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Review

A Comparative Study on Smart Windows Focusing on Climate-Based Energy Performance and Users' Comfort Attributes

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Abstract: A facade can control interaction between the building and the environment. Advancements in control technologies and material science give the opportunity of using smart windows in a high-performance facade to improve the building's energy performance and users' comfort. This study aims to propose practical recommendations for smart windows' implementation over various climate zones across the world. To follow this aim, 54 studies published from 2013 to 2022 collected from architecture, engineering, and material science databases and have been reviewed, and seven types of smart windows including electrochromic, photovoltachromic, gasochromic, thermochromic, photochromic, hydrochromic, and Low-E have been identified. Moreover, the thermal properties and visual features of smart coatings used in the windows and their impacts on energy efficiency and users' comfort were recognized. Then, a comparative study was conducted to identify and propose the most efficient coating utilized in the structure of smart windows across different climate zones.

Keywords: building performance; smart windows; responsive facades; users' comfort; energy efficiency

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1. Introduction

The building industry is responsible for 40% of global energy consumption annually, which leads to almost 39% of carbon emissions worldwide [1]. Consequently, buildings could account for global warming and other environmental disasters. Among the many different building components, it has been proven that building façades could significantly control buildings' energy consumption and carbon emissions [2]. Recent advancements in control technologies and material science have provided opportunities to develop high-performance facades [3]. As a type of high-performance facade, a responsive facade can change its functions, features, and behavior in response to environmental stimuli and occupants' needs and preferences to improve thermal, visual, and acoustic performance and reduce energy consumption in buildings [3–5]. Responsive facades can be categorized into different types based on control technologies used in their structure, including mechanical-based, electromechanical-based, information-based, and material-based technologies [4–6]. Considering the drawbacks of mechanical-based, electromechanical-based, and information-based types, designers and scholars have expanded the application of smart materials in the design and development of responsive facades [6]. Smart materials can alter their inherent properties with application of external stimuli, such as stress, temperature, moisture, pH, electrical fields, and magnetic fields in a controlled fashion [7,8]. Smart coatings are thin films applied on the surfaces of objects such as windows to provide capabilities for the glass to dramatically adjust its own color transparency and consequently its reflective properties upon exposure to various environmental stimuli [9,10]. Different types of smart coatings such as electrochromic, gasochromic, Photovoltachromic, Thermochromic, Photochromic Hydrochromic, and Low-E have been utilized to develop smart windows for responsive facade systems [11–19]. Reviewing more than 50 studies with the keywords of smart windows published between 2013–2020 reveals only one or two types of smart coatings have been considered as the scope of the review studies [14,16,20–22]. However, reviewing the existing literature shows the absence of a comparative study considering entire types of smart windows with their practical applications in high-performance buildings [23–25]. Only a few studies focused on the effectiveness of coating technologies used in smart windows on energy consumption and users' comfort [23–25].

This study identified multiple advanced smart glazing. Then, a comparative analysis was conducted by considering smart window properties, including thermal transmittance rate (U-value), solar heat gain coefficient (SHGC), light-to-solar gain ratio (LSG), shading coefficient (SC), visible transmittance ratio (T_{vis}), solar transmittance ratio (T_{sol}), visible transmittance (VT), and reflectance to explore the efficient applications of smart windows in various climate zones worldwide [26–32]. Color-coded continent maps associated with Koppen climate classification were utilized to depict efficient smart window types in every climate zone considering the thermal properties and visual features of smart coatings. A comparative analysis of existing smart windows provides a useful resource for educators, researchers, and building industry professionals and offers benefits to their practices, educational, and research activities.

2. Methodology

Academic research databases including ScienceDirect, Scopus, and Web of Science were used to identify research articles with smart window types in their titles, abstracts, or keywords published between 2013–2022. It needs to be noted that the databases exploration in this study was limited to only seven types of smart windows including electrochromic, photovoltachromic, gasochromic, thermochromic, photochromic, hydrochromic, and Low-E. As eligibility criteria, unrelated, duplicated, unavailable full texts, or abstract-only papers were excluded manually from the search results. Among various identified studies, research articles focused on the effectiveness of smart coating technologies on energy efficiency and/or users' comfort were selected for further analysis. Alongside original research studies, previous review articles in smart windows have been explored manually by searching references from included studies or/and reviews. A meta-analysis approach was used to analyze the included articles. In the meta-analysis approach, scientists combine statistical results from previous studies focusing on a specific topic to outline patterns, relationships, or contradictions [33]. In addition, the Sections 5 and 6 of the selected articles were screened to extract information regarding the thermal properties, visual features of smart coatings and climate zones that windows were tested.

3. The Koppen-Geiger Climate Classification System

The Koppen-Geiger system is a classification that divides all climates into five significant zones, including tropical, arid, temperate, cold/continental, and polar. The implemented classification criteria are based on precipitation levels, temperature patterns, and vegetation [33]. Every climate zone and its associated subgroups are presented in two or three letters. The first letter represents climate zones including Tropical (A), Arid (B), Temperate (C), Cold/Continental (D), and Polar (E). While, the second letter indicates the level of precipitation and contains f (Af), m (Am), w (Aw), W (BW), S (BS), s (Cs, Ds), w (Cw, Dw), f (Cf, Df), T (ET), F (EF), representing Rainforest, Monsoon, Savannah, Desert, Steppe, Dry summer, Dry winter, and without dry season, Tundra, and Frost, respectively.

The third letter represents prevailing temperature as h (for B as hot), k (for B as cold), a (for C and D) as hot summer, b (for C and D) as warm summer, c (for C and D) as cold summer and d (for D) as very cold winter [34–37]. Hence Koppen-Geiger system represents 31 different climate combinations. These climatic zones and their associated subgroups are represented in Table 1.

Table 1. Koppen-Geiger Climatic Classifications and Names.

Major Category	Full Category	Name	Description
A	Af	Tropical Rainforest Climate	Tropical Rainforest Climate
	Am	Tropical Monsoon Climate	Tropical Monsoon Climate
	Aw	Tropical Wet Savannah Climate	Tropical Savannah with Dry Winter
	As	Tropical Dry Savannah Climate	Tropical Savannah with Dry Summer
B	BWh	Hot Desert Climate	Hot Desert Climate
	BWk	Cold Desert Climate	Cold Desert Climate
	BSh	Hot Semi-arid Climate	Hot Steppe Climate
	BSk	Cold Semi-arid Climate	Cold Steppe Climate
C	Cfa	Humid Subtropical Climate	Humid Temperate Climate with Hot Summer
	Cfb	Temperate Oceanic Climate	Humid Temperate Climate with Warm Summer
	Cfc	Subpolar Oceanic Climate	Humid Temperate Climate with Cold Summer
	Cwa	Monsoon-Influenced Humid Subtropical Climate	Temperate Climate with Dry Winter and Hot Summer
	Cwb	Subtropical Highland Climate	Temperate Climate with Dry Winter and Warm Summer
	Cwc	Cold Subtropical Highland Climate	Temperate Climate with Dry Winter and Cold Summer
	Csa	Hot Summer Mediterranean Climate	Temperate Climate with Dry and Hot Summer
	Csb	Warm Summer Mediterranean Climate	Temperate Climate with Dry and Warm Summer
	Csc	Cold Summer Mediterranean Climate	Temperate Climate with Dry and Cold Summer
D	Dfa	Hot Summer Humid Continental Climate	Humid Cold Climate with Hot Summer
	Dfb	Warm Summer Humid Continental Climate	Humid Cold Climate with Warm Summer
	Dfc	Subarctic Climate	Humid Cold Climate with Cold Summer
	Dfd	Extremely Cold Subarctic Climate	Humid Cold Climate with Extremely Cold Winter
	Dwa	Monsoon Influenced Hot Summer Humid Continental Climate	Cold Climate with Dry Winter and Hot Summer
	Dwb	Monsoon Influenced Warm Summer Humid Continental Climate	Cold Climate with Dry Winter and Warm Summer
	Dwc	Monsoon-Influenced Subarctic Climate	Cold Climate with Dry Winter and Cold Summer
	Dwd	Monsoon-Influenced Extremely Cold Subarctic Climate	Cold Climate with Dry and Extremely Cold Winter
	Dsa	Hot, Dry Summer Continental Climate	Cold Climate with Dry and Hot Summer
	Dsb	Warm, Dry Summer Continental Climate	Cold Climate with Dry and Warm Summer
	Dsc	Dry Summer Subarctic Climate	Cold Climate with Dry and Cold Summer
	Dsd	Dry Summer Extremely Cold Subarctic Climate	Cold Climate with Dry Summer and very Cold Winter
E	ET	Tundra Climate	Tundra Polar Climate
	EF	Ice Cap Climate	Frost Polar Climate

4. Smart Windows

Smart windows refer to glazing that implements smart coatings to react to the environmental stimuli by changing solar radiation, radiant energy, and visible light to increase energy efficiency and human comfort in buildings [11,16,23,38,39]. These types of windows can highly reduce the need for cooling, heating, and electric lighting in buildings and enhance windows' performance mechanically, chemically, and physically [38,40]. Hence, the building's heating ventilation and air conditioning (HVAC) and electrical energy demand decrease [41,42]. Smart switchable windows respond to alterations in heat, electricity, gas activation, and light by implementing mechanisms including, thermochromism, electrochromism, gasochromism, and photochromism [43,44].

4.1. Different Kinds of Smart Windows

Casini (2018) categorized smart windows into two significant subcategories based on the intellectuality of the material's performance (high-fixed performance and smart performance). High-fixed performance windows include anti-reflectance, Low-E, anti-scratch, and easy-to-clean windows. Also, smart performance windows are defined as self-cleaning, self-heating, passive dynamic control, active dynamic control, energy generation windows, and traditional solar protection system consisting of static solar protection glazing, static shading system, and dynamic shading system [39].

In addition, smart windows can be categorized into passive and active windows based on their controlling system. Electrochromic, gasochromic, and photovoltachromic are controlled actively by changing the electrical field, pouring gas, or changing voltage, respectively. On the other hand, thermochromic, photochromic, hydrochromic, and low-E windows change their features passively by reacting to environmental stimuli, including temperature, light intensity, hydration, and radiation [42].

Passive dynamic control windows provide solar radiation control passively without the presence of an active external system. However, Active dynamic control windows require an external activation system to perform [7,40]. Table 2 provides an overview of previous studies on seven types of smart windows published between 2013–2022. A comparative review was conducted to highlight utilized methods, and dependent and independent variables in the reviewed papers.

Table 2. Different Studies on Smart Windows and Their Application in Buildings.

No.	Study	Year	Coating Type/Independent Variable	Dependent Variables	Methods
1	[44]	2014	Electrochromic	Building Energy Efficiency & cost efficiency	Simulations
2	[45]	2015	Electrochromic	Energy consumption	Simulations
3	[46]	2016	Electrochromic	Visual Comfort & Building Energy Efficiency	Review
4	[46]	2016	Electrochromic	Energy saving & Visual comfort	Laboratory & Physical experiment
5	[47]	2017	Electrochromic	Thermal comfort, Visual comfort & Energy consumption	Simulations
6	[48]	2018	Electrochromic	Energy efficiency with indoor comfort	Review
7	[49]	2020	Electrochromic	Visual comfort, Building energy efficiency & Control Strategies	Review
8	[17]	2021	Electrochromic	Building Energy Efficiency & Visual Comfort	Review
9	[20]	2021	Electrochromic	Visual comfort & Building energy efficiency	Review
10	[50]	2021	Electrochromic	Building energy efficiency & Cost efficiency	Simulations
11	[13]	2014	Photovoltachromic	Building energy efficiency & Visual Comfort	Laboratory & Simulation & Physical experiment
12	[51]	2016	Photovoltachromic	Visual comfort & Building energy efficiency	Laboratory & Simulations
13	[52]	2018	Photovoltachromic	Building energy efficiency (Lighting, Cooling, & Heating demand)	Laboratory & Simulation
14	[53]	2020	Photovoltachromic	Visual comfort & Building energy efficiency	Laboratory & Simulations
15	[54]	2020	Photovoltachromic	Building energy efficiency	Laboratory & Physical experiment
16	[12]	2016	Gasochromic & electrochromic	Energy consumption	Simulation
17	[21]	2021	Gasochromic & electrochromic	Energy consumption	Simulation
18	[55]	2019	Gasochromic	Visual comfort & Building energy efficiency	Simulations
19	[56]	2021	Gasochromic	Building energy efficiency	Laboratory & Simulations
20	[57]	2020	Gasochromic, thermochromic &electrochromic	Energy consumption	Simulation
21	[40]	2013	Thermochromic	Energy-saving potentials & Thermal comfort	Review
22	[45]	2015	Thermochromic	Energy efficiency cooling load	Laboratory
23	[58]	2015	Thermochromic	Thermal comfort, Visual comfort & Energy consumption	Simulations
24	[15]	2018	Thermochromic	Energy-saving performance	Review
25	[59]	2018	Thermochromic	Visual comfort & Building energy efficiency	Laboratory & Simulations

Table 2. *Cont.*

No.	Study	Year	Coating Type/Independent Variable	Dependent Variables	Methods
26	[42]	2019	Thermochromic	Energy-saving performance, Thermal & Visual comfort	Review
27	[60]	2019	Thermochromic	Building energy efficiency	Laboratory & Physical experiment & Simulations
28	[61]	2019	Thermochromic	Visual comfort	Physical experiment & Simulations
29	[62]	2020	Thermochromic	Building energy efficiency	Laboratory & Physical experiment
30	[63]	2021	Thermochromic	Visual comfort	questionnaires
31	[64]	2021	Thermochromic	Building energy efficiency	Simulations
32	[65]	2022	Thermochromic	Building energy efficiency	Laboratory & Simulations
33	[66]	2022	Thermochromic	Building energy efficiency	Laboratory & Simulations
34	[23]	2020	Thermochromic & Electrochromic & Hydrochromic	Energy consumption with heat storage	Laboratory & Simulation
35	[24]	2018	Photo-thermochromic	Energy consumption	Laboratory & Simulation
36	[67]	2021	photo-/electro-driven &Thermochromic	Energy efficiency	Review
37	[14]	2019	Photochromic & Electrochromic & Thermochromic	Energy consumption	Simulation
38	[68]	2017	Photochromic	Energy performance	Simulation
39	[69]	2017	Photochromic	Optical properties	Laboratory
40	[70]	2018	Photochromic	Visual comfort	Laboratory & Simulations
41	[71]	2018	Photochromic	Visual comfort & Building energy efficiency	Laboratory & Simulations
42	[72]	2019	Photochromic	Building energy efficiency	Laboratory
43	[73]	2019	Photochromic	Visual comfort & Building energy efficiency	Laboratory
44	[74]	2020	Photochromic	Visual comfort & Building energy efficiency	Laboratory & Physical experiment
45	[17]	2021	Photochromic	Building energy efficiency	Laboratory & Simulation
46	[75]	2022	Photochromic	Visual comfort	Laboratory & Simulations
47	[76]	2018	Hydrochromic	Visual comfort & Building energy efficiency	Laboratory & Simulations
48	[18]	2020	Hydrochromic	Visual comfort	Laboratory & Physical experiment
49	[77]	2020	Hydrochromic	Visual comfort	Laboratory & Physical experiment
50	[78]	2021	Low-E & Electrochromic	Visual comfort	Review & Simulations
51	[22]	2019	Low-E	Building energy efficiency & CO_2 emissions	Simulations
52	[79]	2019	Low-E	Building energy efficiency	Laboratory & Physical experiment
53	[19]	2021	Low-E	Visual comfort, Building energy efficiency & Resistance	Laboratory & Physical experiment & Simulations
54	[80]	2022	Low-E	Visual Comfort	Simulations

4.2. Electrochromic Smart Windows

Electrochromic (EC) windows are classified as active smart windows. EC smart windows' performance is based on electric charge transfer between the anode and cathode (electrical conductors) [81]. The structure of an electrochromic window is made of glass (Polyester), transparent electrical conductors (anode and cathode), electrochromic coatings, and electrolytes [48]. Transferring ions from the cathode to the anode activates electrochromic material that changes the window's optical features by using a low voltage. Figure 1 shows the structure of electrochromic windows. An electron barrier and an ion conductor layer (electrolyte) are located at the center of the structure, and the two electrochromic (EC) coatings (Tungsten oxide, WO_3) surround the electrolyte. One of the EC layers is connected to the anode, and the other is attached to the cathode (ion banking). Applying a voltage between the anode and cathode will activate ion transfer, and simultaneously the electrochromic material balances this ion transfer which is the reason for optical characteristic changes in the EC windows [82]. Reversing the voltage and implementing short-circuit will reverse the color modification [48]. The electrochromic windows' transition time takes 7–20 min to switch from clear to the tinted stage and vice versa, which gives an appropriate time for occupants' eyes to get used to the lighting conditions [47,49]. Electrochromic windows are usually built as double or triple-glazed units (with two or three panes) to provide enough space for electrolyte material [21]. A summary of various electrochromic glazing characteristics is shown in Table 3. Several scholars previously studied the energy efficiency of smart windows (SW) based on climate and buildings' orientation and visual comfort.

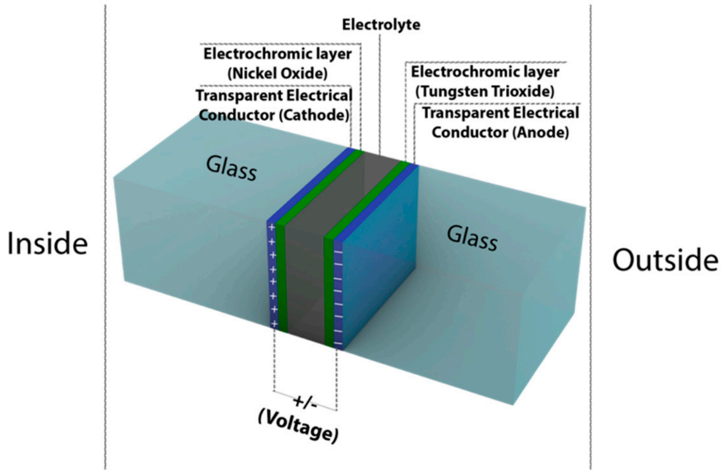


Figure 1. Electrochromic smart window structure [48].

Table 3. Different Types of Smart Windows and Their Physical Characteristics.

Type	Reference	U-Value	SGHC	LSG	SC	T_{vis}	T_{sol}	VT	Reflectance
Electrochromic	[47] [14] [68] [39] [21] [57]	1–1.6 2.2	0.09 0.64–0.15 0.49–0.09 0.6–0.05	1.32–0.22	0.74–0.16	0.75–0.01	0.52–0.01	0.73–0.14	0.168
Gasochromic	[39] [21] [57]	0.9–1.03	0.65–0.28 0.75–0.14 2.6	NA	NA	0.54	0.46	0.54–0.15 0.75–0.01	0.161
Thermochromic	[14] [42] [57]	2.76–1.31	0.31–0.12 0.65	NA	0.542–0.255	0.6–0.043	0.49–0.02 0.53	0.545–0.023	0.078
Photochromic	[14] [68]	5.7–5.9	0.26–0.71	1.79	0.31–0.81	0.83–0.48	0.78–0.09	0.79	0.12
Low-E	[68] [22] [12]	3.58	0.26	1.4–1.3	0.31	0.8–0.478	0.570–0.212	0.55	0.576–0.04
Single Clear Glass	[68] [12] [57]	5.41 2.8	0.82–1.02 0.75	2.73–1.42	0.94	0.74 0.89	0.74	0.88	0.12

4.2.1. EC Windows' Energy Efficiency Based on Koppen-Geiger Climate Zones

Previous studies generally proved the energy efficiency of EC windows in warm and hot regions (Af, Am, As, Aw, BSh, BWh, Cfa, Cfb, Csa, Csb, Cwa, Cwb). In a study about electrochromic smart windows, scientists simulated the energy consumption of the window for 40 scenarios (ten cities and four major geographical orientations) [47]. The simulations for 85% of the scenarios showed effective energy saving using electrochromic windows, especially in warmer U.S. regions such as Miami (Am), New Orleans (Cfa), Atlanta (Cfa), and San Francisco (Csb). Also, in all scenarios, using electrochromic smart windows reduced the heat peak load [47]. Moreover, a reduction of 8.43% in energy consumption and 8.89% in heating, cooling, and lighting was reported by Brzezicki (2021) by reviewing other studies [20]. Most of those studies were conducted in warm and hot regions, or during summer in cold regions. In another review study, Sibilio et al. (2016) concluded that electrochromic windows can improve the energy efficiency of buildings from 39% to 59%. It has been stated that the orientation, controlling strategy, and environmental conditions (cold/warm regions) influence these numbers. The most energy consumption reduction occurred in west-oriented windows, while this consumption reduction is not significant for north-facing windows [47,83–86]. Another study simulated the energy efficiency of an electrochromic Bioinspired Adaptive Facade (BFA) for two locations in Melbourne, Australia (Cfb) and a city in Texas, United States (BSh) [50]. For the building in Melbourne, the designed system showed a 9.3–23.5% and a 14.6–19.6% improvement in Texas, United States, in energy efficiency [50]. In different regions of the United States, studies showed an improvement in energy demand reduction by a maximum of 45–50% [49].

For cold regions and south-facing scenarios (15% of 40 scenarios), the results showed a negative effect on energy consumption because of low internal gains or high infiltration rates and rising cooling loads [47]. However, in a review paper, Cannavale et al. (2020) concluded that in cold climates, electrochromic windows are able to reduce energy loads by 50% and 60% in the west and south-oriented windows, respectively [49]. Brzezicki (2021) stated that using electrochromic windows reduces the heat load in cold regions during summer (BWk, BSk, Dsa, Dsb, Dwa, Dwb, Dfa, Dfb) [20]. The electrochromic window simulated in Tällberg et al. (2019) for Trondheim, a city in Norway (Dfc), decreases energy transfer ranges between 6–22% for different samples compared to regular windows. Another comparative study showed that electrochromic windows are efficient during cooling seasons in Mediterranean climates (Csa, Csb, Csc, Cwa, Cwb, Cwc, Cfa, Cfb, Cfc) [44]. Consequently, EC windows are most effective in hot and warm regions or during warmer seasons.

4.2.2. EC Windows' Energy Efficiency Based on Window Orientation

Tavares et al. (2014) compared electrochromic windows by studying different thermal comfort parameters, including exterior dry bulb temperature, interior dry bulb temperature, and incident radiation [44]. It has been concluded that west-oriented electrochromic windows show the most remarkable improvement in buildings' energy efficiency. The comparison study between conventional single-pane, double-pane, and electrochromic windows in different orientations demonstrated 62% energy demand enhancement on the west side compared to the east side of the building for electrochromic windows in Mediterranean climates (C category) [44]. In Milan, Italy (Cfb), the EC decreased energy consumption by 39.5%, while in Messina, Italy (Csa), this reduction was 64% for south-oriented windows [49].

The study done by Dussault & Gosselin (2017) showed that electrochromic windows have a positive effect on thermal comfort. Generally, using electrochromic windows decreases near-infrared (NIR) transmissions and partially increases thermal comfort in buildings [20]. Furthermore, low cooling demand due to the application of electrochromic glass enhances thermal comfort in hot climates by reducing overheated hours in buildings [21]. Therefore, EC windows are appropriate to be used in warm and hot climates (A, BWh, BSh, and majority of C classification) in the west or south-oriented windows.

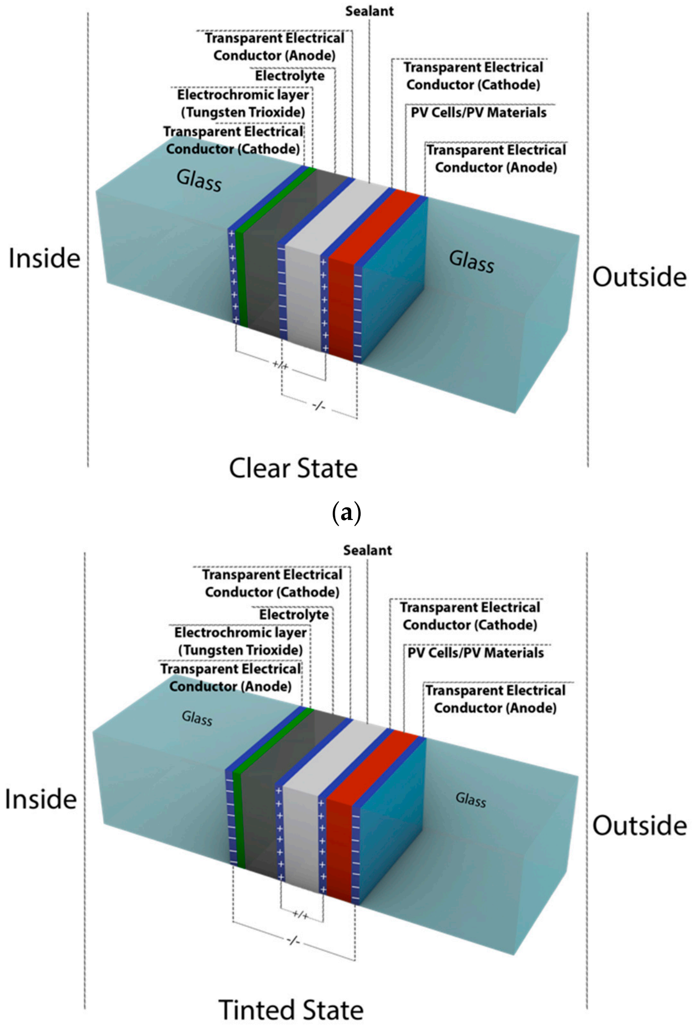
4.2.3. EC Windows' Visual Comfort

As previously mentioned, Dussault & Gosselin (2017) studied multiple scenarios for electrochromic smart windows in a simulated office building in ten different cities, four major orientations, the application of EC or regular windows, and three windows to wall ratios (WWR) (0.33, 0.50, 0.67). Results showed that in two scenarios the visual comfort improved compared to the regular windows [47]. The best visual comfort in electrochromic windows is achievable by using electrochromic and titanium oxide-coated glasses simultaneously [20]. According to Tällberg et al. (2019), daylight gain of electrochromic windows used in Trondheim, Norway (Dfc) demonstrated marginal changes (94–102%). Thus, the electrochromic windows do not affect visual comfort in cold climates. Moreover, the daylight performance in Madrid, Spain (Csa) for electrochromic windows is in the range of 71–80% compared to the regular windows. As a result, the EC windows increase visual comfort in temperate climates (C category). Since the daylight transfer of EC windows in Nairobi is 71–84% of the regular window's daylight transfer, it can be concluded that EC windows increase visual comfort in hot climates (A category and BWh, BSh) [14].

Overall, electrochromic windows save 60% of the building's artificial light demands, reduce cooling load by up to 26%, and reduce glare, reflection, and discomfort near the windows [39]. Energy efficiency simulations of EC windows showed a high energy consumption decrease in warm, hot, and very hot climates (A, BWh, BSh, and C categories), during summer in cold climates (BWk, BSk, Dsa, Dsb, Dwa, Dwb, Dfa, Dfb), and in west and south oriented windows. However, EC windows' energy performance in cold climates and during winter (BWk, BSk, Csc, Cwc, Cfc, Dsc, Dsd, Dwc, Dwd, Dfc, Dfd, ET, EF) is not efficient. Since EC windows' reaction is time-consuming, they are unsuitable for climates with severely changing climate conditions. Also, EC windows do not alter visual comfort in cold climates due to their inefficiency and lower reaction rates in these regions (BWk, BSk, Csc, Cwc, Cfc, Dsc, Dsd, Dwc, Dwd, Dfc, Dfd, ET, EF) [87,88]. In contrast, using EC windows increases the building's visual comfort by 16–29% in warmer environments [47]. Thus, EC windows are only suitable for warm, hot, and very hot regions with intense sunlight, south and west-oriented windows, and during summer (Af, Am, As, Aw, BSh, BWh, Cfa, Cfb, Csa, Csb, Cwa, Cwb).

4.3. Photovoltachromic Smart Windows

One of the drawbacks of EC windows is their need for an external power source to provide activation voltage. This voltage leads to more electricity consumption by EC windows [17]. Hence, scientists proposed photovoltachromic (PVC) systems which integrate EC glazing systems with photovoltaic materials that produce the required activation voltage for the EC part of the PVC windows [55,56]. The optical and thermal properties of PVC windows are illustrated in Table 3. As shown in Figure 2, in the structure of PVC windows, installed PV material on the outer surface of the glass is connected to the transparent conductors of the EC part of the window. Protons transfer between the PV cell's anode and cathode by absorbing sunlight energy and activating the EC materials [54]. Since PVC windows are entirely activated by PV cells, it is considered an active smart window.



(**a**)

(**b**)

Figure 2. Photovoltachromic smart window structure (**a**) Clear state (**b**) Tinted state [54].

4.3.1. PVC Windows' Energy Efficiency Based on Koppen-Geiger Climate Zones

Similar to EC windows, PVCs perform differently in various climates to save energy. Whereas studies conducted on the energy efficiency of PVC windows are limited, they demonstrated potential energy efficiencies in different locations with different climates. In the previous studies, PVC windows' energy efficiency is simulated and evaluated based on climate zones, their energy production, window-to-wall ratio (WWR), and window orientations [53–56,89–93]. Pierucci et al. (2018) studied photovoltachromic windows (PVC) in three regions, including BWh, Csa, and Cfb climates. Their findings demonstrate that PVC increases buildings' energy efficiency in BWh regions by decreasing cooling demands through controlling sunlight absorptions [52].

In a study conducted by Fiorito et al. (2020), the energy-saving potentials of PVC windows were investigated in six cities across Australia (Aw, 2 Cfa regions, Csa, 2 Cfb regions). Results showed a regular energy-saving potential of up to 20% for all cold and cool climates [53]. However, Pierucci et al. (2018) stated that PVCs negatively impacted heating demands by decreasing light absorptions [52].

In hot climates (A category and BWh, BSh), the window-to-wall ratio (WWR) should be high to reach maximum energy efficiency of up to 32% compared to regular windows [90,91].

In tropical regions (A category), energy demand decreased by 6% to 14%, and this reduction for sub-tropical regions (C category) was 6% to 20% considering WWR and window orientation [53]. Favoino et al. (2016) studied the role of controlling systems on the energy efficiency of PVC windows in Sydney (Cfa), Rome (Csa), and London (Cfb) [51]. Compared to the passive strategies, active controlling PVC windows can save 2–12% energy in temperate climates (C category). Because of Rome's (Csa) low heating and cooling demands, switchable glazing can enhance energy efficiency by decreasing lighting energy consumption. In other climates, an active controlling strategy is beneficial for reducing heating or cooling demand or both [51].

4.3.2. PVC Windows' Energy Efficiency Based on Window Orientation and WWR

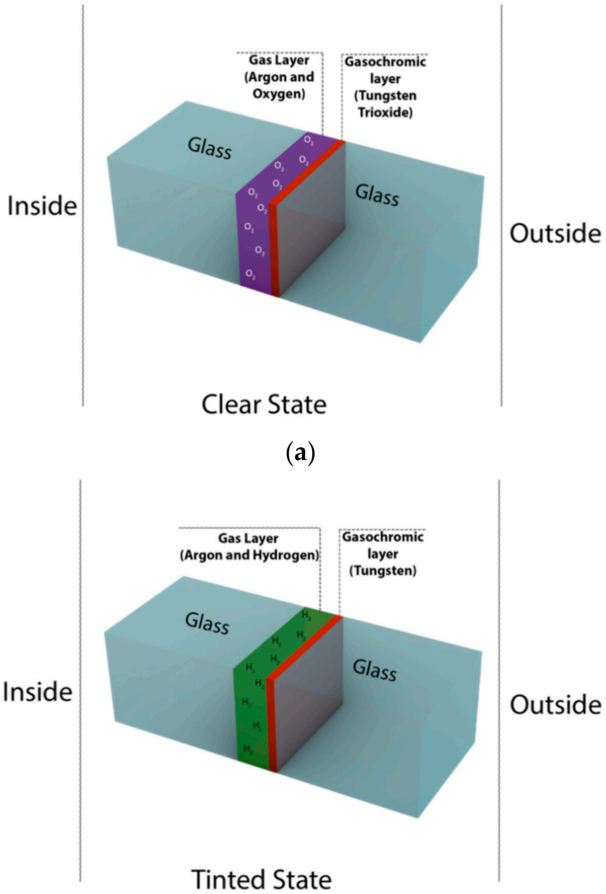
In moderate climates (C category) with hot summers like Australia (Cfa and Csa), north-oriented (sun-facing side) PVC windows reduced energy demand by 23% to 25%, followed by 19–20% in the east and west-oriented windows and 8–10% for south-oriented (sun-rear side) windows. In moderate climates with cold winters (Cfb), using PVC windows lowers the cooling demand by 41%. However, overall, buildings' energy demand with high WWR can be reduced by 32% and 28% in north-oriented and east/west-oriented windows, respectively [53].

One of the disadvantages of photovoltachromic windows is the untransparent photovoltaic section of the window that blocks vision. Pugliese et al. (2020) solved this drawback by proposing a new photovoltachromic window design. The mentioned study has connected three transparent efficient PV cells to produce 2.5-volt power to activate electrochromic material [54].

Photovoltachromic (PVC) windows decrease light absorption and increase thermal comfort in hot regions and during summer, while the thermal comfort for cold regions and in winter decreases by using PVC windows (BWk, BSk, D category and Cfb) [13,53–55]. Therefore, this type of smart window can be used in NetZero buildings to generate the required energy for the PVC window function and other electricity-consumptive activities.

4.4. Gasochromic Smart Windows

Gasochromic (GC) windows respond to infrared (IR) rays by implementing chemochromic coatings that will be triggered by hydrogen or oxygen gases [40,57]. Since another system should pump the gas and activate gasochromic material, GC windows are considered active smart windows [12]. Most GC windows imply porous Tungsten trioxide (WO_3) as the chemochromic films that can be directly coated on the inner side of the exterior glazing pane. However, other gasochromic materials, including Nickel oxide (NiO) and Magnesium alloys, can be coated on GC windows as alternative materials [55]. Different physical characteristics of GC windows have been demonstrated in Table 3. Similar to EC windows, GC smart windows (SWs) react to the solar heat by sunlight absorption, not sunlight reflection. This absorption causes windows to overheat themselves and prevents overheating interior spaces. Gasochromic windows are produced as double or triple-pane units to provide an empty space for pouring the gas. Gasochromic windows' reaction time to sunlight alterations is 20 s up to one minute [21]. As shown in Figure 3, the structure of GC windows consists of two glass panes divided by a space filled with activating gases and the gasochromic layer coated on the interior surface of the outer glass [39]. Hydrogen (H_2) and oxygen (O_2) pour the argon-filled space by sensing changes in the level of the IR rate [12]. The hydrogen mixture with the porous WO_3 changes the color of the smart coating to dark blue. The more tungsten trioxide absorbs H_2, the more a gasochromic window will become more tinted. Exposing WO_3 to oxygen causes the GC window recovers its transparency [12,40,94–96]. The performance of GC windows can be improved by decreasing responding time by injecting water into the structure of the WO_3 and making the chemochromic film more porous [39]. GC windows' equipment requires extra space due to their need for a gas resource which can be challenging for designers. In contrast, GC windows' low reaction time is an advantage for buildings [12,94].



(**a**)

(**b**)

Figure 3. Gasochromic smart window structure and its operational process (**a**) Clear state (**b**) Tinted state [39].

4.4.1. GC Windows' Energy Efficiency Based on Koppen-Geiger Climate Zones

Gasochromic windows react to solar gain ten times quicker than electrochromic windows. Thus, SHGC (Solar heat gain coefficient) and VLT (Visible light transmission) values of gasochromic windows alter quickly. This high SHGC alteration increases the capacity of solar heat gain during winter and solar heat rejection during summer. Accordingly, this window type is more suitable for regions with cold winters and hot summers, including humid continental climates (Dfa and Dfb) [39]. Previous studies in GC windows' energy efficiency followed two strategies including energy efficiency based on climates and coating materials.

In a study conducted by Feng et al. (2016), the energy consumption of GC windows is simulated for five different cities (representing 3 Dwa regions, and 2 Cfa regions) in China. The study's results illustrated that gasochromic windows reduced HVAC (heating, ventilation, and air conditioning system) loads by 28.4% compared to regular single-pane clear glass in Harbin, China (Dwa). Using GC windows in all five climates reduced the HVAC loads by 25–35% [12].

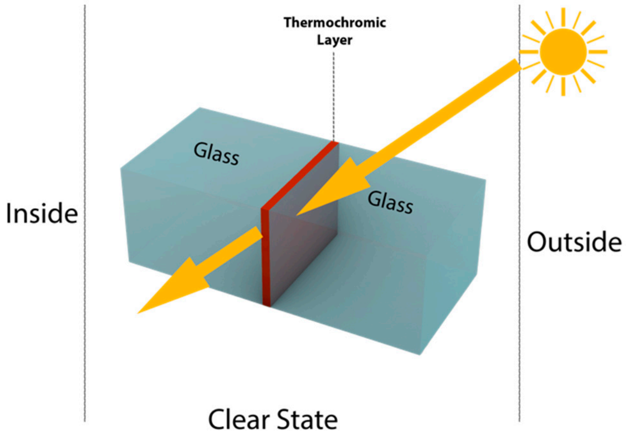
4.4.2. GC Windows' Energy Efficiency Based on Coating Materials

Additionally, scientists simulated magnesium yttrium (Mg-Y) gasochromic windows for an office building in five different climates in China and compared their energy efficiency and visual comfort performance with WO_3 gasochromic windows and regular double-glazed (DG) windows [55]. Researchers simulated all three types of glazing for five typical climate zones in China (2 Dwa regions, 2 Cfa regions, and Cwb). The results showed a 27% improvement in energy efficiency for Mg-Y gasochromic window (GC) compared to DG (double-glazed) windows. However, the difference between WO_3 and Mg-Y GC windows was marginal, simulations revealed enhancements in visual comfort for Mg-Y GC windows compared to WO_3 GC and DG windows. By using Mg-Y GC windows, useful daylight illuminance (UDI) improved by 15%, 7%, 20%, 3%, and 1% for Harbin (Dwa), Beijing (Dwa), Hangzhou (Cfa), Kunming (Cwb), and Guangzhou (Cfa), respectively compared to WO_3 GC windows [55]. Gasochromic windows improved thermal comfort in Cfa and Cwb and reduced cooling demand in buildings [21,57,58]. In Guangzhou (Cfa), Kunming (Cwb), Hangzhou (Cfa), Beijing (Dwa), and Harbin (Dwa) climates, the cooling energy consumption decreased by 10% using Mg-Y as the coating material instead of WO_3 [55]. In an experimental study, researchers developed a gasochromic film from WO_3/SiO_2 to be printed on the surface of windows. Transmittance and energy shielding for that film is 0.9 and 0.84, respectively [56].

Generally, the glazing technologies with lower U-values, including GC windows, are more suitable for hot climates (A category, BWh, BSh, and C category with a and b as the second letter), while windows with higher U-values increase passive thermal comfort in colder regions (BWk, BSk, C category with c as third letter, D and E categories) [21].

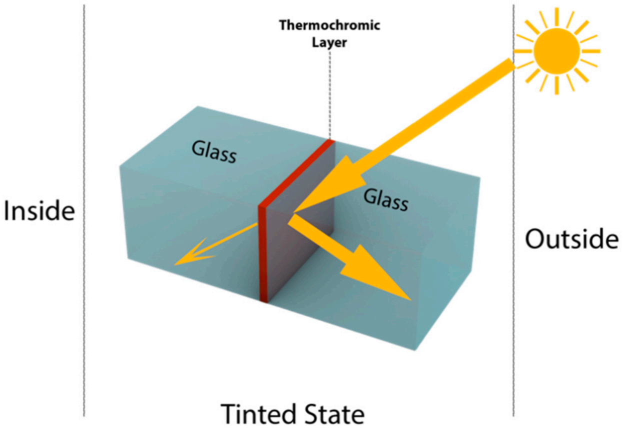
4.5. Thermochromic Smart Windows

Thermochromic (TC) windows are categorized as passive smart windows using thermochromic coatings, containing vanadium oxide (VO_2). TC windows modify the heat intensity and infrared solar rays (IR) inside the building when the environment's temperature exceeds TC coating's transition temperature resulting in window's color tint alterations [43,61,97]. The sunlight collides with VO_2 molecules and causes light rays refraction, which alters solar rays' wavelength resulting in building's heat gain reduction. Various light wavelength poses different levels of solar energy entering buildings. Since light refraction by VO_2 extends solar rays' wavelength, the solar energy level coming through windows reduces [60]. The structure and functionality of TC windows are illustrated in Figure 4. TC windows' physical attributes are summarized in Table 3.



(**a**)

Figure 4. *Cont.*



(**b**)

Figure 4. Thermochromic smart window structure (**a**) Clear state (**b**) Tinted state [60].

4.5.1. TC Windows' Energy Efficiency Based on Koppen-Geiger Climate Zones

Thermochromic windows decrease energy consumption in heating, ventilation, and air conditioning (HVAC) systems by reducing windows' heat gains [42]. By comparing different thermochromic windows' energy-saving performances, researchers concluded that the alteration in climate zones has a more significant impact on annual energy saving than the type of thermochromic material or location of coated materials on the window [42].

Previously, scholars conducted research studies to estimate TC windows' energy efficiency based on climate and coated materials. Lin et al. (2022) proposed a thermochromic smart window using water molecules as thermal barriers with a T_{sol} of 58.4%, thermal reflectance of 57.1%, and luminance transmittance of 78.3%. Simulation results showed that this newly proposed TC window moderates the indoor temperature in nighttime and daytime during all seasons for a residential building in four cities, including Anchorage (Dsc), Beijing (Dwa), Hong Kong (Cwa), and Abu Dhabi (BWh) [65]. Scholars from the University of Nottingham simulated five thermochromic coatings for China's Dwa, Cwb, and Cfa climatic conditions, which showed an overall enhancement in energy saving and desired illumination of 19.9% and 15.52%, respectively [59]. All five designed thermochromic coatings decreased energy consumption and undesired daylighting in warmer regions, while only two improved energy and daylighting efficiency in cold regions. Since thermochromic smart windows mainly reduce energy consumption by preventing heat entrance, they are not appropriate for cold regions (BWk, BSk, C category with c as third letter, D, and E categories) [59]. In similar studies conducted for the Asia Pacific area (A category), thermochromic windows saved 35.9 kWh/m^2 energy annually. In addition, in fifteen Mediterranean cities (C category) and insular semi-arid and arid regions (B category), TC windows reduced cooling energy demand [66,68]. A simulated thermochromic window demonstrated 75.6% and 81.3% enhancement in ΔT_{IR} and ΔT_{solar}, respectively, and a 69.5% reduction in Irradiance [61]. Tällberg, Jelle, et al. (2019) simulated energy delivery for thermochromic windows for Trondheim city (Dfc) that illustrated a 97–132% range energy consumption compared to the regular windows [14].

4.5.2. TC Windows' Energy Efficiency Based on Coating Materials

A study of thermochromic windows revealed a 19.9% building energy-saving enhancement and 54% energy demand reduction compared to typical double-glazed systems [42]. Moreover, VO_2-coated glazing can save 21.7 kWh energy annually in a residential room compared to typical clear windows. Scientists proposed a new structure of vanadium dioxide (VO_2) coating for thermochromic windows inspired by cephalopod to improve privacy and energy efficiency in buildings [66]. This proposed coating material decreases the visible transmittance of thermochromic windows from 60% to 17%. In another similar study, scientists casted VO_2 inspired by the kirigami, a Japanese method of cutting and folding papers, to achieve a solar transmittance difference (ΔT_{sol}) of 37.7% [62,64]. Decreasing windows' solar transmittance reduces heat transfer through windows resulting in a building's energy efficiency.

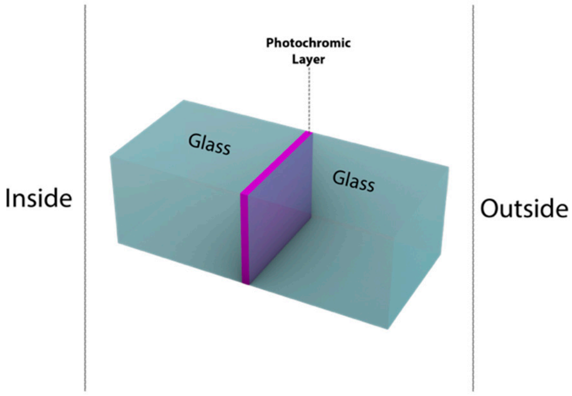
4.5.3. TC Windows' Visual Comfort

Thermochromic SW changes color to react to temperature variations, providing a pleasing color tone for occupants and enhancing visual comfort in buildings. Studies of thermochromic windows showed a significant improvement in visual comfort and UDI near the window, while this comfortability highly decreases with distance from the window [24,43]. Overall, studies showed that the daylight performance of thermochromic windows increased by 15.5% compared to standard double-glazing (DG) windows [42].

Generally, thermochromic windows show energy savings in lighting and cooling ventilation. Moreover, a higher window to wall ratio (WWR) increases the energy-saving ability of thermochromic windows [40]. Scientists concluded that the highest thermochromic windows' efficiency would be achieved by coating VO_2 (Vanadium dioxide) on the inner side of the exterior glass in a double pane thermochromic window [40]. The highest energy saving achievable by DG VO_2 coating strategy is 85%. The decreasing transitional temperature in thermochromic windows results in more tinted hours, which causes an increase in lighting and heating energy demand [40]. Previous studies showed that TC windows can improve energy efficiency by 19.9% and 43% [24,41,43].

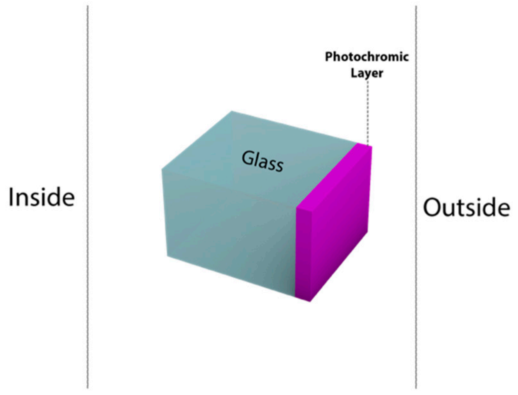
4.6. Photochromic Smart Windows

Photochromic (PC) materials react to light intensity by altering their tinted properties in specific ultraviolet wavelengths (UV) [17]. Photochromic (PC) windows are passively activated smart windows containing a thin layer of photochromic coating. PC windows become more tinted by exposure to UV light with short wavelength (high energy), while in long wavelength conditions or dark hours, they retain their clear state. Different organic and non-organic materials can be utilized as a photochromic coating that should be solved in a solvent to be coated [17,98]. The structure of a multilayered PC window is shown in Figure 5 [70]. The optical features of these windows are summarized in Table 3.



(**a**)

Figure 5. *Cont.*



(**b**)

Figure 5. Photochromic smart window structure with (**a**) double glass and (**b**) multilayer PC coating [70].

4.6.1. PC Windows' Energy Efficiency Based on Koppen-Geiger Climate Zones

Photochromic windows are more effective for visual comfort rather than thermal comfort [17,41]. In previous studies, scientists simulated and evaluated the PC windows' energy efficiency based on climatic zones. PC windows also enhance visual comfort, resulting in artificial lighting reduction, which leads to lowering buildings' energy consumption [41]. Previous studies on the energy efficiency of PC windows are based on climate zones, PC coating's structure and material, and visual comfort.

Zeng et al., (2017) simulated photochromic glazing systems' energy saving for six different US climates, consisting of Am (Miami), Cfa (Gainesville and Atlanta), and Dfa (Richmond, Chicago, and Minneapolis) [68]. They achieved 4.1, 8.2, 19, 29.7, 39.4-, and 47.5-MWh energy savings for each city, respectively. In addition, this study showed a 92.7% heating energy reduction and 20.1% cooling energy reduction in buildings using photochromic systems compared to regular glazing systems. The heating reduction for electrochromic windows, double pane low-E windows, and insulating double pane windows were 56.7%, 52.2%, and 73%, compared to regular windows. The study's results illustrated that photochromic windows are the most suitable glazing systems for cold regions (BWk, BSk, Cfc, Csc, Cwc, D, and E categories) [68].

Cannavale et al., (2021) conducted comprehensive research on the energy efficiency of a spirooxazine-based PC window for a multi-story office building in Brindisi, Italy (Csa) [17]. The scientists simulated the heating, cooling, and visual performance of the proposed PC coating and compared the results to the performance of regular windows under the same conditions. Results showed a significant reduction in cooling energy consumption by 4079 kWh annually for the south-oriented window using PC window compared to a regular window. Moreover, the decrease in artificial lighting demand saved 3711 kWh annually compared to solar-controlled windows [17].

4.6.2. PC Windows' Energy Efficiency Based on Material's Structure

From an experimental study, scientists developed a photochromic window with electricity generation potential, which results in energy consumption and production [72]. Similarly, You & Karazhanov (2020) produced a photochromic film using yttrium oxyhydride (YHO) to be implemented on smart windows or optical sensors [74]. According to the above-mentioned study, the yellow and transparent photochromic films' color tint was mitigated by decreasing temperature and light intensity. Thus, casting these films on smart photochromic windows will increase energy efficiency and visual comfort [74]. Researchers developed a photochromic film in a laboratory that converts visible light to ultra-violate light [71]. These scientists deployed a multilayer PC film which improved solar energy and light intensity absorption by 7 and 5.5 more times compared to a single photochromic layer. Consequently, applying this material to windows results in considerable energy savings and visual comfort in buildings [71]. Photochromic smart windows prevent NIR (near infrared) rays in hot regions (A category, BWh, BSh, Cfa, Cfb, Csa, Csb, Cwa, and Cwb) and reduce the building's cooling energy consumption. While in cold climates (BWk, BSk, Cfc, Csc, Cwc, D, and E categories), PC transfers NIR light to prevent high heating energy demands [68]. Thus, this photochromic glazing prevents extreme heating and cooling in buildings and increases thermal comfort.

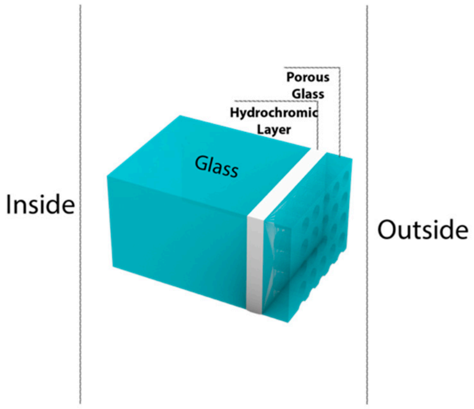
4.6.3. PC Windows' Visual Comfort

Hočevar & Opara Krašovec (2018) developed a photochromic dye lasting more than 12 months, which reduced the visible transmittance (T_{vis}) by 41% [70]. Similarly, L. Wang et al. (2019) proposed a photochromic material produced from transparent wood to improve visual comfort and energy efficiency [73]. In another research, a photochromic fluorescent coating is developed by combining photochromic and photoluminescent materials to continue the light emission after the source elimination. The developed film is scratch-resistant, hydrophobic, and possesses tensile strength [75]. This PC window changes its color to green and white in low and high material concentration regions under ultra-violate light intensity that can produce gentle lighting and save energy in buildings [75].

Overally, Tällberg et al. (2019) indicated that the energy leakage of photochromic windows is between 88–103%, compared to regular windows depending on different climates [14]. However, previous research on photochromic windows revealed that the performance of PC windows is highly dependent on the PC coating material attributes. Thus, different types of PC windows could perform differently under the same environmental conditions. On the other hand, currently conducted studies showed significant heating and lightning energy savings in cold climates. Regarding the high potential of PC windows in energy consumption reduction, further studies should be developed to prove previous findings.

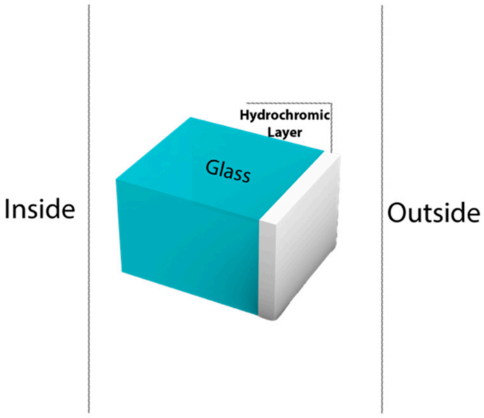
4.7. Hydrochromic Smart Windows

Hydrochromic (HC) materials change their clarity and color intensity based on humidity in the atmosphere [18]. HC materials can be coated on windows to enhance energy efficiency. The structure of HC coatings is highly porous in the micro or nanoscale. Figure 6 shows how hydrochromic materials diffuse light rays by absorbing a small amount of water. The optical characteristics of HC windows change by humidifying and dehumidifying. The wet HC coating is opaque, and by losing humidity, it becomes more transparent [18].



(**a**)

Figure 6. *Cont.*



(**b**)

Figure 6. Hydrochromic smart coating structure with (**a**) porous glass and (**b**) multilayer HC coating [18].

HC Windows' Energy Efficiency and Visual Comfort

The investigations on hydrochromic windows are limited, and further studies should be conducted to reveal the potential of this SW to enhance a building's energy efficiency. To the best of our knowledge, most of the previous studies simulated the visual comfort of HC windows and a limited number of them studied HC windows' energy efficiency. Thus, there is a gap in understanding HC windows' true thermal comfort and energy efficiency.

Scientists developed a porous poly-dimethylsiloxane (PDMS) film inspired by Diphylleia grayi (Skeleton flower) that changes its color intensity by water absorption [76]. This film reacts to humidity within almost 9 min and reaches transmittance of 1% in wet mode from 82% in the dry mode, which could result in increased energy efficiency in buildings under humid weather conditions (Af, Cfa, Cfb, Cfc, Dfa, Dfb, Dfc, and Dfd) [76].

Pyun et al. (2020) developed a hydrochromic film with the original blue color, which changes its color to cranberry or violet in the presence of hydration. According to their findings, the window color is blue in dry and hot conditions, while in wet and cold weather, the color turns to violet [18]. Yoo et al. (2020) introduced a new structure for hydrochromic films, changing their transparency in moisture situations. In this study, the optical transmittance difference between haze and transparent stages is almost 70%. In the scattering phase, the wavelength passing the glass increases by 10%, which causes a reduction in light energy, which consequently will improve visual comfort. The highest transmittance reduction in the white phase was almost 50% for this hydrochromic glass, and the diffusive transmittance was enhanced by 10% in the tinted stage compared to the bleached stage. Thus, this hydrochromic smart window increases visual comfort in humid environments [77].

Accordingly, HC smart windows are beneficial for hot and humid environments to increase visual and thermal comfort and energy efficiency. HC windows change their state from clear to blurry by absorbing moisture from the surrounding environment or implemented devices [76].

4.8. Low Emissivity Smart Windows

Low emissivity (Low-E) coatings are silver-based materials that reflect mid-length IR solar rays (5 µm) to provide thermal barrier surfaces [79]. Low-E windows implement Low-E coatings on their surface to prevent heat transfer through windows. In contrast to the chromic windows, transparency would remain intact in Low-E glasses. Low-E smart windows passively react to changes in the IR intensity. The high price of Low-E (silver-based) materials and the complexity of the vacuum casting strategy required for producing Low-E glasses are the drawbacks of this type of glazing [79]. Figure 7 and Table 3 illustrate the Low-E window structure, functions, and characteristics.

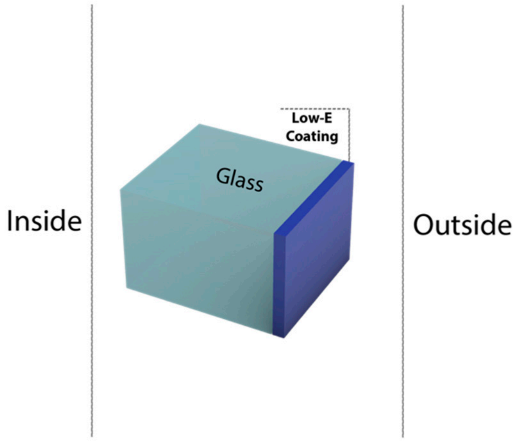


Figure 7. Low-E windows' structure and function [79].

4.8.1. Low-E Windows' Energy Efficiency Based on Koppen-Geiger Climate Zones

Studies on Low-E windows' energy performance revealed considerable potential in enhancing a buildings' energy efficiency in all climate zones. Since interior heat during winter leaks out, the Low-E coating mitigates this heat reflection [98]. Since absorbing moisture changes the color of Low-E material over time, scientists developed thin layers of aluminum nitride (AlN) and silver (Ag) to produce a long-lasting moisture resistance Low-E coating [19]. This low-cost, newly produced material had SHGC of 0.54, VT of 80%, and emissivity of 4.8% [19]. Grosjean & le Baron (2022) measured and analyzed optical features of Low-E windows in 12 different cities in different climates for multi-years [80]. The cities included Beijing (Dwa), Birdsville (BWh), Casleo (BWk), Dakar (BSh), Helsinki (DFb), Neon Wood (CFb), La Parguera (Am), Mezairaa (BWh), Palaiseau (CFb), American Samoa (Af), Seoul (Dwa), and Singapore (Af). According to this study, Low-E glazing can reduce by 5% the longtime transmittance in pollutant climates or with high air mass and aerosols. However, in tropical climates (A category), this transmittance has increased by 1% [80].

4.8.2. Low-E Windows' Energy Efficiency Based on Coating's Implementing Location

The most influential factor in Low-E windows' energy performance is the location of Low-E coating on the windowpanes in different climates [22]. Low-E material can be coated on a double pane glazing in four different positions on the glass. Figure 8 illustrates all four casting locations for Low-E coatings on a double-glazed pane (DGP) window [22]. Consequently, the Low-E layer should be coated on the closest surface of the window to the window side with higher temperatures. Hence, in warm, hot, and very hot climates (A category, BWh, BSh, Cfa, Cfb, Csa, Csb, Cwa, and Cwb), the Low-E coating should be applied to the inner or outer surface of the outer pane (position a or b, according to Figure 8). Following a similar strategy, in cool, cold, very cold, and subtropical climates (BWk, BSk, Cfc, Csc, Cwc, D, and E categories), Low-E coating should be located on the inner or outer surface of the inner pane (position c or d, according to Figure 8). However, most of the previously conducted studies on Low-E evaluated the energy performance based on environmental conditions rather than on the position of the coating. Thus, there is a gap in the Low-E window study.

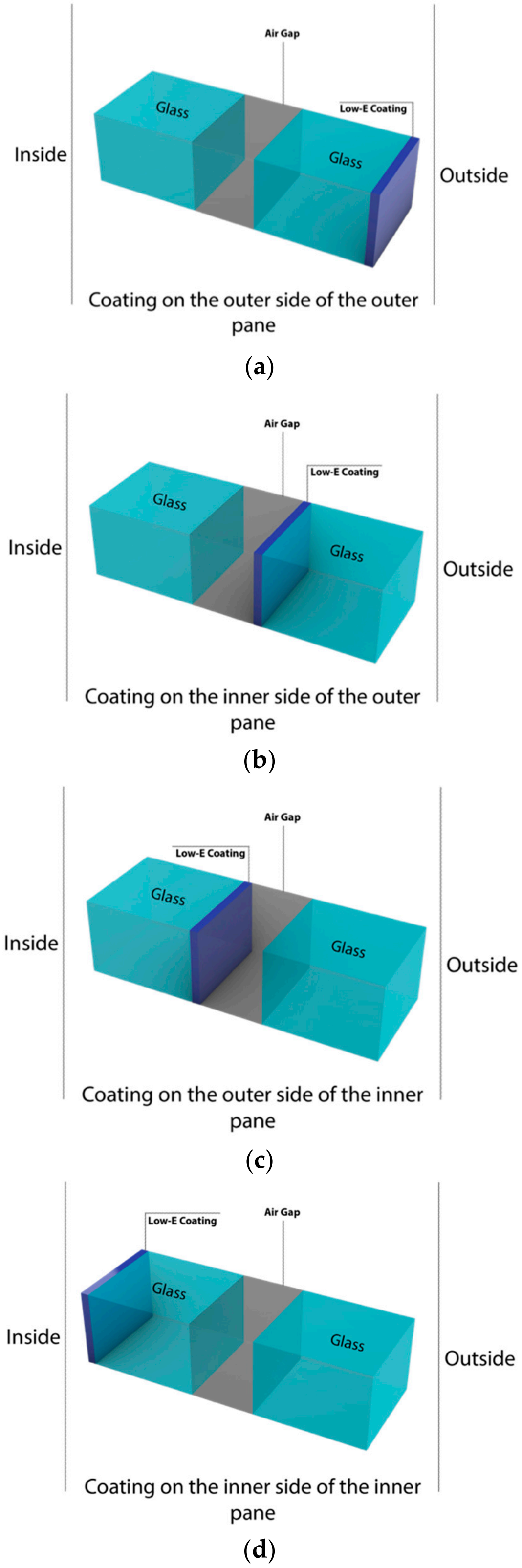


Figure 8. Low-E coating positions on DGP windows coating on the (**a**) outer side of outer pane (**b**) inner side of outer pane (**c**) outer side of inner pane (**d**) inner side of inner pane [22].

4.8.3. Low-E Windows' Energy Efficiency Based on Material's Structure

Amirkhani et al. (2019) studied the energy consumption reduction of single-glazed units and double-glazed units (SGU and DGU) for thinsulate-coated Low-E windows. This study demonstrates 3% and 16.8% heating energy consumption reduction, 20% and 19.8% cooling energy consumption, and 2.7% and 4% total energy consumption reduction for SGU and DGU low-E windows, respectively, in Berkshire, UK (Cfa) [22]. These scientists produced and proposed implying silver nanowires/polyvinyl butyral (AgNWs/PVB) coating as the low-E material on windows. The analysis demonstrated visible light transmittance of 83% and reflectivity of mid-infrared (mid-IR) to 69.8%, as well as considerable physical and chemical resistance for this Low-E window [79].

Hence, Low-E windows can reduce buildings' heating, cooling, and lighting energy consumption based on adjusting coating position and structure according to the climate type.

A summary of different smart windows and their physical characteristics can be found in Table 3. It should be noticed that based on the differences in the materials used in reports for the same kind of SWs, a range of numbers has been indicated for each characteristic containing minimum and maximum numbers reported by previous research.

5. Discussion

Smart windows are classified into two active and passive systems containing seven types: electrochromic (EC), photovoltachromic (PVC), and gasochromic (GC) as active smart window systems, and photochromic (PC), thermochromic (TC), hydrochromic (HC), and Low-E as passive systems. A literature study shows that applying EC and TC windows in warmer regions (A category, BWh, BSh, Cfa, Cfb, Csa, Csb, Cwa, and Cwb) can improve buildings' visual and thermal comfort and energy efficiency. PVC and TC smart windows are more suitable for hot climates due to their ability to prevent increasing light intensity in hot regions (A category and BWh, BSh). Based on previous studies, PC windows are the only smart window option in cold environments (BWk, BSk, Csc, Cwc, Cfc, D, and E categories) since they demonstrated the highest efficiency. Also, GC windows can be implemented on buildings in arid regions with cold winters and hot summers (BWh, and BSh), for instance desert areas.

In comparison, Low-E coatings' position can be modified based on the climatic condition to reach maximum efficiency. For instance, coating Low-E material on the interior facing side of the window will be appropriate for cold regions, and coating the material on the interior rear-facing side will be suitable for warmer regions. Finally, HC glazing changes its color based on humidity in the environment. Thus, it is more effective in humid regions (Af, Cfa, Cfb, Cfc, Dfa, Dfb, Dfc, Dfd) to prevent heat transfer.

A study in hot climates showed TC, EC, and GC smart windows decreased daylight gain by 51%, 35%, and 39%, respectively, compared to clear regular windows [57]. Based on Tällberg et al. (2019) study, it has been concluded that in cold climates (BWk, BSk, Csc, Cfc, Cwc, D, and E categories) the electrochromic and photochromic windows generally increase the energy efficiency of the building, while the thermochromic windows either do not change or decrease the building's energy efficiency. The total heat transfer through windows in Madrid, Spain (Csa) for electrochromic, thermochromic, and photochromic is 60–72%, 83–166%, and 75–101%, respectively, compared to regular windows [14]. Moreover, the total heat leakage for Nairobi, Kenia (Cfb) for electrochromic windows compared to the regular windows is 64–75%, for thermochromic windows is 82–158%, and for photochromic windows is 102–124% [14]. Electrochromic windows decreased the cooling demand by 61%. In contrast, the heating demand increased by 6%, and the lighting demand increased by 447%, according to Tällberg et al. (2019) study. However, since the most energy consumption in the buildings is due to cooling and heating demand, the harsh increase in lighting demand would not affect the building's energy requirements considering the significant decrease in cooling energy consumption [14]. In the study conducted by Marchwinski (2021), researchers compared EC, GC, and Low-E glass to evaluate buildings' energy demand reduction [21]. The results demonstrated a slightly higher efficiency of EC for cooling demand reduction and higher efficiency of GC for heating demand reduction. Electrochromic and Gasochromic windows reduced the simulated building's energy demand by 25–35% and 27–31%, respectively [21]. Feng (2016) conducted a study to compare the energy efficiency of electrochromic (EC) and gasochromic (GC) windows in Shanghai, China (Cfa) [12]. The study results indicated that EC and GC smart windows annually decreased 12.3% and 10.5% of buildings' energy consumption compared to single clear windows in this city. For other Chinese cities studied in Feng et al., EC and GC each reduced 27–31% and 25–35% of HVAC load, respectively, compared to the regular transparent window. A low U-value and high SHGC are desired in Dwa to decrease heat loss and increase heat gain [12]. Nageib et al.'s (2020) simulation for hot arid climate (BWh, BSh) showed energy consumption reduction for EC windows compared to regular clear windows and rising energy consumption for GC and TC windows in the same climate conditions [57]. Table 3 presented smart window properties retrieved from the reviewed studies. The properties included thermal transmittance rate (U-value), solar heat gain coefficient (SHGC), light-to-solar gain ratio (LSG), shading coefficient (SC), visible transmittance ratio (T_{vis}), solar transmittance ratio (T_{sol}), visible transmittance (VT), and reflectance.

The information aggregated in Table 3 could help to classify and visualize the appropriate types of smart windows for different climate zones. Therefore, through Figures 9–14, it has been shown how different types of glasses could be mapped to different geographical regions over various continents. Figure 9 presents Koppen-Geiger climate zones in North America. As Figure 9 shows, Phoenix (AZ) is located in the hot desert zone (BWh) highlighted in red color. Considering smart window properties (Table 3), EC, PVC, GC, TC, Low-E are proposed to be utilized in the hot desert zone (BWh).

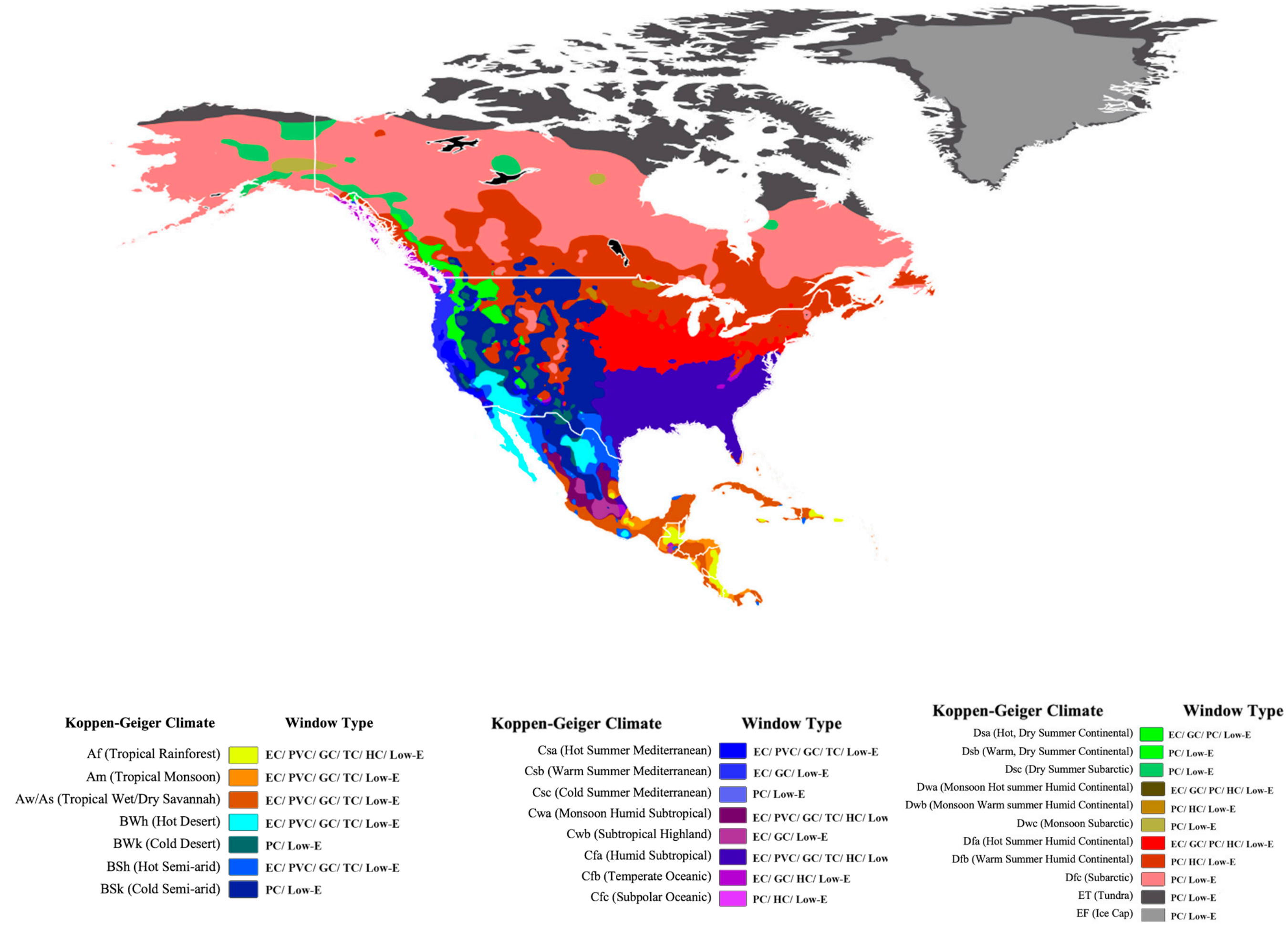


Figure 9. North America map with applicable smart window types [33].

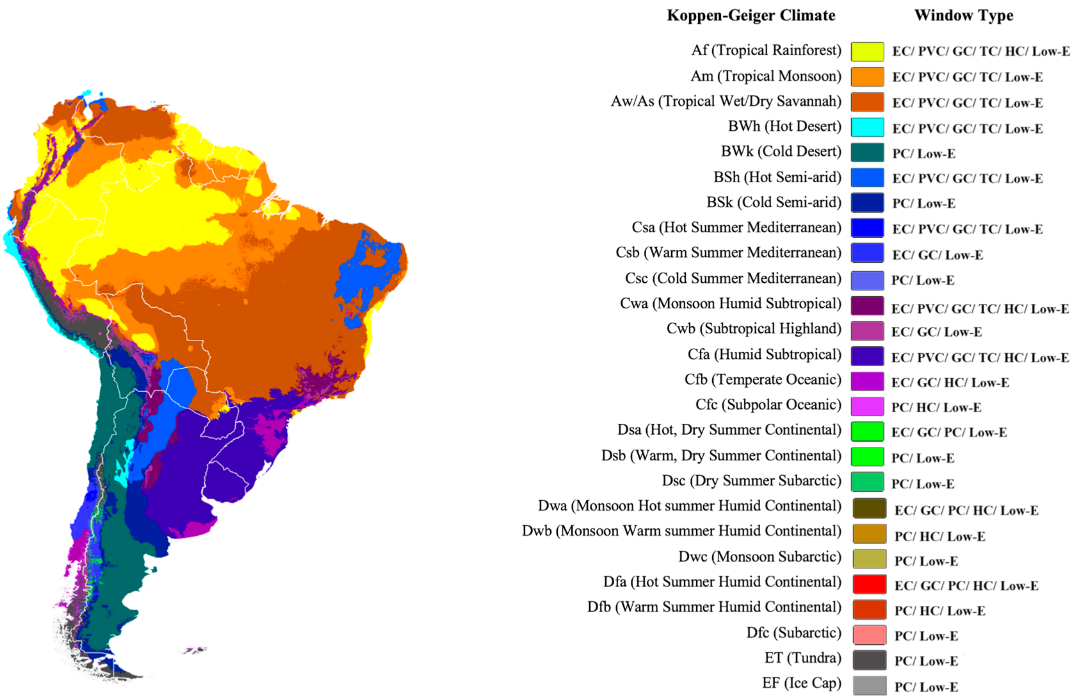


Figure 10. South America Map with applicable smart window types [33].

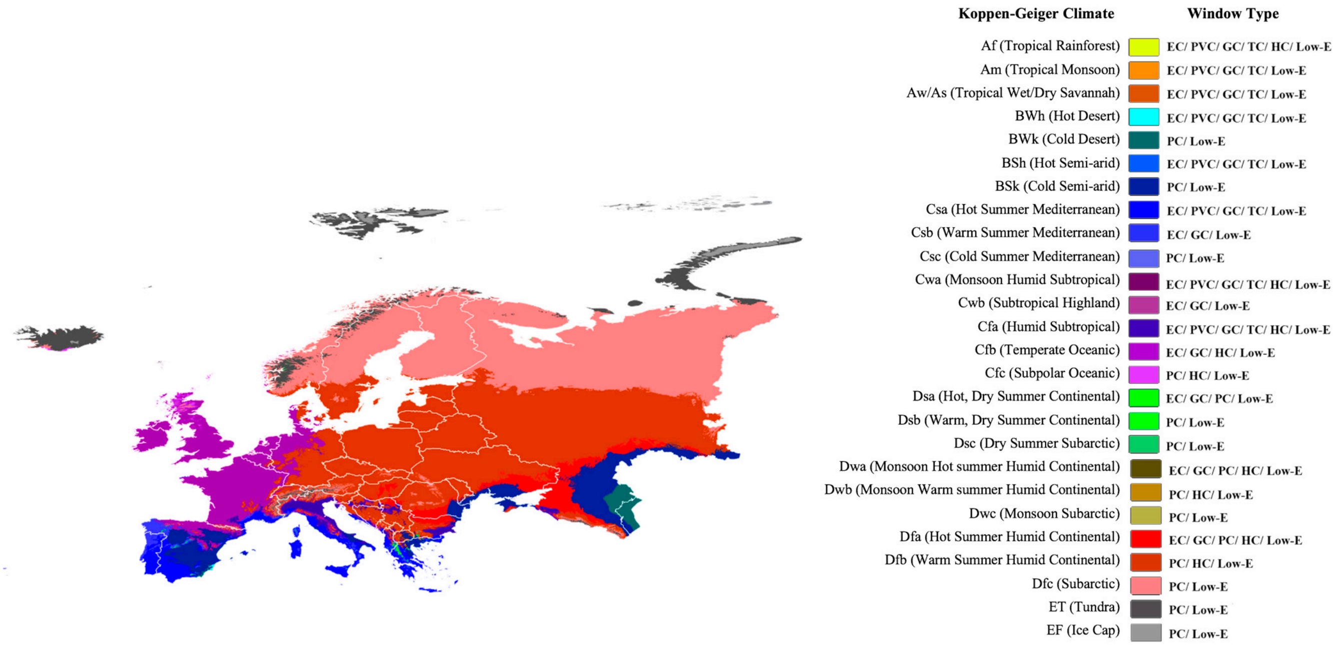


Figure 11. Europe Map with applicable smart window types [33].

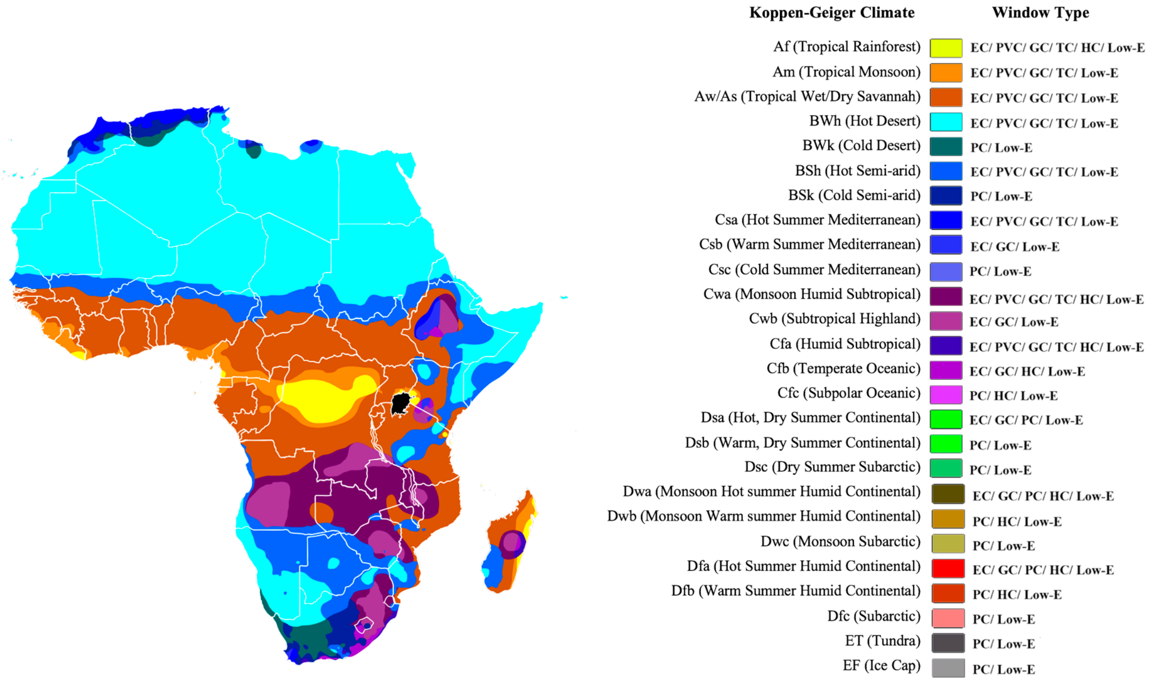


Figure 12. Africa Map with applicable smart window types [33].

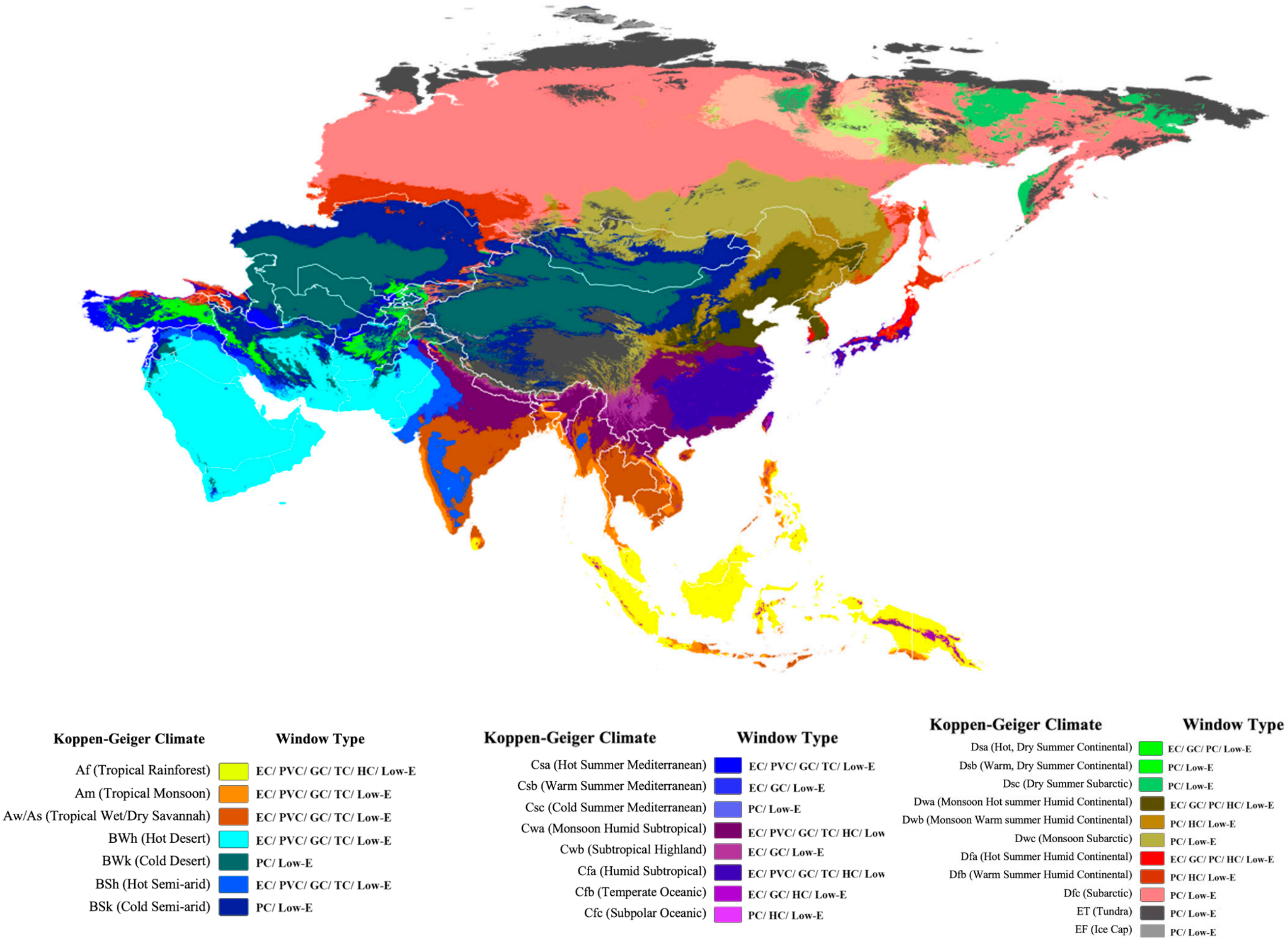


Figure 13. Asia Map with applicable smart window types [33].

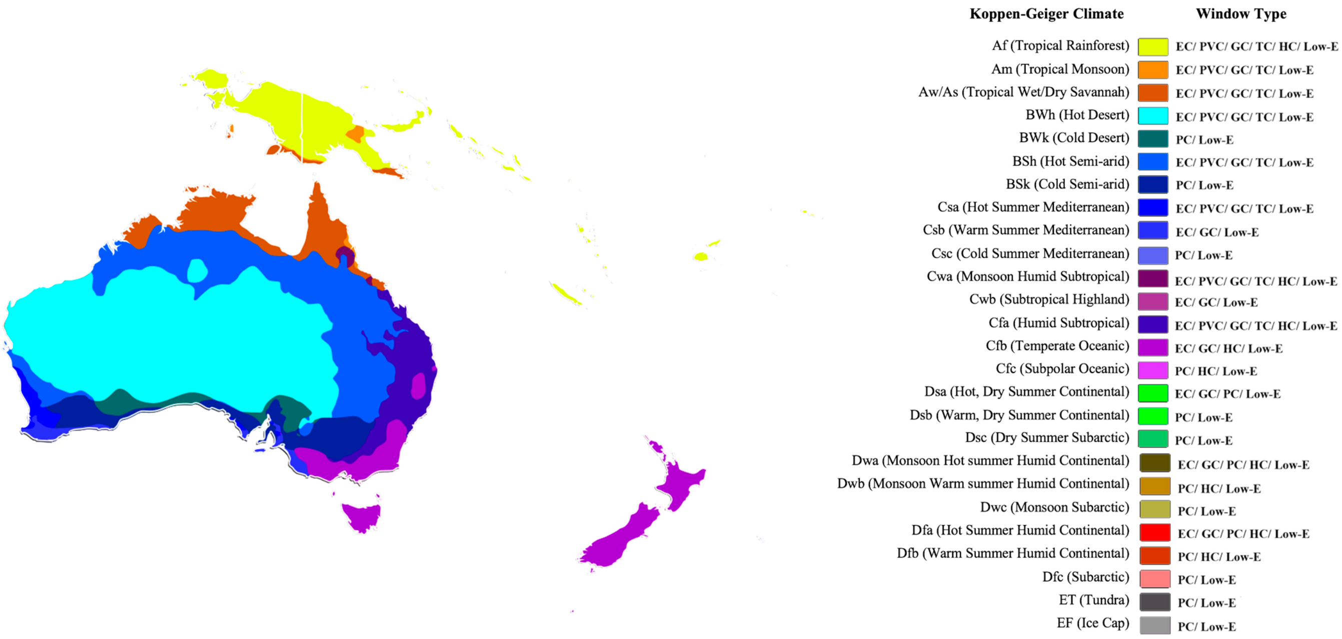


Figure 14. Oceania Map with applicable smart window types [33].

A comparison summary of studied smart windows, their energy consumption reduction, their visual comfort, advantages and disadvantages, and their colors, along with their pros and cons, were presented in Table 4. In addition, considering the thermal and visual properties of studied windows, the appropriate implementation climate zones were proposed for every studied window types.

Table 4. Different Types of Smart Windows, their energy efficiency potential, best performing climate, and pros and cons.

Type			Pros	Cons
1-Electrochromic	Energy Efficiency improvement	6–64%	• Gradual adaptability of the eye to the light alteration • Highest Energy efficiency in the warm climate • The most developed smart window category	• Expensive • Not applicable for harsh environments • Multiple coating layers • Requires external power (voltage) source • The EC coating must be cast only on transparent conductors • Active system
	Visual Comfort	16–60%		
	Colors	Blue		
	Best Performing Climates	Af, