not provide performance guarantees or otherwise make claims regarding the performance of finished building envelopes that incorporate their products. Different installers might be responsible for different stages of facade assembly and window installation; no single entity among product manufacturers, contractors, or installers generally takes responsibility for the energy performance of the finished facade. As a result, there can be a significant difference between the specified and as-built performance of the envelope, and at no point during construction will defects that affect energy performance be intentionally identified and corrected.

In addition, in typical retrofits—especially for the opaque envelope—the required teardown and reconstruction of the facade is disruptive for building occupants and might even preclude occupancy, thereby adding significant costs (e.g., lost rents, relocation) for occupants or building owners. Conversely, window and opaque envelope retrofits often provide multiple nonenergy benefits, including improved aesthetics, improved occupant comfort and productivity, and reduced ambient noise intrusion. Although these nonenergy benefits can be accrued with any type of window retrofit to some extent, both the energy and nonenergy benefits are larger for higher efficiency windows, while the incremental cost of choosing high-performance windows is minimal compared to the overall project cost. Therefore, although nonenergy benefits might drive the building owner to pursue the upgrade, it is critical to inform the owner of the efficiency benefits that will be lost (and likely never regained) by choosing code-minimum windows.

Private-sector market entities—including building material suppliers, window manufacturers, and the construction industry—could develop programs that encourage system-level assessment of window upgrades in conjunction with other building subsystems to encourage holistic implementation. Though governments can assist in encouraging the development of such programs, industry is in the best position to lead these efforts, which can incorporate industry-driven standards, certification, and verification. Industry engagement might also result in pursuit of much more comprehensive retrofit projects, which can increase overall construction industry revenue and value; reduce energy costs and increased property values for building owners; and reduce energy use and lower peak electricity demand across the United States.

Direct and indirect financial incentives available from municipalities and utilities can be incorporated as part of the valuation of prospective upgrades. In many cases, these programs offer incentives for specific upgrades based on the total energy savings or emissions reduction impact of individual upgrades across a region or operating territory. More comprehensive upgrades appropriate for an individual building, particularly envelope component upgrades, often have limited overlap with available incentives. As a result, building owners frequently eschew the system-level retrofit strategy discussed here and in Section 4.1 in favor of approaches that minimize capital costs and only include individual upgrades that align with available incentives.

5.2.1 Financing

Significant recent developments in business models and associated financing mechanisms for residential rooftop solar have increased interest in developing novel financing mechanisms for building energy efficiency investments (particularly in the retrofit market) as a way of reducing customer acquisition costs, increasing quality and customer confidence in the finished product, and lowering capital barriers (particularly for residential customers). In some cases, rooftop solar financing programs include the most cost-effective building energy efficiency measures so that they can be packaged to derive a better return on investment. Packaging a major facade upgrade with high-performance windows would derive greater savings and could increase property values. Property-assessed clean energy (PACE) programs were developed to alleviate the capital burden of energy efficiency retrofits. PACE programs tie financing for retrofits to the property, which can then be transferred to subsequent owners if the upgrading owner does not retain the property long enough to repay the loan [100]. Recent challenges with the execution of residential PACE programs can be remedied in part through careful program design and oversight [100]. Commercial PACE programs can also benefit from thoughtful program structure and lessons learned from residential PACE programs [101].

Building-specific retrofit solutions supported by detailed energy models can benefit both the residential and commercial markets; the modeling results are used to determine guaranteed energy savings and financing can be developed around those savings [95]. This approach is similar to that used in residential rooftop solar financing. Particularly for the residential sector, these packages can also incorporate warranties and maintenance contracts that help engender homeowner confidence in installation quality and reduce the maintenance effort for the homeowner [95]. Third-party entities might emerge to both execute and finance these packages (as has occurred in the solar industry), because the guaranteed energy savings derived from the energy modeling used for project selection and customization might enable securitization, creating new energy efficiency investment vehicles. These upgrades could also be financed through an energy savings performance contract executed by an energy service company, where the energy service company amortizes the efficiency upgrades against the anticipated energy savings [102]. Regardless of the financing instrument, incorporating energy efficiency upgrades into property appraisals would ensure that those upgrades are perceived by buyers as comparable to aesthetic upgrades. This would also enable efficiency upgrades with long payback periods to be explicitly captured in the value of the property, thus enabling capital recovery at the time of sale. Incorporating energy expenditure risk assessment into mortgage underwriting could also help improve the ability of owners to absorb the cost of efficiency upgrades.

