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FINAL PROJECT REPORT

Next Generation Window and Building Envelope Systems

Research, Development, and Demonstration Opportunities

Gavin Newsom, Governor

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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solutions, foster regional innovation and bring ideas from the lab to the marketplace. The CEC and the state's three largest investor-owned utilities—Pacific Gas and Electric Company, San Diego Gas & Electric Company and Southern California Edison Company—were selected to administer the EPIC funds and advance novel technologies, tools, and strategies that provide benefits to their electric ratepayers.

The CEC is committed to ensuring public participation in its research and development programs that promote greater reliability, lower costs, and increase safety for the California electric ratepayer and include:

- Providing societal benefits.
- Reducing greenhouse gas emission in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs first with energy efficiency and demand response, next with renewable energy (distributed generation and utility scale), and finally with clean, conventional electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

Next Generation Window and Building Envelope Systems is the final report for the Next Generation Window and Building Envelope Systems project (Contract Number 300-15-009) conducted by Guidehouse. The information from this project contributes to the Energy Research and Development Division's EPIC Program.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the CEC at ERDD@energy.ca.gov.

ABSTRACT

This report examines advanced window and building envelope systems and recommends further research activities to hasten their broad market adoption. This study:

- Assessed the current state-of-the-art and future technology options in windows and building envelope systems.
- Evaluated the barriers to commercial-scale use in California.
- Identified the market segments that present the most promising opportunities.
- Recommended research, development, and demonstration initiatives to overcome identified, existing barriers to broad adoption.

Incorporating research from primary and secondary sources, emerging energy-efficient technologies were investigated in three spaces: windows, insulation, and air sealing. Primary barriers to high-performing products include high costs, lack of customer awareness of their benefits, manufacturer reliance on market pull (where the market needs a product and designers then make a product to fill that need), and lack of stricter energy-efficient building codes. If these barriers can be overcome, next-step markets to target include the passive house community in the near term and the retrofit space in the long term. High-potential implementation opportunities exist in prefabricated wall retrofits for multifamily housing and housing with thin building envelopes, such as manufactured homes.

Keywords: window, building envelope, insulation, air sealing, energy efficiency, emerging technology, manufactured homes

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EXECUTIVE SUMMARY

Introduction

Window and building envelope systems determine a building's heating, cooling, and ventilation requirements. Together, these end-uses have historically accounted for more than 30 percent of residential building and more than 40 percent of commercial building energy use in California. Improving window and building envelope insulation and envelope sealing performance can reduce heating, ventilation, and air conditioning (HVAC) loads, subsequently reducing both energy use and the capacity and cost of HVAC systems.

More efficient window and building envelope technologies contribute to California's mandated goal of doubling the state's energy savings from energy efficiency, which would in turn reduce the need to generate electricity from the fossil fuels that contribute to climate change. California's relatively high number of sunny days makes window-technology energy savings particularly effective. Despite great energy savings potential, however, the high cost of retrofits remains a crucial barrier to wider implementation. Additionally, many consumers are unaware of the energy benefits of utilizing more efficient technologies, leading to diminished adoption of these measures by manufacturers due to lack of demand. Broader adoption of high-performance window and building envelope technologies by manufacturers and contractors will increase the likelihood of their implementation in consumers' buildings.

Addressing research gaps and overcoming barriers to the broader market adoption of promising high-performance window and building envelope systems are essential components of California's mandated greenhouse gas reduction targets. This report analyzes the current and potential values of these technologies to California through both performance and cost analyses, and further assesses primary barriers to their wider adoption. It then identifies market segments where potential impacts would be greatest and recommends research initiatives for the California Energy Commission (CEC) that could improve the technology's performance and overcome market barriers that prevent their more widespread market adoption.

Project Purpose

This project was funded through the state's Electric Program Investment Charge (EPIC) program, created with ratepayer funds through the California Public Utilities Commission (CPUC). The CEC administers the bulk of the research performed through the EPIC program, along with the state's three large investor-owned utilities. This project gained a deeper understanding of window and building envelope technologies and their largely untapped energy-saving potential. The project also developed specific research initiatives to overcome barriers to broader adoption of these energy-saving technologies in buildings throughout California. Several objectives guided the research for this project, including to:

- Assess current state-of-the-art and future technology options in window and building envelope systems.
- Evaluate the barriers to commercial-scale development in California.
- Identify market segments with the most promising market opportunities.
- Recommend RD&D initiatives to overcome both technology and market barriers.

Research findings will contribute to CEC recommendations for future funding opportunities and implementation with industry, commercial, residential, and other interested parties around the state.

Project Approach

Guidehouse performed a detailed literature review and conducted 11 interviews with research laboratories, academia, and manufacturers to accurately determine the costs, performance, and technical characteristics of emerging window and building envelope technologies, and to assess current barriers to their adoption. From this research, the research team identified the most promising future market segments and RD&D initiatives that align with project goals.

Project Results

Guidehouse's literature review encompassed emerging technologies at various levels of technology development in the following categories:

- Windows
    - Highly Insulating Windows
    - Low-Emissivity Films
    - Switchable and Dynamic Glazing
    - Automated Mechanical Facades
- Insulation
    - Ultra-Low Thermal Conductivity
    - Tunable-Phase Change Materials
    - Environmental Heat Sinks
- Improved Air Sealing Methods
    - Use of Foam-Board Insulation
    - Spot-Sealing Spray Foam
    - Whole-Building Automated Air-Sealing
    - Weather Strips and Gaskets

The team also interviewed building-envelope industry experts from research labs, academia, and manufacturers. The findings summarized four categories of barriers.

- High Costs
- Lack of Customer Awareness of Benefits
- Manufacturer Reliance on Market Pull
- Lack of Stricter Building Energy Codes

The research team also identified four major market opportunities.

- Residential and Commercial Retrofits
- Passive Houses: Passive House design focuses on building construction that requires little supplemental heating or cooling to provide year-round comfort. Passive House designers accomplish this through superinsulation, air sealing, passive heating (solar

gain), and effective ventilation. The Passive House community welcomes high-performance technologies that further its energy-efficiency performance goals and awards certifications and accreditations that support them. Though this market may be small, the awareness and acceptance of the technology by this community will likely encourage earlier adoption of the emerging technologies identified in this study.

- Prefabricated Wall Retrofits for Multifamily Housing
- Existing Housing with Thin Building Envelopes

Due to the complex influence window and building envelope systems on a building's heating, ventilation, and air conditioning (HVAC) energy consumption, the team conducted a simplified modeling exercise that estimated energy savings from the technologies studied in this project. The team sought alternate resources, such as published academic or industry research, to estimate energy savings associated with emerging technologies that could not be modeled directly.

Guidehouse compiled the energy savings results and other performance metrics for each technology studied and developed estimated research targets for the next five years. Not all products were given specific targets across all performance metrics. For example, some technologies were already very high performing, so research focused on reducing costs.

In addition to the core work of this study, Guidehouse provided targeted insights on a related solicitation for EPIC grant funding: (GFO-19-307) Advancing Envelope Technologies for Single Family Residential Buildings, Low-Rise Multifamily Buildings, and Mobile Homes. This solicitation was released at the same time as the research conducted by the Guidehouse team, so case studies in this report include this research as it relates to the three groups involved in the solicitation.

- Group 1: Demonstrate Fenestration Advancements in Existing Low-Rise Multifamily and Single-Family Residential Buildings in Disadvantaged or Low-Income Communities
- Group 2: Develop, Test and Validate Innovative Exterior Prefabricated Envelope Packages for Low-Rise Multifamily Building Retrofits
- Group 3: Develop and Test Advanced Envelope Measures for Single-Family Mobile Homes

Recommended Research, Development, and Demonstration Initiatives

The project team developed a set of recommended initiatives to overcome challenges faced by the window and building envelope systems analyzed in this study. Each of the recommended initiatives would advance CEC statewide energy-efficiency goals, but some would have greater impacts than others by providing opportunities where high-efficiency options are neither available nor cost-effective.

Based on project research, the project team recommends that the CEC pursue the initiatives summarized here and fully described in Chapter 5.

Windows

- Conduct research into novel or upgraded manufacturing materials to improve window performance.

- Research ways to manufacture glass or modify its material properties so that it does not require tempering.
- Research methods that integrate energy storage into electrochromic windows.
- Increase industry and public awareness of the benefits of dynamic windows.
- Bridge gaps between emerging technology developers and manufacturers.

Insulation

- Increase R-value per inch in insulation for buildings with limited envelope space.
- Reduce the cost and increase the use of microencapsulated-phase change materials.
- Develop highly reflective asphalt particles for shingles.
- Improve the manufacturing process for vacuum-insulated panels.

Air Sealing

- Highlight the benefits of high-efficiency air sealing.
- Develop whole building air sealing retrofit technologies that do not require full building renovation.

Recommendations in this report do not in and of themselves guarantee funding; activities will be evaluated in the context of all potential activities that the CEC considers while achieving its mandated, statewide energy-efficiency goals.

Benefits to California

Installing some combination of these technologies in all of California's buildings could save over 1,600 GWh annually of electricity from lower customer demand, $675 million in utility customer energy bill savings (electricity and gas), and 2.2 million tons (or 2-million metric tonnes) of carbon dioxide air emissions. Additional benefits include peak demand savings and non-energy benefits such as greater building comfort for occupants. These benefits would also help achieve statewide greenhouse gas emission reductions and other environmental goals.

CHAPTER 1: Introduction

The purpose of this report is to gain a deeper understanding of emerging energy-efficient window and building envelope (everything in a building that shields the living space from the outdoors) technologies, recommend paths for their commercial expansion, and in the process advance California's aggressive mandates to reduce the greenhouse gas (GHG) emissions that accelerate global warming by reducing the need for the fossil-fuel-generated electricity required to heat and cool less energy-efficient buildings. This project is part of the state's Electric Program Investment Charge (EPIC) program, adopted with ratepayer funds by the California Public Utilities Commission (CPUC) and largely administered by the California Energy Commission (CEC). Residential and commercial buildings throughout California have energy-intensive heating, ventilation, and air conditioning (HVAC) systems that heat, cool, and ventilate the indoor spaces where residents live and work, and emerging technologies, state policies, and global industry trends together provide the opportunity to both reduce electricity consumption and contribute to California's progressive environmental goals. This project also examines current barriers to broadly retrofitting older, energy-inefficient buildings with energy-efficient windows and other components and recommends further research, development, and demonstration (RD&D) support to ease and hasten this transition.

Background

Building energy requirements for HVAC and lighting account for over half of a building's energy use. Improving the energy efficiency of windows, insulation, and sealing can reduce HVAC energy loads and ultimately defray the initial cost of HVAC equipment over time. California's relatively high number of sunny days additionally makes window technology a particularly attractive energy-efficient choice. A barrier to broad implementation, however, is that window and building envelope system retrofits are expensive.

Windows

Windows play a crucial role in a building's energy use since they transfer heat and light from the ambient environment. A window's performance is determined by its resistance to heat transfer through conduction and convection, its ability to block radiative heat from the sun, and its ability to transmit light. Factors to consider when choosing new windows include frame materials, glazing and glass features, gas fills between panes, and the local climate.

Insulation

Insulation slows down the conductive flow of heat, and its performance is determined by its material, method of installation, and thickness, which is limited to a wall's dimensions. Typical materials include mineral wool, cellulose, plastic foams, fiberglass, and natural fibers, while high-efficiency products may use materials that include aerogel, phase-change materials (PCMs), and closed-cell spray foam. Air sealing can improve the performance of insulation.

Air Sealing

Air sealing is measured in units of air changes per hour at 50 pascals of pressure differential (ACH50). A lower ACH50 value indicates better air sealing that can reduce HVAC energy needs in a building. Air sealing is typically applied during normal construction processes through adding insulation and house wraps, caulking, and weather stripping. Advanced methods combine insulation installation with sealant.

These topics are further examined in detail in Chapter 2 and throughout this report.

Report Objectives

This report describes state-of-the-art window and building envelope technologies and recommends specific activities for their statewide adoption in California buildings. The report had several primary objectives.

