A 20-YEAR INDUSTRY PLAN FOR WINDOW TECHNOLOGY

WINDOW INDUSTRY TECHNOLOGY ROADMAP

OFFICE OF BUILDING TECHNOLOGY, STATE AND COMMUNITY PROGRAMS
ENERGY EFFICIENCY AND RENEWABLE ENERGY • U.S. DEPARTMENT OF ENERGY
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NAHB Research Center
National Fenestration Rating Council (NFRC)
Pella Corporation
Plate Glass Manufacturers Council (PGMC)
PPG Industries
Velux
Viracon
Window and Door Manufacturers Association (WDMA)
A NEW INITIATIVE

The U.S. Department of Energy's Office of Building Technology, State and Community Programs (BTS) is facilitating a new industry-led initiative to develop a series of technology roadmaps. The roadmaps identify key goals and strategies for different areas of the building and equipment industry. The Window Industry Technology Roadmap is one of the first sponsored by BTS.

A Window to the Future

The American window industry has taken an important first step in defining its future in response to changing market and business conditions. The industry faces exciting new opportunities but also serious challenges. New technology is expected to play a pivotal role in addressing these conditions, as well as assisting window manufacturers in competing in the marketplace. The pace of technological development should continue to respond to trends in new construction and retrofit that place a premium on energy conservation, enhanced quality, fast delivery, and low installed cost.

The Window Industry Technology Roadmap represents the collaborative efforts of window industry professionals, government, environmental organizations, and research groups. These individuals contributed to a dynamic process that ultimately produced general consensus on a vision for the future and the pathways for achieving it.
In September 1998, the window industry began the process of developing the Technology Roadmap with a one-day Executive Visioning Forum held in Chicago. During this forum, industry participants discussed their current situation and outlined a long-range vision for maintaining and building their competitive market position. This vision discussion led to the development of the vision statement below.

The core of the workshop explored the critical need to meet the vision in the areas of:

1. Windows as an integral part of a building “system”
2. Active, smart glass and windows
3. Informed consumers at all levels
4. More glass and windows used in buildings
5. Windows as an environmental solution
6. Windows as an energy source

Advanced window technology can lower production costs and create high-profit, innovative products to compete with other materials. Recognizing the importance of cooperative technology planning, the window industry organized a Window Technology Roadmap Workshop, held in January 1999 in Leesburg, Virginia. Over 30 representatives from the fenestration industry, government, environmental organizations, and research groups met to complete an industry-wide plan for achieving the industry vision. This collaborative workshop helped identify key targets of opportunity, technology barriers, and research priorities to meet the vision. These are summarized in the table on the next page.

A WINDOW TO THE FUTURE

VISION STATEMENT

In 2020, consumers recognize windows as affordable “appliances in the wall” that are active and interactive parts of a true building system. Windows offer added value by providing energy, entertainment, and information with enhanced comfort, lighting, security, and aesthetics, in harmony with the natural environment.

1 The term “window” in the vision statement, as well as in the document, refers to fenestration products, including windows, doors, and skylights.
### SELECTED HIGH-PRIORITY ACTIONS FOR THE WINDOWS INDUSTRY

<table>
<thead>
<tr>
<th>Market Actions</th>
<th>Policy Actions</th>
<th>Technology Actions</th>
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</table>
| **NEAR-TERM (0–3 YEARS)** | • Establish partnerships through collaborative work among multiple stakeholders and resource groups.  
• Conduct a value-based market analysis.  
• Support, specify, and identify applications for improved technology, including breakthrough materials and manufacturing processes.  
• Provide incentives such as financing programs and low interest loans, perhaps as an expanded ENERGY STAR component. | • Combine the three existing codes by supporting the International Code Council (ICC), professional lobbying, or creating a core industry group.  
• Educate local building inspectors.  
• Develop communication channels among building industry groups to address integration issues in areas of education, research, and collaboration. |
| **MID-TERM (3–10 YEARS)** | • Establish a regionally sensitive national building code. | • Define standards and protocols for integrating different building components.  
• Develop strategies and hardware necessary to optimize integrated building systems.  
• Define performance metrics for comfort, system integration, energy, cost, and environmental impacts.  
• Develop methods for measuring the value of integrated systems.  
• Establish a system for rating products on the basis of durability.  
• Define appropriate durability and warranty periods for different window components. |
| **LONG-TERM (10–20 YEARS)** | • Develop analytical tools to assist manufacturers in designing and marketing efficient windows.  
• Develop methods to measure and prove durability of fenestration products.  
• Support, specify, and identify applications for improved technology, including breakthrough materials and manufacturing processes.  
• Develop products that encourage consumers to upgrade as features advance (replaceable, portable, modular, high value). | • Develop long-term photovoltaic products that can be integrated in fenestration products.  
• Develop superior insulating materials and components for fenestration products.  
• Develop integrated electronics in fenestration products. |
| **CROSSCUTTING (ONGOING)** | • Educate stakeholders and end users on true long-term cost benefits of high-performance products. | • Develop products that encourage consumers to upgrade as features advance (replaceable, portable, modular, high value).  
• Understand current technology and potential applications and specify technology needs as identified by user expectations. |
ECONOMIC, SOCIAL, AND TECHNOLOGY TRENDS
SHAPE INDUSTRY VISION

STATE OF THE WINDOW INDUSTRY
In addition to over 400 window fabricators, the window industry includes glass manufacturers, vinyl and aluminum extruders, wood suppliers, distributors, retailers, and contractors. Serving primarily residential and commercial markets, window sales exceeded 1,200 million square feet and $7 billion in 1997. Owing to their increasing versatility, windows make up a striking portion of wall area in new construction—13 percent in new residences to 50 percent in large office buildings. The window industry of today is a vibrant, modern set of businesses and is well positioned for the challenges it will face in the next two decades.