5.2.2 Window Market Awareness

Challenges arising from information asymmetry (faced by building owners/consumers and by architects, engineers, contractors, and installers) can be addressed by several means, including enhanced labeling and recognition programs, readily accessible data resources, and enhanced training programs for contractors and code enforcement officials. The National Fenestration Rating Council (NFRC) was established through congressional authority and today it provides a critically needed energy performance evaluation basis for residential window policies. DOE helped ensure this by providing direct financial support and technical support through the national laboratories to the NFRC. The ENERGY STAR recognition program (administered previously by DOE and now by the Environmental Protection Agency) has played a key role in getting consumers to buy energy-efficient windows [103]. The current market share of low-e glass is more than 90% in the residential sector because of these successful programs.

While the commercial fenestration market has seen increases in low-e glass market share, it still lags the residential market by approximately 30%–40%. The commercial market is more complex than the residential market; commercial windows often involve detailed purchasing contracts and the market includes both factory-built punched opening windows and site-fabricated curtain wall systems. As a result, the NFRC residential program could not be simply applied to commercial windows. NFRC established a sophisticated commercial window rating program with significant support from DOE, yet market acceptance has been low. NFRC is currently reassessing its program and is in the process of incorporating improvements and trying to find ways to reduce technical burden for the industry. To better understand the commercial market for not only window energy performance and window R&D, but to assist stakeholders in pursuing market transformation, NFRC is pursuing additional market characterization in collaboration with LBNL and with support from DOE. A full range of policy strategies could be pursued by stakeholders to accelerate the adoption of low-e and other high-performance window features in the commercial sector if there were increased transparency of the energy performance of commercial fenestration.

5.2.3 Whole Building Market Awareness

Beyond window component policies driven from foundational energy performance metrics, much more effort could be pursued to increase windows' prominence in whole-building policy schemes. Residential home energy performance evaluated through Home Energy Score (shown in Figure 22, for example, might also provide valuable comparative information for consumers, though these scores do not separately capture window performance. These scoring systems also do not capture the nonenergy benefits of a high-performance envelope, which might be critical to creating market pull for envelope upgrades. Energy auditing and disclosure measures enacted in several municipalities can provide information to buyers and prospective tenants regarding energy performance of properties, and thus might have the potential to influence the resale or rental value of otherwise comparable properties [104]. Providing these data in a form that is readily understandable and in a location that minimizes or eliminates effort to obtain the data are critical to achieving the desired effect [104]. For commercial buildings, these factors could be addressed by prominently displaying whole-building performance grades based on audit data near the building entrance or, for all building types, providing the relevant score in property search tools [96].

For the building construction industry, improving awareness of novel window-integrated envelope technologies could come through a variety of channels. Existing mechanisms for publicizing new products—trade shows, publications, social media, and company websites—continue to be relevant. Additional opportunities to expose building owners and, indirectly, the construction industry to new technologies might be through energy audits, which could be accompanied by upgrade suggestions that incorporate novel materials and methods when envelope upgrades are appropriate. BTO's integration teams support field studies to validate the performance of innovative transparent facade products. However, utility and energy efficiency nonprofit case studies might benefit from incorporating nonenergy benefits such as comfort, aesthetics, and effect on property valuation. These studies could also be used to build confidence among the architecture, engineering, and construction industry in specifying and installing novel products. Field and validation study results will be most impactful if they are made available through channels already regularly accessed by the industry and should be presented such that the results are easily interpreted. These results can also be further supported by simultaneously providing guidance on how to incorporate novel materials into typical construction practices.

