

Review

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From Efficiency to Sustainability: A Review of Low-Emission Glass

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Abstract

Low-emission (low-E) glass is an energy-efficient glazing technology developed to minimize heat transfer while maximizing visible light transmittance, offering significant energy savings of up to 50% in buildings. Initially developed in response to the 1970s energy crisis, low-E glass has evolved with advanced soft and hard coating technologies, further enhanced by nanotechnology to improve performance, durability, and multifunctionality.

This paper reviews the historical development, coating innovations, and environmental benefits of low-E glass, highlighting its role in reducing energy consumption, lowering carbon footprints, and supporting sustainability standards. The article provides a comprehensive review of international and regional standards, as well as all necessary certifications for glass with low E coating. The results show that compliance with these standards impact significant role in the acceptance of the product and the development of its market. Future prospects for low-E glass include cost reduction through advanced manufacturing techniques, improved recyclability, and potential integration with renewable energy systems and smart technologies. The paper concludes that low-E glass remains a key enabler of sustainable construction and has the potential for wider applications in industries such as automotive and solar energy.

Keywords Low emission glass, Nanocoating, Energy consumption, Sustainability, Energy-efficient building

Introduction

Low-emission (low-E) glass is a type of energy-efficient glazing designed to improve building performance by reducing heat transfer while maximizing visible light transmittance. Developed in response to growing demands for better insulation in buildings, low-E coatings were first commercialized in the 1980s. These coatings are nano layers of metallic oxides applied to glass surfaces. Over time, advances in material science have improved their

durability, optical clarity, and thermal performance, making low-E glass a cornerstone of modern energy-efficient building design [1,2,3].

Buildings account for nearly 30–40% of global energy consumption and a significant portion of carbon dioxide (CO₂) emissions. The heating, cooling, and lighting of buildings are energy-intensive processes that require efficient solutions to mitigate environmental impacts. With urbanization on the rise, the demand for energy-efficient



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technologies like low-E glass has become a priority to achieve net-zero energy goals [4-7].

Climate change and sustainability goals are the most significant issues for developing energy efficient building materials. The Paris agreement and subsequent global policies emphasize reducing greenhouse gas emissions and transitioning to sustainable practices. In this context, energy-efficient building materials are essential for achieving energy conservation targets. The Intergovernmental Panel on Climate Change (IPCC) also highlights the critical need for low-carbon technologies in urban infrastructure.

Furthermore, Adoption of frameworks such as LEED (Leadership in Energy and Environmental Design), BREEAM (Building Research Establishment Environmental Assessment Method), and Passive House standards drives the need for innovative materials like low-E glass [38,39,24]. These certifications prioritize energy savings, resource conservation, and environmental health.

Low-E glass is engineered to minimize energy loss and improve indoor thermal comfort by reducing ultraviolet (UV) and infrared (IR) radiation. It achieves this through a transparent, microscopic coating applied to one or more of its surfaces. The coatings are designed to reflect radiant heat while allowing natural daylight to pass through, making them highly effective for windows, skylights, and facades. The low E coating applied on surface as hard coat and soft coat. Low-E glass has transitioned from being a niche solution for thermal efficiency to a pivotal element of sustainable building design. By reducing energy consumption, enhancing occupant comfort, and supporting global decarbonization efforts, it underscores the vital role of advanced materials in shaping the future of construction. Future innovations in low-E glass technologies will likely focus on further reducing environmental impacts, improving recyclability, and integrating with renewable energy systems [1, 7-8].

Low E glasses reduce heat loss in winter and minimizes heat gain in summer and correspondingly by maintaining indoor temperatures, it reduces reliance on heating and cooling systems, leading to significant energy savings. This coatings on glass blocks up to 99% of harmful UV rays, which can fade interior furnishings and cause health risks and allows optimal daylight penetration, reducing the need for artificial lighting [1-2].

2. Evolution of low-emission glass: history, development, and environmental benefits.

The evolution of Low-E glass reflects a significant transition from simple coatings to highly advanced, multi-functional materials. From the energy crises of the 1970s to the current focus on environmental sustainability, Low-E

glass continues to play a crucial role in reducing energy consumption and supporting global climate goals. Its ongoing advancements promise further improvements in energy efficiency and environmental impact in the years to come [9].