- Analyze potential window and building enveloped technologies and their suitability for California buildings.
- Identify technical, market, and policy barriers to broad adoption of these systems.
- Assess promising market segments in California for installation of these technologies.
- Make specific recommendations to the CEC on potential RD&D activities that could spur further development of the most promising technologies.

Technology and Market Scope

This report examines window and building envelope systems for residential and commercial buildings in California and focuses on technologies that best apply to retrofits. These technologies fell into several categories.

- Windows
    - Highly Insulating Windows
    - Low-Emissivity Films
    - Dynamic Glazing
    - Automated Mechanical Facades
- Insulation
    - Ultra-Low Thermal Conductivity
    - Tunable-Phase Change Materials
    - Environmental Heat Sinks
- Improved Air-Sealing Methods
    - Use of Foam-Board Insulation
    - Spot-Sealing Spray Foam
    - Whole-Building Automated Air Sealing
    - Weather Strips and Gaskets

Project Approach

Guidehouse undertook a detailed literature review and conducted 11 interviews with manufacturers and research institutes in its research of emerging window and building envelope technologies and assessed current barriers to their broader adoption. From this research, the team also determined the most promising market segments for alignment with CEC goals and environmental mandates. Table 1 describes the structure of this report.

Table 1: Chapter Descriptions

Chapter	Brief Description
Executive Summary	Summary of entire report for wider audience.
1. Introduction	Brief section describing the report background, objective, and technology / market scope.
2. Characterization of Promising Emerging Window and Building Envelope Systems	Characterization of promising technologies in three technology areas: windows, insulation, and air sealing. Performance metrics are reported as relevant to each technology and may include the following, among others: R-value, fire rating, cost, and application.
3. Barriers to High Performing Windows and Building Envelope Systems	Summary of key barriers to retrofit installation of high-performance window and building envelope technologies and potential tools and strategies for addressing these barriers.
4. Market Opportunities for Windows and Building Envelope Systems	Summary of most promising and impactful segments for high performance window and building envelope technology.
5. Research Recommendations	Collection of RD&D initiatives that includes activity description, specific research areas and goals, how they bridge an identified gap, and expected outcomes.
6. Case Studies	Findings specific to GFO-19-307: Advancing Envelope Technologies for Single Family Residential Buildings, Low-rise Multifamily Buildings, and Mobile Homes, which was released while this study was being conducted.
7. Benefits to Ratepayers	Description of the benefits of this research to ratepayers.

Source: Guidehouse.

CHAPTER 2: Characterization of Promising Emerging Window and Building Envelope Systems

This chapter provides an overview of residential and commercial window and building envelope systems, including baseline performance metrics and high-efficiency technologies identified in this research.

Baseline Construction

The research team began by collecting information on performance metrics for baseline construction practices for the three main technology categories studied. These provided the foundation for a comparison of emerging technologies. Table 2 outlines both key performance metrics for each technology area and baseline values for each building type examined in this study.

Table 2: Baseline Construction Performance Metrics

Technology Area	Metric	Residential Single Family and Low-Rise Multi-Family Buildings	Manufactured Housing	Commercial Buildings
Windows	R-value	R-3 to R-5*	R-2 to R-3†	R-3 to R-5*
Insulation	R-value	Walls: R-13 – R-20* Roof: R-38	Walls: R-13† Roof: R-30	Walls: R-20* Roof: R-38
Air Sealing	ACH50	3-5‡	3-5‡	3-5‡

*** 2015 International Energy Conservation Code.**
† HUD Manufactured Housing Working Group Term Sheet.
‡ Air Leakage Guide: Building Technologies Program.

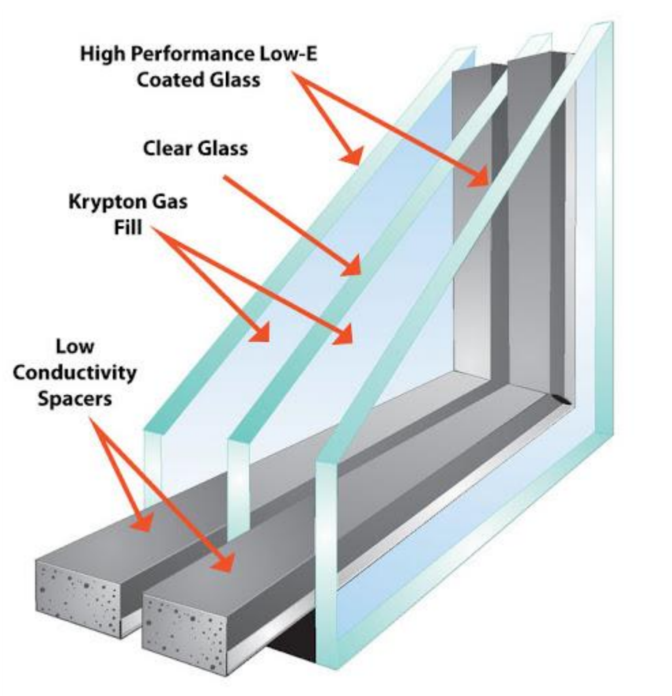
Source: Guidehouse.

Windows

Windows in buildings allow passage of light and heat. Improvements in their thermal performance are critical to energy-efficient building design since they play a major role in heating and cooling energy consumption, accounting for roughly 30 to 50 percent of transmission losses through building envelopes.

Typical window construction consists of a frame (made of wood, vinyl, aluminum, or fiberglass), double- or triple-glass panes, low-emissivity (low-E) films, gas fill (in some cases), and spacers, as shown in Figure 1Figure 1.

Figure 1: Triple Pane Low-E Window Construction



Components of a triple pane low-e window.

Source: Above and Beyond Construction.

The performance of a window is measured by three primary metrics: R-value, solar heat gain coefficient (SHGC), and visible transmittance (V_T).

- R-value quantifies the thermal resistance of a material. A higher R-value implies higher resistance to heat flow (lower conductivity) through a given thickness of material and therefore better insulation. U-factor is the inverse of R-value and indicates the rate of heat loss. The lower the U-factor, the more insulating the window. The R-value and U-factor can represent either a whole-window or center-of-glass value. For consistency with the National Fenestration Rating Council (NFRC), this study uses whole window R-values and U-factors when evaluating the technologies studied.
- SHGC refers to the fraction of solar radiation admitted through a window. The lower the SHGC, the less heat is transmitted into the building and the greater its shading ability.
- V_T is the amount of visible light that passes through a window. Generally, a higher V_T is preferred for daylighting reasons, but this is more difficult to achieve while decreasing the SHGC.

Target window performance metrics may differ by climate zone since heating and cooling loads vary. For example, in cooling-dominated climates, windows that lower solar heat gain with a low SHGC may be preferred. Conversely, in heating-dominated climates, a window with a high SHGC will be preferred since it is more effective at collecting solar heat during the winter.

This section covers three main categories of high-performing window technologies: highly insulating windows, switchable/dynamic glazing, and low-E films.

Highly Insulating Windows

Highly insulating windows (HIWs) are high-performance windows composed of multi-pane glazing systems, gas fills, and a window frame that work together to reduce air-to-air heat transfer through glazing. The multiple glass panes are sealed and held together structurally along their perimeters by varying edge seal systems, whose main purpose is to keep the glass panes separated at equal distances, preventing infiltration of water vapor and leaking of the gas fill between the panes. Edge seal components include a spacer bar, desiccant, and sealant. Typical gas fills include inert gases, such as krypton and argon, that further reduce heat transfer. Highly insulating windows can incorporate low-E films and reflective glass coatings to increase desired performance. Table 3 describes the best-in-class products identified.

- Fixed windows cannot open; Their sole components are the glass and frame, which together reduce maintenance, increase air tightness and insulation, and reduce cost when compared with casement windows.
- Casement windows, also known as operable windows, are often paired with screens. They are more expensive and require more maintenance. Their insulative performance is reduced when compared with fixed windows.
- Vacuum insulated glass is an emerging window technology where two fully tempered glass panes are sealed, creating a vacuum in the space between them, eliminating the need for fill gases. Conduction and convection losses associated with fill gas are also eliminated, reducing heat loss. In comparison with standard triple-insulated glass units (IGUs), vacuum IGUs with low-E films are thinner and lighter and have both better thermal insulating performance and lower reflection. The technology has been successfully demonstrated in commercial refrigeration but is now emerging in window applications for new construction and retrofits in the United States.
- “Skinny” triple-pane windows are an emerging drop-in window technology where a piece of very thin glass, approximately 1 mm thick, is inserted into the standard IGU cavity. A second low-E coating is added to the glass facing the second cavity. The new center glazing is held in place in the cavity but is not part of the sealant and spacer structure, which simplifies assembly, reduces costs, and improves durability. These windows have no significant weight change over industry standard double-pane units and fit into existing cross-sections, which reduce the need to change framing systems. Their main advantage is that they can be installed in almost any existing window frame and can be manufactured at low marginal cost while at the same time providing significant energy savings when compared with typical low-E windows.

Table 3: Best in Class — Highly Insulating Windows

Product	R-Value (whole window)	SHGC	V_T	Application	Cost ($/ft²)
Highly Insulating Glass, Casement	7.14	0.13	0.26	Residential, Commercial	Installed Cost: $55+
Highly Insulating Fixed High-Profile Window	10	0.15	0.30	Residential, Commercial	Installed Cost: $55+
Vacuum IG Hybrids with Low-E Glass Coatings	12 (center of glass)	Not specified yet	Not specified yet	Residential, Commercial	Installed Cost: $66+
Skinny Triple Pane Window	Between 8 and 10	Not specified yet	Not specified yet	Residential, Commercial	Commercially unreleased, but $6-$8 installed cost premium compared to double pane.

Source: Guidehouse.

Dynamic Glazing

Dynamic glazing has the fully reversible ability to change its performance properties, including U-factor, SHGC, and V_T. This variation in performance properties from this dynamic glazing is beneficial, for example, when solar heat gain is desired in cold climates or when solar heat reduction is desired in hot climates.

Increasing market penetration of dynamic windows, especially in the retrofit market, will result in significant building energy savings compared with baseline windows. Dynamic windows have a larger market than HIWs because they are better suited for a wider variety of climate types. They provide significant building energy savings in areas with both high cooling and high heating loads due to their dynamic nature and ability to adjust performance metrics to best suit climate needs. In contrast, HIWs are best suited to colder, heating-dominated regions because of their highly insulative properties and are less appropriate for hotter climates. There are two main types of dynamic windows commercially available today: thermochromic and electrochromic.

- Thermochromic windows change their performance metrics as sunlight hits the glass. When the sun warms the window, the thermochromic elements, which are embedded in a polyvinyl butyl interlayer, darken and create a tinting effect over the window. As the sunlight decreases, the glass and interlayer cool, and the window returns to its clear state. This alters the visible light transmittance, SHGC, and U-factor. There is no need for electrical input, which makes this passive technology highly attractive in the retrofit market. In addition, thermochromic windows are installed in the same manner as other windows and can be installed in operable windows and doors, increasing their market applicability.
- Electrochromic windows have an electrochromic coating that consists of five micro-thin layers applied onto insulating glass units. The tint of the glass is controlled directly by

the amount of voltage applied to the glass. Applying low voltage darkens the coating as lithium ions and electrons transfer from one layer to another. Removing the voltages causes the ions and electrons to return to their original layers and the glass lightens and returns to its clear state. Electrochromic glass requires a very small amount of electricity to operate, roughly 0.05 watts/ft^2. Their current application is to date solely in the commercial sector.

Although dynamic windows greatly reduce heating and cooling demand in buildings, their current steep cost greatly limits widespread market adoption. Thermochromic windows cost roughly \$30/ft^2 and electrochromic windows cost roughly \$60/ft^2. The high cost of high-performance dynamic windows is the dominant barrier to greater market penetration. The primary research goals, therefore, focus on cost reduction to increase their accessibility.

Table 4 shows the best-in-class switchable and dynamic glazing products identified in this study.