Installation quality can also be improved by incorporating fault-tolerant characteristics into novel window technologies, protecting against improper installation and possibly improper system assembly configuration. Furthermore, proper installation not only ensures long-term moisture durability and energy performance, but also reduces air leakage. Such benefits are not often factored into the value proposition of replacing windows. While these changes may not explicitly incentivize investment in envelope energy efficiency, by creating conditions in which the building construction industry and building owners and tenants all perceive incentives or value in improving building energy performance, window upgrades will be adopted alongside other efficiency measures.

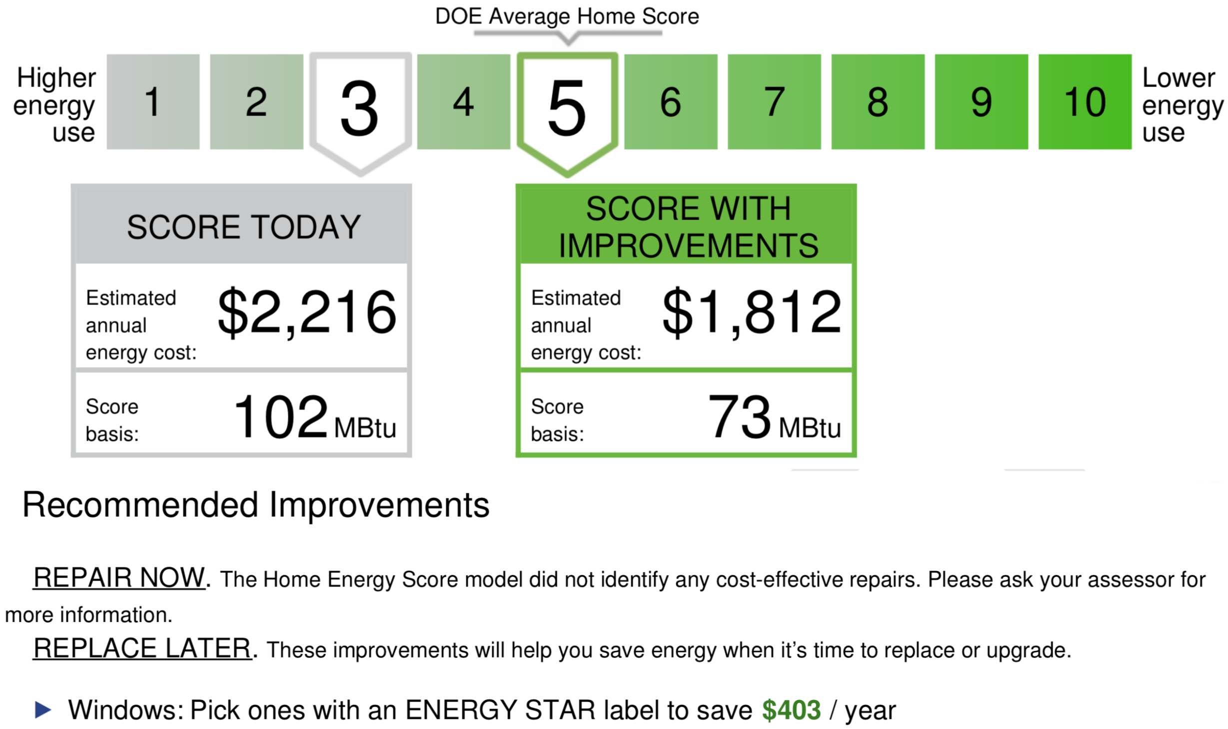

Figure 22. Home Energy Score reports can be used to highlight improvement opportunities for homeowners with specific actionable feedback on what retrofits can deliver energy savings, including window performance improvements. Similar building performance evaluations for commercial buildings can provide valuable insights to building owners, and disclosure of these data or similar information about building energy performance can also provide useful information to prospective tenants in both the residential and commercial sectors. Images are extracts from a Home Energy Score report, which includes much greater detail on all of the components in a home that relate to energy use.

5.3 Stakeholder Engagement in Technology Implementation

BTO is interested in working with any and all stakeholder organizations and entities that can help accelerate the R&D, deployment, and widespread adoption of novel, affordable, high-impact window technologies. Different stakeholders can serve different roles in the technology development and market transformation process depending on their constituencies and access to capital, as well as their ability to convene other stakeholders, coordinate with other stakeholders, and directly conduct technology R&D. Table 14 includes an array of possible supporting activities for stakeholders.

