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Review

Topology Morphing Insulation: A Review of Technologies and Energy Performance in Dynamic Building Insulation

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Abstract: Topology morphing insulation enables the on-demand switching of thermal properties between insulative and conducting states through shape change. The adaptive nature of these systems allows them to regulate heat transfer by dynamically altering insulation materials or systems in response to changing conditions, including environmental factors, electrical grid dynamics, and occupant requirements. In this article, we highlight the potential of topology morphing insulation for advancing building envelope design, improving energy efficiency, and facilitating on-demand adjustments in effective thermal conductivity. We provide a comprehensive overview of topology morphing insulation, delving into its underlying principles, mechanisms, and potential applications. This review explores cutting-edge research and the potential application of insights from non-building concepts, such as nature, textiles, and origami. Additionally, it examines crucial aspects such as actuation mechanisms, effectiveness, lifecycle considerations, sustainability implications, and manufacturing feasibility. We discuss the potential benefits and challenges associated with implementing topology morphing insulation solutions. Thanks to its transformative capabilities, topology morphing insulation holds tremendous promise for advancing building envelope design, driving energy efficiency improvements, and facilitating responsive changes in effective thermal conductivity.

Keywords: topology morphing insulation; switchable thermal insulation; building insulation; grid-responsive building envelopes; energy efficiency; energy savings; heat transfer

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1. Introduction

Buildings have a significant impact on both the well-being and ecology of communities. They consume enormous quantities of material, accounting for 38% of total energy use in the United States, with 31% of building energy being used for heating, cooling, and ventilation [1]. Moreover, with the increasing adoption of electric vehicles and other technologies, energy consumption continues to rise, resulting in a 4% increase in building energy between 2020 and 2021 in the United States alone [2]. By 2050, total energy use is projected to increase an additional 15% [3].

This surge in demand has spurred numerous worldwide commercial, government, and research endeavors aimed at devising strategies for constructing a more efficient and adaptable electrical grid [4–7]. Many of these have sought to incorporate smart buildings, that is, modern structures that integrate advanced technologies and systems, including sensors and data analysis, to optimize energy efficiency, comfort, security, and occupant well-being through with automatic real-time adjustments. Several such initiatives have been led by the United States Department of Energy [8,9]. Smart buildings and the building envelope work together to enhance energy efficiency by participating in demand-response programs and enabling grid-interactive capabilities, resulting in a more sustainable and optimized energy ecosystem. However, the building envelope serves a unique role that smart buildings cannot fully replicate, as it acts as the physical barrier to control heat and mass (air and moisture) transfer, ensuring energy efficiency and thermal comfort within a structure. By improving the protective insulation system in the building envelope, undesired heat and moisture transfer are minimized, directly reducing building-related energy consumption and demand on the electrical grid.

The building envelope consists of many materials and components, as illustrated in Figure 1. Energy-efficient buildings ensure occupant thermal comfort through insulation, which minimizes heat and mass transfer between the interior and exterior environments [10,11]. Effective insulation reduces the need for excessive heating or cooling, resulting in energy savings. Traditionally, research into building insulation properties such as thermal conductivity remained static (non-time varying) until the beginning of the 21st century, when research began to explore insulation with dynamic (time-varying) properties [12] with the aim of enhancing the performance and adaptability of insulation materials. Centuries of development and use of static insulation has led to reliable, affordable, and simple designs and methods for installation as a result of manufacturers fabricating insulation for construction. However, static insulation cannot exploit advantageous thermal conditions to reduce heating/cooling requirements while adapting to occupant comfort [8,13,14].

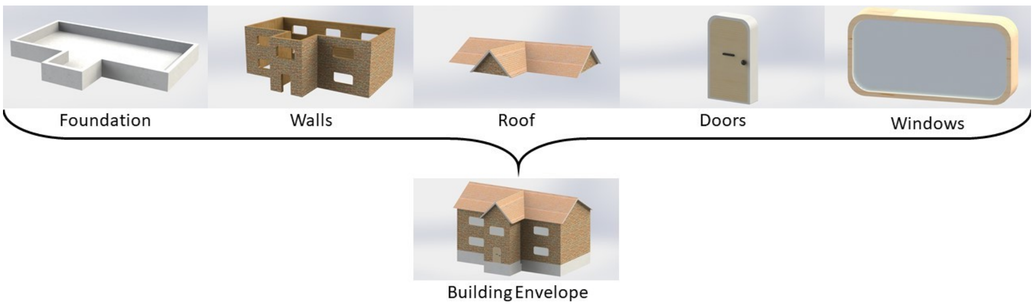


Figure 1. The building envelope, comprising the opaque and translucent components, acts as a barrier between the building's interior and the external environment. The opaque envelope encompasses the walls, roofs, floors, and doors, while the translucent envelope comprises elements such as windows.

Dynamic or time varying insulation possesses tunable thermal properties, enabling switching between insulative and conductive states, thereby creating an energy-efficient and comfortable indoor environment [8,13–16]. Many novel dynamic insulations, such as Phase Change Materials (PCMs) [17–27] and thermochromic materials [25,28–32], have sought to regulate heat transfer within each component of the building envelope. The body of research on dynamic insulation has undergone significant expansion in the last decade, prompting the creation of multiple review articles aimed at consolidating and summarizing the extensive findings in this field; for more details, see the review articles in [13–18]. However, most of the research discussed in these articles targets dynamic insulation materials, such as phase change or thermochromic materials, technologies involving air flow (e.g., permodynamic façade or multi-stage vacuum insulated panels), or insulation solutions that are actuated using Shape Memory Alloys (SMA) or thermobimetals. These insulations and the related actuation methods are designed to shift between insulative and conductive states at a temperature that is predetermined during manufacturing. Deciding on this temperature poses a potential challenge in light of research on occupant comfort, which indicates that comfortable temperatures ranges typically fall between 14.15 °C and 30.7 °C [33,34]. While the range is highly dependent on climate [33,34], other factors, such as the difference in temperature between the interior and exterior of a structure, predicted and current weather patterns, humidity, and seasonal changes, raise additional considerations regarding the effective utilization and control of these predetermined inflection points in dynamic insulation as a method of maintaining optimal occupant comfort within the desired thermal comfort range.

Interest in dynamic insulation is high because it offers significant potential for improving the energy efficiency of buildings across various climate zones. Studies have shown energy savings ranging from 7% to 42% in different climates [35]. Figure 2 provides a comprehensive visual of savings within the United States. Dehwah et al. [36] conducted simulations revealing that the utilization of proportional control for thermal properties in dynamic roof insulation can yield an extra 32% in savings compared to employing a binary control strategy. Nonetheless, it is noteworthy that a binary strategy might achieve cooling energy savings of up to 42% in comparison to static insulation, as shown by Menyhart et al. [35]. These findings underscore the potential effectiveness of dynamic insulation in optimizing energy efficiency and realizing substantial cost reductions, positioning it as a viable solution for enhancing the overall energy efficiency of buildings.

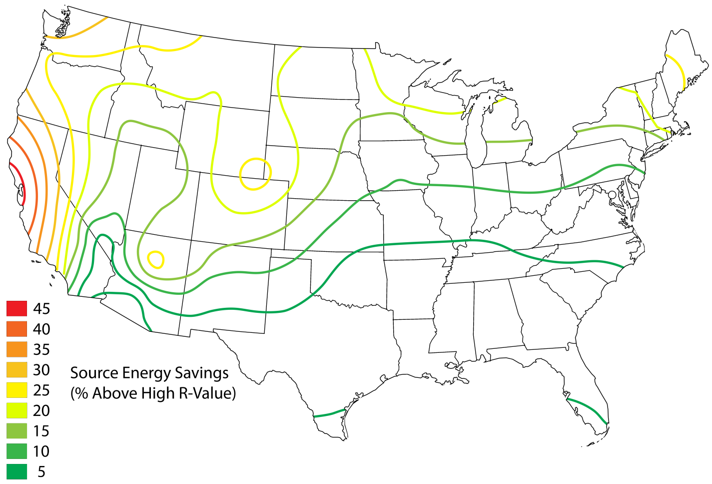
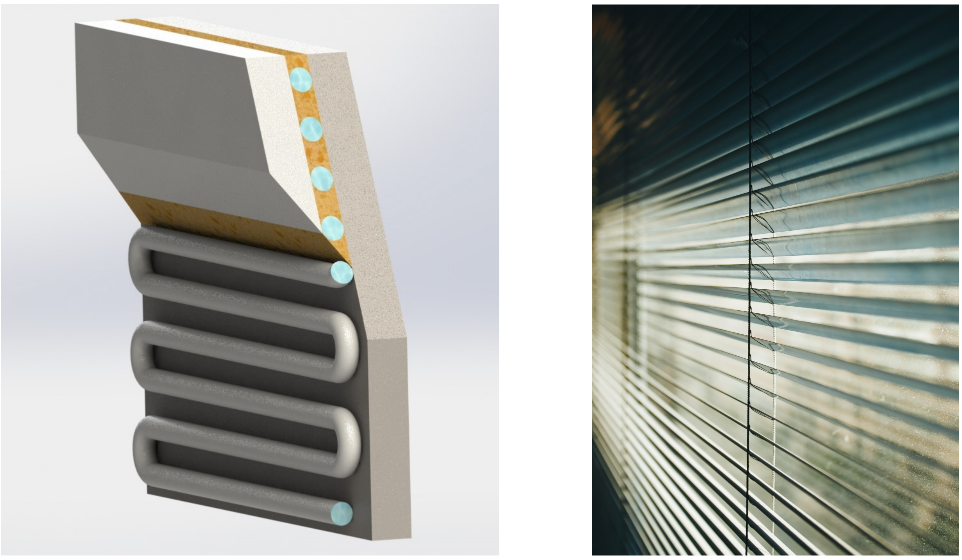


Figure 2. Contour map showing the percentage of energy savings when using dynamic insulation with properties that can be controlled. The contours showing the total energy savings of dynamic insulation are calculated with respect to static insulation with the highest recommended R-value mandated by local building codes or regulations. Image redrawn from [35].

Within the realm of dynamic insulation, a specific subset exists wherein the inflection point can be selectively activated, similar to flipping a light switch. Prominent examples of this subset include pipe-embedded and topology morphing insulation (see Figure 3) [14]. Topology morphing insulation, unlike pipe-embedded insulation, undergoes system-wide topological changes, as opposed to systems involving a fan, pump, or valve, in which the local change only interacts with an enclosed fluid. Geometry plays a significant role in influencing heat transfer. The shape, size, and arrangement of objects or surfaces can impact how heat is conducted, convected, and radiated (see Figure 4). Therefore, varying the geometry impacts the distribution and dissipation of heat while influencing the overall thermal behavior of a system. However, topology morphing insulation encounters a unique problem that differentiates it from the other types of dynamic insulation. In order to allow the insulation to change shape, sufficient clearance needs to be provided to accommodate its movement without interfering with other building components or systems. In-depth discussions on topology morphing insulation, including challenges such as this one, have received minimal attention in existing review articles on dynamic insulation.

The present article provides context and analysis on topology morphing insulation. In this review article, we primarily concentrate on examining dynamic insulation for residential structures, as these structures offer greater design flexibility compared to commercial buildings. However, it is important to note that the concepts and principles discussed in these studies can be actively applied to commercial buildings as well. The remainder of the article is organized as follows: Sections 3–5 introduce insulation technologies as categorized by the dominant mode of heat transfer (conduction, convection, and radiation) controlled by the technology; Section 6 discusses technologies that simultaneously regulate multiple modes of heat transfer, including subsections exploring shape change concepts from non-building applications that can provide additional inspiration for future advancements of topology morphing insulation for building applications; and finally, in Section 7, the previously presented insulation technologies are compared by examining their methods of actuation, size scales, location on the building envelope, and manufacturing processes, followed by a discussion of potential future research directions for this technology.



(a) (b)

Figure 3. (**a**) Pipe-embedded insulation controls heat transfer within the building envelope by modulating the fluid flow within pipes using pumps and valves. Image redrawn from [37]. (**b**) Topology morphing insulation adapts its shape to regulate heat transfer. This image showcases Venetian blinds, a prevalent type of window covering that effectively limits radiative heat transfer. Image courtesy of Ave Calvar Martinez, via Pexels, licensed using Pexels License [38].

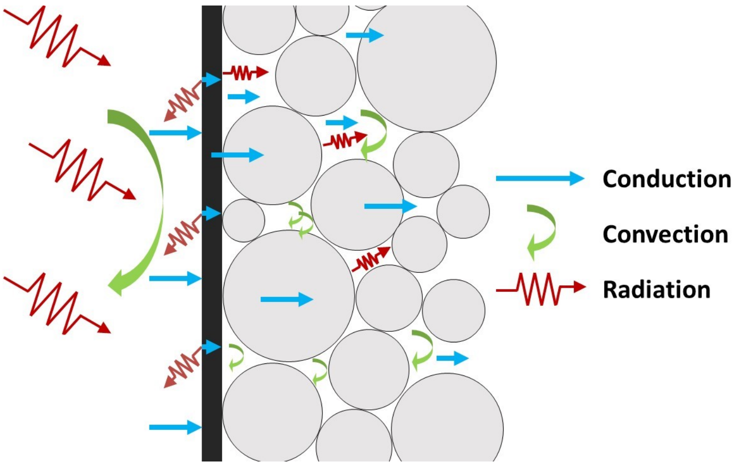


Figure 4. In porous insulation materials such as cellulose, heat conduction occurs through two distinct pathways: one that directly traverses the material itself, and another that transfers heat into the material through its pores. Image redrawn from [39].

2. Data Collection Process

In curating articles for this review on topology morphing insulation, a meticulous selection process was undertaken. This article focuses on topology morphing building insulation and incorporates examples from various fields which might inspire further research. To identify relevant sources, a systematic search was conducted in prominent scientific databases, including Engineering Village, IEEE Xplore, PubMed, ScienceDirect, and Google

Scholar. Searches were conducted using a combination of keywords such as 'switchable insulation', 'adaptive insulation', 'dynamic thermal management', 'building envelope', 'thermal switches', 'conceal and reveal', 'morphing insulation systems', and 'moveable insulation'. Both websites and scientific articles that explored the use of topology morphing insulation in building-related contexts, including residential, commercial, and industrial structures, were considered.

The non-building parts of the data selection process delved into exploring additional fields that might inspire further research in building insulation. To identify articles beyond the realm of building science that could provide innovative insights into topology morphing insulation, a broader search strategy was implemented by casting a wider net across interdisciplinary databases, encompassing materials science, mechanical engineering, biomimetics, and related fields. Examples of search terms used in this phase include 'flat-foldable origami', 'compactable origami', 'heat transfer origami', 'deployable heat shield', 'vasoconstriction', 'heat regulation', 'textile heat control', and 'shape-changing'. Websites and scientific articles that presented unconventional applications, novel materials, or inspiring concepts that could be adapted for building insulation purposes were considered. However, this review primarily focuses on technologies that have direct applications in the context of buildings. This interdisciplinary approach aimed to foster creativity and open new avenues for research in the domain of topology morphing insulation, expanding the scope of this review beyond traditional building-related literature. Therefore, articles presenting foundational concepts related to potential heat transfer regulation approaches do not align with the focus of this review article, and have been omitted.

3. Conduction

3.1. Theory and Static Insulation

Conduction is a mode of heat transfer that occurs through direct contact between materials. It involves the transfer of heat energy from higher-temperature regions to lower-temperature regions within a solid or fluid medium. This process relies on molecular interactions, and is characterized by the material's thermal conductivity; it can be represented as follows:

$$q_x = -kA\frac{dT}{dx} \tag{1}$$

where q is the local heat conduction rate, k is the material's thermal conductivity, A is the cross-sectional area perpendicular to the heat flow, and dT/dx is the differential temperature gradient. The thermal conductivity of a material can be modified by adjusting the material composition, cross-sectional area, thickness, structure, porosity, coatings or surface treatments. The path taken by heat through conductive heat transfer can be changed by adjusting the cross-sectional area or the thickness of the material.

Conduction plays a vital role in controlling the direct heat flow through the building envelope. To target conduction, effective insulation materials with low thermal conductivity, such as cellulose, fiberglass, or polyurethane, are commonly used [13,40,41]. State-of-the-art technologies, such as aerogels [42–48] and vacuum insulated panels [49–55], can be employed to further enhance thermal resistance and minimize conductive heat transfer.

3.2. Dynamic Insulation Technologies

Conduction-dominant topology morphing insulation manipulates the heat flow path to alternate contact between a fluid, a solid, or both. Transitioning between conductive and insulative states requires displacement in both fluid-based and solid insulation. However, fluids do not have a defined shape, easing the transition between insulating and conducting states, as the fluid can be transported elsewhere through pipes. Designs such as that by Al-Nimr et al. [56] control conduction by changing between fluids with different thermal conductivities, as illustrated in Figure 5. In order to effectively utilize conduction as the dominant heat transfer mechanism, dynamic solid insulation material is essential, as it can inhibit or limit convection by minimizing fluid movement.

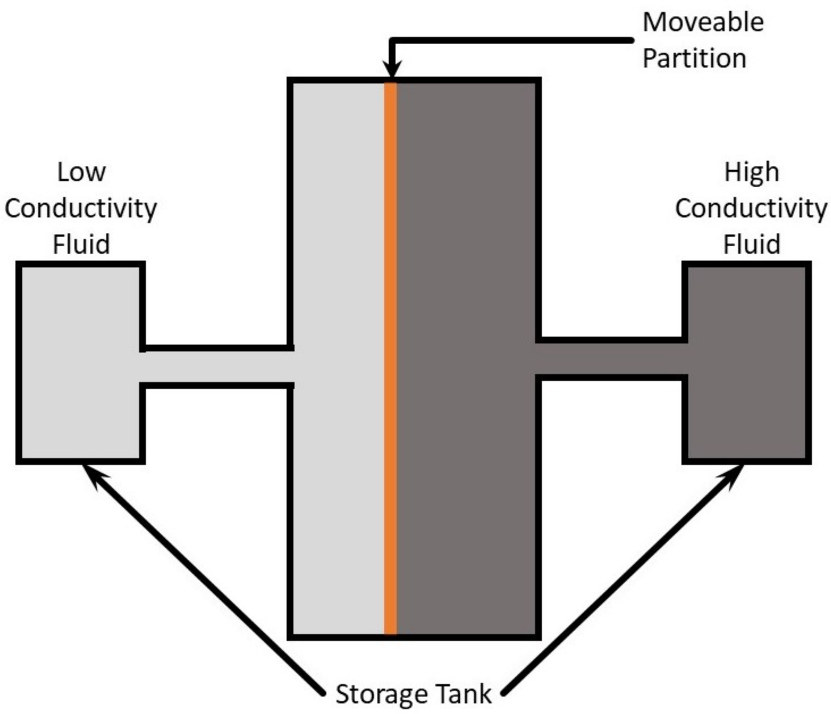
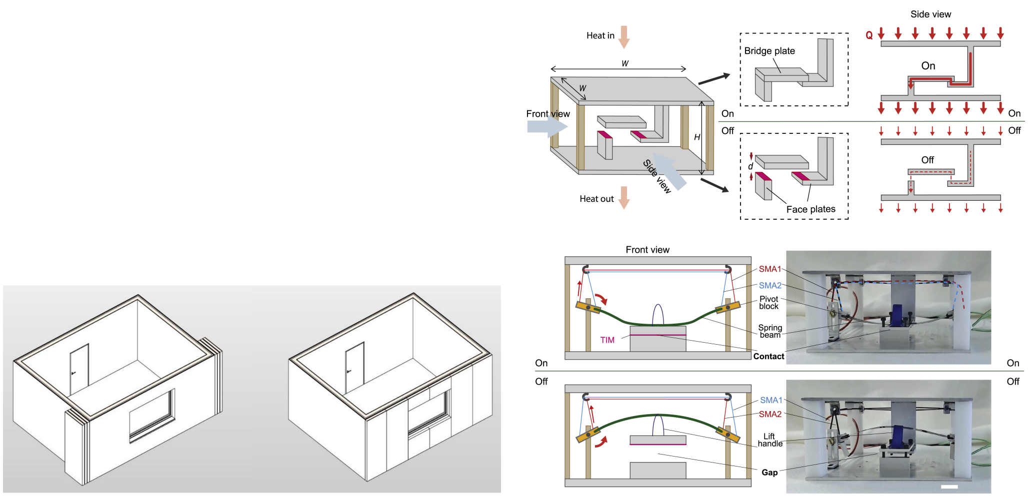


Figure 5. By adjusting the thermal conductivity of the fluid by either changing the fluid itself or manipulating its properties, it becomes possible to regulate the heat transfer through the insulation. Redrawn from [56].

Solid insulation material can be split into two categories, large motion and small motion, based on the distance that the insulation must move when shifting state. Large motion significantly impacts the design and storage, as shown in Figure 6a. The research of Iffa et al. has demonstrated the effectiveness of switching between insulative and conductive states by manually installing XPS insulation in a wall cavity [57]. Similarly, Badura et al. [58] stowed and deployed large insulative panels on the opaque part of the building façade. Designs such as these require the insulation to be displaced significantly when shifting states.



(**a**) (**b**)

Figure 6. (**a**) Large moveable panels of insulation designed for storage and motion, illustrating their potential for adaptive thermal regulation in building envelopes. Reprinted from [58], licensed under CC-BY-3.0. (**b**) Precise control with minimal mass displacement through small moveable insulation. Reprinted from [59], licensed under CC-BY-NC-ND-4.0.

In contrast, smaller feature sizes limit movement, allowing for the insulation to be more compact and space-efficient during deployment, as depicted in Figure 6b. These designs can be strategically placed within the building envelope, taking advantage of areas where a small expansion or contraction can effectively modify its shape. This offers flexibility in terms of design options and integration with other building components, such as within walls or attics. Knotts et al. [60] and Miao et al. [59] developed thermal switches which utilize mechanical contact between metal fins and plates, respectively. One method for regulating conduction involves combining fluid and solid insulation approaches, with inflatable components utilized to establish contact and encourage conductive heat transfer [60,61].

3.3. Concepts from Non-Building Applications

Conductive heat transfer is a fundamental principle that extends beyond buildings and finds application in various sectors. It plays a crucial role in numerous functions that permeate daily life and the technological landscape. By comprehending and controlling conductive heat transfer, it is possible to improve design and innovation capabilities while gaining a more holistic understanding of the interactions between different elements.

Continuing our exploration of methods for controlling conductive heat transfer, thermal switches are emerging as pivotal factors in regulating thermal conductivity; see Figure 7a. These switches can manipulate particle orientation through magnetic fields [62] or utilize thermal expansion in moving parts that respond to temperature changes [63–65]. Other methods leverage phase change [66], employ electrostatic actuation [67], or utilize small fins [68,69] to displace elements and create efficient pathways for heat transfer.

Microsystems employ various techniques to manipulate heat transfer, including the modulation of surface–fluid contact [70–73]. Small motion enables microsystems to operate within their limited displacement range, allowing them to carry out their intended functions within their limitations (shown in Figure 7b). Therefore, small displacements that regulate heat transfer play a crucial role in enhancing their effectiveness. Similarly, contact-driven mechanical–thermal switches find applications in cryogenics [74] and telescoping devices for furnaces [75], highlighting the diverse and wide-ranging implications of heat transfer manipulation.

Textiles provide a relatable and practical context for managing heat transfer, as illustrated in Figure 7c. Simple examples include how humans manipulate heat flow by wearing or removing coats (similar to how animals grow hair) [76] and manipulate their body shape when sleeping [77,78]). However, advancements in the textile field have yielded more sophisticated applications, such as separating layers of fabric to create air pockets [79–83]. Modifying fiber diameter or employing expanding woven fibers enables heat regulation as well [84]. This active research field has witnessed significant progress in thermal management of textiles, as documented in a comprehensive review [85], and encompasses concepts directly relevant to conduction-dominant building insulation.

A unique source of inspiration that remains relatively unexplored in this space comes from the field of origami. Origami mechanisms have the ability to shift between multiple positions [86]. By integrating foldable origami-inspired insulative panels into the building envelope, similar to the folded insulation introduced by Badura et al. [58]), origami insulation can expand or collapse to adjust the effective thermal conductivity of the insulation, as in the origami tessellation researched by Cai et al. [87] (see Figure 7d).

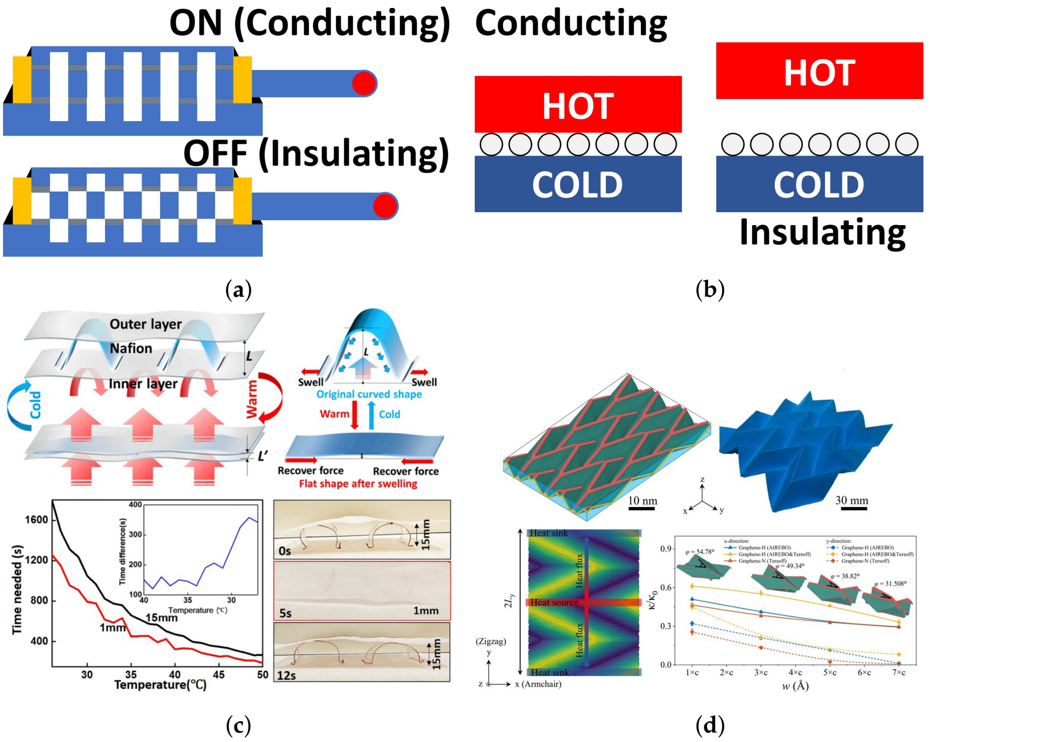


Figure 7. (**a**) A thermal switch is a device that selectively controls the flow of heat based on changes in temperature, providing an on/off functionality for thermal management. Image redrawn from [68]. (**b**) Microsystems leverage conduction phenomena at a miniature scale for efficient thermal management and heat transfer. Image redrawn from [70].; (**c**) Actuation of textile-based cavity through thermo-moisture response. Adapted from [81], licensed under CC-BY-4.0. (**d**) The shape-changing nature of origami can be utilized to tune thermal conductivity. Adapted from [87], used with permission.

3.4. Enhancements, Considerations, and Prospects

In this section, we aim to provide readers with an overview of conduction-dominant topology morphing insulation and related non-building concepts by compiling valuable data from various articles. To facilitate this, we present Tables 1 and 2. Table 1 offers insights into topology morphing insulation systems, predominantly those intended for application in building environments. These tables compile key information extracted from the articles, including the study type, prototype scale, target location for the designed insulation, reported energy savings, and other reported data. In certain cases data were missing for varied reasons, including designs that had not been tested for heat transfer, reported values that were not applicable, and the source being a review article or patent. It should be noted that the research studies are categorized by method into Theoretical, Simulation, Review, Physical, or Patent (where the insulation has no supporting published work). Only studies in the *Physical* category involved developed prototypes.

Conduction is typically the primary mode of heat transfer throughout the building envelope, with the exception of the façade, where radiation dominates. This is evident in Table 1, which indicates that most conduction-dominant topology morphing building insulations have been designed for installation within the opaque building envelope. By impeding conductive heat transfer, these insulative materials significantly enhance the overall thermal performance of the building. They play a crucial role in maintaining comfortable internal conditions while minimizing energy consumption.

Most insulation, both static and dynamic, uses solid materials. Using a fluid as the primary insulation introduces an additional layer of complexity to the building's thermal dynamics. While fluid insulation offers flexibility in storing the insulation, switching between fluids can induce convective currents within the system, temporarily disrupting the overall heat flow and potentially causing unintended cooling effects, as discussed by

Song et al. [79] in a study on air-inflatable garments. Therefore, meticulous selection and management of fluid insulations are crucial to mitigate undesirable thermal implications. Furthermore, the insulation concepts discussed in this section, although primarily designed for walls (with the exception of the façade), can be extended to other areas within the building envelope, including roofs, ceilings, or floors. For instance, heat conduction into the ground has significant implications for the building's energy consumption [88–90], highlighting the need for insulation specifically designed to regulate this heat loss.

Table 1. Large and small displacement of researched conduction-dominant building insulations in [56–61].

ID	Study Type	Prototype Scale	Target Location	Actuation	Location	Energy Savings (System)	Reported Data
[56]	Theoretical		Opaque Envelope	Pressure			k Range 0.025–0.64 $(\text{W}/(\text{m}\ ^\circ\text{C}))$
[57]	Physical	Lab	Wall	Manual			R-Value Range of 0.03–0.28 $((\text{m}^2\ ^\circ\text{C})/\text{W})$
[58]	Simulation		Wall		Potsdam, Germany		U-Value Range of 0.266–0.567 $(\text{W}/(\text{m}^2\text{K}))$
[59]	Physical	Lab	Envelope	Electrical		0.22 kWh/house per day	k Range of 0.043–0.559 $(\text{W}/(\text{mK}))$
[60]	Physical	Lab	Wall, Roof	Electromechanical			11–61% Temperature reduction compared to polyisocyanurate composite
[61]	Patent		Wall	Pressure			

Solutions from nature may appear attractive when considering conductive-dominating thermal regulation; see Table 2 for related data. As previously discussed, numerous animals, including humans, employ strategies such as adding layers (e.g., growing fur or donning a coat) or altering their body shape to reduce thermal conductivity. However, implementing similar concepts in the context of buildings can prove impractical. Encasing or relocating part of a structure, especially for multi-story buildings, presents considerable challenges and limitations, including actuation, zoning, airspace (especially as the height of a building approaches a skyscraper), and shading of or from other buildings. Textile-based biomimetic designs offer promising opportunities for building insulation, as textiles face similar challenges in providing thermal comfort, and innovative approaches utilizing expandable textiles can be explored to mimic the insulating properties of bird winter plumage.

Researchers have been investigating expandable textiles to harness the air pockets created during shape change [79–83]. This approach can be particularly well-suited for elements of the building envelope that already possess pre-existing cavities, such as the spaces between frames. The expansion of fabric to create air pockets offers several advantages. First, it leverages the low thermal conductivity of air (or another gas, such as argon), which can effectively impede heat transfer. Second, the flexible and adaptable nature of fabric enables it to conform to various shapes and sizes of cavities, ensuring a customized and efficient insulation solution. Additionally, this approach can use knowledge gathered from adjacent research in vacuum-insulated panels [55] or gas-filled panels [91]. Such combinations provide a means of actuation while offeringf the potential for reducing thermal conductivity.

Textiles can contribute to the advancement of origami-inspired insulation by offering flexible components, including hinges, that can be incorporated into various sections of the building envelope. However, certain practical considerations must be addressed. These include ensuring a zero Poisson ratio (a non-zero Poisson ratio would allow for air infiltration and convection) and avoiding expansion into structural elements such as framing, drywall, and sheathing.

Research on building envelope insulation tends to overlook thermal bridges. Thermal bridges are localized areas within a building envelope that experience significantly higher heat flow, primarily through conduction, as compared to the surrounding regions, e.g., studs or window frames [92,93]. Failure to address thermal bridges can compromise the energy efficiency of a structure and the thermal comfort of the occupants. Although research on conduction-dominant topology morphing insulation is relatively limited, reducing thermal bridging caused by studs presents an opportunity for exploration to further improve heat transfer within the building envelope. A potential path could involve replacing structural supports with insulation materials capable of modulating thermal properties while maintaining structural integrity. This area of research holds promise for effectively mitigating thermal bridges and enhancing energy efficiency in buildings.

Table 2. Conduction-dominant topology morphing insulation approaches and concepts from fields outside the scope of building science.

Application	ID	Study Type	Prototype Scale	Actuation	Reported Data
Engineering	[62]	Physical	Lab	Magnetic	Ratio R-Value$_{ins}$/R-Value$_{con}$ of 30%
	[63]	Patent			
	[65]	Patent			
	[64]	Patent			
	[66]	Physical	Lab	Thermal	C Range (W/K) 0.018–0.45
	[67]	Physical	Lab	Electromechanical	
	[68]	Physical	Lab	Electrical	
	[69]	Physical	Lab	Thermal	"60–80% discrepancy in heat transfer capacity"
	[70]	Physical	Lab		R Range (W/K) of 129 ± 43
	[71]	Physical	Lab		
	[72]	Physical	Lab	Electrical	Ratio $\lambda_{con}/\lambda_{ins}$ of 2.8
	[73]	Physical	Lab	Multiple *	Ratio R$_{ins}$/R$_{con}$ of 71.3
	[74]	Physical	Lab	Pressure	R$_{con}$ (W/K) of 10^{-6}
	[75]	Physical	Full Scale	Mechanical	λ_{ins} (W/(mK)) of 1.1
Textiles	[79]	Physical	Lab	Pressure	Ratio R-Value$_{ins}$/R-Value$_{con}$ of 0.2–1.4, Extracted from plot
	[80]	Physical		Pressure	R-Value Range ((m^{2}K)/W) of 0.1876–0.5022
	[81]	Physical		Thermo-moisture	
	[82]	Physical		Thermal	
	[83]	Physical		Pressure	Ratio Clo$_{ins}$/Clo$_{con}$ ** of 15
	[84]	Physical		Thermal	
Nature/Biology	[77]	Review			
	[78]	Physical		Thermal	***
Origami	[87]	Simulation			λ Range (W/(mK)) of 204.8–1856

* The publication uses electrical, pressure, and gravitational actuation mechanisms. ** Clo is a unit of measurement used for clothing, where 1 $clo = 0.155$ m^2 °C/W [94]. *** Garden Warblers can reduce their rate of heat loss by 54% by sleeping with the head tucked into the feathers.

4. Convection

4.1. Theory and Static Insulation

Convection is the conduction of thermal energy into an advecting fluid. The fluid's movement removes thermal energy added into the fluid away from the wall–fluid interface. Convection can be characterized by Newton's Law of Cooling, as provided below:

$$q = \bar{h} A_s (T_s - T_{\text{inf}}) \tag{2}$$

where q represents the total heat transfer rate, $\bar{h}$ is the average convection coefficient, A_s is the surface area of the interface, and T_s and T_{inf} represent the surface and fluid temperatures, respectively. The heat transfer coefficient is influenced by various factors: fluid properties such as velocity, thermal conductivity, density, and viscosity; surface characteristics such as roughness, geometry, and orientation; and cavity properties such as size, orientation, and aspect ratio. By manipulating these properties and the exposed surface area, it is possible to influence convective heat transfer.

Convection significantly influences every aspect of the building envelope, and is commonly associated with air infiltration. Wind-driven air influences the heat on the exterior of the building envelope; meanwhile, within the envelope, such as in wall cavities, the presence of a fluid causes convective currents, including wind-driven air infiltration, which can collectively undermine the efficiency of insulation [8,95]. Static insulation aims to minimize convection by obstructing fluid pathways and utilizing materials with low permeability to prevent fluid penetration. In practice, as Figure 8 illustrates, this is achieved by reducing the size of pores within the material and minimizing gaps between the insulation material(s) and the building envelope in order to inhibit airflow around the material [8,11].

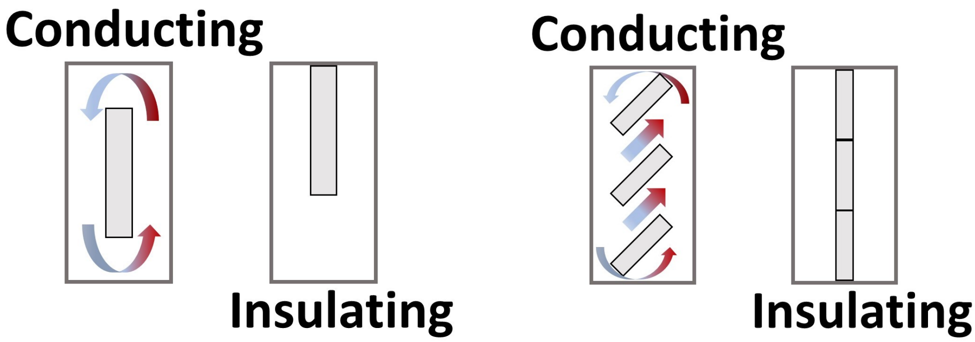
(**a**) (**b**)

Figure 8. (**a**) Batted insulation has small cavities designed to prevent convection; however, improper installation can create pockets that allow convection. Image by Tomwsulcer, through Wikimedia Commons, licensed under CC0 1.0 [96]. (**b**) Methods of combating installation issues include the use of a foamed insulation or addition of a sealant to close the gap between the insulation and nearby building components, which prevents airflow. Image courtesy of dunktanktechnician via Flickr, licensed under CC-BY-2.0 [97].

4.2. Dynamic Insulation Technologies

Convection-dominating topology morphing insulation controls a fluid by trapping and releasing it to regulate the fluid movement within the building envelope. The transition between conductive and insulative states depends on the specific modifications implemented. Factors such as the size, shape, and arrangement of the modified features, along with airflow patterns, play crucial roles in influencing the convective heat transfer characteristics within the insulation system.

Convection can be intentionally promoted in the insulation system by strategically incorporating openings that facilitate air movement. These openings create pathways for convective heat transfer within the insulation layer. This approach was explored by Pflug et al. [98,99] and Dabbagh et al. [100] (in a design that has been the subject of multiple experiments [101,102], including a full-scale test [103] and several multimodal cases, discussed below) by developing insulation systems that incorporate translating and rotating internal elements, respectively, as depicted in Figure 9. In these studies, the researchers investigated the optimal linear and angular displacements in order to enhance the promotion of free convection.



(**a**) (**b**)

Figure 9. Images showcasing innovative design elements that promote or inhibit convection through (**a**) translation and (**b**) rotation mechanisms for enhanced heat transfer control. Images respectively redrawn from [98,100].

4.3. Concepts from Non-Building Applications

The field of textiles has witnessed advancements in innovative designs that aim to harness convection for enhanced heat transfer, offering potential applications in building materials. Zhong et al. [81] and Schmidt et al. [104] have introduced designs incorporating opening flaps in textiles to encourage free convection, as depicted in Figure 10a. These designs facilitate heat flow through the textile, promoting convective heat transfer and potentially contributing to improved thermal performance and energy efficiency in buildings.

Drawing inspiration from the thermoregulation mechanisms of animals, valuable insights can be gained for the design of convection-controlled heat transfer systems, particularly in the context of topology morphing building insulation. Animals offer intriguing strategies for optimizing heat flow through convection. For instance, Hornbills have evolved the ability to regulate heat by dilating the blood vessels in their beaks [105] (see Figure 10b), while many mammals adjust the orientation of their hair to promote or discourage air circulation, thereby influencing their thermal comfort [106]. Convection plays a crucial role in the plant kingdom as well, as plants control the size of their stomata to regulate evapotranspiration, a process closely linked to convection [107,108].

Origami-inspired mechanisms can enable the regulation of convection through the manipulation of geometry by incorporating textured surfaces or protrusions that disrupt airflow and induce turbulence. This turbulence enhances convective heat transfer by facilitating air mixing, promoting efficient heat exchange between the insulation and the surrounding environment. Engineering designs include fins [109,110] and heat shields [111], which have been specifically developed (or can be adapted) to effectively control convective heat transfer; see Figure 10c. These examples demonstrate the potential of origami-inspired solutions in optimizing heat management and thermal performance in various applications.

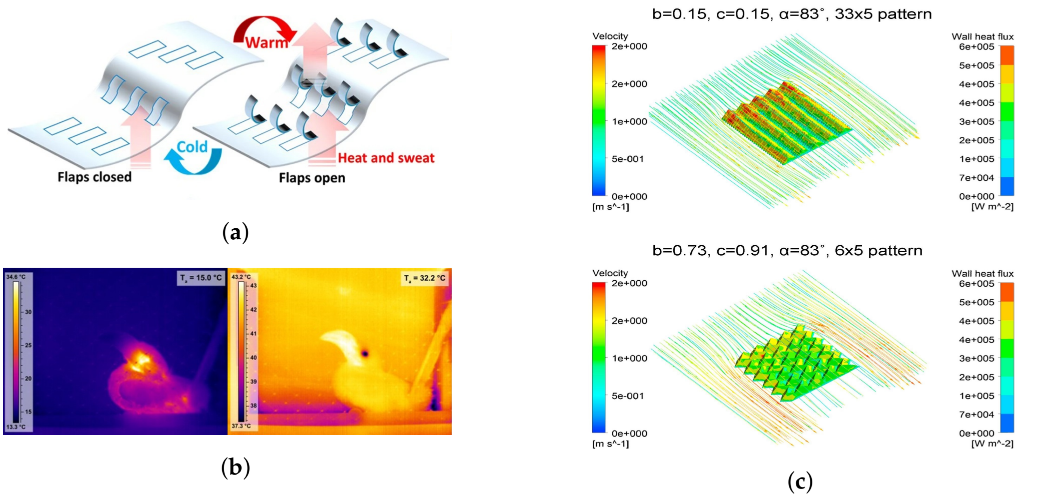


Figure 10. (**a**) Textiles with dynamic flaps offer an innovative approach to regulating convection by adjusting airflow and enhancing heat transfer control. Adapted from [81], licensed under CC-BY-4.0. (**b**) Thermal images of the Southern Yellow-Billed Hornbill. Under increased temperatures, the hornbill's beak becomes hotter than the surrounding environment. Adapted from [105], licensed under CC-BY-4.0. (**c**) Adjusting this origami-inspired design to change its shape would leverage shape manipulation to alter surface roughness, enabling enhanced control over convection and heat transfer processes. Adapted from [110], used with permission.

4.4. Enhancements, Considerations, and Prospects

In this section, we aim to provide readers with an overview of convection-dominant topology morphing insulation and related non-building concepts by compiling valuable data from various articles. To facilitate this, we present Tables 3 and 4.

Convection exerts an influence on every component of the building envelope, as fluid motion occurs across its entirety, facilitating the transfer of heat away from the surface of a structure. Only a limited amount of research has been conducted on convection-dominated topology morphing insulation for building applications, with only two distinct cases identified in the literature (refer to Table 3).

Convection poses challenges within the building envelope, as fluid motion can lead to the transfer of heat across its components, potentially compromising the thermal performance of the structure. Limited research has been conducted on convection-dominating topology morphing insulation for building applications, with only two distinct cases identified in the literature; refer to Table 3. The limited number of designs specifically targeting convection while isolating other modes of heat transfer may be attributed to the effectiveness of controlling convection in conjunction with other modes of heat transfer.

The topology morphing insulation shown in this section specifically targets both the translucent and opaque parts of the building envelope. When designing insulation for windows, transparency is a crucial consideration. If the insulation blocks visible light during any phase, this may discourage its adoption. Therefore, it is recommended to actuate the panels from the edges in order to maximize the visible space in the window. The extensive research by Krarti et al. [100,101,103,112] has demonstrated that the angle of the rotating panels impacts heat transfer. This angle depends on the orientation within the structure, as it may vary between walls and ceilings. It is worth noting that these design principles are applicable to any part of the building envelope.

These same principles can be extrapolated to other solutions found in various other fields; see Table 4 for related data. The incorporation of flaps in textiles for clothes, the manipulation of hair on animals, the dilation of blood vessels in Hornbill beaks, and the control of stomata in plants all share common factors that influence their effectiveness in regulating convection. Factors such as surface texture, geometry, and the disruption of airflow play crucial roles in promoting or discouraging convective heat transfer and optimizing thermal management. Origami introduces another variable to consider when designing insulation to regulate convection. By altering the conduction-dominant origami design discussed in Section 3.3 to have a positive or negative Poisson ratio, gaps would appear around the device, which would promote convection and allow for air infiltration.

Table 3. Convection-dominant topology morphing building insulation approaches and concepts.

ID	Study Type	Prototype Scale	Target Location	Actuation	Energy Savings (System)	Reported Data
[98]	Simulation		Window		29.6%	U-Value Range (W/(m^2 K)) 0.9–1.7 measured for cooling load
[99]	Physical	Lab	Façade			U-Value Range (W/(m^2 K)) 0.72–1.76
[100]	Physical	Lab	Wall	Electromechanical		R-Value Range ((m^2 °C)/W) 0.38–2.3

Table 4. Convection-dominant non-building insulation approaches and concepts.

Application	ID	Study Type	Prototype Scale	Actuation	Notes
Textiles	[81]	Physical	Lab	Thermo-moisture	6.56°C temperature drop in one minute
	[104]	Physical	Lab	Electromechanical	1.66°C change between insulating and conducting states
Nature/Biology	[105]	Physical		Thermal	Heat dissipated at a peak rate of 25.1 W/m^2
	[106]	Review			
	[107]	Simulation			
	[108]	Review			
Origami	[109]	Physical		Thermal	"Heat transfer enhancement up to 37%"
	[110]	Simulation			
	[111]	Simulation		Electromechanical	

It is important to acknowledge that convection-dominant insulation necessitates large cavities in order to minimize the effects of conduction, and that geometrical changes can influence the other modes of heat transfer. Furthermore, as of the time of this writing the authors have not come across relevant examples of topology morphing building insulation incorporating forced convection. This observation points to a promising direction for further research, as the examples of convection-dominant insulation discussed in this paper exclusively depend on natural convection.

5. Radiation

5.1. Theory and Static Insulation

Radiation encompasses the transfer of thermal energy through electromagnetic waves, specifically, infrared radiation. Unlike conduction and convection, radiation can occur without the need for either a medium or direct contact between materials. For most relevant applications, net radiation can be represented as follows:

$$q_{rad} = \epsilon \sigma A \left(T_s^4 - T_{surr}^4 \right) \tag{3}$$

where q_{rad} represents the radiative heat transfer rate, ϵ is the surface emissivity, σ is the Stefan–Boltzmann constant, A is the exposed surface area, and T_s and T_{surr} represent the surface and surrounding temperatures, respectively. By making modifications to the surface composition or texture, replacing materials, or applying additional layers/coatings, the emissivity of a surface and the fraction of energy leaving one surface that is intercepted by another can be adjusted, offering control over the magnitude and direction of radiative heat transfer between objects.

For buildings, the dominant source of radiation is the sun, which emits solar radiation that directly heats up the building envelope. Radiative heat transfer is prominent both on the building envelope's exterior, where it is exposed to both solar and ambient emissions (such as the façade and roof), and within the translucent envelope, where radiation directly heats the structure. Moreover, radiative heat transfer can be significant indoors, especially in the roof area where temperature variations tend to be more pronounced. Radiative heat transfer is influenced by several variables, including the surface area exposed to radiation, the emissivity of the surface, and the reflectivity and absorptivity characteristics of the materials involved. To better utilize radiation, various techniques can be employed in both the opaque and translucent building envelope. In general, techniques such as low-emissivity coatings, reflective materials, and radiant barriers are common and effective strategies to enhance thermal insulation and reduce heat gain caused by radiation. These measures help to control the amount of thermal energy transferred through radiation, thereby improving energy efficiency in buildings.

In the opaque envelope, solar radiation is not transmitted directly into the building envelope. Therefore, to prevent heat gain due to radiation it is necessary to employ effective strategies that focus on minimizing the absorption and maximizing the reflection of solar radiation by the building materials and surfaces. Radiation-targeted insulation, such as the application of reflective material like metallized polymer films [113,114], is typically integrated within the building envelope, specifically on the inner side of the static insulation layer. This placement aims to reduce thermal radiation and reduce heat gain caused by solar radiation. Figure 11a illustrates this arrangement, which has been proven to be particularly effective in warmer climates [115–117]. Multiple layers of low-emissivity coatings or radiant barriers, known as multi-layer insulation (as depicted in Figure 11b), have been widely employed to achieve significant reductions in thermal radiative heat transfer in various applications, including on the International Space Station [113,118–120].

Unlike the opaque building envelope, solar radiation can directly penetrate the translucent envelope into the interior of the structure, highlighting the importance of selecting appropriate glazing. Double or triple glazing with low-emissivity coatings and spectrally selective coatings effectively reduces the amount of solar radiation entering the building while allowing transmission of visible light [11]. Strategies that minimize heat gain, including complementary shading devices such as blinds or awnings, can further control the transmission of solar radiation [121–124].

Moreover, state-of-the-art technologies enable dynamic control over radiative heat transfer. These cutting-edge solutions include paired thermochromic and PCMs or other dynamic glazing systems [25,30,125–127], and enable buildings to adapt to changing environmental conditions and optimize energy performance while ensuring occupant comfort.

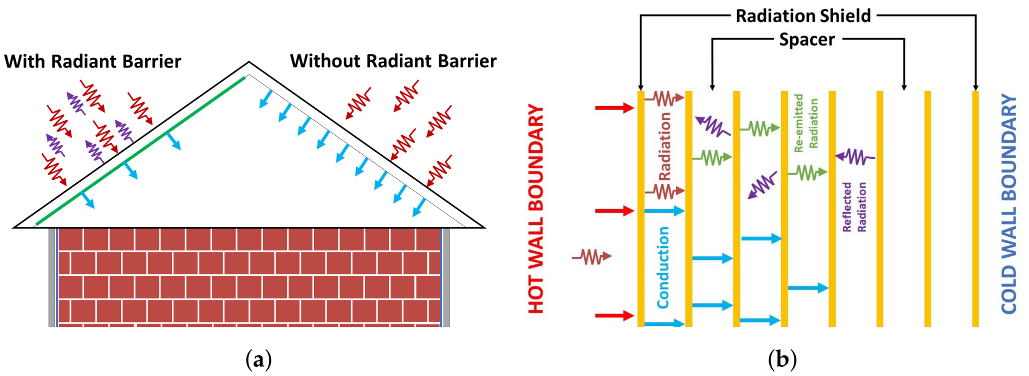


Figure 11. (**a**) Example of a radiant barrier applied under roofing. (**b**) Cross-section of a multi-layer insulation system, showcasing the arrangement of low-emissivity coatings and radiant barriers for effective heat transfer reduction. Image redrawn from [128].

5.2. Dynamic Insulation Technologies

Allowing radiation to heat the home during certain parts of the year while rejecting it during other times can be a strategic approach to optimize energy efficiency and thermal comfort. Harnessing solar radiation can be beneficial during colder months, such as winter, as it provides a renewable and passive heat source, thereby reducing the reliance on active heating systems. This can lead to energy savings and lower utility bills. However, during hotter months, especially in warmer climates, allowing excessive solar radiation to enter the home can result in overheating, leading to increased cooling demands and discomfort for occupants. By incorporating dynamic control strategies in insulation systems, such as switching between insulating and conducting states, it becomes possible to selectively utilize or reject radiation based on seasonal variations and desired indoor conditions. This intelligent and adaptive approach enables homeowners to strike a balance between harnessing beneficial radiation for heating during colder seasons and minimizing unwanted heat gain during warmer periods, ultimately promoting a more sustainable and comfortable living environment. Such an approach holds significant promise for advancing energy-efficient building design and contributing to the broader goal of sustainable and resilient construction practices.

Due to the significant impact of solar radiation on buildings, and in light of these opportunities for advancing energy-efficient building design, researchers have extensively explored the field of radiation-dominated topology morphing insulation. Active manipulation of radiative heat transfer involves controlling the properties of surfaces exposed to radiation, including surface area, absorptivity, reflectivity, and transmissivity. As a result, insulation solutions incorporate elements which 'conceal and reveal' to selectively inhibit or promote the flow of heat; these primarily appear on façades or within the translucent envelope. Figure 12 illustrates an example of such strategies.

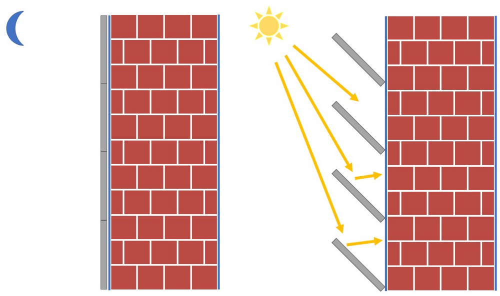
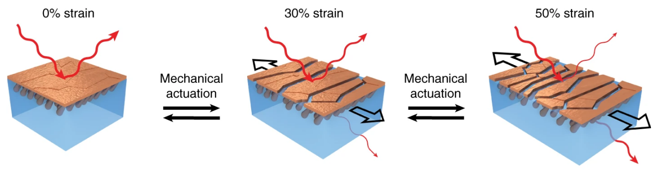


Figure 12. An image showcasing a dynamic surface design that regulates radiative heat transfer by selectively concealing and revealing elements with high absorptivity and reflectivity properties. Adapted from [129] and research by Burdajewicz et al. [130].

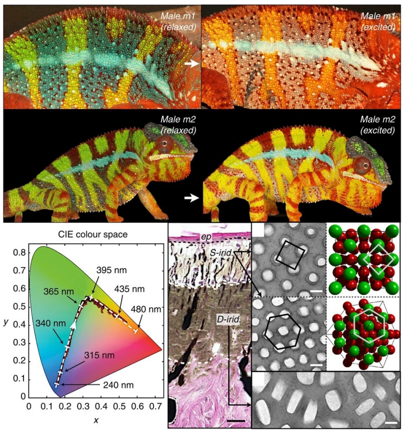
Radiation control through manipulating the exposed surface area has received considerable research. A range of solutions have been developed to achieve these objectives, such as blinds, shades, and awnings [130–143], mirrors [144,145], and rotating windows with PCMs [146]. These references provide valuable insights into the extensive research conducted in this field, and a more comprehensive understanding of the methods and techniques employed to control radiative heat transfer can be obtained by consulting additional sources [147–152].

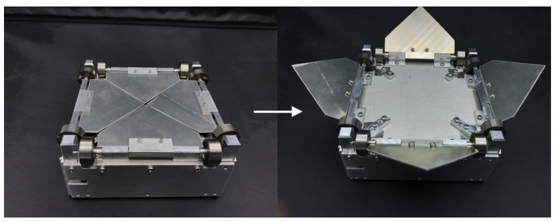
5.3. Concepts from Non-Building Applications

Textile-based radiation control presents promising solutions for managing heat transfer. The first design is a Janus membrane, which has distinct properties on each side of the textile. One side exhibits high absorptivity, while the other is highly reflective [153]. Taking inspiration from nature, researchers have developed other textiles with unique properties. For instance, Leung et al. [154] designed a textile inspired by squid skin, which allows radiation to pass through when subjected to strain-induced stretching; see Figure 13a. Similarly, Zhang et al. [155] created a textile that mimics the curling behavior of leaves, incorporating a thermochromic material to assist with absorption and reflection.



(a)





(b) (c)

Figure 13. (**a**) Schematic showing the fabrication process of a bioinspired design of a thermoregulatory composite material. Adapted from [154], licensed under CC-BY-4.0. (**b**) Reversible color changes and optical responses of chameleons, depicting the structural features. See the work by Teyssier et al. for more details [156]. Adapted from [156], image licensed under CC-BY-4.0. (**c**) Passively deployed radiator panels for CubeSat featuring bimetallic coils, capable of unfolding with a turn-down ratio of 5.4. The turn-down ratio is a ratio between the highest and lowest radiative heat loss achieved by a system or device. Image by Cannon et al. [157], used with permission.

The natural world provides a wealth of examples showcasing diverse strategies for regulating radiative heat transfer. Desert iguanas and hyraxes demonstrate adaptive behaviors such as seeking shade to cool down, while Californian desert hares extend their ears to radiate away heat [158]. Chameleons change their color through the active tuning of a lattice of nanocrystals located in the top layer of their skin cells [156], as illustrated in Figure 13b. By adjusting the spacing between these nanocrystals, chameleons can selectively reflect certain wavelengths of light, resulting in a remarkable display of vibrant colors.

Moving from nature to technological solutions, deployable devices offer innovative approaches for controlling radiation. One example is a multi-layer deployable membrane which changes shape, much like the aforementioned tulips [159]. Researchers have explored solutions where radiation dominates, e.g., in space, and have explored a variety of potential solutions designed for deployment, including radiation shields [160–162] and radiators [157,163,164] to manage heat dissipation (for example, the radiator shown in Figure 13c). Furthermore, novel geometries have been designed to regulate radiation absorption by taking advantage of the exposed surface area of a cavity [165,166]. These advancements demonstrate the potential of deployable and origami devices in effectively controlling radiative heat transfer, contributing to improved thermal management in various contexts.

5.4. Enhancements, Considerations, and Prospects

In this section, we aim to provide readers with an overview of radiation-dominant topology morphing insulation and related non-building concepts by compiling valuable data from various articles. To facilitate this, we present Tables 5 and 6.

Table 5. Radiation-dominant topology morphing building insulation approaches and concepts.

ID	Study Type	Prototype Scale	Target Location	Actuation	Location	Energy Savings (System)	Reported Data
[130]	Simulation		Façade				40× more conductive
[131]	Physical	Building	Window		Newfoundland, Canada	∼14%	
[132]	Physical	Window	Window	Electromechanical			
[133]	Physical	Window	Window	Electromechanical			
[134]	Physical	Lab	Façade	Thermal			
[135]	Physical	Lab	Window	Electrical			∼60% transmission of solar range
[136]	Simulation		Façade				
[137]	Simulation		Window				
[138]	Physical	Building	Window	Electromechanical	Lund, Sweden		U-Value Range of 1.3–2.4 (W/(m^2 K))
[139]	Simulation		Window			<90%	
[140]	Simulation		Window				
[141]	Physical	Building	Window	Electromechanical			
[142]	Physical	Building	Window	Thermal			
[143]	Simulation		Window			>50%	Heating and cooling energy use
[144]	Physical	Lab	Window	Electrical			
[145]	Physical	Lab	Window	Electrical			
[146]	Simulation		Window			28.7%	Energy savings is compared to static PCM window

The primary focus in research on the control of radiative heat transfer lies in mitigating the substantial heat flux of solar radiation during the day as compared to other heat sources. From a radiation perspective, exploring designs that allow access to or limit exposure to the cold night sky might have potential, as the sky can act as a heat sink. This approach can be likened to insulation that leverages the sky and ground for heat management [167]. However, in the context of topology morphing insulation, one potential strategy involves selectively enhancing emissive or radiative properties to efficiently reflect sunlight while freely emitting long infrared radiation, which dominates at typical temperatures. Furthermore, systems that store solar energy, such as Zhang's rotating window with PCMs [146], need to incorporate mechanisms for heat discharge based on user comfort. Therefore, it is valuable to investigate alternative topology morphing insulation designs that consider accessing or restricting exposure to the cold night sky in order to expand the range of effective approaches for managing radiative heat transfer in buildings.

Façade-based designs face the additional challenge of being directly exposed to the outdoor elements and visual appeal. Despite potential energy savings, occupants may choose to forgo façade-based insulation due to maintenance requirements. Unlike insulation used in walls or roofs, aesthetic considerations present a unique challenge for radiation-limiting insulation on building façades. The primary focus during façade updates tends to be enhancing aesthetic appeal, with energy performance taking a secondary position [168]. Similarly, research on windows often revolves around implementing shading or blocking specific light wavelengths. For instance, studies on natural light in buildings have emphasized the direct correlation between access to natural light and occupants' emotional well-being [169]. Additionally, privacy considerations play a significant role in window research, even though these factors may not directly align with energy efficiency goals. Nevertheless, they should be given due consideration.

In the realm of radiation control with textiles, nature, and origami, several applications share common characteristics; see Table 6 for related data. Most of these applications involve the regulation of exposed surface area size to influence the behavior of light. By manipulating the exposed surface area, gaps can be created in the barrier, allowing radiation to pass through and be absorbed by the surface underneath. This concept has been explored on façades, but not extensively within the building envelope. Regulating radiative heat transfer within building insulation could potentially channel heat into a conductive pathway, facilitating its dissipation into the structure, or provide avenues for the heat to be dispelled. Research conducted by Choi et al. and Dusen et al. [170,171] has highlighted the significant role of radiation in walls, which can result in undesirable heat gain or losses.

Table 6. Radiation non-building approaches and concepts. The variables α, ϵ, ρ, M_e, and M_k respectively represent the absorptivity, emissivity, and reflectivity and the degradation factors for radiative heat transport and conductance.

Application	ID	Study Type	Prototype Scale	Actuation	Reported Data
Textiles	[154]	Physical	Lab	Electromechanical	ρ Range 0–67%
	[153]	Physical	Lab		ϵ Range 0.476–0.973
	[155]	Physical	Lab	Thermal	ϵ Range 28–95%
Nature/Biology	[156]	Physical			45% decrease in sunlight absorption
	[158]	Physical			
	[172]	Review			
Origami	[157]	Physical	Lab	Thermal	turn-down ratio > 5
	[159]	Physical	Lab	Electromechanical	
	[160]	Physical	Lab	Thermal	turn-down ratio range 12:1–35:1
	[161]	Physical	Lab		Effective conductance and emmittance degradation factors of $M_k = 0.58 \pm 0.1$ and $M_e = 2.36 \pm 0.16$, respectively
	[162]	Physical	Lab		α Range 0.0006–0.002
	[163]	Physical	Lab	Thermal	"A heater power saving of 25 W at −20 °C"
	[164]	Physical			"Heat transfer coefficient that was 1.9 times higher than that of the flat substrate"
	[165]	Simulation			
	[166]	Physical	Lab	Thermal	turn-down ratio 7.5

When examining nature and textiles, designs that require flipping the insulation present spatial limitations, particularly if implemented within the building envelope, e.g., inside walls. Drawing inspiration from the chameleon's adaptive color control mechanism, a building solution based on similar principles could offer significant benefits. For instance, pairing the concepts of the origami cavity with chameleon-inspired crystals holds potential for application in buildings. However, building insulation applications require both very low costs and the ability to produce in high volumes; thus, the solution would need to be readily manufactured economically. By tessellating a design pairing these concepts, it could be feasible to spectrally select the absorbed wavelengths, which could offer a reliable alternative to thermochromic or electrochromic materials. Additionally, the dynamic radiation shielding and strain-induced textile approaches show promise, provided that the material, when stretched or moved, can be effectively stored without displacing other parts of the building envelope. Exploring these concepts further could yield innovative solutions for enhancing thermal performance and radiation control in buildings.

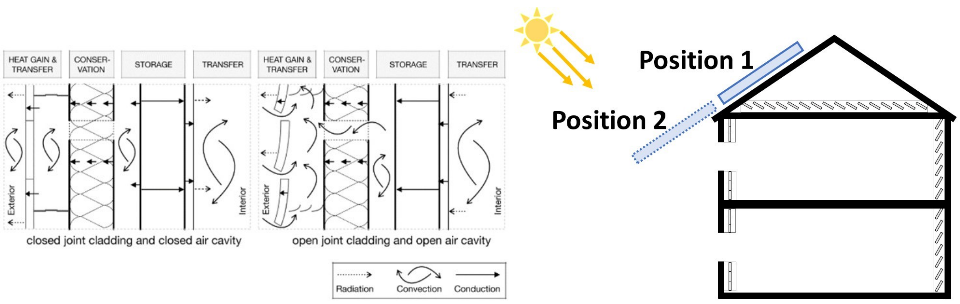
6. Multimodal

6.1. Theory and Static Insulation

The term 'multimodal' is used to characterize insulation materials and systems that aim to manipulate multiple modes of heat transfer simultaneously. Insulation that seeks to regulate the complex nature of heat transfer often integrates diverse materials, surface treatments, geometries, and structures to optimize the ability to regulate heat conduction, convection, and radiation. Static insulation incorporates features to simultaneously control multiple modes of heat transfer within the building envelope. In the opaque envelope, static insulation such as traditional batting insulation or rigid foam boards often have a reflective layer, which restricts the transfer of heat by conduction and radiation, respectively. In the translucent envelope, coatings applied to glass surfaces help to reduce the transmission of infrared radiation, and double-glazed windows are often filled with insulating gases such as argon, which adds additional resistance to conductive heat transfer between the glass panes [11].

6.2. Dynamic Insulation Technologies

Multimodal topology morphing insulation exhibits significant potential in effectively regulating heat transfer within the building envelope by simultaneously addressing multiple modes of heat transfer. There are instances when heat transfer through conduction and/or convection may oppose radiative heat transfer. In such cases, strategically managing distinct modes or even behaviors within specific wavelengths can yield advantages [173–177]. Many of multimodal insulation types take the form of blinds or shades [102,178–180] These systems employ a mode-switching mechanism in which the dominant mode transitions from conduction (with many small convection limited cavities) to convection by opening up to create a single large cavity with sufficient space for fluid flow. One approach utilizes a façade to regulate radiative heat transfer and leverages deflection to control cavities for convection [181], as depicted in Figure 14a. Two other systems employ a combination of elements, one of which is illustrated in Figure 14b, including rotating panels within the opaque envelope and shading (with two of these systems also controlling heat flow through the glazing) [101,102,112], as illustrated in Figure 14c.



(a) (b)

Figure 14. (a) A multimodal insulation design featuring a façade that bends components to create cavities and regulate radiation, enabling effective control of each mode of heat transfer. Reprinted from [181], image licensed under CC-BY-4.0. (b) Multimodal insulation employing multiple integrated techniques to optimize thermal performance and energy efficiency. The depicted system utilizes a cool roof and a rotating panel system to respectively regulate radiative and convective heat transfer. The rotating panel design shown in Figure 9b is used within the opaque envelope. Image redrawn from [101].

6.3. Concepts from Non-Building Applications

Nature offers fascinating examples of heat transfer control mechanisms. Many animal species utilize temporary structures in the form of nests or dens to regulate heat [76,182]. The movement of animals within or exiting from these structures alters the flow of heat. Other biological adaptations include growing and shedding fur, which modulates conduction, while specific hair structures can regulate convective heat transfer [106]. In the plant kingdom, Rhododendron leaves curl in response to dropping temperatures, reducing surface area and minimizing heat loss due to radiation and conduction [183]. Similarly, with textiles, Zhang et al. [184] designed a material that expands to regulate transmission of radiation while simultaneously controlling conductive heat transfer. In colder climates, the crimping of animal hair traps air, effectively decreasing thermal conductivity while altering the impact of radiative heat transfer [185].

The engineering field adopts similar applications to enhance heat transfer control. Researchers have explored origami-inspired radiators, as demonstrated by Grinham et al. [186] and Zhu et al. [187], which can be reshaped to optimize radiation and convection through exposed surface area. Movable insulation layers have been researched for excavation sites to manage heat transfer during mining processes. Heat emission onto workers can be prevented by minimizing gaps and adjusting insulation placement [188]. In photovoltaic systems, Chen et al. [189] designed photovoltaic thermal collectors that employ thin films to regulate radiation and conduction by adjusting the gap between the photovoltaic panel and the film. These engineering examples highlight the application of multimodal strategies for effective control of heat transfer.

6.4. Enhancements, Considerations, and Prospects

In this section, we aim to provide readers with an overview of topology morphing insulation and related non-building concepts that regulate at least two modes of heat transfer by compiling valuable data from various articles. To facilitate this, we present Tables 7 and 8.

Multimodal insulation with topology morphing capabilities aims to regulate heat transfer by prioritizing certain modes at different stages. Blinds and shades are commonly utilized in the translucent building envelope to regulate heat transfer. It is worth noting that there are two specific applications that have been designed with the opaque envelope in mind, as radiation plays a role within the opaque envelope [178,179]. However, a significant disadvantage of blinds and shades is their tendency to be designed for deployment parallel to gravity. This poses a challenge if these designs are applied to other locations in the building envelope, such as the roof, as they can deflect out of plane, creating convection-promoting gaps during the insulative state . To overcome this challenge, future designs of such blinds need to account for the deflection that occurs when they are deployed in orientations other than parallel to gravity.

Surprisingly, there has been limited research exploring the integration of multiple solutions to comprehensively evaluate energy efficiency benefits. We were only able to identify three such solutions [101,112,181], i.e., similar findings with non-building concepts. These studies demonstrate that combining complementary strategies has the potential to provide a more efficient building envelope compared to relying on a single solution alone. Drawing inspiration from animals that naturally adapt to their surroundings using various thermoregulation mechanisms, such as growing hair or changing their position, it is evident that building insulation requires multiple insulation solutions to regulate its thermal properties effectively. Integrated solutions can provide the capability to utilize multiple systems in achieving this goal.

With the increasing demand on the electric grid, dynamic behavior in building systems becomes paramount. Humans need to adapt their technologies to enhance efficiency. One profitable strategy would be for human-built structures to possess the capability to respond to various demands, including comfort requirements, weather conditions, and grid demands. By intelligently manipulating its structure and material properties, topology morphing multimodal insulation can effectively regulate heat transfer by adapting to different thermal conditions. Through transitioning between states, multimodal insulation can strategically regulate each mode of heat transfer as needed. This dynamic approach allows the insulation system to optimize its performance, effectively meeting efficiency requirements by adapting to specific environmental conditions and energy efficiency goals.

Table 7. Multimodal topology morphing building insulation approaches and concepts.

ID	Study Type	Prototype Scale	Target Location	Actuation	Location	Energy Savings (System)	Reported Data
[101]	Simulation		Opaque Envelope		Phoenix, AZ	63%	
[102]	Simulation		Opaque Envelope, Glazing		Various European countries	44%	Heating energy end-use
[112]	Simulation		Window, Roof		El Paso, TX	109%	Net energy savings achieved through on-site photovoltaic electricity generation.
[178]	Theoretical		Wall				R-Value Range 0.13–3.42 $\left((\mathrm{m}^2\mathrm{K})/\mathrm{W}\right)$ and $\gamma = 0.5$
[179]	Physical	Partial Building	Wall, Window			30%	U-Value Range 0.35–2.7 $\left(\mathrm{W}/(\mathrm{m}^2\mathrm{K})\right)$
[180]	Physical	Partial Building	Window	Electromechanical			*
[181]	Theoretical		Façade	Thermal			

* Cellular shades reduced HVAC energy use by 16.6 ± 5.3% when compared to standard vinyl blinds, and addition of shades reduced the average U-Factor by 0.22 $Btu/hrft^2\ {}^\circ F \approx 1.25\ \mathrm{W}/(\mathrm{m}^2\mathrm{K})$

Table 8. Multimodal topology morphing insulations from various fields outside the scope of building science.

Application	ID	Study Type	Actuation	Reported Data
Textiles	[184]	Physical	Thermo-moisture	τ Relative Change 35.4
Nature/Biology	[76]	Review		
	[106]	Review		
	[182]	Review		
	[183]	Physical		
	[185]	Physical	Moisture	
Origami	[186]	Physical	Electrical	Cooling rate 55–67% higher than flat device
	[187]	Physical		
	[188]	Simulation		
	[189]	Simulation		Convective losses reduced by 60%

7. Discussion

This section presents a comprehensive analysis and comparison of key aspects pertaining to topology morphing insulation in the context of building envelope design and energy efficiency. It critically evaluates the potential and challenges of topology morphing insulation by examining actuation mechanisms, manufacturing processes, and scales of prototypes and simulations. The analysis sheds light on the advantages, limitations, performance metrics, durability, and reliability of these systems, considering factors such as cost-effectiveness and compatibility with existing building infrastructures. Furthermore, it explores the environmental impact of topology morphing insulation, including its potential for reducing energy consumption and greenhouse gas emissions throughout the building life cycle. The discussion encompasses future research directions and emerging challenges, such as scalability, integration with smart building systems, and optimization of control strategies. By providing a thorough and rigorous assessment, this review article aims to facilitate informed decision-making in building design and construction practices to promote enhanced energy efficiency and improved thermal performance.

7.1. Study and Device Scale

Research in the field of building insulation and related technologies encompasses a wide range of scales. As depicted in Tables 9 and 10, the devices used in these studies primarily consist of simulations and lab-scale prototypes, with the exception of devices controlling radiation. Notably, there are no prototype tests that have encompassed a whole building. While simulations and laboratory-scale devices are frequently employed to validate concepts in research articles, it is important to recognize their inherent limitations.

Table 9. Categorization of studies focusing on topology morphing insulation methods in the context of building insulation. Data taken from Tables 1, 3, 5 and 7.

Mode	Physical	Patent	Simulation	Theoretical
Conduction	3	1	1	1
Convection	2		1	
Radiation	10		7	
Multimodal	2		3	2

While it may appear straightforward to explore numerous topology morphing insulation designs to identify effective solutions, it is paramount to take into account essential factors such as actuation mechanisms and manufacturing feasibility. Except for shades and blinds, topology morphing insulations in large-scale production are currently not available on the market. Furthermore, the production of fiberglass insulation reached 1.2 million metric tons in the United States in 2021, accompanied by installation costs as affordable as $\$1/ft^2$ [190]. Considering these significant production volumes, in order to foster market adoption it is critical for any effective solution to be long-lasting, manufactured at a low cost, and have simple actuation methods and control inputs. The careful selection of appropriate actuation mechanisms is indispensable in achieving the desired shape-changing behavior, while meticulous consideration of manufacturing constraints becomes pivotal for practical implementation. Overlooking these critical factors during the design phase of topology morphing insulation could hinder the translation of promising simulation results into real-world applications or guide researchers toward concepts that are impractical to manufacture.

Table 10. Scaling of building insulation prototypes, exploring prototypes across different scales. Prototypes are sorted based on where they were tested. Prototypes tested in the laboratory could be of sufficient size for testing within a structure; however, they were not evaluated within an actual building. Data taken from Tables 1, 3, 5 and 7. Note: "N/A" denotes cases where the prototype scale was not discussed, such as in simulations of specific geometries.

Mode	Prototype Scale			N/A
	Lab Test	Partial Building	Whole Building	
Conduction	3			3
Convection	2			1
Radiation	4	5		8
Multimodal		2		5

7.2. Actuation

Actuation methods play a crucial role in the functionality and effectiveness of topology morphing insulation systems. Familiarity with the available actuation choices can optimize the effectiveness of the morphing insulation while contributing to the enhancement and refinement of ongoing research in the design of this insulation type.

Researchers have explored various actuation methods for topology morphing insulation, including mechanical, thermal, electrical, and pneumatic approaches, as shown in Table 11. Mechanical actuation uses mechanical components such as hinges, springs, or motors to induce the desired motion and transformation of the insulation. Thermal actuation relies on temperature changes to trigger the shape change or phase transition of the insulation material. Electrical actuation utilizes electrical stimuli such as voltage or current to drive the actuation process. Pneumatic actuation involves the use of air or another gas to generate pressure that deforms or the insulation or triggers its deployment. Research into actuating topology morphing insulation may benefit from discussion in other disciplines, such as the examples and methods shown in Tables 11 and 12. The choice of actuation method depends on various factors, including the specific application, desired performance, cost, and practical considerations. Each approach has its own benefits and drawbacks.

For example, mechanical actuation methods offer precise control and can be easily integrated into the insulation system. However, they may introduce mechanical complexity and potential points of failure. Thermal actuation methods can be advantageous in terms of simplicity and energy efficiency, but may require careful management of temperature changes and thermal insulation to prevent unintended actuation. For instance, the actuation mechanism may need to be artificially heated or cooled to trigger the change between insulating and conducting states. In contrast, while electrical actuation provides flexibility and programmability, it may require additional power sources and electrical components, increasing complexity and potentially leading to reliability issues. Pneumatic actuation offers a lightweight and versatile option, although it typically requires a compressed air supply and sealing mechanisms to maintain pressure. While it is possible to manually add or remove insulation from a building, this process necessitates access to the cavities where the insulation is stored, which might be aesthetically displeasing to occupants and could make the procedure cumbersome. However, the inclusion of an actuation mechanism specifically installed into the insulation could make manual adjustment more cost-effective. Different actuation methods may have varying degrees of efficiency, precision, and controllability. By considering these factors, researchers can optimize the design and operation of topology morphing insulation systems, leading to improved energy efficiency and thermal performance.

Ideally, topology morphing insulation systems should incorporate actuation methods that ensure reliability and safety. For instance, in the case of static vacuum insulated panels it is crucial to their design to have multiple points of failure to prevent a single failure compromising the insulation's performance. With topology morphing insulation, the system should be designed to fail in the insulating state in order to provide static insulation in the event of actuation failure.

There are other practical reasons for research in topology morphing insulation, including simulations, to always include actuation methods. First, actuation methods play a crucial role in enabling the dynamic alteration of insulation materials or systems, which is the fundamental principle of topology morphing insulation. By incorporating an actuation method into a design, researchers can explore and evaluate the effectiveness of different techniques in achieving the desired changes in the physical characteristics of the insulation and how the actuation method might impact the effectiveness of the insulation.

Second, actuation methods are essential for understanding the practical implementation and feasibility of topology morphing insulation in real-world applications. By studying and comparing various actuation methods, researchers can assess factors such as energy requirements, control mechanisms, response times, and reliability. This information is crucial for determining the viability and scalability of topology morphing insulation technologies in different contexts, ranging from small-scale prototypes to full-scale building systems.

Incorporating actuation allows researchers to identify and address issues such as mechanical constraints, material compatibility, integration with existing building systems, and long-term durability. By studying actuation methods alongside other aspects of topology morphing insulation, researchers can develop comprehensive and practical solutions that can be effectively implemented in real-world applications.

Table 11. Actuation methods for topology morphing insulation designed for buildings, where "N/A" indicates missing data or the actuation method was not discussed in the corresponding research. Data taken from Tables 1, 3, 5 and 7.

Mode	Actuation Methods					N/A
	Electrical	**Manual**	**Electromechanical**	**Pressure**	**Thermal**	
Conduction	1	1	1	2		1
Convection			1			2
Radiation	3		4		2	8
Multimodal			1		1	5

Table 12. Actuation methods for topology morphing insulation designed for non-building devices, where "N/A" indicates missing data or the actuation method was not discussed in the corresponding research. Data taken from Tables 2, 4, 6 and 8.

Mode	Actuation Methods							N/A
	Electrical	Magnetic	Electromechanical	Pressure	Thermal	Thermo-Moisture	Moisture	
Conduction	3	1	1	5	5	1		7
Convection			2		2	1		4
Radiation			2		4			9
Multimodal	1					1	1	7

Simulations that do not consider actuation play a valuable role in estimating climate requirements for insulation, projecting energy performance, and conducting cost analyses. For instance, studies such as Menyhart et al. [35] and Dehwah et al. [191] have demonstrated the usefulness of such simulations in evaluating the potential benefits and cost effectiveness of topology morphing insulation. However, it is important to note that a significant number of the reviewed articles lacked discussion or indication of how the devices can be actuated. This gap is evident in Tables 11 and 12, which present the actuation methods used in building insulation designs and non-building concepts. The absence of actuation considerations limits the practical implementation and realization of topology morphing insulation systems. Therefore, future research should aim to address this gap by incorporating actuation mechanisms into research, as this enables a more comprehensive analysis of the performance and feasibility of topology morphing insulation in real-world applications.

Further examination reveals that among the materials used to actuate topology morphing insulation, such as air [79–81], bimetals [65,157,160], carbon nanotubes [184], metals (e.g., compliant micro-mirrors) [63,64,144,145], PCMs (expansion during phased change used to connect components) [66,142], and SMAs [59,69,84,104,109,134,160,163,164,181], among the most common are SMAs, PCMs, and metals. Using these materials as the form of actuation reflects the aforementioned issues around dynamic insulation materials. Relying solely on a single actuation behavior may not be the most optimal approach. Many common actuation materials exhibit shape change in response to a single stimulus, often involving temperature. However, uniform and fixed behavior throughout the insulation system may not be desirable, particularly when considering diverse preferences, wall locations (in the context of a single sensor triggering shape change), and varying seasons [36,151,152]. The choice between automatic temperature-based inputs or other control algorithms, as well as the scale of control regions (such as controlling an entire house as one variable, specific walls, or localized regions within a wall), should be carefully considered in order to tailor the insulation's behavior effectively. Therefore, an ideal approach may involve topology morphing insulation that employs an actuation method capable of responding to a desired stimulus for transitioning between insulating and conducting states on demand.

7.3. Manufacturing

Including manufacturing methods in research on topology morphing insulation is essential, for similar reasons as the inclusion of actuation methods. A comprehensive understanding of the manufacturing processes associated with topology morphing insulation is crucial for assessing its scalability and practicality in real-world applications. Different manufacturing methods can vary in terms of complexity, cost-effectiveness, and compatibility with existing insulation manufacturing processes. By considering manufacturing aspects, researchers can evaluate the feasibility of mass production and integration of topology morphing insulation into the building construction industry. Analyzing manufacturing helps to identify potential challenges and opportunities related to cost, efficiency, and market adoption. By addressing manufacturing considerations, researchers can ensure that their proposed designs are theoretically effective, economically viable, and compatible with current manufacturing practices.

The selection of appropriate manufacturing methods is of utmost importance in determining the performance and characteristics of insulation materials or systems. These methods directly influence crucial parameters such as material composition, structure, surface properties, and overall quality, which are instrumental in achieving the desired thermal properties, durability, and mechanical performance of topology morphing insulation. By optimizing these parameters and choosing cost-effective manufacturing processes, researchers can develop efficient and reliable insulation solutions [192–195]. Furthermore, understanding manufacturing methods provides valuable insights into the materials and resources required for insulation production (refer to sources such as Schiavoni et al. [40] and Kumar et al. [41] for comparisons of various insulation materials). This knowledge allows researchers to assess the availability and environmental impact of selected manufacturing processes, aligning with the increasing demand for eco-friendly and sustainable construction practices. By considering sustainable manufacturing techniques, researchers can contribute to reducing the carbon footprint associated with topology morphing insulation production and promote the principles of green building and sustainable design.

It is likely that a range of different manufacturing processes will be required for topology morphing insulation. Topology morphing building insulation research has utilized a diverse array of materials, including insulation and actuation materials: acrylic [133], air [60,68,79,81,104], bimetals [181], glass fiber [132,159,160], metal [60,64,66,69,70,144,145,154,164,166], multi-layer insulation [161,163], PCMs [146], polyisocyanurate foam [60,100], polystyrene [57,131], and polyurethane [79,80,84]. Incorporating dynamic materials such as PCMs in certain approaches enhances the space- and time-varying capabilities of topology morphing insulation. It is important to recognize the limitations of relying solely on a single material, as different scenarios may require diverse solutions. Sheet materials, which offer efficient storage, protection against environmental factors, and versatility in packaging and handling, are advantageous for this purpose. Their lightweight nature not only contributes to cost savings, it can simplify the storage and transportation processes. Moreover, the integration of various sheet materials enables the incorporation of additional features such as energy storage using PCMs, moisture barriers, radiation shielding, and integrated sensors. This multi-material approach significantly enhances the functionality and performance of topology morphing insulation, expanding its potential applications and effectiveness in regulating heat transfer across a wide range of contexts.

7.4. Evaluation Metrics

Comparing the effectiveness of insulation technologies poses a considerable challenge in the field of building envelope research. One of the major obstacles arises from the diversity of methods used by researchers to quantify the effectiveness of their insulation designs. Different studies may adopt various performance metrics, e.g., energy savings, U-value, heat transfer coefficient, effective thermal conductivity, absorption ratio, and relative change of transmission, making it challenging to directly compare the outcomes and draw meaningful conclusions. To address this issue and improve the research in this domain, it is essential to standardize the metrics used for evaluating the effectiveness of insulation systems. By establishing a common benchmark, researchers will be able to compare their dynamic insulation designs against static insulation, facilitating comparisons with other dynamic insulation solutions.

A promising metric that can effectively address this need is the U-factor ratio, which is defined as the ratio of the U-factor of the conducting state to that of the insulating state. The U-factor, sometimes known as the thermal transmittance or heat transfer coefficient, is a measure of the rate of heat transfer through a building material or assembly. The U-factor is the reciprocal of the R-value, a common measure of thermal resistance in buildings, and is a widely recognized measure of thermal transmittance, indicating the rate of heat transfer through the material or assembly. By employing the U-factor ratio as a standardized metric, researchers can directly compare the thermal performance of dynamic insulation designs in both conducting and insulating states. This standardized approach can provide a consistent and clear way to evaluate the relative effectiveness of various topology morphing insulation solutions across different research studies.

Implementing a standardized metric such as the U-factor ratio and providing the U-factor of at least one state, i.e., insulating or conducting, not only enhances comparability in dynamic insulation research, it promotes further advancements in the field. Researchers can leverage this common benchmark to identify design improvements, assess the impact of different actuation methods, and optimize the thermal performance of topology morphing insulation for specific applications. Ultimately, such standardization will lead to more efficient and reliable insulation solutions, fostering progress in energy-efficient building design and contributing to the broader goal of sustainable and resilient construction practices.

7.5. Applications by Building Envelope Component

Designing topology morphing insulation with a specific target location on or within the building envelope impacts the limitations of the device. Different components of the building envelope exhibit varying heat transfer mechanisms and environmental conditions; for instance, the roof experiences more solar radiation than the floor. By focusing on a particular part, designers can customize insulation solutions to effectively regulate heat transfer in specific areas. Additionally, each part of the building envelope may have unique requirements and limitations in terms of available space, structural considerations, and aesthetic integration.

The distribution of topology morphing insulation designs across various components of the building envelope, as shown in Table 13, indicates that most existing research targets the wall or façade. Notably, there are no solutions for the floor and very few for the roof. The roof, for instance, has significant potential for energy savings, as indicated in the researched by Dehwah et al. [36], and is generally an easier place to for installation, involving less displacement of occupants than other locations. Several proposed designs, especially multimodal cases, involve elements that are designed for multiple components of the envelope; for instance, the configuration depicted in Figure 9b is visible across the opaque envelope, as illustrated in Figure 14b. While research on topology morphing insulation applied across the entire building envelope is currently limited (see Table 13), its significance emerges when accounting for diverse thermal conditions across envelope sections. Enabling the application of envelope-wide topology morphing insulation offers cohesive energy efficiency, comfort, and adaptable designs tailored to various climates and occupant needs throughout the building structure, extending beyond the conventional focus on the building envelope alone.

Table 13. Variety of topology morphing insulation designs targeted at specific components within the building envelope, including designs intended for the entire opaque envelope. Note that several multimodal insulation targets multiple components of the building envelope; therefore, the total count here is larger than that in previous tables. Data taken from Tables 1, 3, 5 and 7.

Mode	Component of Building Envelope				
	Façade	Roof	Wall	Window	Opaque Envelope
Conduction		1	4		2
Convection	1		1	1	
Radiation	3			14	
Multimodal	1	1	2	4	2

7.6. Enhancements, Considerations, and Prospects

Dynamic insulation regulates heat transfer by employing elements that transition between insulating and conducting states. The responsiveness of these elements is directly linked to energy efficiency, and depends on factors such as application (e.g., north-facing versus south-facing walls), climate, desired thermal performance, and occupant comfort expectations. These factors might lead to various intervals governing when the system switches states, (ranging from seasonal, diurnal, and hourly variations to minute or second intervals); however, there is a switching delay during the transition between states of the system. Systems designed to respond faster experience increased wear compared to those switching on a diurnal or seasonal level. A shorter response time may be preferred to allow for fast adaptation to rapid changes in external conditions, while a longer response time may be acceptable for applications with slower fluctuations [147]. Balancing the switching delay when changing insulating states against energy savings is essential for ensuring the longevity and value of topology morphing insulation. Ongoing research and development efforts should include elements indicating the switching delay of a design and its impact on the system's heat transfer. By understanding and addressing the challenges associated with response times, researchers and designers can further enhance the performance and effectiveness of dynamic insulation in achieving energy efficiency and thermal comfort in buildings.

7.6.1. Dynamic Control Algorithms

Dynamic control algorithms play a crucial role in precisely determining the switching point of insulation states, offering significant advantages in regulating the thermal properties of building insulation [35,36,137,149,151,152,196,197]. These algorithms utilize computational models, optimization techniques, and real-time data to dynamically adjust the characteristics of the insulation system. By continuously monitoring indoor and outdoor conditions, such as temperature, humidity, occupancy and occupant comfort, and external factors such as connections to grid and weather stations, these algorithms enable automated adjustments that can optimize the control of heat flow through the structure. This dynamic response ensures efficient energy management by reducing heat loss or gain during varying thermal conditions, ultimately optimizing energy efficiency, thermal comfort, and overall building performance. Incorporating dynamic control algorithms in studies for topology morphing insulation allows researchers and designers to evaluate the effectiveness and efficiency of the insulation in diverse scenarios, leading to improvements in design, control strategies, and energy management practices. This iterative process contributes to the development of more advanced and optimized insulation solutions.

Despite the significant amount of research into these algorithms, there has been very little experimental validation. As the size of topology morphing insulation prototypes increases beyond lab-scale, it will become necessary to compare the predicted efficiency of these algorithms to experimental data. This includes fatigue testing of the insulation while checking the reliability of the actuation methods. Unlike other forms of dynamic insulation, e.g., thermochromic materials, PCMs, and piped-insulation, which do not move, topology morphing insulation's components suffer from repeated strain, the results of which are not included in most topology morphing insulation control algorithm research.

7.6.2. Life Cycle Assessment

Life Cycle Assessment (LCA) plays a crucial role in evaluating the environmental and economic viability as well as the long-term sustainability of topology morphing insulation solutions. LCA is a systematic method that evaluates the environmental impacts of a product, process, or system throughout its entire life cycle [198,199]. It considers inputs, outputs, and potential environmental impacts at each stage, guiding sustainable design decisions and identifying areas for improvement. LCA quantifies and compares indicators such as emissions, energy consumption, water use, and waste generation to promote environmentally sustainable practices. By assessing the total cost of ownership, including energy consumption, maintenance, and potential replacement costs, LCA offers insights into the benefits of adopting topology morphing insulation. This method enables the comparison of insulation options and the identification of cost-effective solutions for specific contexts. Integrating LCA into decision-making optimizes both thermal performance and financial feasibility. LCA findings support sustainable building practices and environmentally conscious choices. Many existing studies on building insulation LCA can offer insights for researchers and designers.

Researchers have conducted LCAs for various static and dynamic insulation materials, including bio-based insulation [200,201], nano-insulation [202], PCMs [203], polyurethane [204], thermochromic materials [205], and XPS [206]. However, there is a noticeable absence of LCAs specific to topology morphing insulation, with the exception of a few studies on blinds [207,208]. This gap in the existing research presents a challenge, as without LCAs dedicated to topology morphing insulation certain potential issues, such as the impact of sun damage on materials such as polystyrene leading to higher water absorption [209], may remain undiscovered in many topology morphing insulation designs. Flaws that might be revealed through LCAs could go unnoticed in lab tests or simulations of these designs, making LCA an essential tool for comprehensive assessment.

7.6.3. Applicable Concepts from Non-Building Applications

Insulation research in building science can be enriched by exploring other fields for inspiration and insights. Beyond traditional building concepts, the study of natural adaptations and engineered mechanisms for regulating heat transfer holds great promise for future advancements. Researchers can draw inspiration from diverse sources, such as the thermoregulation mechanisms of animals and plants, to understand the principles and strategies employed in heat transfer control. Furthermore, fields with similarities to building insulation, such as textiles and spacecraft thermal control, offer valuable insights and practical inspiration due to shared restrictions and challenges. Textiles and topology morphing building insulation share such common requirements as flexibility, durability, standardized thermal performance, and motion limitations. These similarities make textiles, especially clothing made of state-of-the-art textiles, an excellent source of inspiration for the development of innovative insulation solutions. Similar to buildings, spacecraft are exposed to time-varying irradiation, and must adjust to variations in heat generation within the body of the structure. By drawing upon knowledge and techniques from these related fields, researchers can explore new approaches and materials that have the potential for scalability and practical application in the building industry. This interdisciplinary approach has the power to revolutionize building science and drive the development of energy-efficient technologies and designs for a more sustainable built environment.

Other potential applications might come from compliant mechanisms. These mechanisms, designed to achieve motion and flexibility through the inherent deformation of materials rather than traditional rigid components, can offer unique advantages in insulation applications. Bimetals [65,157,160], compliant micro-mirrors [126,135,144,145], blinds and shades [121,123,180], and SMAs [59,69,84,104,109,134,160,163,164,181] are a few examples of topology morphing insulation using compliance. The ability to achieve precise, controlled motion without the need for traditional mechanical components makes these attractive options for topology morphing insulation.

When designing compliant topology morphing insulation, factors such as the Poisson ratio must be carefully controlled. Research into mechanical metamaterials [210–215] offers a unique avenue of application; metamaterials have internal cavities, and the entire deformation geometry of the structure can be controlled through the Poisson ratio. However, in order to incorporate compliant mechanisms into insulation at an affordable cost, future research will have to carry out design from a manufacturing perspective. One low-cost approach could be to use sheet materials such as textiles and manufacture the insulation flat, i.e., in the conducting state. Manufacturing from this perspective could enable further exploration of biomimetics (such as the unexplored behaviors observed in [216,217]) and textiles. This method of manufacturing a new set of compliant mechanism devices has the potential to pave the way for innovative and cost-effective solutions in the field of topology morphing insulation.

7.6.4. Challenges

Several additional engineering and practical considerations deserve attention. Among them, regulating cavity size is a fundamental challenge. Most topology morphing insulation relies on the thermal resistance of a gas (usually air), while heat flow is controlled by changing the cavity size. However, shape-changing insulation must be able to survive the fatigue induced by repeated shifts between the insulating and conducting states.

Closely related to the consideration of cavity size is the relationship between insulating materials, specifically, the volume fraction of insulating material to gas within the insulation system. When the volume fraction of insulating material increases, the thermal properties of the material become more critical, as the properties of the gas begin to dominate and convection has a greater influence over the system's heat transfer. This relationship between cavity size and material composition is not unique to insulation; for instance, the thermal properties of spray polyurethane foam depend on internal bubble sizes [218,219]. However, cavities in topology morphing insulation change their shape, and maintaining the U-value requires the cavity sizes to remain consistent in each state (i.e., insulating or conducting). As with traditional insulation, the insulative properties of topology morphing insulation can be improved with future material enhancements provided that the material can withstand the required conditions, including fatigue. In this way, designs that can consistently maintain the cavity size can lead to an increased U-factor ratio as the R-value of the solid insulating material rises.

Regulation of air and moisture permeation in topology morphing insulation systems is another unaddressed challenge. Traditional insulation materials often rely on airtight barriers to mitigate unwanted air and moisture infiltration, thereby ensuring the longevity and efficiency of the insulation. However, topology morphing insulation, with its dynamic nature and shape-changing capabilities, can be susceptible to air and moisture permeation. As insulation systems transition between insulating and conducting states, maintaining an effective seal against air and moisture infiltration becomes more complex. The infiltration of moisture, in particular, can lead to reduced thermal performance, mold growth, and structural degradation over time.

These challenges must be comprehensively addressed in order to facilitate the effective integration of topology morphing insulation into the consumer market. Any insulation system, including topology morphing variants, needs to comply with local building codes and fire safety regulations in order to ensure the safety and well-being of occupants. Moreover, to ensure widespread adoption these systems must be designed and installed in a manner that construction workers are familiar with and can efficiently work with, whether in the form of batts, foam boards, or other common insulation methods. To further promote adoption and align with emerging trends in smart or grid-responsive buildings, researchers should explore the potential incorporation of sensors and feedback systems. These additions could enhance the adaptability and controllability of topology morphing insulation, making it a more valuable and attractive choice for both builders and homeowners.

8. Conclusions

Topology morphing insulation offers innovative solutions for optimizing heat transfer control and reducing energy consumption in buildings. By dynamically altering insulation materials and systems to adapt to changing environmental conditions and regulate heat transfer, this approach opens up new possibilities in building envelope design. These advancements have the potential to yield substantial energy savings (up to 109% relative to static shading insulation, including energy created through photovoltaics [112]), thereby contributing to the broader goals of sustainability and energy efficiency in the construction sector.

Researchers should consider the specific mode of heat transfer targeted by their insulation designs, and should be aware of their integration within the building envelope and potential adaptations for other components. Factors such as cost, market adoptability, sustainability, reliability, and high U-value ratios should be thoroughly reviewed during the design process. Manufacturing processes and actuation mechanisms, along with their impacts on the proposed insulation, require careful consideration as well. The timing of state transitions in topology morphing insulation systems is critical, and the integration of dynamic control algorithms, real-time monitoring, and computational models enables precise adjustments for improved thermal performance. Life cycle assessment provides valuable insights into the economic and environmental benefits of adopting topology morphing insulation solutions. However, researchers should not limit themselves to exploring insulating systems within the building energy space. Drawing inspiration from natural adaptations and exploring other non-building concepts can inspire innovative insulation designs that mimic or enhance natural heat transfer mechanisms. Balancing response time and system durability is crucial for effective implementation, and ongoing research and development efforts are focused on refining response time, material properties, and control strategies to optimize performance and reliability.

Despite its potential, the practical implementation of topology morphing insulation hinges on resolving critical manufacturing challenges at reasonable cost. While the concept shows immense potential in theory, addressing manufacturing feasibility is crucial for its real-world application. The transition from theoretical research to practical and scalable solutions necessitates overcoming these manufacturing barriers. Successful resolution of these challenges could pave the way for the seamless integration of topology morphing insulation systems into buildings, driving significant advancements in energy efficiency and occupant comfort.

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Abbreviations

The following abbreviations are used in this manuscript:

LCA	Life Cycle Assessment
PCM	Phase Change Material
SMA	Shape Memory Alloy
XPS	Extruded Polystyrene Insulation
C	thermal conductance
Clo	unit of thermal insulation, where 1 $clo = 0.155\ \mathrm{m}^2\ °\mathrm{C/W}$
M_e	degradation factor for radiative heat transport
M_k	degradation factor for radiative heat conductance
R_{con}	conducting thermal resistance
R_{ins}	insulating thermal resistance
R-Value$_{con}$	conducting R-value
R-Value$_{ins}$	insulating R-value
k	thermal conductivity
α	radiative absorptance
ϵ	emissivity
γ	usage effectiveness factor ($R_{\mathrm{ins}}k/L$)
λ_{con}	thermal conductivity conducting state
λ_{ins}	thermal conductivity insulating state
ρ	radiative reflectance
τ	radiative transmittance

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