2.1. Early Developments in Glass Coatings

The origins of Coated Glass were in 1920s-1950s. the Early research on the basic coated glass focused on minimizing glare and controlling light transmission for aesthetic and functional purposes. Early coatings used basic metal oxides, offering minimal energy-saving benefits. In 1960s the reflective coatings, often made of metallic oxides, emerged to reduce heat gain in buildings. They were effective in blocking solar heat (reducing cooling loads) but lacked insulating properties for cold climates. As well, the coatings often created a mirror-like appearance, limiting their aesthetic appeal.

The Birth of Low-E Glass Technology backs to 1970. The 1970s energy crisis drove demand for energy-efficient building materials. Low-E coatings were developed to minimize heat transfer while allowing visible light to pass through. The first generation used a “hard coat” (pyrolytic) process, applying tin oxide onto molten glass during production [9].

2.2. Advancements in Low-E Technology

In the 1980, soft coat low-E technology, developed through vacuum deposition (sputtering), allowed precise application of silver and metal layers to the glass surface. Soft coats achieved emissivity as low as 0.02, significantly reducing heat transfer. In the following sections, the advantages and disadvantages of soft and hard coatings will be further discussed.

In 1990s, the manufacturers began applying multiple layers of low-E coatings to enhance both thermal insulation and solar control and the dual and triple low-E coatings were developed. They had customizable performance, were tailored coatings for different climates and building orientations and improved visible light transmittance while reducing solar heat gain. Modern Low-E Glass Technologies were generated from 2000.

Passive Low-E were designed for cold climates to maximize solar heat gain while minimizing heat loss and solar control low-E were optimized for warm climates to reflect solar heat. Innovations in protective layers made soft coat low-E more robust and user-friendly. From 2010, low-E glass began to be combined with other energy-efficient technologies like triple glazing and argon gas fills. Correspondingly, manufacturing processes emphasized reduced carbon footprints [6, 10-11].

2.3. Role of nanotechnology

Nanotechnology plays a significant role in enhancing the energy performance of low-emission (low-E) glass. By manipulating materials at the nanoscale, innovations in nanotechnology offer improvements in various properties of low-E glass, including thermal insulation, solar control, durability, and functionality. Nanotechnology has significantly advanced the energy performance of low-e glass by enabling more efficient, durable, and multifunctional coatings. The ability to control heat transfer, enhance solar control, improve durability, and integrate renewable energy sources makes nanotechnology a key driver in the continued development of energy-efficient glazing solutions. As this technology continues to evolve, nanotechnology promises even more sophisticated and effective low-E glass products that meet the growing demands for sustainability, energy efficiency, and environmental responsibility in building design. Nanotechnology allows the creation of ultra-thin coatings that can reflect a higher proportion of infrared (IR) radiation while maintaining high visible light transmission (VLT). Nanostructured layers can be used to create a more effective barrier to heat transfer. These coatings can reduce the amount of heat that escapes during cold weather and prevent excessive heat gain in hot weather, thus improving the thermal performance of low-E glass [7,12].

Furthermore, the incorporation of silver nanoparticles into the low-e coating can increase its ability to reflect heat, providing better thermal insulation with minimal impact on visible light. Silver is known for its high reflectivity, especially in the infrared spectrum, which makes it highly effective at reducing heat loss and improving energy efficiency. Nanoparticles can enhance the glass's ability to block infrared radiation (solar heat gain) without compromising visible light transmission.

This provides better control over the amount of solar heat entering the building, particularly in regions with high solar radiation. By reducing solar heat gain, nanotechnology helps lower the demand for cooling, thereby improving the energy efficiency of buildings [7].

Nanotechnology has noteworthy role in enhanced solar control and heat gain management.

Selective low-E glass utilizes nanostructured coatings that can reflect unwanted infrared (IR) radiation while allowing a high percentage of visible light to pass through. This ensures that buildings remain cool in the summer while still benefiting from passive solar heating in winter. Such selective coatings can be fine-tuned to optimize both thermal insulation and solar heat gain, depending on the specific climate and building requirements.

In addition to enhancing energy performance of low-E glass, nanotechnology allows the development of

self-cleaning surfaces for low-E glass by creating hydrophobic (water-repellent) and oleophobic (oil-repellent) surfaces. These coatings make it easier for rainwater to wash away dirt, dust, and other contaminants, reducing the need for frequent cleaning. This not only extends the life of the glass but also maintains the energy performance of the low-E coating by preventing the buildup of dirt that could reduce its efficiency. The photocatalytic properties of certain nanoparticles (like titanium dioxide) can also help break down organic dirt and pollutants when exposed to sunlight, making cleaning more efficient and reducing maintenance costs.

Also, the durability and longevity such as scratch resistance and anti-reflective and anti-abrasive properties of low E glass can be improved with nanotechnology [12]. Nanomaterials improve the scratch resistance of low-E coatings, making them more durable. This is particularly important because the coating must retain its energy-efficient properties over the long term, especially in environments with high wear and tear (e.g., large commercial buildings or windows exposed to harsh weather conditions). Nanostructured hard coatings can help enhance the hardness of the low-E layer, reducing the likelihood of damage and maintaining the glass's energy efficiency. Moreover, nanotechnology can be used to produce coatings that not only improve energy performance but also resist abrasions and reflectivity, ensuring that the glass retains its aesthetic appeal and functional efficiency over time [12-13].

Multifunctional glass with energy and environmental benefits, is one of the nanotechnologies achievements. Nanotechnology enables the development of multifunctional low-E glass that integrates energy generation, such as solar photovoltaic cells, into the glass. Low-E glass with embedded solar cells powered by nanomaterials offers the dual benefit of solar energy generation and thermal regulation. This can help buildings become self-sustaining in terms of energy use, reducing overall energy consumption. Nanotechnology contributes to the development of smart glass, which can change its thermal or optical properties in response to environmental stimuli. For example, electrochromic and photochromic coatings, which can alter their properties based on electrical voltage or light exposure, are enhanced by nanotechnology. This allows low-e glass to dynamically adjust to changing temperature and light conditions, improving energy savings by controlling heat gain and loss in real-time [7,13].

3. Coating technologies for low-E glass:

The two primary types of coatings used in low-e glass are soft-coat and hard-coat technologies. These coatings differ in their manufacturing processes, performance, du-

rability, and applications.

Soft-coat low-e glass coatings are applied using vacuum deposition techniques, such as magnetron sputtering, where a thin layer of metal (usually silver) is deposited onto the glass surface. The coating is applied in a vacuum chamber, and the metal is sputtered onto the glass using high-energy particles. The soft-coat layer is typically applied to one or both inner surfaces of a double or triple glazing unit (insulated glass unit, IGU) to ensure better performance. Soft coatings consist of a multilayer structure of dielectric/metal/dielectric (DMD) that contains of a highly conductive metal layer, such as silver, copper, or gold, sandwiched by transparent dielectric layers, such as TiO₂, ZnO, or SnO₂ [4]. Figure 1 displays a schematic of multilayer coatings. Each layer play its specific role in the specification of final coating which will not addresses

here as it has been discussed in various articles [4]. In the other hand, hard-coat low E hard-coat low-E glass is produced by applying a metal oxide layer directly onto the glass surface during the float glass manufacturing process. This is typically done through pyrolytic deposition, where metal oxide materials (like tin oxide) are applied at high temperatures. The coating bonds chemically with the glass, making it an integral part of the glass surface. The coating is durable and can be exposed to environmental conditions without needing to be encapsulated in an insulated glass unit. Each coating type offers its own set of advantages depending on the building's requirements, climate, and budget considerations.

Table 1 compares these two types of coatings in terms of production process, performance and durability [4,7,14-15].

Table 1: Comparison of soft-coat vs. hard-coat low-E glass

Feature	Soft-coat low-E glass	Hard-coat low-E glass
Manufacturing Process	Vacuum sputtering (applied in a vacuum chamber)	Pyrolytic coating (applied during float glass production)
Performance	Superior thermal insulation and solar control	Lower performance in insulation and solar control
Durability	More fragile, requires encapsulation in IGUs	Durable, can be exposed to the environment
Aesthetic	Clearer appearance, minimal reflection	Slightly reflective, can appear tinted at angles
Applications	Ideal for high-performance insulated glass units (double/triple glazing)	Can be used in single glazing or insulated glass units
Cost	Higher due to advanced production technology	Lower, more affordable manufacturing process
Energy Efficiency	Better U-value, better SHGC, better insulation	Higher U-value, less effective solar control
Climatic Suitability	Best for hot climates or climates needing superior insulation	Suitable for general use, especially in colder climates or single-glazed windows