Table 14. Stakeholders that interface with energy efficiency and buildings can help accelerate R&D and the widespread market adoption of innovative, high-performance, affordable windows outlined in this report. Windows have not always gained attention from energy efficiency advocates; these possible activities are based on general energy efficiency policy strategies and the IEA Envelope Roadmap [25].

Stakeholder	Suggested Supporting Activities
Governments	• Invest in and manage a portfolio of R&D projects comprising the high-priority technology areas identified in Section 3 • Conduct field validation studies of high-performance window systems and validate electric grid economic benefits and remuneration opportunities • Pursue wide availability of commercial fenestration performance metrics • Demonstrate potential by implementing high-performance technologies into their own buildings • Develop system-level tools that increase the benefit and value of high-performance window systems, possibly including nonenergy benefits
Nonprofits/ Nongovernmental Organizations	• Convene state and local partners to build knowledge infrastructure around the value of high-performance envelopes • Demonstrate novel building envelope technologies to build manufacturer and consumer awareness of energy savings potential and other benefits • Investigate actions that could increase market demand for innovative windows • Adopt window performance criteria as part of high-performance window programs (e.g., require commercial NFRC-rated windows to be disclosed as part of whole-building performance qualification)
Manufacturers	• Pursue investment in earlier-stage R&D with federal risk sharing and low-TRL offtake • Work with researchers and academia to build capacity around R&D program structure to manage risk and maximize project spinoff or offtake • Establish, in collaboration with partners, system-level benefit sales tools
Researchers/Academia	• Pursue novel technology and material research in the areas described in Section 3 • Collaborate with manufacturers and industry partners on transitioning research successes from lab scale to being production ready • Leverage professional societies, trade associations, and nongovernmental organizations to share research findings and follow-on development opportunities

National Laboratories	• Provide advanced component evaluation equipment and facilities that provide enabling capabilities to the windows industries • Pursue novel technology and material research in the areas described in Section 3 • Collaborate with manufacturers and industry partners on transitioning research successes from lab-scale to production-ready technologies • Conduct comprehensive research on the energy performance and durability of novel high-performance envelope materials and assemblies to build industry confidence • Support nongovernmental organizations, utilities, manufacturers, and others to ensure scientifically rigorous methods are employed in system-level tools and serve as neutral third party for the consumer's interest
Architects, Engineers, and Builders	• Expand use of life-cycle costing and work with clients to promote life-cycle costing when evaluating new construction and deep retrofit projects to fully assess system-level benefits • Develop full-value assessments including energy and nonenergy benefits to reduce the likelihood of "value engineering" resulting in the downgrading of window design performance
Utilities	• Work with local and state partners to identify opportunities for energy efficiency and peak demand reduction • Offer broad-based programs for whole-window and wall retrofits, as well as integrated facades that combine electric lighting, controls, and dynamic solar control • Investigate actions that could increase market demand for innovative windows.

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Appendix A Establishing Technology Performance and Price Targets

This appendix outlines the methodology by which technology price and performance targets are established for the window technology categories in Section 3. Price and performance targets are based on future impacts calculated using Scout, a software tool that estimates U.S. energy use, carbon dioxide emissions, and operating cost impacts of building energy conservation measures (ECMs).

Approach for Establishing Technology-Level Targets

Prospective technology targets are limited to unit-level total installed price and energy performance. Lifetime, a third key technology parameter, is kept consistent with comparable baseline technologies. In the context of defining these goals, "baseline" refers to the business-as-usual scenario or characteristics of the typical incumbent technology or product. Goals for technology cost and performance at market entry are set through the following process:

1. Set the desired market entry year
2. Set the segment(s) of baseline energy use to which the technology applies[12]
3. Set a desired energy performance value or range for the technology at market entry
4. Set a cost-effectiveness threshold for the technology at market entry
5. Determine the unit-level installed cost that satisfies the cost-effectiveness threshold, given the above parameter values.