Table 4: Best in Class – Dynamic Glazing

Product	SHGC	V_T	Application	Cost (\$/ft^2)
Electrochromic Windows	0.41 for Clear State 0.09 for Fully Tinted	0.60 for Clear State 0.01 for Fully Tinted	Commercial	Installed Cost: \$60/ft^2
Thermochromic Windows	0.31 for Clear State 0.13 for Fully Tinted [for clear glass]	0.54 for Clear State 0.08 for Fully Tinted [for clear glass]	Residential, Commercial	Installed Cost: \$30/ft^2

Source: Guidehouse interviews with subject-matter experts.

Low-Emissivity Films

A low-E film is a microscopically thin metal oxide layer deposited directly on the surface of one or more of the glass panes during window manufacturing. This film helps reduce the overall U-factor of the window and directly affects the SHGC, either increasing or lowering the value as desired. Regarding V_T, spectrally selective low-E coatings exist that can reflect certain wavelengths while remaining transparent to others. They are commonly used to reflect the infrared, heating portion of the solar spectrum while admitting visible light, a combination highly desirable in residential settings. These coatings help create windows with low U-factor and SHGC that maintain a high V_T.

Low-E films are advantageous for retrofits because they adhere directly onto existing glass windows to reflect radiant heat, with minimal occupant disturbance. They are inexpensive alternatives to replacing entire windows and can last for up to 15 years.

Windows manufactured with low-E films typically have a 10 to 15 percent cost premium when compared with baseline windows but can reduce energy loss by up to 50 percent.

There are two main processes for low-e coatings: sputtered and pyrolytic. Sputtered coatings are multilayered coatings of metals, metal oxides, and metal nitrides that are deposited on glass or plastic film in a vacuum chamber in a process called physical vapor deposition. Sputtered coatings typically use one of more layers of silver to achieve their heat reflecting properties. Sputtered coatings have emittance as low as 0.02, significantly lower than pyrolytic coating emittance.

A typical pyrolytic coating is a metallic oxide that is bonded to the glass while it is in a semi-molten state. The process by which the coating is applied to the glass is called chemical vapor deposition. This type of coating is more durable than sputtered coatings and can withstand exposure to air and glass-cleaning products without damaging the coating. The pyrolytic low-e coating is used mostly in sealed insulating-glass units with the low-E surface facing the sealed air space.**Error! Bookmark not defined.**

Window manufacturer product information includes the effect of low-E coatings on the U-factor for the window unit. Table 5 describes the best-in-class technology identified by the research team.

Table 5: Best-in-Class Technology - Low-Emissivity Films

Product	Emissivity	V_T	Application	Cost ($/ft^2)
Silver (Ag) Thin Films with Alternative Seed Layers	< 0.09	> 0.8	Residential, Commercial	$12-15

*** Debusk.**

Source: Guidehouse.

Low-E Coating Deposition Process Highlights: High-Rate Plasma-Enhanced Chemical Vapor Deposition and Optimized Sputtering Techniques

Researching next-generation low-E films and low-E film deposition methods is critical to improving the performance of various windows. Low-E films play a crucial role in the insulating and visible transmittance properties of windows. High-rate, plasma-enhanced chemical vapor deposition is a manufacturing process for low-E films that provides high-solvent and corrosion resistance and thermal and chemical stability. Additional advantages of this technique include a high deposition rate and more potential film chemistries. Increased durability and the opportunity to create more film chemistries could together open up new research in the low-E film category.

In addition, there have been advancements in creating low-E coatings that allow for high V_T. M. Ferrara et al. studied AlN-Ag-based low-E sputtered coatings for high V_T windows. Their study investigated an optically selective low-E filter suitable in mild-to-hot climates, designed and fabricated on glass using the sputtering technique. The researchers maximized the sputtering process parameters, layer sequence of the stacked structure, and the thicknesses of the layers to develop an optical filter with the highest V_T (80 percent), coupled with an emissivity value as low as possible (8 percent). They concluded that these thermo-optical parameters were largely effective in energy-saving glazing technologies. Their research paper includes details of successful deposition methods of the layers and the formulation used to create this optimal coating. The research also concluded that the sputtering fabrication process is well suited for scaling up to high-yield, low-cost industrial production.

Insulation

Building-envelope insulation breaks thermal bridging between the exterior and the interior of a building. This is normally done with a thermally insulating material either in wall or roof cavities or on the exterior of a wall. Insulation's performance is generally measured in R-value. While total R-value determines its performance, products are also often measured in R-value per inch, or contain both R-value and thickness (in inches).

Insulation performance is determined by its material, method of installation, and space available. A thoroughly insulated home can save heating and cooling costs when compared with a poorly insulated one. It is important, however, to correctly install the right insulation for specific applications, such as location within the building envelope, the type of building, and the climate zone. Certain types of insulation are better suited for specific components of a building and may be better at trapping or rejecting heat. Correctly installed insulation also reduces thermal bridging. Insulation can be made of several materials including mineral wool, cellulose, plastic foams, fiberglass, or natural fibers. High-efficiency insulation can be made of aerogel, PCMs, or closed-cell spray foam.

Due to its heat-insulating properties, good insulation can also provide a fire barrier. Generally, fire ratings are determined by a construction material's ability to slow the spread of flames throughout a building once a fire starts. Insulation materials can also influence fire-spread prevention.

This study organized high-performance insulation into three types: ultra-low thermal conductivity, thermal storage with tunable PCMs, and environmental heat sinks.

Ultra-Low Thermal Conductivity

Ultra-low thermal conductivity describes insulation with thermal resistance higher than R-6 per inch. The team researched three product types with wide market availability: structurally insulated panels (SIPs), closed-cell spray foam, and rigid foam boards; and two product types not yet widely adopted: aerogel blankets and vacuum-insulated panels (VIPs). Table 6 shows performance metrics for these product types.

- SIPs are prefabricated wall panels that include an insulating material (usually a type of plastic foam) on the interior, surrounded by structural construction material. These are loading-bearing panels that can form both the interior and exterior of buildings. They prevent thermal bridging due to the precision of their factory construction. They also reduce waste from typical on-site construction due to processing standardization.
- Closed-cell spray foam is an effective insulating option for both new and existing buildings. An application nozzle sprays plastic closed-cell foam into an existing cavity or onto a surface, where it expands and hardens. Spray foam can also add to a building's air tightness since it expands to fill spaces that would otherwise leak.
- Rigid foam boards are made of rigid plastic foam that provides additional R-value on top of existing insulation. Foam boards can be cut to fit specific applications and can be an effective retrofit option. Additionally, foam boards can provide better air sealing than fiberglass or cellulose insulation; If installed correctly, they provide another vapor and air barrier, resulting in a more tightly insulated building.
- Aerogel is an extremely low-density material like a gel, but with gas instead of liquid in the gel. It is highly insulative and can be made into thin forms of building insulation, such as blankets that are installed on top of existing insulation or in place of traditional insulation for better insulation in thin walls.

- VIPs are manufactured insulated panels with an outer casing or membrane that surrounds a rigid core of insulation, often made from fiberglass, aerogel, or fumed silica. The casing is then evacuated of gas, extremely reducing heat transfer. Because of this vacuum, VIPs have ultra-high R-value per inch performance. However, their materials and the evacuation process are expensive.

Table 6: Best-in-Class Ultra-Low Thermal Conductivity

Product	R-Value per Inch	Thickness (Inches)	Fire Rating	Application	Cost ($/ft^2)
Structural Insulated Panel*	6.9	4, 6.5, or 8.25	Class A	Walls, Roof	$6+
Closed Cell Spray Foam**	7	1	Class A	Walls, Ceilings, Attic	$1.29
Rigid Foam Board†	6	1	1, 2, 3 or 4-hour	Walls, Ceilings, Attic	$0.92
Aerogel Blanket‡	10.3	0.2 or 0.4	Non-combustible	Walls, Ceilings, Attic	$4-6
Vacuum Insulated Panel††	60	0.94	Class A	Walls, Ceilings, Attic	As low as $7

***Thermocore.**
****Foam It Green.**
†RMax.
‡ Insulation for Building and Construction.
††Panasonic Corporation of North America.

Source: Guidehouse.

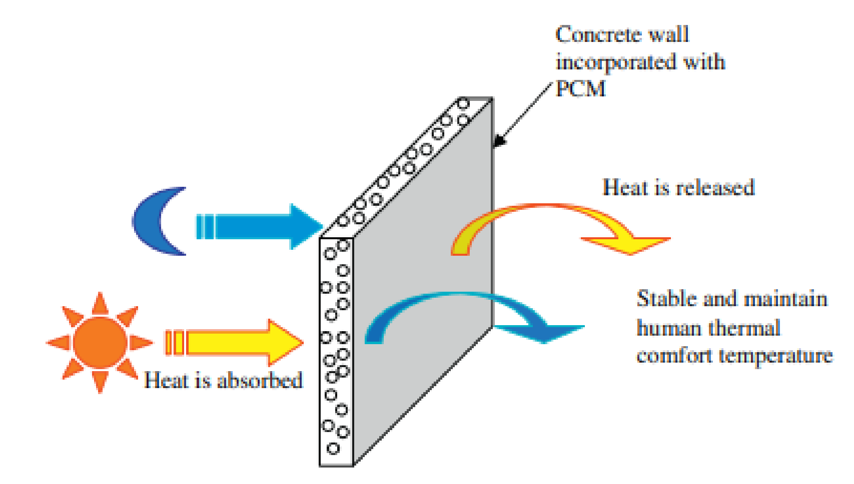
Thermal Storage with Tunable Phase-Change Material

PCMs absorb and release heat while changing phases (melt or freeze). Once a material reaches its freezing or melting point, it absorbs or releases a great amount of heat before changing phase. This can be incorporated into insulation or support materials to negate the effect of the environment on the interior temperature of the building. Many PCMs are made of paraffin wax-type materials; some newer examples include biodegradable bio-based materials. PCMs for use in construction rely on changing phases between liquids and solids.

The team researched two types of PCM insulation – microencapsulated PCM and PCM blankets. Table 7 shows the best-in-class products examined for this study.

- Microencapsulated PCMs are added to masonry material such as concrete and gypsum drywall boards. In masonry, the PCM can become part of the structural components of a building instead of just its insulation and adds thermal mass. A group at the University of California, Los Angeles is researching the use of low-cost PCMs in this application to reduce a building's HVAC power use. Figure 2 shows this process.
- PCM blankets are visually similar to other standard insulation products. A sheet of insulative material containing PCM inside of it can be installed as stand-alone insulation or together with existing insulation.

Figure 2: Microencapsulated Phase Change Materials in Masonry



A demonstration of how PCM integrated into concrete insulates a concrete wall.

Source: Ling 2013.

Table 7: Best-in-Class Phase Change Materials

Product/ Technology	Thermal Storage Capacity	HVAC Energy Savings	Fire Rating	Application	Cost
Microencapsulated in Masonry Material	95 Btu/lb of PCM	5–32%‡	Bio-based PCMs are effective at fire resistance	Walls	$1.50-$7.50/lb of PCM*
PCM Blanket†	110 Btu/ft^2 of blanket	25–35%	Meets or Exceeds ASTM E84	Walls, Roof, Attic	$2.55-3.75/ ft^2

***Kosny 2013.**
†Phase Change Energy Solutions.
‡Thiele 2015.

Source: Guidehouse.

Environmental Heat Sinks

A heat sink in a system exists at a lower temperature than the rest of the system so that heat will flow into the sink via diffusion. Environmental heat sinks direct heat straight into the environment rather than to part of the building. An example of this is a radiant barrier on a roof, which redirects heat from the sun back into the air, rather than allowing it to be absorbed into the building materials and then conducted into the interior of the building. Heat sinks generally work better in cooling-dominated climates. The team researched three types of environmental heat sinks, all related to roofing reflectance. Table 8 contains the characteristics of the best-in-class environmental heat sinks examined.