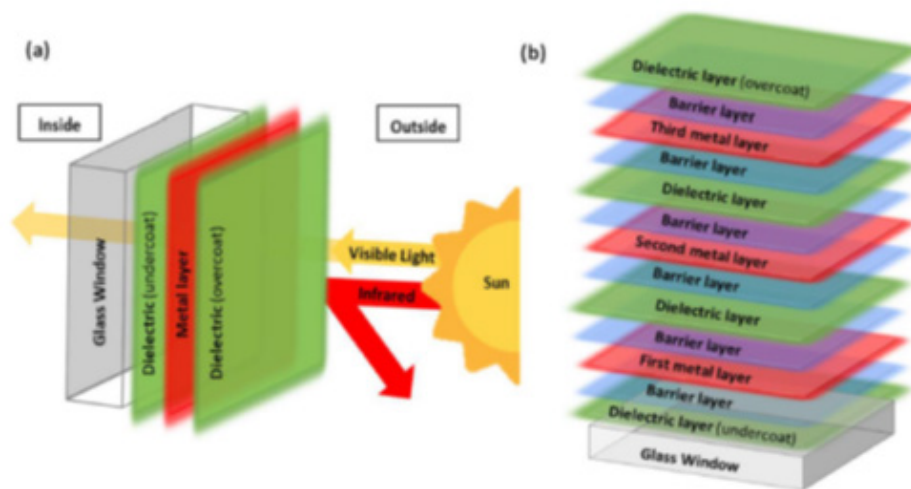


Fig. 1: (a) The schematic of low emission coating on glass, (b) multilayer low emission coating [4]

4. Sustainability and energy performance

The main goal of using low E coating on glass is Energy Savings. The low emission glass reduces heating and cooling loads by 30-50% compared to standard glass. They also, decreases reliance on fossil fuels for energy generation.

Using low E glass mitigates greenhouse gas emissions from buildings, which account for nearly 40% of global energy consumption. Modern low-E glass is designed for long life cycles and can be recycled, contributing to a circular economy. Additionally, enhanced thermal and acoustic insulation improves living conditions while reducing energy costs.

The focus on energy efficiency addresses immediate energy savings but does not always consider broader sustainability goals. The sustainability low-emissivity (low-E) glass can be assessed through a variety of metrics, focusing on energy savings, environmental impact, and lifecycle benefits [7,10-11,16]. Figure 2 illustrates a schematic representation of the interaction between solar radiation and low emissivity glass.

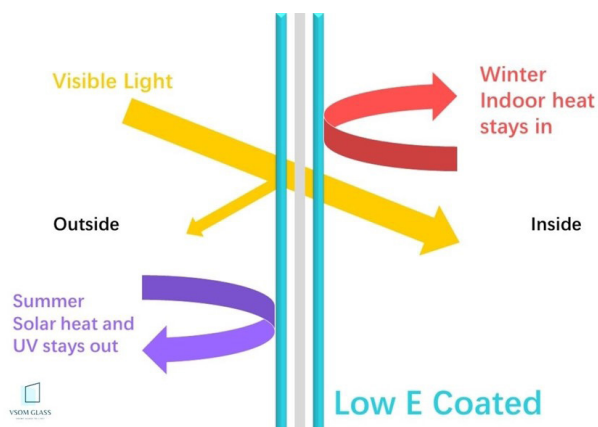


Fig. 2: The interaction between solar radiation and low emissivity glass.

4.1. Energy efficiency

Low-E glass works by reducing the transfer of heat through windows, which makes it highly effective for maintaining indoor temperatures. This means the glass keeps heat inside during the winter and outside during the summer, leading to lower energy consumption for heating and cooling. The thermal insulation performance is often measured by the U-value, which for low-E glass is significantly lower compared to standard glass, typically ranging from 0.2 to 1.0 W/m²K depending on the configuration (double or triple glazing) [6].

Additionally, low-E glass has an optimized Solar Heat Gain Coefficient (SHGC), which determines how much solar radiation it transmits or blocks. This helps balance

heating and cooling needs, making it suitable for different climate zones. It also maintains high levels of natural light transmission, typically 60-90%, ensuring that buildings can rely on daylight rather than artificial lighting [2,10]. Figure 3 compares the energy performance of low-E glass with normal glass.

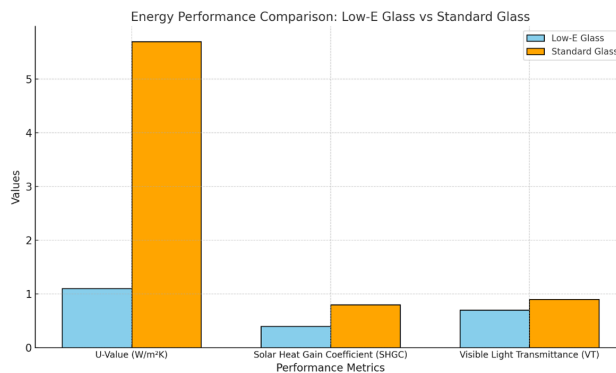


Fig. 3: Energy performance comparison between low-E glass and glass without coating.

4.2. Energy savings and cost efficiency

The energy-saving potential of low-E glass is one of its most important sustainability benefits. By reducing heat loss in colder months and minimizing solar heat gain in warmer months, it can cut annual energy usage for heating and cooling by 30-50%. Over time, these energy savings translate into significant cost reductions and lower dependency on fossil fuels. Furthermore, the reduced demand on heating, ventilating and air conditioning (HVAC) systems means these systems can be smaller, leading to cost savings during installation and reduced operational loads [7].

4.3. Carbon footprint and lifecycle benefits

While the production of low-E glass involves energy-intensive processes, the material's carbon payback period is relatively short, typically just 1 to 3 years. This means the carbon emissions saved through reduced energy use in buildings quickly outweigh the emissions generated during manufacturing. Over its lifespan, low-E glass can reduce a building's total carbon emissions by up to 30% compared to buildings with standard glass. This makes it a critical component in achieving net-zero energy goals [17].

4.4. Long-term performance and durability

Low-E glass is designed for long-term use, with coatings that maintain their effectiveness for 20-30 years, especially when part of insulated glazing units (IGUs). Its durability ensures consistent energy performance over

decades, contributing to the sustainability of the building. Additionally, because it requires minimal maintenance and performs well over time, it reduces both financial and environmental costs in the long run [7].

4.5. Environmental and indoor quality

Beyond energy savings, low-E glass enhances indoor environmental quality. By reducing temperature fluctuations and allowing in ample natural light, it creates a more comfortable and aesthetically pleasing indoor environment. This reduced reliance on artificial lighting not only saves energy but also improves well-being and productivity for occupants.

Recent innovations are making low-E glass more sustainable. For example, solar-control low-E coatings, Reduce cooling loads in hotter climates. Dynamic low-E glass incorporates electrochromic or photochromic technologies to adjust light and heat transmission based on environmental conditions. Moreover, low-E coatings paired with photovoltaic cells contribute to energy generation.

The glass is also compatible with modern green building certifications like LEED and WELL, helping projects meet stringent energy efficiency and environmental standards.

In conclusion, low-E glass is a prime example of how innovative materials can support sustainability. By reducing energy use, lowering carbon emissions, and enhancing comfort and performance, it plays a vital role in sustainable building practices, making it an essential consideration for architects and builders aiming to create efficient, eco-friendly structures [18].

5. Market trends and adoption

Low-emission (low-E) glass has experienced significant growth in global adoption, driven by increasing demand for energy-efficient building materials and stringent regulations on energy consumption. Here's an overview of the market trends and adoption patterns.

5.1. Market growth and size:

The global low-e glass market is expanding at a steady rate, with a compound annual growth rate (CAGR) of approximately 6–8% over the last decade. This growth is driven by the construction of energy-efficient residential and commercial buildings. By 2024, the low-e glass market is projected to surpass \$35 billion, with demand rising in North America, Europe, and emerging economies in Asia-Pacific.

In the North America and Europe, there is strong adoption due to stringent energy efficiency regulations. In Asia-Pacific rapid urbanization and infrastructure development are driving demand in countries like China, India,

and Southeast Asia [19-20].

5.2. Drivers of Adoption:

Governments worldwide are setting targets to reduce greenhouse gas emissions and improve energy efficiency. Low-E glass is a critical solution for achieving these goals, particularly in the building sector, which accounts for a significant portion of global energy use. The Adoption of low E glass is strongly influenced by energy performance standards such as U.S. "Energy Star" certification, European Union's "Energy Performance of Buildings Directive (EPBD)" and Global green certifications like "LEED, BREEAM, and WELL".

Low-E glass reduces heating and cooling costs by up to 50%, making it an attractive investment for building owners and developers.

Low emission glass has applications in different sectors including residential Buildings commercial and industrial buildings and automotive and transportation. Increasing demand for energy-efficient housing has led to widespread use of low-e glass in windows, skylights, and patio doors. Adoption is higher in commercial real estate, particularly in office buildings, hotels, and retail spaces, where energy savings translate to lower operational costs. The automotive industry is increasingly incorporating low-e glass to enhance fuel efficiency and passenger comfort [19-20].

5.3. Key trends in the market:

Advances in coating technologies (e.g., double-silver and triple-silver coatings) are enhancing thermal insulation and solar control. Integration low E glass with smart glass solutions, such as electrochromic or photochromic glass, is gaining traction, enabling dynamic control of light and heat transmission. Customization and aesthetics is another key factor in the market. Manufacturers are offering customizable low-E glass solutions, including tinted and decorative options, to cater to architectural demands. Finally, sustainability is a critical factor in developing the market of low E glass. The market is shifting toward eco-friendly production methods and recyclable materials, addressing lifecycle sustainability concerns [19-20].

5.4. Challenges in adoption

The upfront cost of low-E glass remains a barrier, particularly for residential markets in developing regions. Also, in some markets, end-users and contractors lack awareness of the long-term benefits of low-E glass, limiting its adoption. Another challenge is complex installation. Proper installation is critical to achieving the desired energy performance, and a lack of skilled labour can hinder adoption in certain regions. The regional insights have

impacted the adoption of low emission glasses. In North America, The U.S. and Canada are leading markets due to energy efficiency mandates and consumer awareness. The EU has strict energy performance standards, driving high adoption rates in residential and commercial sectors. Likewise, China and India are emerging as major markets due to rapid urbanization, but adoption is slower in rural areas due to cost sensitivity. Nevertheless, in the Middle East and Africa adoption is growing in regions with extreme climates, particularly in high-end commercial and hospitality sectors [19-20].

5.5. Future prospects

Despite the increasing development of low-emissivity glass, the future prospects of this product depend on various factors, which are mentioned below. These factors emphasize the role of governance and regulation in the development and adoption of a product.

- Government incentives: Increased subsidies and tax benefits for energy-efficient building materials could accelerate adoption.
- Affordable production technologies: Advances in manufacturing processes, such as magnetron sputtering, are expected to reduce costs, making low-E glass more accessible.
- Global infrastructure development: Expanding urbanization and large-scale infrastructure projects, particularly in Asia and Africa, present significant opportunities for low-E glass adoption.

The low-E glass market is positioned for sustained growth as energy efficiency becomes a priority for policymakers, developers, and consumers. Its adoption is expected to expand further with technological advancements and increased awareness of its environmental and economic benefits [19-20].

6. Global standards and regulations

Low-E glass is subject to a broad set of global standards and regulations aimed at promoting energy efficiency, improving building performance, and ensuring safety. Standards like those from ISO, ASTM, and EN, as well as certification programs like Energy Star, CE marking, and BREEAM, are critical for ensuring the product meets required energy-saving goals. Compliance with these regulations also helps reduce environmental impact, improve sustainability, and promote energy conservation in the built environment. Here's an overview of key global standards and regulations related to Low-E glass:

6.1. International standards

- ISO 9050: 2003, this standard outlines the methods for determining the optical properties of glass, including

transmittance, reflectance, and emissivity. Low-E glass is assessed under this standard to verify its energy-saving properties, which are critical in building design [21].

6.2. European Union standards

- EN 12898: 2019, specifies methods for determining the emissivity at room temperature for glass and coated glass surfaces [22].
- EN 673: 2011, outlines how to determine the thermal transmittance (U-value) of glass products, including low-E glass. Low-E coatings generally improve the U-value by reducing heat loss, making the glass more energy efficient [23].
- EN 1096: This series of standards covers the performance characteristics of coated glass, which includes low-E glass. The standards define the testing of glass coatings in terms of durability, appearance, and energy efficiency [24].
- EU Energy Performance of Buildings Directive (EPBD) This directive requires that buildings meet specific energy performance standards. Low-E glass plays a key role in meeting these standards by improving insulation and reducing heat loss [25].
- CE Marking, low-E glass products in the EU are often required to carry the CE mark, indicating they meet EU safety, health, and environmental protection standards.

6.3. North American standards and regulations

- ASTM E 1980 – 11, provides guidelines for the temperature-dependent emissivity of materials such as low-E glass, which affects its thermal performance [26].
- ASTM C1376, covers the requirements for heat-strengthened and tempered glass products, which are commonly used in low-E glass applications to enhance safety and performance [27].
- ASHRAE 90.1 (Energy Standard for Buildings Except Low-Rise Residential Buildings), this is a key standard in the U.S. that regulates energy efficiency in buildings, including the use of energy-efficient glass like low-E glass to reduce heating and cooling energy consumption [28].
- NFRC (National Fenestration Rating Council) Certification in North America, low-E glass is often tested and certified by the NFRC, which evaluates and labels products based on their energy performance, including U-value, solar heat gain coefficient (SHGC), and visible transmittance (VT). This helps consumers select energy-efficient glazing options.

6.4. International energy efficiency standards

- ISO 50001, Low-E glass is recognized in the context of this standard, which focuses on improving energy performance. This standard is widely adopted by organizations aiming to

improve energy efficiency within their buildings [29].

- Building Code Requirements (International Code Council- ICC), many national and regional building codes around the world reference energy efficiency standards, which include the use of low-E glass to meet thermal insulation requirements for windows and facades.

6.5. Environmental regulations

- REACH (Registration, Evaluation, Authorisation, and Restriction of Chemicals): Low-E glass must comply with REACH regulations in the EU, which govern the use of hazardous substances. This includes ensuring that the coatings used in low-E glass are free from harmful chemicals.
- Lead-free Standards: Low-E coatings must comply with global regulations that limit or eliminate the use of lead and other harmful substances in the production of glass.

6.6. Labelling and certification programs

- Energy Star (U.S. and Canada) Energy Star certification is awarded to products that meet strict energy efficiency standards. Low-E glass can qualify for Energy Star labeling, which is a valuable tool for consumers and businesses seeking energy-efficient solutions.
- BREEAM (Building Research Establishment Environmental Assessment Method) BREEAM is a global sustainability assessment method for buildings. It takes into account the use of energy-efficient materials like Low-E glass in its scoring system for new and existing buildings.
- LEED (Leadership in Energy and Environmental Design) LEED is a green building certification system widely used worldwide. It includes credits for using energy-efficient materials, including low-E glass, as part of the overall building design.

6.7. Global trends

- Net zero energy building standards: as countries move toward carbon neutrality, low-E glass becomes an integral part of net-zero energy building designs. It reduces heating and cooling needs and plays a key role in reducing a building's carbon footprint.
- Sustainability goals as part of international agreements like the Paris agreement, governments are pushing for stricter energy efficiency regulations in buildings. This includes encouraging or mandating the use of Low-E glass to reduce energy consumption.

7. Challenges and future opportunities

Low-emissivity (low-E) glass represents an essential technology in energy conservation and sustainability. Its ability to control heat transfer through glass has made it a cornerstone in the construction industry, particularly

for energy-efficient windows. However, its adoption and effectiveness are still challenged by various technical, economic, and environmental factors. At the same time, evolving technology and broader applications offer significant opportunities for this innovation to expand across sectors. Here's a more detailed explanation of the challenges and opportunities:

7.1. Current challenges in low-E glass

One of the most prominent challenges lies in the high production costs and technological limitations of low-E glass. Manufacturing requires complex processes like sputtering, where thin layers of metal oxides (often including silver) are deposited onto the glass. These coatings must be highly uniform and precise to achieve optimal energy performance. However, this technology is expensive due to the equipment, energy consumption, and use of rare materials. For instance, silver, a critical component for many low-E coatings, is both costly and vulnerable to supply chain disruptions. Furthermore, these manufacturing methods are not easily scalable, limiting their cost-effectiveness for mass adoption [1,4]. Another issue relates to recycling and end-of-life management. Low-E glass has a layered structure, with coatings that are chemically bonded to the surface. This complexity makes it difficult to recycle through conventional means. Various recycling facilities are not equipped to separate the coatings from the base glass, leading to either down-cycling into lower-value products or disposal in landfills. Down-cycling often results in the loss of valuable materials, such as the metallic layers, and diminishes the potential to reintroduce the glass into high-value applications. Furthermore, as the adoption of low-E glass grows, the lack of efficient recycling systems presents a growing environmental challenge.

The concept of a circular economy, where materials are reused and recycled to minimize waste, is not yet fully realized in the low-E glass industry. Most current production models operate linearly, focusing on creating and distributing new products without accounting for the lifecycle of the materials. Design practices that prioritize recyclability, such as making coatings easier to separate, are not yet widespread. This lack of integration between production, use, and recycling contributes to inefficiencies and environmental impacts.

Expanding the use of low-E glass into other sectors, such as automotive, solar energy, and industrial applications, also poses unique challenges. In the automotive sector, for example, low-E glass must withstand vibration, temperature extremes, and exposure to moisture while maintaining its performance. In solar applications, low-E coatings must balance their heat-reflective properties with

high solar transmittance, which is critical for maximizing the efficiency of photovoltaic cells. These sector-specific requirements necessitate further optimization of the technology [30].

7.2. Future opportunities for low-E glass

Despite these challenges, the future for low-E glass is bright, with significant opportunities for advancement and broader application. One of the most promising areas is the development of cost-effective production methods. Emerging technologies, such as atomic layer deposition (ALD) and roll-to-roll coating processes, have the potential to reduce costs while maintaining high performance. These methods allow for more precise control over the coatings, improving their quality and reducing material waste. Additionally, researchers are exploring alternative materials for coatings, such as doped polymers or nano-structured films, which could lower costs and reduce dependency on rare metals like silver.

Recycling and end-of-life management also represent a key area for improvement. Innovations in separation techniques, such as chemical or thermal processes that can effectively remove coatings from glass, could transform recycling practices. Closed-loop recycling systems, where materials are recovered and reused to produce new low-E glass, would significantly reduce waste and resource consumption. Moreover, adopting design-for-recycling principles, such as standardizing glass and coating compositions, would make recycling more efficient and feasible. These changes, supported by regulatory incentives and infrastructure investments, could create a more sustainable lifecycle for low-E glass.

Integrating low-E glass into a circular economy is another opportunity. Manufacturers could implement take-back programs to collect used glass, refurbish it, and reintroduce it into the market. Similarly, recovering valuable materials from the coatings, such as silver or other oxides, would enhance resource efficiency and lower environmental impacts. Collaboration between manufacturers, recyclers, and policymakers is essential to creating a system that supports these practices.

In terms of application, low-E glass is poised to expand significantly beyond traditional building windows. In the automotive sector, its ability to reduce heat transfer can lower air conditioning loads, improving fuel efficiency and reducing emissions in vehicles. Advances in durability and multifunctionality, such as adding self-cleaning or anti-fogging properties, could further enhance its utility in this market. For solar applications, researchers are optimizing coatings to strike the right balance between reflecting infrared heat and allowing maximum sunlight to reach solar cells. These improvements could make low-E

glass a vital component of both photovoltaic panels and concentrated solar power systems.

The integration of low-E glass with smart technologies also presents exciting opportunities. Combining low-E coatings with dynamic glazing technologies, such as electrochromic or thermochromic materials, can create “smart windows” that adapt to changing environmental conditions. These windows could automatically adjust their transparency to optimize light and heat levels, significantly improving energy efficiency in buildings. Moreover, embedding sensors or IoT technology into low-E glass could enable advanced energy management systems, further enhancing their role in sustainable development [31].

8. Conclusion

low-emission (low-E) glass represents a cornerstone of sustainable building design, offering substantial energy savings and contributing to global efforts in reducing carbon emissions. Its development, from basic coatings to advanced nanotechnology-enhanced solutions, has led to significant improvements in performance and durability. Standardization and governance systems can play a crucial role in the development and acceptance of low E glass in the market. The usage of this product can significantly contribute to energy savings and help reduce issues arising from energy shortages. However, challenges such as high production costs, recycling difficulties, and slow adoption in emerging markets continue to hinder its widespread use. Despite these obstacles, the future of low-E glass looks promising, with opportunities for cost-efficient manufacturing, enhanced recyclability, and integration with renewable energy systems and smart technologies. As industries such as automotive and solar energy begin to explore its potential, low-E glass is poised to play an even more significant role in the transition toward a sustainable and energy-efficient future. By addressing these challenges and expanding its applications, low-E glass has the potential to become an essential material in both construction and broader technological sectors.

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Declarations

Ethics approval and consent to participate

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Consent for publication

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Competing interests

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