In this report we use total installed price instead of cost (which is used in some other BTO R&D opportunity reports), because of the substantial contribution of installation labor and other costs to the price of windows seen by building owners. Given that project price is often identified as a barrier to adoption of high-performance windows and window retrofits more generally, we emphasize the importance of price, not cost, to realizing widespread market adoption.

Scout

Prospective technology definitions corresponding to the technology areas identified in Section 3 were created and assessed using Scout[13] [8] , an open-source software tool developed by BTO for estimating the national energy use, carbon dioxide emissions, and operating cost impacts of building-related ECMs. Scout simulates the impact of one or more ECMs on baseline case projections of national building energy use through 2050. Baseline case data are drawn from the EIA Annual Energy Outlook (https://www.eia.gov/outlooks/aeo). ECMs are defined primarily by the segment of baseline energy use they apply to, their market entry and exit years, and their installed price (or cost), energy performance, and lifetime.

Individual ECM energy savings impacts are derived from a unit-level comparison of the ECM's energy performance with that of a comparable baseline case technology. Scout estimates ECM impacts under two different technology adoption scenarios: 1) a technical potential scenario, where an ECM captures its entire applicable baseline energy use segment(s) on market entry and retains a complete sales monopoly in subsequent years, and 2) a maximum adoption potential scenario, where an ECM only captures the portion of its baseline energy segment associated with new construction, equipment replacement/retrofit at end of life or wear out, and a small fraction of elective replacements in advance of end of life. Given a portfolio of ECMs that apply to the same baseline energy use segments, Scout can apportion overlapping segments across competing ECMs [105, 106].[14] In addition to overall energy impact, Scout also assesses the cost-effectiveness of individual ECMs under multiple financial metrics.

Baseline data in Scout include energy use, equipment/technology installed stock size, building stock size and growth, and technology cost, performance, and lifetime. These data are mostly derived from the EIA's Annual Energy Outlook. The Annual Energy Outlook data are, in turn, derived from the National Energy Modeling System. For this

[12]Although goals are communicated at the sector level (residential versus commercial), sector-level goals combine outcomes from all of the major building types that comprise each sector.
[13]Scout is available online at: https://scout.energy.gov.
[14]Based on the technology choice models for residential and commercial buildings used in the National Energy Modeling System.

report, the 2018 Annual Energy Outlook provided most of the required input data apart from technology price and performance.

Baseline technology definitions for the building envelope are derived from a combination of sources. For windows, the baseline technology represents the incumbent that would be adopted in the absence of higher-performing alternatives. Total installed prices are derived from RSMeans building construction databases (https://www.rsmeans.com).[15] Technology performance is based on current International Energy Conservation Code and ASHRAE building codes adopted in various regions, accounting for lag in code adoption by state [107] and with a projection applied to future improvements in codes based on trends in window performance improvements in past code revisions and expert judgment regarding the potential for further technology performance improvements along the current trajectory in the codes. For residential windows, the current ENERGY STAR performance specification and the regional sales shares of ENERGY STAR-qualified windows are also incorporated into the baseline performance definition.

Windows Technology Goal Definitions

Technologies included in the windows ECM definitions encompass the primary opportunities for energy efficiency: windows, dynamic glazing and shading, and daylight redirection. The ECMs were applied to both residential and commercial buildings except in the case of daylight redirection, which is limited to commercial buildings. These ECMs are intentionally defined generically to encompass a wide range of potential technology- or component-specific approaches to achieving the performance and installed price targets for that technology type. Product lifetimes were set equal to the baseline or typical existing technologies for each ECM.

The windows ECM encompasses the entire window package—sash, frame, and IGU. Performance is characterized by R-value to represent the overall insulating performance of the package, thus the specified targets can be achieved through improvements to the frame, IGU, or both. Currently available windows vary widely in their rated performance [108] and installed price; this target was established with awareness of the limitations of currently available approaches for improving R-value.

Dynamic windows and window attachments are represented by a single ECM, generically describing any glazing or shading system that can reject a variable fraction of the solar spectrum that contributes to heating in response to detected or incident solar radiation. These systems include electrochromic and thermochromic glazing and automated attachments. Current electrochromic systems typically have a ΔSHGC of 0.35 to 0.4, from about 0.1 to between 0.4 and 0.5 SHGC. To increase energy savings by capturing additional passive solar heating, the target ΔSHGC was increased to 0.6, yielding a nominal upper bound of 0.7 SHGC.

The daylight redirection ECM includes a variety of approaches for drawing visible light into the core of a building from glazing at the facade. Many of these technologies could apply to both residential and commercial buildings, but this ECM focuses on commercial buildings because of their occupancy hours and floor plate depths that typically exceed natural daylight penetration. Lighting energy savings from daylighting can vary widely by application, but have been observed to average around 30% [52]. Seeking to improve performance beyond the current state-of-the-art, this ECM sets the nominal performance level to 50% by aiming for improvements in efficacy and redirection penetration depth.

The indicated price for daylight redirection for commercial buildings assumes that the light redirection system is applied to the entire glazed area in a building. It is likely that a daylighting system would be applied to only clerestory windows or the top portion of windows. A technology that applies to only half of the total glazed area, for example, could have a market-acceptable installed price of double that shown in Table 11. Although the lighting penetration depth yielded by a daylighting system is not prescribed in this target, penetration depths will affect the total lighting energy savings, so technologies that yield greater depths have higher efficacy and will yield greater savings, thus increasing the market-acceptable installed price.

Total installed price targets were developed for each ECM based on the performance targets previously articulated. Simple payback was used as the financial metric for this report to establish the goals for each individual technology area, corresponding to a particular ECM. Total installed prices are evaluated for payback periods ranging from 3 to 10 years. These payback periods are significantly shorter than the typical lifetimes of windows, but using much

[15] Based on RSMeans data, baseline total installed prices are $48.40/ft^2 for residential windows and $56.20/ft^2 for commercial windows.

longer payback periods could lead to excessively high prices, which can inhibit adoption. The goals defined for this report are based on the technical potential scenario and do not account for competition between ECMs. As a result, the energy savings are maximized for each ECM, and thus the installed price or installed price premium is maximized, because simple payback is based on operating energy cost savings. These assumptions are consistent with a future in which the technologies articulated in this report are widely adopted. Energy savings from these window technologies might be reduced if next-generation, high-performance HVAC technologies are aggressively adopted, because those technologies would reduce heating and cooling energy use that could otherwise be offset by high-performance transparent facades. Regardless, advanced transparent facade technologies will still enable long-term reductions in energy use for existing buildings and reduce tradeoffs between improving access to light and views enabled by increased glazed area and ensuring occupant thermal and visual comfort.

Limitations

An important limitation of this goal-setting methodology is its reliance on a limited valuation of ECM costs and benefits that is based only on installed price and operating energy cost savings from performance gains. This valuation excludes potential changes in nonenergy operating costs, which are difficult to assess for new-to-market or future technologies. Moreover, this approach excludes other potentially important benefits that are challenging to assess quantitatively, such as improved occupant comfort, employee productivity, or employee health. In a strictly payback-focused decision frame, these factors cannot be readily included. It is also not clear whether consumers can readily incorporate these nonquantitative factors into their decisions, and without that information, any additional benefits might not merit inclusion in a goal-setting context.

Among the various window technologies reflected in this report, many must meet various other performance requirements that might affect or be affected by their energy performance but are not directly captured in Scout ECM definitions. These factors can include code-mandated requirements (e.g., window structural performance) or relate to consumer acceptance or market viability (e.g., glare control with visible light redirection). Though these factors might not directly influence energy performance, they nonetheless remain important to incorporate into a complete assessment of the viability and relevance of novel technology R&D.

The representation of operating cost savings arising from window performance improvements in Scout necessarily pools savings across wide swaths of the existing and projected future building stock. As a result, the total installed price or price premium targets reflect a stock-wide average. Although this target is appropriate given BTO's focus on national energy savings (not savings within individual buildings), it obscures the potential for higher-priced technologies to enter the market in existing buildings that have poorly performing windows. These buildings could see much larger energy savings than are reflected in the Scout analysis, and if simple payback is an appropriate metric for a given project, the total installed price for window (and/or attachment) retrofits could be much higher than this report's target while still realizing a customer-acceptable payback period.