- Reflective roof coating is an aftermarket product that improves the solar reflectance of a roof. Advanced roof coatings can be made of nanoacrylic technology with a backbone made of a reflective and non-conductive fabric. Non-advanced roof coatings can be made of acrylic or other simple plastic material and applied like paint.

- Radiant barriers reflect radiated heat away from the surface that it covers, whether walls or roofs. These are often manufactured from multi-layered aluminum or other reflective materials and can be double-sided to reflect heat back into the building and into the atmosphere, or single sided to reflect heat in one direction.
- Foil insulation is both a radiant barrier and insulation. It is made of insulation material with a reflective foil surface.

Table 8: Best-in-Class Environmental Heat Sinks

Product	Solar Reflectance	Fire Rating	Application	Cost ($/ft^2)
Reflective Roof Coating*	0.95	Class A	Roof	$1.10 ($110/gallon)
Radiant Barrier**	0.97	Class A	Attic	$0.20
Foil Insulation†	0.96	Class A	Attic, Basement Walls	$0.42

***2011. MultiCeramics.**
****2020. Ultima-FOIL.**
†Double Bubble Insulation.

Source: Guidehouse.

Air Sealing

Air sealing reduces the transfer of air and moisture between the ambient outside environment and the building interior. This is measured in air changes per hour at 50 pascals of pressure (ACH50). Installation methods and materials can achieve a lower ACH50, which indicates a tighter building envelope. The HVAC energy savings from air sealing and the ACH50 code requirements differ by climate zone. Table 9 shows the performance metrics of the air sealing technologies studied.

- Automated whole building air sealing is an aerosol fog-sealing technology. A building is first pressurized with a blower door before sealant is fogged into the open space and carried by pressure into gaps in the building's envelope, which it then seals. Currently, this process is only used in residential new construction.
- Spot-sealing spray foam can also fill and seal cracks and gaps where air infiltrates a building. It cures in under an hour and does not require professional application.
- Sill gaskets protect against air leakage and moisture in much the same way as spot-sealing spray foam.

Table 9: Best-in-Class Air Sealing Products

Product	ACH50	Install Time	Fire Rating	Application	Cost
Automated Whole Building Air Sealing*	<1	<1 day	Unknown	Whole home	$1.50-4.50/ft^2 of conditioned space
Spot-Sealing Spray Foam†	Varies	<1 hour	Class A	Whole Home	$13.34 for 24 oz (42 liters of treatment)
Sill Gasket†	Varies	Varies	Class A	Foundation Wall	$7.50 for a 50-ft roll at 5.5” thick

***2018. AeroBarrier**
†2020. Air Sealing Products

Source: Guidehouse

Process Highlight: Use of Rigid Foam-Board Insulation

Using rigid foam-board insulation instead of loose fill or other materials can simultaneously increase the R-value of space and decrease air leaks. Products vary in price, generally have a Class A fire rating, and can be applied to walls, ceilings, and roofs.

CHAPTER 3: Barriers to Adoption of High-Performance Windows and Building Envelope Systems

While highly efficient window and building envelope technologies do exist commercially, various factors limit their adoption, especially in California. Much of California's climate is temperate, especially in areas of dense population; energy-efficient technologies would show greater energy-saving benefits in more extreme climate areas. Additionally, though energy savings opportunities exist in retrofitting older (pre-1980) buildings to current code standards, retrofits are costly and investor-owned utilities cannot claim "to-code" savings. The payback period is even longer for buildings that operate intermittently, like schools.

Considering these factors, the team conducted interviews with building-envelope industry experts including research labs, academia, and manufacturers. Many barriers center around market and consumer factors instead of technological difficulties; highly efficient technology already exists commercially. Synthesized findings fall into four categories of barriers across three technology areas.

- High costs
- Lack of customer awareness of benefits
- Manufacturer reliance on market pull
- Lack of stricter building energy codes

High Costs

Many high-efficiency technologies cost significantly more than standard building envelope technologies, for both new construction and retrofits. The added labor associated with performing retrofits can be especially high for older buildings. Additionally, older, less-efficient buildings are often owned or occupied by low-income populations that cannot afford retrofits.

Windows

The manufacturing process and materials involved in window construction are expensive. Windows are made up of many different components—like gas fills, spacers, and ultra-thin glass—that require unique manufacturing techniques to combine into the final insulated glass unit (IGU). As window technologies continue to evolve, manufacturing costs continue to affect the product prices. For example, tempering glass is a time- and cost-intensive manufacturing process. Finding alternatives to tempering could significantly bring down costs. High tempering costs are exacerbated as higher-performing IGUs require more panes of glass. In the future, cost savings could accrue through new developments in automated manufacturing.

Production volumes for emerging window technologies are often very low. This prevents cost reductions that would come from manufacturing economies of scale. For example, the electrochromic window market is primarily limited to the Class A office spaces, often in newer steel and glass constructions, where solar heat gain and glare control are important non-energy benefits. In many cases, it takes emerging technology developers years before they can even enter the low-rate production manufacturing stage. Demonstrated market pull is critical to persuading manufacturers to produce new technologies.

High installation costs for advanced window technologies hamper their broader adoption. Window installation costs, which vary greatly among installers, are labor-intensive and expensive. Variations in window technologies, from dynamic to highly insulating, create unique installation needs, especially for retrofits. Many highly insulating windows are thicker than the current installed windows they replace; window thickness and weight also add to both transportation and labor costs. The lack of high-performance "drop-in" replacement windows for the retrofit market also keeps costs high and reduces the impetus for development of automated installation practices.

Insulation

VIPs are expensive for several reasons. Their inner insulation is made of expensive insulating materials such as fumed silica or aerogel. Effectively vacuum sealing the panel around the inner insulation takes time, and if the casing tears, the whole panel must be replaced. Early stage research is in progress to develop self-healing vacuum seals to address this issue. The evacuation of air is the central aspect of this technology's performance. Currently, these vacuums can relax over time or perforate without visual detection, leading to concerns about the product's longevity. Moreover, VIP size cannot be adjusted once it is manufactured, so essentially each panel is custom-built and changes during construction are difficult, costly, or can reduce panel performance.

High R-value-per-inch insulation materials are very expensive to manufacture. Many consumers who would most benefit from thinner insulation, such as those living in manufactured homes or older buildings, cannot afford costly retrofits; this limits the market for insulation made from aerogels, which are costly to manufacture.

Reflective technologies for high-sloped roofs often require a full roof replacement, making them an especially expensive energy-efficient option. Most reflective roof technology is functional and accessible for low-sloped and flat roofs, which can be covered with reflective white-cap sheets that create a weatherproof seal. However, while low-sloped roofs can be repaired, high-sloped roofs are often made of asphalt-based shingles, which are lighter and cheaper than other materials. High-sloped roofs are not built to sustain heavier materials, so retrofitting those roofs would require shingles of similar weight and construction.

Air Sealing

The sealant material used in whole-building automated air sealing is expensive. Even though this method requires less labor than spot-sealing approaches, the material is a high-cost product.

Conversely, spot-sealing methods are inefficient and time-consuming, resulting in high labor costs and envelopes that may remain poorly sealed when compared with the performance of automated air sealing.

Lack of Customer Awareness of Benefits

Without greater consumer awareness of these technologies' energy benefits, further market penetration will be slow for these high-efficiency products.

Cross-Cutting

Building owners, particularly for tenant-occupied buildings, use upfront costs as a primary deciding factor so they often don't view advanced windows or building envelope technologies as viable options when compared with baseline products. Once these products come down in price, shifting the purchasing lens to return on investment instead of short-term cost, these consumers are more likely to see their energy-saving benefits.

Windows

Contractors are often unaware of the benefits of these products since information about many high-efficiency windows has not been widely publicized in industry literature. Providing accessible and easy-to-understand information on the latest energy-efficiency trends in window technology is crucial in the effort to keep both consumers and contractors informed. This knowledge can increase selection of more efficient window technologies over time.

Many energy-modeling platforms are not equipped to accurately depict newer glass technologies. This precludes building designers from uncovering and demonstrating the real energy savings from these emerging technologies. Accurately predicting savings through modeling is a key impetus for broader adoption of the technology. Software tools designed by the Lawrence Berkeley National Laboratory both rates windows in the National Fenestration Rating Council database and designs more efficient windows. These tools are also used in the Passive House community. Building designers use an array of software to model window characteristics including WINDOW, THERM, Radiance, Optics, COMFEN, RESFEN, and EnergyPlus. As new window technologies are developed, it will be important to keep up with ways to promote these technologies for inclusion in software. For example, since there are no current methods for evaluating vacuum glazing, software tools are being developed to further evaluate and maximize their performance. Similarly, only a handful of new building-modeling applications currently include electrochromic windows as a technology option. These barriers to supporting and developing new technology features have caused the benefits of certain niche or emerging window technologies to be overlooked. Therefore, expanding modeling capabilities to include all commercially available and emerging technology is critical and will greatly increase their acceptance.

Air Sealing

Many consumers are unaware that their building leaks in the first place, let alone that they could reap many benefits from proper sealing. Unfortunately, there is no comparable test to the blower-door test for large commercial buildings. Without a reliable testing method, building owners and managers cannot fully understand the air infiltration properties of their buildings.

Manufacturer Reliance on Market Pull

Innovation takes investment, and manufacturers do not yet see enough financial reward to take on the risk of investing in emerging energy-efficient window technologies.

Windows

Without demonstrated market pull, emerging technology developers struggle to influence the manufacturers that produce them. It is time- and cost-intensive for developers to convince both consumers and manufacturers of the viability of these emerging energy-efficient products, so addressing this information gap will encourage both more rapid development and greater acceptance of more efficient windows.

Insulation

Manufacturers are unwilling to invest in scaling production without demonstrated market pull, so without the economies of scale technologies like aerogel insulation will continue to be expensive.

Air Sealing

Whole building air sealing is a new technology that faces barriers in the retrofit space. Though incentives exist for consumers to better seal their buildings through government and utility weatherization programs, obstacles to whole-building air sealing have prevented manufacturers from developing advanced products for retrofits.

Lack of Stricter Energy Codes

Energy codes do not require very high efficiency envelope measures to achieve current baseline performance. Adopting stricter codes would unquestionably generate energy savings, but the market must be able to provide needed compliant products.

Windows

Building codes do not require high R-value or dynamic window technologies in either new or retrofit applications for both the residential and commercial sectors. The high cost of high-efficiency products must be addressed before the performance floor can be raised. Otherwise, the new technologies' high cost will up-end the industry.

Insulation

Manufactured housing is regulated by the United States Department of Housing and Urban Development (HUD), which has less stringent insulation requirements than California's Title 24. If manufactured housing becomes part of the solution to the state's affordable housing crisis, this market may quickly expand.

Air Sealing

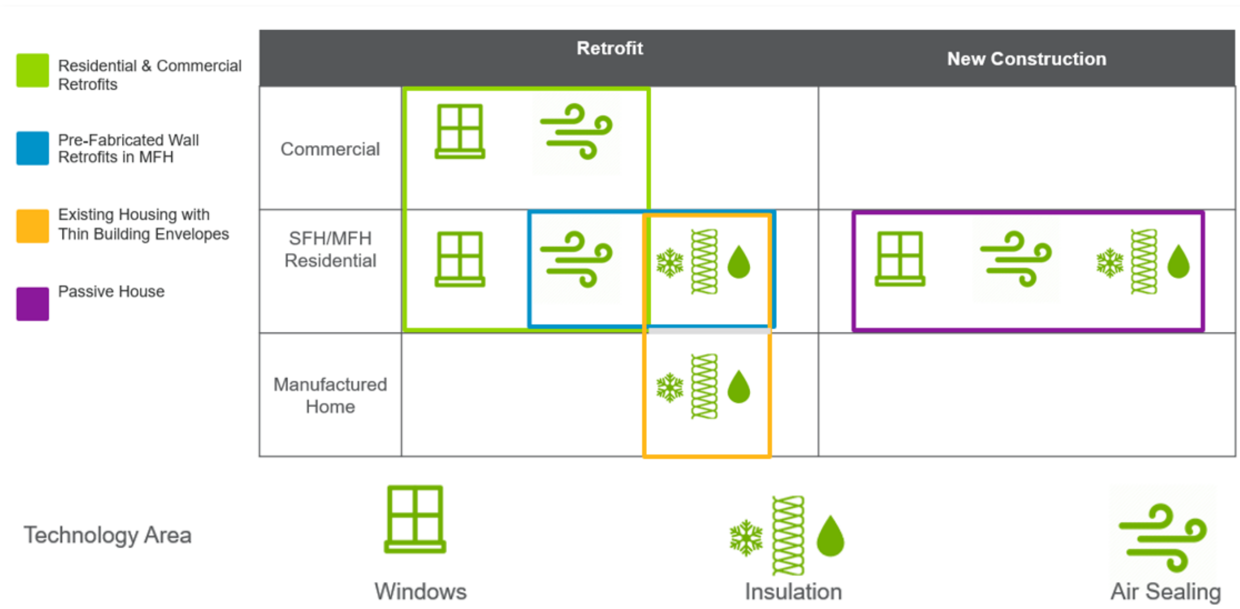
International Energy Conservation Code® (IECC) building energy codes do not require air tightness below 3 ACH50, and there is no enforcement mechanism to bring existing buildings into compliance because, until recently, there hasn't been a way to install comprehensive air sealing.

CHAPTER 4: Market Opportunities for Windows and Building Envelope Systems

After interviewing building-envelope industry experts, the team identified four major market opportunities. This list does not cover all possible market opportunities but rather highlights the most promising ones. These opportunities include markets for all three technology areas and are shown in Figure 3:

- Residential and Commercial Retrofits
- Passive Houses
- Prefabricated Wall Retrofits in Multifamily Housing
- Existing Housing With Thin Building Envelopes

Figure 3: California Opportunity Markets



This graphic depicts the way that the opportunity markets cut across the different technologies, building types, and building vintages.

Source: Guidehouse.

Residential and Commercial Retrofits

Many high-efficiency window and air sealing technologies are not currently realized as retrofit applications but could still generate significant energy savings in this market.

Windows

Thermochromic windows can be easily installed in existing buildings but face high costs and a lack of consumer awareness of their energy-saving benefits.

Electrochromic windows need a solution to the electric wiring requirement, such as integrated energy storage, to make them viable for retrofits. This would eliminate the added labor cost of hiring electricians.

Air Sealing

Whole-building automated air sealing in existing residential buildings can generate high energy savings. Current retrofit applications require extensive preparation, so this method only currently applies to new construction.

Air sealing existing commercial buildings can provide significant energy savings. Currently, however, commercial retrofits require extensive time and labor, which discourages air sealing beyond minimum code requirements. In order to take advantage of whole-building automated air sealing, an infiltration testing technology similar to the blower-door test, would also be required. The significant time that retrofits require is also a barrier to commercial building owners and managers interested in improving their buildings' air sealing.

Passive Houses

Passive House construction focuses on designing buildings that require little supplemental heating or cooling to provide year-round comfort. Passive House designers optimize performance through superinsulation, air-sealing, passive heating (solar gain), and effective ventilation. This community welcomes high-performance technologies that contribute to Passive House performance goals and awards Passive House certifications and accreditations to support them.

Windows

The Passive House community exemplifies the impact that codes and standards can have on product integration into the residential sector. High-performance window adoption is growing in the multifamily space thanks to municipal code changes that drive stakeholders to build to similar passive-energy standards.

Insulation

The Passive House community provides an excellent market opportunity for high-performance insulation technologies to gain market share and exposure. In addition to increasing building energy efficiency, higher performing insulation contributes to the Passive House goal of reducing noise.

Air Sealing

Passive House construction features air-sealing as part of a building's energy efficiency and temperature and moisture control. Passive House also has goals that reduce drafts and the infiltration of outdoor air pollutants, achieved through tight building envelopes.

Prefabricated Wall Retrofits

Energiesprong, a European retrofit initiative, organizes various suppliers and contractors to outfit multifamily housing with over-the-current-wall improvements with minimal intrusion on the home occupant. In North America, there are currently limited options for this approach, though high energy-savings potential exists in multifamily housing if this model were eventually realized. This approach would require engaging manufacturers to increase the availability of products and coordinating with contractors and building owners to finance and conduct these retrofits.

Insulation

Relatively few manufacturers in North America provide this type of add-on building envelope retrofit. One of the primary barriers is the requirement that each project be custom built.

Air Sealing

Improved air sealing without vacating buildings would be of tremendous benefit to the prefabricated wall approach. The need to vacate the building during sealing is a barrier for both residents and building owners.

Existing Housing with Thin Building Envelopes

Many older residential buildings have thinner building envelopes than standard new construction.

Insulation

Thin envelopes do not have the necessary space to install additional insulation over the existing insulation, as would typically be done. Manufactured homes are generally not as energy efficient as more permanent construction in many respects. These homes often use thinner framing and are occupied by lower-income residents, so this market would certainly benefit from lower-cost, high R-value-per-inch insulation.

Other Opportunity Markets

Guidehouse most thoroughly studied the preceding opportunity markets. Three additional markets of interest are commercial retrofits, new construction across sectors, and manufactured housing.

Commercial Retrofits

Commercial retrofits can be costly and time consuming. Additionally, many commercial building owners and operators cannot afford to have their buildings out of service for long periods of time, so retrofit technologies must have shorter install times than they would in residential applications. While residential buildings have the option of whole-home automated air sealing, larger commercial buildings do not yet have a comparable option.

New Construction

New construction could realize greater energy savings by committing to greater standardization. This includes SIPs and other forms of modular construction. Additionally, new construction of large commercial buildings does not currently have a method to test overall air infiltration the way a blower door test does for smaller buildings.

Manufactured Housing

While many of the efficient technologies profiled would be technically feasible for use in manufactured housing, the high costs are especially limiting in this sector, which generally serves a lower-income population. Manufactured housing has a low window-to-floor ratio of only 12 percent, which makes window improvements less cost-effective than in other buildings. The relatively short lifetime of manufactured housing also reduces the likelihood of retrofits in the first place; while more permanent structures may endure for hundreds of years, these homes may last only 30 years. The manufactured housing industry would more likely benefit from new technologies that could be integrated into the factory construction process. SIPs, spray foams, and radiant barriers could enter the market in that way. New technologies still face barriers to widespread adoption at this stage, but if wider implementation generated cost savings in the construction process, greater adoption could follow. The only existing incentive for more efficient manufactured homes is the ENERGY STAR certification program that still covers less than half of today's market.

CHAPTER 5: Research Recommendations

Due to the complicated influence that window and building envelope systems have on a building's HVAC energy consumption, the research team conducted a simplified modeling exercise to estimate energy savings from each of the technologies studied in this project. The results for a single-family two-story home provided the foundation upon which research recommendations were developed.

Modeling

To determine the energy benefit of the technologies described in this report, the research team used BEopt™ (Building Energy Optimization Tool), a software tool developed by the National Renewable Energy Lab. BEopt™ is a graphic user interface for the EnergyPlus software, which models a building's annual energy consumption. BEopt™ requires existing home and model design parameters to simulate a building's energy use. For existing home parameters, the team used a prototypical two-story home with parameters based on National Institute of Standards and Technology (NIST) suggested values, which are explained in the following Prototypical Home section.

The same baseline model was used for each simulation. To test energy savings from a new technology, the team modified the technology's parameter(s) in the baseline file (creating the model design file), then simulated its annual energy use. That annual energy use was then compared with the baseline model's energy use. This process was repeated for four window scenarios, six insulation scenarios, and three air-sealing scenarios.

The team modeled each scenario for California climate zones 3 and 13: a coastal climate zone and a central valley climate zone, respectively. The objective was to compare the effects of differing climates on building energy consumption, specifically on heating and cooling loads, from installing high-performance window and envelope technologies.

Climate Zones

Climate zone 3 (CZ3) is a coastal climate zone that includes San Francisco and Oakland. These areas have year-round moderate temperatures with winter precipitation and coastal fog during the summer months. Areas further inland have less fog and wind but higher summer heat. Climatic design priorities include insulation, reduced infiltration, passive solar in the winter, and shade and natural ventilation in the summer. CZ3 is a heating-dominated climate zone, but the climate is mild enough that overall energy consumption is relatively low when compared with other California regions.

Climate zone 13 (CZ13) is a central valley climate zone and includes Fresno. This climate zone has ideal weather conditions for farming – abundant sunlight and higher summer humidity than other central valley areas, resulting in high air-conditioning energy consumption. CZ13 has rainfall between November and April and a very cold winter, with north winds that can blow for several days at a time. There is also extremely thick low fog, called Tule fog, in the winter. This region has both high heating and cooling loads, with almost as many coolingdegree days as heating-degree days. These weather profile calls for increased insulation, reduced infiltration, passive solar in the winter, and shade and cooling in the summer.

Overall, the heating loads are similar in both climate zones, with CZ3 being slightly higher. However, the cooling load in CZ13 is significantly higher than in CZ3.

Prototypical Home for Baseline

The team used the NIST Prototype Residential Buildings for Energy and Sustainability Assessment guidelines to create the prototypical two-story single-family home used in the BEopt™ simulations. The prototypical home is based on the 2009 IECC code and aligns with parameters in BEopt™, making it a suitable reference for the analysis. Table 10 shows the parameters used.

Table 10: Prototypical Home Parameters

Technology	BEopt™ Parameters
Walls	Wood Stud: R-19 Fiberglass Batt, 2x6, 16-inch
Ceilings/Roof	Ceiling: R-30 Cellulose, Vented Roof: Asphalt Shingles, Medium
Foundation/Floors	Slab: Uninsulated Carpet: 40%
Windows and Doors	Window Area: 15% of conditioned floor space. Two 4 ft. high windows on each side of the house for each floor (16 total). Width is based on fraction of total wall area represented by each side. Window: Low-E, double pane, non-metal, air, L-gain Door Area: 40 ft^2 Doors: Wood Eaves: 1 ft. overhang
Airflow	Air Leakage: 3 ACH50 Mechanical Ventilation: 2010 exhaust, 50 ft^3/min
Space Conditioning	Central AC: SEER 13 Room AC: None Furnace: Gas Furnace AFUE 78% Ducts: No leakage because ductwork is assumed to be within the conditioned space, which leads to zero energy loss from the ductwork.
Space Conditioning Schedules	Cooling Set Point: 75 degrees Fahrenheit Heating Set Point: 72 degrees Fahrenheit

Source: Guidehouse.

Windows

The baseline window used in the prototypical home is a double-pane, low-E window with U-factor of 0.37 (R-2.70) and SHGC of 0.30. BEopt™ required, for performance metrics, the number of panes, U-factor, SHGC, and the frame material to simulate window technology in the model. Emerging technologies that do not have one or more of those metrics cannot be modeled, so the team sought alternate resources, such as published academic or industry research, to estimate energy savings from those technologies.

The analysis was also limited to the effects of U-factor, SHGC, number of panes, and frame material because there was no way to test additional parameters (like V_T) in the model. Electrochromic and thermochromic windows were also excluded from the analysis because of their dynamic properties. The research team instead leveraged existing studies to measure the thermal performance of these dynamic window technologies in residential buildings.

The team modeled three unique window technologies with varying performance metrics to more accurately estimate their effects on single-family home energy consumption in California. Table 11 lists the window technology scenarios modeled and their performance metrics.

Table 11: Window Model Run Parameters

Window Technology	U-Factor	SHGC
Baseline: Double Glazing Low-E Classic Window	0.37	0.30
Highly Insulating Window (casement)	0.14	0.13
Highly Insulating Window (fixed)	0.10	0.15
Triple Pane Low-E Window – Higher SHGC	0.18	0.40
Triple Pane Low-E Window – Lower SHGC	0.17	0.27

Source: Guidehouse.

Insulation

The baseline insulation used in the model was R-19 Fiberglass Batt. BEopt™ requires R-value, cavity space, framing space, and framing factor as inputs to simulate insulation technology in the model. The analysis was limited to the effects of R-value, radiant barriers, and insulation type. For emerging technologies, such as PCM insulation, modeling was not an option, so the team sought alternate resources to estimate energy savings for those technologies.

The team modeled six unique insulation technologies with varying performance metrics to determine their effects on single-family home energy consumption in California. Table 12 lists the insulation technology scenarios modeled and their performance metrics.

Table 12: Insulation Model Run Parameters

Insulation Technology	R-value	Radiant Barrier	Insulation Type
Baseline: Fiberglass Batts	19	N	Fiberglass Batt
Insulation Structural Insulated Panel (SIP)	31	N	SIP
Insulation Closed Cell Spray Foam	36	N	Closed Cell Spray Foam
Insulation Rigid Foam Board	34	N	Extruded Polystyrene Board
Insulation Aerogel	29	N	Aerogel Blanket
Insulation Vacuum Insulated Panel (VIP)	60	N	Vacuum Insulated Panel Board
Radiant Barrier	19	Y	Radiant Barrier

Source: Guidehouse.

Air Sealing

Air sealing is measured on a whole-home basis in BEopt™. The team modeled four air-sealing scenarios in BEopt™ to more thoroughly understand the effects of building-envelope air tightness on single family home energy consumption in California. Table 13 lists the insulation technology scenarios modeled and their performance metrics.

Table 13: Air-Sealing Modeling Parameters

Air-Sealing Technology	ACH50
Baseline: IECC Most Stringent Requirement	3
Automated Whole Building Air Sealing	1
Spot Foam/Sill Gasket/Use of Rigid Foam Board Insulation	2
IECC Least Stringent Requirement	5

Source: Guidehouse.

Results

The results of the modeling simulation show the heating and cooling load savings after installing high-performance technologies in residential homes in two California climate zones. These upgrades save up to 38 percent in heating and 20 percent in cooling energy (not from the same technology and climate zone), which amount to only $100 on an annual gas bill and $60 on an annual electricity bill. These costly retrofits would make for a long payback period, which discourages homeowners from making them.

Windows

The results highlight the difference between residential casement and fixed windows and varying SHGC. The results from the model window technologies are shown in both Table 14 and Table 15.

In CZ3, both casement and fixed HIWs provide significant heating and cooling savings when compared with the baseline. The cooling savings are magnified, however, because the baseline cooling load is not very high – only 68 kWh for the whole year. Therefore, even a small change in energy consumption results in a larger percent of savings though the cost savings remain small. Because CZ3 is a heating-dominated climate, the percent savings for the heating load are significant.

The triple-pane low-E window is highly insulating and saves a lot of energy in heating-dominated regions. However, it also prevents heat from leaving the home. Triple-pane low-E windows still provide energy benefits in this region because the insulative properties reduce heat loss in the winter.

The cost analysis shows the greatest savings from reduced-heating and minimal-cooling cost savings. Triple-pane windows do not have a high enough R-value to reduce cooling load in this climate zone, which has a very low cooling load to begin with. Nevertheless, the highest-cost savings in this climate zone are achieved by the triple pane window with a high SHGC. CZ3 is a moderate, heating-dominated climate in which passive solar is recommended to boost heating savings. While the highly insulating window technologies analyzed (with higher R-value and lower SHGC) provided both heating and cooling savings, the heating savings from windows with high SHGC provided the greater cost savings.

The highly insulating windows, both casement and fixed, are especially beneficial in this climate because they trap the heat in the cold winters with their highly insulating properties and reduce the cooling load in the summer due to low SHGC. The triple-pane low-E windows provide higher heating savings due to higher SHGCs than the baseline, which provides a passive solar heating boost. This higher SHGC also creates heat gain inside the house that increases the summer cooling load. Triple-pane windows, with their higher SHGC, would not be the best fit for this climate zone. The cost analysis supports these conclusions; although the electricity savings are minimal, low SHGC is important in this climate zone to lower cooling loads.

Overall, annual energy cost savings from high performance windows make it difficult to justify their installation costs. Communicating the best window type for buildings, based on their climate zones is critical to determine the highest payback.

Table 14: Climate Zone 3 Window Modeling Results

Window Technology	Performance Metrics	Heating Consumption (Therms/Year)	Heating Percent Savings	Heating Cost Savings/ Year	Cooling Consumption (kWh/Year)	Cooling Percent Savings	Cooling Cost Savings/ Year
Baseline: Double Glazing Low-E Classic Window	R-2.70 SHGC 0.30	210	—	—	68	—	—
Highly Insulating Window (casement)	R-7.14 SHGC 0.13	189	10%	$24.63	24	64%	$7.29
Highly Insulating Window (fixed)	R-10 SHGC 0.15	169	20%	$48.91	36	47%	$5.35
Triple-Pane Low-E Window – Higher SHGC	R-5.56 SHGC 0.40	133	37%	$92.23	159	NA	NA
Triple-Pane Low-E Window – Lower SHGC	R-5.88 SHGC 0.27	159	24%	$61.17	83	NA	NA

***Negative energy savings are shown as 'NA' because these scenarios do not accurately reflect resident behavior. Faced with a need for increased cooling, residents are likely to simply open windows to release heat through natural ventilation.**

Source: Guidehouse Modeling

Table 15: Climate Zone 13 Window Modeling Results

Window Technology	Performance Metrics	Heating Consumption (Therms/Year)	Heating Percent Savings	Heating Cost Savings/ YearError! Bookmark not defined.	Cooling Consumption (kWh/Year)	Cooling Percent Savings	Cooling Cost Savings/ Year
Baseline: Double Glazing Low-E Classic Window	R-2.70 SHGC 0.30	193	—	—	1788	—	—
Highly Insulating Window (casement)	R-7.14 SHGC 0.13	170	12%	$26.47	1428	20%	$59.69
Highly Insulating Window (fixed)	R-10 SHGC 0.15	156	19%	$43.60	1477	17%	$51.56
Triple-Pane Low-E Window – Higher SHGC	R-5.56 SHGC 0.40	136	29%	$66.81	2025	NA	NA
Triple-Pane Low-E Window – Lower SHGC	R-5.88 SHGC 0.27	153	21%	$47.17	1738	3%	$8.29

Source: Guidehouse Modeling

Insulation

The insulation results do not show a simple correlation between increasing R-value and increasing energy savings. For example, closed cell spray foam with an R-value of 36 results in a higher heating load than a SIP with an R-value of 31. This may reflect the qualities of SIPs, which are manufactured and can be standardized in the factory to prevent thermal bridging in a way that onsite assembly may not achieve. The results from the model runs for insulation technologies are shown in Table 16 and Table 17.

Table 16: Climate Zone 3 Insulation Modeling Results

Insulation Technology	Relevant Performance Metric	Heating Consumption (Therms/Year)	Heating Percent Savings	Cooling Consumption (kWh/Year)	Cooling Percent Savings
Baseline: Fiberglass Batts	R-19	210	—	68	—
SIP	R-31	172	18%	77	NA
Closed Cell Spray Foam	R-36	178	15%	77	NA
Rigid Foam Board	R-34	159	24%	83	NA
Aerogel Insulation	R-29	169	20%	80	NA
VIP	R-60	130	38%	104	NA
Radiant Barrier	Has Radiant Barrier	211	0%	56	17%

Source: Guidehouse Modeling

Table 17: Climate Zone 13 Insulation Modeling Results

Insulation Technology	Relevant Performance Metric	Heating Consumption (Therms/Year)	Heating Percent Savings	Cooling Consumption (kWh/Year)	Cooling Percent Savings
Baseline: Fiberglass Batts	R-19	193	—	1788	—
SIP	R-31	163	15%	1750	2%
Closed Cell Spray Foam	R-36	168	13%	1759	2%
Rigid Foam Board	R-34	153	21%	1741	3%
Aerogel Insulation	R-29	161	17%	1750	2%
VIP	R-60	130	33%	1732	3%
Radiant Barrier	Has Radiant Barrier	192	0%	1738	3%

Source: Guidehouse Modeling.

Only the radiant barrier did not produce savings in heating energy in CZ3. In contrast to other technologies, radiant barriers reject heat absorption, resulting in heating loads slightly more than the baseline.

CZ13 has larger cooling needs than CZ3 so there are greater cooling savings available from the modeled insulation technologies. Comparing the heating results from CZ3 to the results of CZ13, there are lower savings in heating consumption in CZ13. This is because CZ13 is a warmer climate with lower overall heating needs.

Air Sealing

In the four scenarios that the team modeled, automated whole building air sealing resulted in the most energy savings in both climate zones for heating. The results from the model runs for insulation technologies are shown in Table 18 and Table 19.

Table 18: Climate Zone 3 Air-Sealing Modeling Results

Air Sealing	ACH50	Heating Consumption (Therms/Year)	Heating Percent Savings	Cooling Consumption (kWh/Year)	Cooling Percent Savings
Baseline: IECC Most Stringent Requirement	3	210	—	68	—
Automated Whole Building Air Sealing	1	192	9%	77	NA
Spot Foam/Sill Gasket/Use of Rigid Foam Board Insulation	2	199	5%	74	NA
IECC Least Stringent Requirement	5	229	NA	62	NA

Source: Guidehouse Modeling.

Table 19: Climate Zone 13 Air Sealing Modeling Results

Air Sealing	ACH50	Heating Consumption (Therms/Year)	Heating Percent Savings	Cooling Consumption (kWh/Year)	Cooling Percent Savings
Baseline: IECC Most Stringent Requirement	3	193	—	1788	—
Automated Whole-Building Air Sealing	1	181	6%	1773	1%
Spot Foam/Sill Gasket/Use of Rigid Foam Board Insulation	2	186	4%	1779	NA
IECC Least Stringent Requirement	5	207	NA	1809	NA

Source: Guidehouse Modeling.

In CZ3, both more efficient scenarios generated energy savings of less than 10 percent. Similar to insulation results, cooling consumption slightly increased in CZ3 with more efficient air-sealing technologies though the overall consumption remained low.

In CZ13, both more-efficient technologies also generated heating savings of under 10 percent, with automated whole-building air sealing delivering the greatest savings. While cooling consumption also slightly decreased, the savings were negligible.

While the results of modeling in both climate zones represent less than 10 percent energy savings for any scenario, these results are compared to the baseline, which is set at the most stringent new construction standard of 3 ACH50. Existing California homes may not be up to the new construction standards, so additional energy savings could be captured by increasing the air tightness of these homes to 3 ACH50 or greater.

Performance Metrics

Guidehouse compiled the performance metrics for each technology and developed research targets for over the next five years.

Windows

Current and target performance metrics and costs for windows appear in Table 20. Many high-performance window technologies are commercially available yet still not widely adopted. The 2025 performance and cost targets compiled below involve increasing V_T while maintaining highly insulative properties and reducing installation costs. Electrochromic and thermochromic technologies do not have major RD&D needs other than cost reduction since wider adoption of these technologies is primarily dependent upon lower cost.

Insulation

Current and target performance metrics, including costs for the insulation technologies studied, are shown in Table 21. Ultra-low thermal-conductivity targets are generally set so that all building types can achieve at least R-12 per inch for the entire wall structure. Technologies that already meet this goal were not assigned performance targets. PCMs and some of the reflective technologies similarly do not have performance metrics targets since their main barriers are high cost and applicability, not performance. Additional research is needed to apply reflective roof coatings to all roof types. Microencapsulated PCMs already significantly reduce heating and cooling energy use but have a wide range of costs. Reducing the cost of microencapsulated PCMs could greatly reduce heating and cooling energy use in the commercial sector.

Air Sealing

Current and target performance metrics including costs for the examined air-sealing technologies are outlined in Table 22. Air tightness is an important metric for energy savings. Results of less than 1 ACH50 are already possible with some of the technologies listed, so no target ACH50 values are listed. For air sealing, the challenge is reducing the cost of more advanced processes, rather than improving the performance of those processes. The TRL value of all but automated whole-building air sealing is already at level 9, so no research is recommended for the three other technologies.

Table 20: Window Performance Metric Table

Technology	Applicable Building Type	Energy Savings	Current Perfor-mance	2025 Target Perfor-mance	Current TRL	2025 Target TRL	Current Cost	2025 Target Cost
Highly Insulating Window (casement)	Operable windows in all residential applications	Heating: 0-12% Cooling: 0-64%	R-7.14 V_t 0.26	R-10 with V_t 0.40	9	9	Installed Cost: $55+/ft^2	Res: cost premium ≤$6/ft^2 Com: cost premium ≤$3/ft^2 compared to 2010 base window***
Highly Insulating Window (fixed)	Fixed windows in all residential and commercial applications	Heating: 0-20% Cooling: 0-47%	R-10 V_t 0.30	R-10 with V_t 0.40	9	9	Installed Cost: $55+/ft^2	Res: cost premium ≤$6/ft^2 Com: cost premium ≤$3/ft^2 compared to 2010 base window***
Vacuum Insulated Glass	Large office	Unreleased	R-12 (center of glass)	Unreleased	8	9	Installed Cost: $66+/ft^2	Cost premium $8/ ft^2 compared to double pane
Triple-Pane Low-E window	Fixed and operable windows in commercial and residential	Heating: 0-37% Cooling: NA	R-5.88 V_t between 0.30 and 0.70	R-10 with V_t 0.60	9	9	~$24/ft^2*	Price Reduction
Skinny Triple-Pane Window	Retrofit applications in both residential and commercial applications	Heating: 0-16% Cooling: 0-7	R-8 to R-10	Unreleased	8	9	NA	Cost premium $6-$8/ft^2 compared to double pane
Thermochromic Window	Applicable except where controlled or fixed V_T is desired for natural light or views	0-30% building savings*	R-4.17 V_t between 0.10 and 0.50	NA	9	9	Installed Cost ~$40+/ft^2*	Cost premium ≤$2/ft^2 compared to double pane***

Technology	Applicable Building Type	Energy Savings	Current Perfor-mance	2025 Target Perfor-mance	Current TRL	2025 Target TRL	Current Cost	2025 Target Cost
Electrochromic Window	Fixed windows in commercial applications	0-20% whole building savings**	R-3.45 V_t varies	NA	9	9	Installed Cost: $60+/ft^2*	Cost premium ≤$8/ft^2 compared to double pane***

***Department of Energy: Suntuitive Sunlight-Responsive Thermochromic Window Systems.**
****SageGlass.**
*****DOE Roadmap for Emerging Technologies.**
†Hart.

Source: Guidehouse.

Table 21: Insulation Performance Metrics

Technolo gy	Applicable Building Type	Installation Approach	Energy Savings	Current Perfor-mance	2025 Target Perfor-mance	Current TRL	2025 Target TRL	Current Cost	2025 Target Cost
SIPs	New construction low-rise wood-framed residential and commercial buildings	Whole wall	Heating: 15-18% Cooling: 0-2%	R-24 – R-50 (depending on thickness)	—	9	—	$6+/ft^2$	<$6/ft^2$
Closed Cell Spray Foam	Can be used in all buildings	Added to other insulation, pre-existing insulation, or fill wall cavities	Heating: 13-15% Cooling: 0-2%	R-7/inch	R12/inch	9	—	$1.30/ft^2$	<$1.17 /ft^2$
Rigid Foam Board	Can be used in all building types	Can be added onto other insulation, existing insulation, or stacked	Heating: 21-24% Cooling: 0-3%	R-6/inch	R12/inch	9	—	$0.92/ft^2$	$0.87 /ft^2$
Aerogel Blanket	Can be used in all building types	Can be added onto other insulation, existing insulation, or stacked	Heating: 17-20% Cooling: 0-2%	R-10.3/inch	R12/inch	7	9	$6/ft^2$	$5/ft^2$
VIPs	Can be used in all building types	Can be used with other insulation, but is unavailable for retrofits	Heating: 33-38% Cooling: 0-3%	R-60 (0.94-inch panel)	—	7	9	$7/ft^2$	$6/ft^2$
PCM Blanket	Can be used in all building types	Walls/ceilings	Heating: 25-35% Cooling: 25-35%*	Thermal Storage: 110 Btu/ ft^2 of blanket	—	8	9	$2.55-3.75/ft^2 (MSRP)	$2/ft^2$

Technology	Applicable Building Type	Installation Approach	Energy Savings	Current Perfor-mance	2025 Target Perfor-mance	Current TRL	2025 Target TRL	Current Cost	2025 Target Cost
Micro-encapsulated PCM in Masonry	New construction masonry buildings	Within structural materials	Heating: 8-25% Cooling: 53-99%†	Thermal Storage: 82-95 Btu/lb	—	6	9	$1.50-7.50/lb of material	Tighter Range: $1.50-$4/lb of material
Reflective Roof Coating	All buildings with low-sloped roofs	Coating on top of the roof	Heating and Cooling: 17-33%‡	Solar Reflectance: 0.95	Applicable to High-sloped Roofs	9	—	$110/ gallon	$100/ gallon
Radiant Barrier	Can be used in all building types	Installed in the attic	Heating: NA Cooling: 3-17%	Solar Reflectance: 0.97	—	9	—	$0.20/ ft^2	—
Foil Insulation	Can be used in all building types	Similar to radiant barrier, but can be used in tandem with insulation	Heating: NA Cooling: 3-17%**	Solar Reflectance: 0.96	—	9	—	$0.42/ ft^2	—

***Phase Change Energy Solutions.**
†Thiele.
‡Levinson.
****Conservative estimate based on radiant barrier.**

Source: Guidehouse.

Table 22: Air Sealing Performance Metrics

Technology	Building Type	Energy Savings	Current ACH50	2025 Target ACH50	Current TRL	2025 Target TRL	Current Cost	2025 Target Cost
Automated Whole Building Air Sealing	All residential and commercial buildings where a blower door test is feasible	Heating: 6-9% Cooling: 0-1%	As low as 0.6	—	7	9	\$1.50-4.50 per ft^2 of floor space	\$1.00 per ft^2 of floor space
Spot Foam	Can be used in all building types	Heating: 4-5% Cooling: NA	Whole building performance is not guaranteed	—	9	—	\$13.34 per can	—
Sill Gasket	Can be used in all building types	Heating: 4-5% Cooling: NA	Whole building performance is not guaranteed	—	9	—	\$7.50 per 50-foot roll	—
Use of Rigid Foam Board Insulation	Can be used in all building types	Heating: 4-5% Cooling: NA	Whole building performance is not guaranteed	—	9	—	\$0.92 per ft^2 of insulation	—

Source: Guidehouse.

Research Recommendations

This section describes recommended RD&D initiatives that the CEC could pursue to address the current technical and market barriers to broader installation of high-efficiency residential and commercial windows and building envelopes. Each of these initiatives would further California's mandated energy-efficiency goals, but some would have more significant impacts by affecting building envelope categories or critical opportunities where high-efficiency options are neither available nor cost-effective today.

Prioritization Methodology

The team developed a set of recommended RD&D initiatives to address these challenges in Chapter 3. The team then first evaluated each initiative based on its impact and feasibility, then each initiative relative to the entire list. Figure 4**Error! Reference source not found.** summarizes the scoring for this prioritization criteria. The team scored each recommendation on a relative 1-5 scale for the following criteria to identify those with the greatest energy efficiency impacts for California buildings:

- Impact: The potential to address key barriers
- Cost Feasibility: The potential to improve cost effectiveness
- Technical Feasibility: The potential for performance advancement

Each of these received a 20-percent weighting. The team also scored each recommendation on a relative 1-5 scale for GHG-emission reduction potential, which received a 40-percent weighting. These scores make up the final priority score. The team also scored each recommendation on a relative 1-5 scale for "Fit with CEC Mission" to identify initiatives that best aligned with the scope, goals, and capabilities of CEC projects.

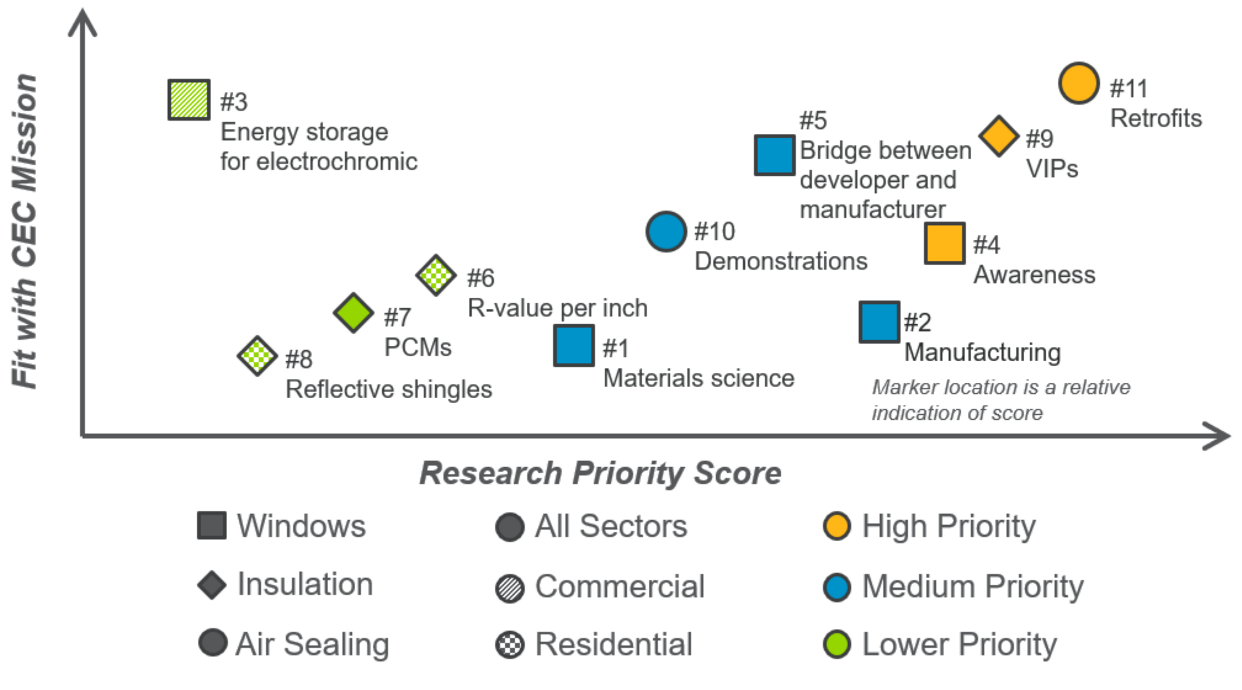
Figure 4: Research Priority Criteria

Source: Guidehouse

The team designated high, medium, or lower priorities for each initiative based on fit with CEC mission, final priority score, and priority for statewide goals, explained in more detail here.

- High-priority initiatives focus on directly addressing known barriers and have high GHG-emission reduction potential.
- Medium-priority initiatives include material and manufacturing process research activities and initiatives for creating market pull with various impacts on known barriers.
- Low-priority initiatives include product development activities that are important but are less aligned with project goals. These initiatives may be led by other state organizations and industry stakeholders in the future.

Figure 5: Research, Development, and Demonstration Initiative Prioritization



Source: Guidehouse

This study recommends the following RD&D initiatives for each of the three technology areas - windows, insulation, and air sealing.

Windows

Windows can significantly reduce heating and cooling loads in both residential and commercial buildings. The retrofit market is larger than the new construction market, but cost to consumers is a major barrier for broader adoption of new, often costly, technologies. It is also critical that window design metrics best serve target climate zones, through activities described here in detail.

1. Conduct materials science research to further improve window performance. New materials such as phase-change materials, aerogel, and low-e coatings should continue to be researched to more effectively target window performance in specific climate zones. For example, thermochromic windows can provide energy savings in climate zones with both high-cooling and high-heating loads, found in California climate zones 9, 10, 11, and 13, and **Error! Bookmark not defined.**, but may not be well-suited to climates that are either heating- or cooling-dominated.
2. Research ways to modify glass so that it does not require tempering. Tempered glass is more flexible and doesn't shatter into large shards, so building codes require tempering under certain criteria for safety reasons. However, the tempering process is expensive and increases production time. Costs are around $25/ft^2 for tempered glass as opposed to $5-$6/ft^2 for plate glass. When installed into their frames, tempered glass windows remain three times more expensive than non-tempered windows. Many customers seek cheaper alternatives to tempered glass such as safety window films. Researching synergies between these safety films and the properties of tempered glass could open new research avenues to help reduce costs.

3. Research ways to integrate energy storage into electrochromic windows, which could remove the need for wiring and increase acceptance of this technology in the retrofit market. This technology's unique labor requirement means that electrochromic windows are not as flexible for retrofits as thermochromic windows, which can be installed like any other IGU. Electrochromic windows consume less than 60 watts per 1,500 ft^2 of window. There is also ongoing research into incorporating solar photovoltaic (PV) technology into windows, so perhaps PV plus a storage solution could be a viable technology. It is unclear if the increased cost of integrated energy storage would be offset by the installation cost savings, but this would expand the retrofit market for this technology.
4. Increase awareness of the benefits of dynamic windows to customers. Multiple industry experts have recommended that technology demonstrations be conducted to inform customers, especially in the residential sector, of the benefits of high-performance windows. Information on qualified installation contractors would also help accelerate the adoption process of this advanced technology. Contractors would also benefit from an online knowledge-sharing platform where relevant case studies and best practices could be shared. Finally, building designers and other industry players using building energy models would benefit from clear representations of the energy savings that dynamic windows provide. Research can be targeted toward determining which segment of building designers use each of the available modeling tools. Understanding if users are segmented by climate zone, building type, building vintage, or some other dimension may help technology developers provide targeted updates to the modeling tools that would provide them the most opportunity. This capability is currently limited. Updates may be further facilitated by either collaborative relationships between technology developers and software developers, or by standard protocols for technology developers to submit their new product specifications to the software developers that use them. The goal is to streamline the modeling process for new technologies so that building designers gain awareness of new technologies and accurate energy savings in their building models.
5. Bridge the gap between emerging technology developers and manufacturers. Technology demonstrations can create market pull from customers but are burdensome to both technology developers and manufacturers. Supporting technology demonstrations would help jump-start the market for new technologies and accelerate their production.

Insulation

While many highly efficient insulation technologies exist, further research into specific technological aspects can improve insulation performance and market reach.

1. Increase R-value per inch in insulation for applications with limited envelope space. Additional research is required to develop a retrofit insulation solution that can achieve a high R-value within the limited wall thickness of some multi-family and manufactured homes.
2. Reduce the cost and increase the use of microencapsulated PCM. Microencapsulated PCM in masonry has promising energy benefits, with larger heating and cooling energy reductions than any insulation technology other than VIPs. Any masonry material could

be modified to contain PCM particles, which could then reduce the energy use of anything built with that material. This can greatly impact commercial construction. The research reviewed here used paraffin octadecane as the PCM though other types of paraffinic PCMs are common. Research is required to reduce the cost of both microencapsulation and PCM price.

3. Develop highly reflective asphalt particles for shingles. Many reflective roof technologies are developed for flat and low-sloped roofs but do not work as well for the more common high-sloped roofs, which are constructed of asphalt-based shingles. Research is required to make the asphalt particles in shingles highly reflective in a cost-effective manner so that reflective roof technology is more accessible to consumers with high-sloped roofs, generally on single-family homes.
4. Improve the process of manufacturing VIPs. VIPs are expensive to manufacture because vacuum sealing is a time-intensive and delicate process due to the fragile advanced vacuum casing. Additionally, if the seal is damaged the whole panel must be replaced. Researchers are in the early stages of developing a self-healing vacuum casing, which would reduce the time required to manufacture and create a more robust product. A pilot demonstration of the existing VIP could create market pull, which would also ultimately reduce costs.

Air Sealing

Both residential and commercial building demonstrations highlighting the benefits of a tight building envelope and further research on improving retrofit solutions would together increase market adoption of air sealing.

1. Highlight the benefits of high-efficiency air sealing. Industry experts have repeatedly recommended technology demonstrations for both consumers and building developers to raise awareness of the advantages of tight building envelopes. Case studies or site demonstrations using highly efficient air sealing could increase demand by alerting consumers to the need for improved air sealing in their own buildings.
2. Develop whole building air sealing retrofit technologies that do not require a full renovation. Further research is required to bring whole-building air sealing processes or technologies to the retrofit market. Manual spot sealing methods cannot achieve the same performance as whole-building solutions. Additionally, the retrofit market would benefit from a whole-building automated air sealing process that could be implemented without removing fixtures, furniture, or other belongings.

CHAPTER 6: Case Studies

Concurrent with this research, the CEC ran a solicitation for EPIC grant funding: (GFO-19-307) Advancing Envelope Technologies for Single Family Residential Buildings, Low-rise Multifamily Buildings, and Mobile Homes. This section presents the findings of this research effort as they relate to the three groups identified in this solicitation:

- Group 1: Demonstrate Fenestration Advancements in Existing Low-rise Multifamily and Single-Family Residential Buildings in Disadvantaged or Low-income Communities – TRL 6-9.
- Group 2: Develop, Test and Validate Innovative Exterior Prefabricated Envelope Packages for Low-rise Multifamily Building Retrofits – TRL 3-5.
- Group 3: Develop and Test Advanced Envelope Measures for Single Family Mobile Homes – TRL 3-5.

Group 1

Group 1 focused on retrofit window technologies at the technology demonstration and deployment stage (TRL 6-9). The research found that some existing window products meet each of the performance metrics in Table 23 individually, but that it is difficult to find products that combine these metrics into a single product. For example, there are windows with U-value of 0.2, but not together with a V_T > 0.6. Finding an R-10 window with V_T > 0.6 is also difficult, so the V_T metric is particularly challenging, though improvements may be developed through additional research.

Table 23: Summary of Performance Goals for Group 1

Technology	Baseline	Research Goal
Fenestration	Residential $14.50/ft^2 with R-5 to R-7 and V_T >0.6*	Cost ≤ $6/ ft^2 with R-10 and V_T >0.6† U-Factor ≤ 0.20 SHGC= 0.20 High Insulating windows designed to replace current stock of low-efficiency window Performance goals are for the whole window

*** Research Gap Analysis for Zero-Net Energy Buildings, Appendices C-Q, pg. 34.**
† 2014. Windows and Building Envelope Research and Development, pg. 19.

Source: GFO-19-307.

Cost targets are ambitious in the near term. The DOE Roadmap states that the focus of R&D for dynamic windows and window films is on installed-cost reductions. DOE cost targets are <= $8/ ft^2 installed-cost premium for dynamic windows and <= $2/ ft^2 installed-cost premium for window film technologies. Near term activities include identifying low capital production equipment and manufacturing processes with both low-cost materials and high-performing metrics.

Group 2

Group 2 focused on prefabricated retrofit packages for low-rise multifamily buildings with the goal of minimizing impacts on building occupants. There are retrofit products that can currently meet the technical specifications outlined in Table 24, but they are not simple enough to install on the exterior of an existing building without vacating it. Energiesprong succeeded in Europe by bringing together manufacturers, highly coordinated supply chain management, and an on-bill financing model to produce a retrofit package that is installed on the exteriors of multi-family buildings.

The Rocky Mountain Institute REALIZE program is creating a program like Energiesprong here in the United States, and NYSERDA has begun work on a pilot. RMI’s experience is that a very limited number of manufacturers is currently interested in creating products or systems for this application. One of their recommendations is to offer incentives to manufacturers that create these retrofit packages.

Table 24: Summary of Performance Goals for Group 2

Technology	Baseline	Research Goal
Prefabricated, integrated facades	• Occupants often must vacate their units during building envelope retrofits • Retrofit takes > 10 days to complete • Does not take advantage of emerging prefabrication technology, such as 3D printing	• Occupants don’t need to vacate their units during the retrofit • Retrofit takes < 10 days to complete • Takes advantage of emerging prefabrication technology
Envelope		Walls: R-26 to R-29 Roof: R-49 Air change: 1-2 ACH50
Reduction in HVAC Energy Use		20% reduction from current building usage

Source: GFO-19-307.

Group 3

Group 3 focused on fire-resistant, newly constructed manufactured housing overseen by the United States Department of Housing and Urban Development (HUD). There are new construction packages that meet the technical specifications laid out in Table 25. The largest barrier is cost since manufactured homes are disproportionately occupied by low-income occupants.

One suggestion might be to develop an incentive or financing model like the Energiesprong or REALIZE models, where customers use energy cost savings to pay the additional mortgage cost. These can be arranged so that the monthly expenditure is the same as it would have been in a home with higher energy costs and a lower mortgage payment.

Table 25: Summary of Performance Goals for Group 3

Technology	Baseline	Research Goal
Characteristics of pre-fabricated homes	Dual fuel homes with Energy Design Rating (EDR) of 100 (this score meets the 2016 International Energy Conservation Code).	All electric mobile homes designed to have an EDR of 0.
Performance	Energy use per square foot using HUD Manufactured Homes Construction Standards published in Code of Federal Regulations under 24 CFR Part 3280	Energy use per square foot using 2019 Building Energy Efficiency Standards for Residential Buildings – Title 24
Fire Resiliency	HUD Standards	Construction practices and techniques to result in a fire resistance rating of at least 2 hours for roofs and exteriors, tempered windows, and back-draft dampers
Envelope	HUD Standards	Walls: R-26 to R-29 Roof: R-49 Air change: 1-2 ACH 50
HVAC Energy Use	HUD Standards	Proposed designs should meet annual electrical use per home when compared to a comparable home built to the 2019 California Code of Regulations Title 24 residential building energy efficiency standards. Energy savings will be based on both simulation and testing of full- scale prototype homes
Cost	Construction Cost $300/ft^2$	Decrease both overall electric and natural gas energy use and decrease in construction cost: $150-200/ft^2$

Source: GFO-19-307

CHAPTER 7: Benefits to Ratepayers

The findings and recommendations in this report are to update the CEC on the current status and future opportunities of advanced window and building envelope technologies in California. The report describes current barriers to expansion of these technologies as well as RD&D initiatives that could overcome these barriers. The CEC could incorporate this information into future EPIC funding solicitations and discussions with manufacturers, researchers, government agencies, and other industry stakeholders that could together reap substantial energy-saving benefits for California ratepayers.

The CEC and its partners could support the development and commercialization of next-generation window and building envelope technologies through research that could ultimately translate into strategies to reduce materials and manufacturing costs and raise public awareness among both consumers and contractors. Improving the energy efficiency of buildings through improved window and building envelope technologies would reduce both overall electricity consumption and peak electricity demand. Installing some combination of these technologies in all of California’s buildings could result in estimated annual savings of over 1,600 GWh, $675 million in customer energy bills (electric and gas), and 2.2-million tons (2-million metric tonnes) of carbon-dioxide emissions. Accelerating the commercialization of these technologies will further support electric ratepayers through greater availability of high-efficiency products and lower utility bills.

LIST OF ACRONYMS

Term	Definition
ACH50	Air changes per hour at 50 pascals of pressure
BEopt™	Building Energy Optimization Tool
CZ	Climate zone
DOE	U.S. Department of Energy
EPIC	Electric Program Investment Charge
ft^2	Square foot
GHG	Greenhouse gas
HUD	U.S. Department of Housing and Urban Development
HVAC	Heating, ventilation, and air conditioning
IECC	International Energy Conservation Code®
IGU	Insulated glass unit
Low-E	Low-emissivity
NIST	National Institute of Standards and Technology
PCM	Phase change material
RD&D	Research, development, and demonstration
R-value	A measure of thermal resistance of a material
SHGC	Solar heat gain coefficient
SIP	Structurally insulated panels
U-value	A measure of the rate of heat loss through a material
VIP	Vacuum-insulated panels
V_T	Visible transmittance

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