CONTEXT FOR THE VISION
In spite of the success of the window industry, significant challenges lie ahead. The industry must continue to meet society’s changing expectations while remaining economically viable and globally competitive. Two dozen window industry members discussed their current situation and established their vision for the future during the Executive Forum held in Chicago in September 1998.

The window industry is in the midst of rapid technological change. Recent developments in glazing, framing, and assembly have dramatically improved the energy conservation potential and quality of new windows. This pace of technological development should continue in response to trends in new construction and retrofit that place a premium on energy conservation, enhanced quality, fast delivery, and low installed cost. Trends in the window industry, economy, and society will drive the window industry of the future, as will uncertainties and the rapid advance of technology.

THE PROCESS
The Window Industry Technology Roadmap represents the collaborative efforts of fenestration experts from private companies as well as government, environmental, and research groups. Major steps in the development process included:

Executive Visioning Forum
When and where: September 1998 in Chicago, Illinois
Who participated: Two dozen window industry executives
Results included: Examination of the current environment and development of a shared industry vision

Roadmapping Workshop
When and where: January 1999 in Leesburg, Virginia
Who participated: More than 30 representatives from industry, government, environmental, and research groups
Results included: Identification of key barriers to achieving the vision and development of specific actions to overcome these barriers

Survey of Workshop Participants
A questionnaire distributed to workshop participants asked respondents to identify specific research needs and rate the investment required, potential contribution toward the vision, and the certainty of success for each. The Technology Roadmap represents the aggregation of those responses.
INDUSTRY TRENDS
Industrial trends reflect vigorous competition in the construction products market:
- Shift toward low-e glazing and new framing materials
- Reduction in production cycle time
- Increased automation
- Development of systems approach to building design
- Declining window prices
- Consolidation of fabricators and contractors

ECONOMIC CLIMATE
Economic trends reveal opportunities for windows to provide additional value to consumers:
- Rise in disposable income
- Growth in replacement market through renovation and upgrading
- A strong economy
- Low energy prices

SOCIAL TRENDS
Social trends hint at changes in consumer perceptions and values:
- Aging population
- Increase in home ownership
- Heightened environmental awareness
- Increased role of women in purchases of home building products

POTENTIAL BARRIERS
Some important trends remain uncertain, and the industry’s vision must be flexible and responsive to:
- Deregulation of utilities
- Housing and construction trends
- Enforcement and compliance of building codes

TECHNOLOGY FACTORS
The window industry is in the midst of the greatest technology change in its 300-year history—a phenomenon that influences industry dynamics into the foreseeable future:
- Opportunity for market differentiation
- Accelerating rate of technology change

REGULATORY TRENDS
Government programs and regulatory efforts have the potential to either enhance or stifle innovation:
- Growing industry participation in the regulatory process
- Growing appeal of ENERGY STAR labeling to consumers
- Reduction in capital gains tax
KEY ELEMENTS OF THE VISION
The vision statement is supported by six vision elements as articulated in the Executive Forum discussion. These are:

1. **Windows as an integral part of the building system**
2. **Active, smart glass and windows**
3. **Informed consumers at all levels**
4. **More glass and windows used in buildings**
5. **Windows as an environmental solution**
6. **Windows as an energy source**

Each of the BTS roadmaps begins with the definition of the industry’s vision for itself in 2020. The 20-year horizon stimulates industry members to imagine their ideal world without concern for present-day barriers.

Executive Forum participants developed their vision of the future using graphical facilitation techniques. Facilitators asked two groups of participants to imagine future cover stories that heralded their success. They envisioned that, in the next 20 years, the U.S. window industry will offer its customers imaginative new products that challenge traditional perceptions. Windows will become **active, integral parts** of building climate, energy, information, and structural systems. **Responsible manufacturing practices, material selection, and energy efficiency characteristics** will combine to also make windows a solution to environmental concerns. To help customers understand the added value that windows offer them over competing building products, members of the window industry will become **premier educators**. All these efforts will increase demand for windows as an alternative to competing building components and appliances, thereby enhancing the industry’s growth and contributing to its strength.

Industry members condensed their vision into the compelling vision statement below.

**VISION STATEMENT**
In 2020, consumers recognize windows as affordable “appliances in the wall” that are active and interactive parts of a true building system. Windows offer added value by providing energy, entertainment, and information with enhanced comfort, lighting, security, and aesthetics, in harmony with the natural environment.
BARRIERS TO THE VISION

In order to achieve the vision, the window industry must overcome barriers. Industry members reconvened in Leesburg, Virginia, on January 5–6, 1999, to identify the key barriers in the areas of technology, market, and policy, and to outline strategies for overcoming them. Participants voted on which barriers to discuss further during the workshop, and specific actions were developed to address the most important barriers. This germinal roadmap emphasized industry’s near-term priorities in each of the three areas: technology, market and policy.

Note: Checkmarks indicate the barriers that were selected for further discussion in the workshop at Leesburg, Virginia. Numbers indicate the number of votes received.

TECHNOLOGY BARRIERS

✓ 15 Lack of integration tools and forms to achieve true system integration
✓ 14 Ambiguous definition of “durability” and its implications for warranty
7 High cost of manufacturing, materials, and research
2 Consumer and corporate mindset against the vision
2 Absence of interconnection and control technologies for building systems
1 Presence of competing technologies such as opaque walls and artificial lighting
1 Long product development and cycle times

Barrier: LACK OF INTEGRATION TOOLS AND FORMS

Actions:
- Define interface standards and protocols for integrating different building system components.
- Develop strategies and hardware necessary to optimize integrated building systems.
- Define performance metrics for comfort, system integration, energy, cost, and environmental impacts.
- Develop methods for measuring the value of integrated systems.

Barrier: DEFINITION OF DURABILITY AND IMPLICATIONS FOR WARRANTY

Actions:
- Establish a system for rating products on the basis of durability.
- Define appropriate durability and warranty periods for different window components.
- Develop products that encourage consumers to upgrade as features advance (replaceable, portable, modular, high value).
MARKET BARRIERS

- ✔ 19 Lack of educated demand
- ✔ 14 High first cost
- 4 Fragmentation in the fenestration and building industries
- 3 Lack of product differentiation by non-cost attributes
- 2 Resistance to partnering among industry members

Barrier: LACK OF EDUCATED DEMAND

Actions:
- Understand the market by clearly identifying the audience.
- Create and use tools.
- Understand current technology and potential applications and specify technology needs as identified by user expectations.
- Establish partnerships through collaborative work between multiple stakeholders and resource groups.

Barrier: HIGH FIRST COST

Actions:
- Educate stakeholders and end users on true long-term cost benefits.
- Conduct a value-based market analysis.
- Support, specify, and identify applications for improved technology, including breakthrough materials and manufacturing processes.
- Provide incentives such as financing programs and low interest loans, perhaps as an expanded ENERGY STAR component.

POLICY BARRIERS

- ✔ 19 Dissimilar, poorly enforced, and inconsistent building codes that contradict DOE and industry goals
- 9 No teeth in code enforcement
- 6 Undermining of local code enforcement by special interest groups
- 4 Limited Congressional support for end-use versus supply-side programs
- 1 Lack of compelling national energy policy
- 1 Lack of Congressional support for integrated roadmaps
- 1 Lack of clarity about how to measure success

Barrier: DISSIMILAR, POORLY ENFORCED, AND INCONSISTENT BUILDING CODES

Actions:
- Combine the three existing codes by supporting the ICC, professional lobbying, or creating a core industry group.
- Develop recommendation for Congressional legislation on establishing a regionally sensitive national building code.
- Develop communication channels among building industry groups to address integration issues in areas of education, research, and collaboration.
MAPPING RESEARCH NEEDS AND STRATEGIES

The two workshops stimulated creative thinking and developed general consensus about the future of the window industry. They also identified interesting market transformation activities needed to support the vision. However, the workshops did not identify research needs and strategies in enough detail to complete the technology roadmap. Time constraints were partially the cause, and participants hesitated to discuss detailed research ideas in front of their competitors, even if the ideas were precompetitive.

To collect the necessary technical information free of the limitations imposed by the workshop environment, DOE distributed a questionnaire to over 20 workshop participants and researchers.

The surveys asked respondents to identify and describe specific research needs in the vision’s five technical elements:

1. **Building integration**—structural, power, and data interconnection between the window and the rest of the building
2. **Information display**—passive, active, or interactive display of text or images
3. **Energy supply and conservation**—annual or, ideally, instantaneous net provider of energy to the building
4. **Environmental harmony**—minimal negative environmental impacts over the product life cycle
5. **Enhanced traditional features**—improved window characteristics

For each research need, respondents also rated the investment required, the potential contribution toward each element of the vision, and the certainty of success. The respondents were contacted by phone to clarify and further develop their responses. The following technology roadmap represents the aggregation of those responses.

TECHNICAL ELEMENTS OF THE VISION

1. **Building integration**
   Structural, power, and data interconnection between the window and the rest of the building

2. **Information display**
   Passive, active, or interactive display of text or images

3. **Energy supply and conservation**
   Annual or, ideally, instantaneous net provider of energy to the building

4. **Environmental harmony**
   Minimal negative environmental impacts over the product life cycle

5. **Enhanced traditional features**
   Improved window characteristics
Respondents identified 65 unique research activities that could move the industry toward its vision by overcoming technical barriers. In alphabetical order, they are:

**ADVANCED HOLOGRAMS**
Produce holographic images on windows

**AEROGELS**
Incorporate non-opaque, highly insulating aerogel into insulating glass units

**ALTERNATIVE GLAZING MATERIALS**
Develop more durable and efficient glazing materials

**ALTITUDE ADAPTIVE IG**
Redesign IG units to eliminate breakage due to bulging at high altitude

**BILLET STOCK FROM RECYCLE**
Develop suitable process for making billet out of recycled aluminum

**BLAST-RESISTANT WINDOWS**
Develop new, cost-effective, architecturally acceptable blast-resistant window materials

**BUILDING ENERGY SOFTWARE**
Develop software to predict the energy performance of a building

**BUILDING INTEGRATION DEMONSTRATION**
Demonstrate an integrated building system with windows

**COATING EQUIPMENT**
Design coating equipment flexible enough to apply a variety of coatings

**COLOR PHOTOCHROMICS**
Expand the color availability of photochromic materials

**DAYLIGHTING RATING**
Provide a rating to measure the amount of daylighting provided by a window

**ELECTROCHROMIC DISPLAY**
Develop “smart” windows

**ELECTROCHROMIC FAILURE MODES**
Identify electrochromic failure modes

**ELECTROCHROMIC SCALE-UP**
Prove electrochromics in commercial window sizes

**ELECTROCHROMIC SERVICE-LIFE PREDICTION**
Develop models to predict service life of electrochromics based on product specs and tests

**ENERGY-EFFICIENT EXTRUSION**
Reduce energy intensity of aluminum extrusion

**ENVIRONMENTALLY BENIGN PHOTOVOLTAICS**
Research and utilize environmentally benign photovoltaic (PV) materials

**EXTERIOR DISPLAY**
Display images on window exteriors

**FINESSTRATION DURABILITY**
Research materials and finishes to extend efficient fenestration life

**FIRE-RATED WINDOWS**
Develop lower-cost alternative materials for fire-rated windows

**GAS RETENTION**
Test and predict gas concentration in IG units

**GLASS/FRAME RATIO**
Increase vision area without a corresponding increase in framing

**HIGH-SECURITY WINDOWS**
Develop new, stronger, cost-effective, architecturally compatible materials for high security

**HOLOGRAMS**
Exploit holography to direct exterior lighting within the interior space

**HOLOGRAPHIC MODELING**
Improve the modeling of the transmission of sunlight through holograms

**IDENTIFY MARKETS FOR PROCESS WASTE**
Find partners to use waste streams from window manufacturing operations

**INSULATING COATINGS**
Develop new colored architectural coatings that reduce conductive heat loss through window frames and sashes

**INSULATING COMPONENTS**
Develop new alloys or composites that reduce conductive heat loss through window components

**INTEGRAL SMART SYSTEMS**
Develop self-contained power supplies, sensors, controllers, and actuators to actively control heat and light transmission through the window

**INTEGRAL WIND POWER RECOVERY**
Integrate components into windows to capture wind energy

**INTEGRAL WIRING**
Incorporate wiring or wiring runs into the window
<table>
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<tr>
<th><strong>INTEGRATED BUILDING ENERGY SYSTEM SOFTWARE</strong></th>
<th><strong>PHOTOCHROMIC SCALE-UP</strong></th>
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<tbody>
<tr>
<td>Develop low-cost, user-friendly software to assess the energy savings inherent in integrated building systems</td>
<td>Prove photochromics in commercial window sizes</td>
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<tr>
<th><strong>INTERIOR DISPLAY</strong></th>
<th><strong>POWER SUPPLY MINIATURIZATION</strong></th>
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<tr>
<td>Display images on window interiors</td>
<td>Develop miniature, self-contained power supplies for active windows</td>
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<tr>
<th><strong>INTERIOR LIGHTING SOURCE</strong></th>
<th><strong>POWER SYSTEM BALANCING</strong></th>
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<tr>
<td>Transmit light from spandrel through ceiling space</td>
<td>Develop power balancing/conditioning components that are integral to the window</td>
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<tr>
<th><strong>INTERIOR PASSIVE LIGHTING</strong></th>
<th><strong>PROJECTED DISPLAY</strong></th>
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<tr>
<td>Develop light shelves for curtain wall and window wall applications</td>
<td>Project images onto windows similar to a “heads up” display</td>
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<tr>
<th><strong>LARGER PV PANELS</strong></th>
<th><strong>PROTOCOL FOR COMMUNICATION</strong></th>
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<tbody>
<tr>
<td>Produce photovoltaic panels in sizes larger than 2’x4’</td>
<td>Develop a means to communicate between various electronic components</td>
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<tr>
<th><strong>LASER IMPRINTING</strong></th>
<th><strong>PV COATINGS</strong></th>
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<tr>
<td>Improve laser imprinting process for holograms on a commercial scale</td>
<td>Develop photovoltaic coatings</td>
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<tr>
<th><strong>LOW-COST IG</strong></th>
<th><strong>PV PANEL COLORS</strong></th>
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<tr>
<td>Develop new ways to produce affordable IG units</td>
<td>Expand the color availability of photovoltaic panels</td>
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<th><strong>LOW-E COATINGS</strong></th>
<th><strong>PV THIN FILM</strong></th>
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<tr>
<td>Develop new generation of scratch-resistant, cleanable coating materials</td>
<td>Incorporate thin-film photovoltaics into fenestration products</td>
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<tr>
<th><strong>MODULAR WINDOWS</strong></th>
<th><strong>PV VISION GLASS</strong></th>
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<tr>
<td>Design new window system with permanent frames and modular windows</td>
<td>Develop semitransparent photovoltaic glazing</td>
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<tr>
<th><strong>MONOCHROMIC ELECTROCHROMIC DISPLAY</strong></th>
<th><strong>RECYCLABILITY</strong></th>
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<tr>
<td>Electrochromic display</td>
<td>Improve ability to disassemble dissimilar window materials for recycling</td>
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<tr>
<th><strong>MONOLITHIC TRANSPARENT INSULATING MATERIALS</strong></th>
<th><strong>SLOPE U-FACTOR</strong></th>
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<tr>
<td>Develop new non-glass insulating materials</td>
<td>Develop a U-factor rating suited to sloped skylights</td>
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<tr>
<th><strong>MULTICROMIC ELECTROCHROMIC DISPLAY</strong></th>
<th><strong>SMART PHOTOCHROMICS</strong></th>
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<tr>
<td>Electrochromic color display</td>
<td>Develop photochromic glazings that also regulate heat transmission</td>
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<th><strong>SOFTWARE TOOLS TO QUANTIFY PERFORMANCE</strong></th>
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<td>Provide a simpler means to quantify performance through use of software</td>
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<th><strong>SOLAR HEAT GAIN</strong></th>
<th><strong>THERMAL MODELING SOFTWARE</strong></th>
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<tr>
<td>Develop a solar heat gain rating suited to skylights</td>
<td>Continue to improve the usability, flexibility, and cost of 3-D thermal models of window systems</td>
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<th><strong>STRONGER SEALANT</strong></th>
<th><strong>THERMOCHROMICS SCALE-UP</strong></th>
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<tr>
<td>Strengthen the sealant bond in structural windows</td>
<td>Prove thermochromics in a commercial size window</td>
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<tr>
<th><strong>SUNSCREENING</strong></th>
<th><strong>UV RESEARCH BY MEDICAL RESEARCHERS</strong></th>
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<tbody>
<tr>
<td>Develop skylight accessories to control conductive and radiant heat transmission</td>
<td>Research to understand the effects of ultraviolet light on humans</td>
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<th><strong>VACUUM GLASS</strong></th>
<th><strong>VENTILATION</strong></th>
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<tr>
<td>Develop commercially viable vacuum glass</td>
<td>Develop fenestration systems that regulate or condition outdoor air for indoor use</td>
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<th><strong>WINDOW SELECTION SOFTWARE</strong></th>
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<tr>
<td>Develop software to select windows based on impacts on building energy consumption</td>
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The research needs span many fields of research and segments of the window industry. All contribute positively to at least one of the vision’s technical elements.
Those interested in pursuing or funding research activities should know how each activity contributes to the overall vision and how much risk the activity entails. Risk applies to both the level of investment and the chances of success. Low investment levels and high likelihood of success equal low risk. Conversely, high investment levels and low likelihood of success equal high risk.

A higher level of risk usually demands a higher financial return. While the vision does not seek to quantify financial benefits, the industry expects that achieving it will mean higher sales and value-added. Thus, a research activity that makes a large contribution to the vision may also produce a large financial return. Companies typically make research decisions based on this balance of risk and potential return. However, in the case of an industry-wide vision, returns may accrue to companies other than those making the investment decision. Different aspects of the vision also may have different associated financial values. For these reasons, organizations that use the roadmap to guide their research should be careful to consider the benefits they can hope to capture.

Besides the differences organizations face in appropriating the returns from research efforts, organizations differ in their capacity and desire to bear risk. Conservative companies or organizations with smaller research budgets may be able to pursue only low-risk activities that offer the highest potential contribution to the vision. They may be able to fund higher-risk activities only through research collaboration and partnerships.

In general, organizations can pursue low-risk activities in the near term since investment levels are lower and there are fewer uncertainties to resolve. High-risk activities, although they may be coupled with higher potential payoffs, are generally appropriate for longer-term study, since there may be higher levels of spending required and more unknowns to explore. In this respect, the Risk–Contribution charts can also serve as a guide to near- and long-term priorities.

**DETERMINING RISK**

**Investment Level**—Respondents assigned a required investment level in relation to their own research budget:
- **Low** Could be funded within own research budget
- **Medium** May require some co-funding
- **High** Will require significant co-funding

**Uncertainty Level**—Respondents also ranked uncertainty on a low–medium–high scale.

**Scoring**—For both investment level and uncertainty level, low was assigned 1 point; medium, 2 points; and high, 3 points. Risk is merely the average of the two rankings, thereby putting it on the same 1 through 3 scale.
1. BUILDING INTEGRATION RESEARCH ACTIVITIES

- Modular windows
- Daylighting ratings
- Life-cycle software/analysis
- Exterior display
- Software tools to quantify performance
- Integral wind power
- Laser imprinting
- Building integration demo
- Slope U-factor
- Solar heat gain
- Sunscreening
- Building energy software
- Identify markets for process waste
- Integral smart systems
- Integral wiring
- Interior lighting source
- Larger PV panels
- PV coatings
- PV vision glass
- EC service-life prediction
- Holographic modeling
- Insulating coatings
- Multichromic EC display
- Coating equipment
- Altitude adaptive IG
- Interior display
- Low-cost IG
- Low-e coatings
- Monochromic EC display
- Monolithic transparent insulating materials
- UV research by medical researchers
- PV panel colors
- Blast-resistant windows
- Alternative glazing materials
- Power supply miniaturization
- Color photochromics
- Glass/frame ratio
- Insulating components
- Smart photochromics
- Window selection software
- Protocols for smart system communication
- Interior passive lighting
- Power system balancing
- EC failure modes
- Electrochromics scale-up
- Environmentally benign PV
- High-security windows
- Holograms
- Billet stock from recycle
- Photochromics scale-up
- Projected display
- Recyclability
- Stronger sealant
- Aerogels
- Energy-efficient extrusion
- Fire-rated windows
- Thermochromics scale-up
- PV thin film
- Advanced holograms
- Fenestration durability
- Electrochromic display
- Gas retention
- Vacuum glass
- Thermal modeling
2. INFORMATION DISPLAY RESEARCH ACTIVITIES

- Exterior display
- Daylighting ratings
- Life-cycle software/analysis
- Modular windows
- Software tools to quantify performance
- Integral wind power
- Laser imprinting
- Monochromic EC display
- Multichromic EC display
- Solar heat gain
- Sunscreening
- Interior display
- Larger PV panels
- Building integration demo
- PV coatings
- Slope U-factor
- EC service-life prediction
- Altitude adaptive IG
- Building energy software
- Coating equipment
- Holographic modeling
- Identify markets for process waste
- Insulating coatings
- Integral smart systems
- Integral wiring
- Interior lighting source
- Low-cost IG
- Low-e coatings
- Monolithic transparent insulating materials
- PV vision glass
- UV research by medical researchers
- PV panel colors
- Alternative glazing materials
- Blast-resistant windows
- Power supply miniaturization
- Color photochromics
- Glass/frame ratio
- Insulating components
- Smart photochromics
- Window selection software
- Projected display
- Holograms
- Photochromics scale-up
- Power system balancing
- EC failure modes
- Electrochromics scale-up
- Aerogels
- Billet stock from recycle
- Energy-efficient extrusion
- Environmentally benign PV
- Fire-rated windows
- High-security windows
- Interior passive lighting
- Protocols for smart system communication
- Recyclability
- Stronger sealant
- Thermochromics scale-up
- Advanced holograms
- PV thin film
- Electrochromic display
- Fenestration durability
- Gas retention
- Thermal modeling
- Vacuum glass
- Ventilation
3. ENERGY SUPPLY AND CONSERVATION RESEARCH ACTIVITIES

- A: Modular windows
- B: Daylighting ratings
- C: Integral wind power
- D: Altitude adaptive IG
- E: Building energy software
- F: Integral wiring
- G: Coating equipment
- H: Integral smart systems
- I: Identify markets for process waste
- J: PV panel colors
- K: Power supply miniaturization
- L: Insulating components
- M: Color photochromics
- N: Blast-resistant windows
- O: Window selection software
- P: Aerogels
- Q: EC failure modes
- R: Power system balancing
- S: Holograms
- T: Interior passive lighting
- U: Billet stock from recycle
- V: Power system balancing
- W: Advanced holograms
- X: Gas retention
- Y: Electrochromic display
- Z: Fenestration durability

- A: Modular windows
- B: Daylighting ratings
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- P: Aerogels
- Q: EC failure modes
- R: Power system balancing
- S: Holograms
- T: Interior passive lighting
- U: Billet stock from recycle
- V: Power system balancing
- W: Advanced holograms
- X: Gas retention
- Y: Electrochromic display
- Z: Fenestration durability
### 4. ENVIRONMENTAL HARMONY RESEARCH ACTIVITIES

<table>
<thead>
<tr>
<th>Risk Level</th>
<th>Contribution Level</th>
<th>Research Activities</th>
</tr>
</thead>
</table>
| Lower      | Lower              | A Daylighting ratings  
Life-cycle software/analysis  
Modular windows  
Software tools to quantify performance |
| Lower      | High               | B Integral wind power  
Laser imprinting  
Slope U-factor  
Solar heat gain  
Sunscreening |
| Lower      | Medium             | C Identify markets for process waste  
Larger PV panels  
Low-e coatings |
| Lower      | Medium             | D Building integration demo  
EC service-life prediction  
Holographic modeling  
Insulating coatings  
PV coatings |
| Lower      | Medium             | E Blast-resistant windows  
Color photochromics  
Glass/frame ratio  
Power supply miniaturization  
Smart photochromics |
| Lower      | Medium             | F Window selection software  
Environmentally benign PV  
Billet stock from recycle  
Energy-efficient extrusion  
Recyclability |
| Lower      | Medium             | G Coating equipment  
Multichromic EC display  
Altitude adaptive IG  
Building energy software  
Integral smart systems  
Integral wiring  
Interior display  
Interior lighting source  
Low-cost IG  
Monochromic transparent insulating materials  
PV vision glass  
UV research by medical researchers |
| Lower      | Medium             | H PV panel colors  
Alternative glazing materials  
Insulating components |
| Lower      | Medium             | I EC failure modes  
High-security windows  
Photochromics scale-up  
Thermochromics scale-up  
Electrochromics scale-up |
| Medium     | Medium             | J Electrochromics scale-up  
Holograms  
Power system balancing  
Projected display  
Stronger sealant |
| Medium     | High               | K Fire-rated windows  
Interior passive lighting  
Protocols for smart system communication |
| Medium     | High               | L Advanced holograms  
PV thin film  
Fenestration durability  
Ventilation |
| Medium     | High               | M Electrochromic display  
Vacuum glass  
Recyclability |
| High       | High               | N Gas retention  
Thermal modeling |

**Note:** The diagram illustrates the relationship between risk and contribution for various research activities in environmental harmony. Each activity is plotted on a grid, with risk and contribution levels ranging from lower to higher.
5. ENHANCED TRADITIONAL FEATURES RESEARCH ACTIVITIES

<table>
<thead>
<tr>
<th>CONTRIBUTION</th>
<th>RISK</th>
<th>LOWER</th>
<th>HIGHER</th>
</tr>
</thead>
<tbody>
<tr>
<td>A Modular windows</td>
<td>G Larger PV panels</td>
<td>M Alternate glazing materials</td>
<td>T Aerogels</td>
</tr>
<tr>
<td>B Daylighting ratings</td>
<td>H Altitude adaptive IG</td>
<td>N Window selection software</td>
<td>U Advanced holograms</td>
</tr>
<tr>
<td>C Exterior display</td>
<td>I PV panel colors</td>
<td>O Fire-rated windows</td>
<td>V PV thin film</td>
</tr>
<tr>
<td>D Life-cycle software/analysis</td>
<td>J Blast-resistant windows</td>
<td>P High-security windows</td>
<td>W Thermal modeling</td>
</tr>
<tr>
<td>E Software tools to quantify performance</td>
<td>K Color photochromics</td>
<td>Q Interior passive lighting</td>
<td>X Electrochromic display</td>
</tr>
<tr>
<td>F Integral wind power</td>
<td>L Glass/frame ratio</td>
<td>R Stronger sealant</td>
<td>Y Ventilation</td>
</tr>
<tr>
<td>G Laser imprinting</td>
<td>M Insulating components</td>
<td>O EC failure modes</td>
<td>O Holograms</td>
</tr>
<tr>
<td>H Building energy software</td>
<td>N Holographic modeling</td>
<td>P Photochromics scale-up</td>
<td>P Electrochromics scale-up</td>
</tr>
<tr>
<td>I Integral smart systems</td>
<td>O PV coatings</td>
<td>Q Power system balancing</td>
<td>Q Holograms</td>
</tr>
<tr>
<td>J Interior lighting source</td>
<td>P PV vision glass</td>
<td>R Protocols for smart system communication</td>
<td>R Holograms</td>
</tr>
<tr>
<td>K EC service-life prediction</td>
<td>P PV coatings</td>
<td>S Thermochromics scale-up</td>
<td>S Holograms</td>
</tr>
<tr>
<td>L Monolithic transparent insulating materials</td>
<td>P PV vision glass</td>
<td>T Thermo-chromic display</td>
<td>T Holograms</td>
</tr>
<tr>
<td>M Multichromic EC display</td>
<td>P PV vision glass</td>
<td>U Gas retention</td>
<td>U Holograms</td>
</tr>
<tr>
<td>N Low-cost IG</td>
<td>Q Power supply miniaturization</td>
<td>V Vacuum glass</td>
<td>V Holograms</td>
</tr>
</tbody>
</table>
Just as organizations may want to emphasize particular vision elements, organizations may want to identify activities based on their area of research expertise or interest. The 60 research activities listed on pages 10–11 were grouped into the following eight research areas:

1. Imaging—display of images or text on the window surface

2. Energy production and supply—development of window-based photovoltaic materials

3. Light transmission—control of radiant light and heat transmission through windows

4. Insulation—control of heat conduction through windows

5. Analytical tools—modeling of window-related phenomena and development of software-based tools

6. Manufacturing—equipment and processes for producing windows and window-related components

7. Design—design of buildings and building systems including windows

8. Electronics—development of integral components for controlling and powering window features

Research areas clarify the extent to which types of research needs contribute to various vision elements. This clarification can help an organization fund or organize efforts in the research areas that best support those vision elements it finds most appealing. For example, DOE may decide to emphasize research in those areas that best contribute to the vision’s energy element. For organizations that conduct research, research areas can help them decide how they might best contribute to the vision based on how well their competencies match each element.

The following is a map for each of the priority research areas by topic.
<table>
<thead>
<tr>
<th>Research Area</th>
<th>Continuing Research</th>
<th>Future Research</th>
</tr>
</thead>
<tbody>
<tr>
<td>Imaging</td>
<td>• Projected display&lt;br&gt;• Interior display</td>
<td>• Electrochromic display&lt;br&gt;• Advanced holograms&lt;br&gt;• Exterior display&lt;br&gt;• Monochromic display&lt;br&gt;• Multichromic display</td>
</tr>
<tr>
<td>Energy Production and Supply</td>
<td>• Larger PV panels&lt;br&gt;• PV vision glass&lt;br&gt;• PV thin film</td>
<td>• Environmentally benign PV materials&lt;br&gt;• PV coatings&lt;br&gt;• PV panel colors&lt;br&gt;• Integral wind power</td>
</tr>
<tr>
<td>Light Transmission</td>
<td>• Electrochromics scale-up&lt;br&gt;• Photochromics scale-up&lt;br&gt;• Thermochromics scale-up&lt;br&gt;• Holograms&lt;br&gt;• Low-e coatings&lt;br&gt;• UV research by medical researchers&lt;br&gt;• Interior lighting source</td>
<td>• Smart photochromics&lt;br&gt;• Color photochromics&lt;br&gt;• Daylighting rating</td>
</tr>
<tr>
<td>Insulation</td>
<td>• Insulating components&lt;br&gt;• Aerogels&lt;br&gt;• Monolithic transparent insulating materials&lt;br&gt;• Vacuum glass&lt;br&gt;• Gas retention</td>
<td>• Insulating coatings&lt;br&gt;• Alternative glazing materials</td>
</tr>
<tr>
<td>Analytical Tools</td>
<td>• Thermal modeling&lt;br&gt;• Building energy software&lt;br&gt;• Solar heat gain&lt;br&gt;• Slope U-factor&lt;br&gt;• Holographic modeling&lt;br&gt;• EC failure modes&lt;br&gt;• Life-cycle software/analysis&lt;br&gt;• Window selection software</td>
<td>• Tools to quantify performance&lt;br&gt;• EC service-life prediction</td>
</tr>
<tr>
<td>Manufacturing</td>
<td>• Billet stock from recycle&lt;br&gt;• Energy-efficient extrusion&lt;br&gt;• Laser imprinting&lt;br&gt;• Low cost of efficient IG</td>
<td>• Recyclability&lt;br&gt;• Coating equipment&lt;br&gt;• Markets for process waste</td>
</tr>
<tr>
<td>Design</td>
<td>• Altitude adaptive IG&lt;br&gt;• Stronger sealant&lt;br&gt;• High-security windows&lt;br&gt;• Glass/frame ratio&lt;br&gt;• Blast-resistant windows&lt;br&gt;• Fenestration durability&lt;br&gt;• Fire-rated windows&lt;br&gt;• Sunscreening&lt;br&gt;• Interior passive lighting&lt;br&gt;• Building integration demonstration</td>
<td>• Modular windows&lt;br&gt;• Ventilation</td>
</tr>
<tr>
<td>Electronics</td>
<td>• Power supply miniaturization&lt;br&gt;• Integral wiring&lt;br&gt;• Power system balancing</td>
<td>• Integral smart system&lt;br&gt;• Protocol for communication</td>
</tr>
</tbody>
</table>
Although product development is essential to the long-term success of the industry, it is a primary basis for competition among companies and is best left to the individual efforts of company proprietary research and development programs. However, studies of the fundamental physical characteristics of windows and complementing technologies are needed. Individual company researchers and product developers should use the results of this fundamental research to advance proprietary product development and to promote competition.

**MEETING LONG-TERM RESEARCH OBJECTIVES**

Achieving the goals identified in this document will require collaboration with government and other industries to leverage research and development funds. Collaboration will be required for the following long-term research objectives:

- Develop long-term photovoltaic products that can be integrated in fenestration products.
- Develop superior insulating materials and components for fenestration products.
- Develop analytical tools to assist manufacturers in designing and marketing efficient windows.
- Develop methods to measure and prove durability of fenestration products.
- Develop integrated electronics in fenestration products.
- Support, specify, and identify applications for improved technology, including breakthrough materials and manufacturing processes.
- Develop products that encourage consumers to upgrade as features advance (replaceable, portable, modular, high value).

**ADDRESSING MARKET AND POLICY BARRIERS**

Research and development alone will not lead to achieving the vision. Government and industry will need to continue working together to address the market and policy barriers facing the window industry. Objectives include:

- Define interface standards and protocols for integrating different building system components.
- Develop communication channels among building industry groups to address integration issues in areas of education, research, and collaboration.
- Develop strategies and hardware necessary to optimize integrated building systems.
- Define performance metrics for comfort, system integration, energy, cost, and environmental impacts.
- Develop methods for measuring the value of integrated systems.
- Establish a system for rating products on the basis of durability.
- Define appropriate durability and warranty periods for different window components.
- Understand current technology and potential applications and specify technology needs as identified by user expectations.
- Educate stakeholders and end users on true long-term cost benefits.
- Provide incentives such as financing programs and low-interest loans, perhaps as an expanded ENERGY STAR component.

**NEXT STEPS**

Several next steps are needed to implement the vision and roadmap and to pursue research opportunities. They include:

- Create an industry task group to address appropriate industry and government roles in implementing the roadmap.
- Establish ad hoc working groups to examine the eight research areas in more depth and develop detailed research plans for each area.
- Simultaneously, DOE will identify areas in the roadmap that coincide with beneficial public policy and align its Federal research agenda accordingly.
- Continue “course correction” meetings with industry to ensure that the roadmap is a living, evolving document.
For more information, contact:

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Washington, D.C. 20585-0121
202-586-1510

Call the Energy Efficiency and
Renewable Energy Clearinghouse at:
1-800-DOE-3732

Or visit the BTS Web site at:
www.eren.doe.gov/buildings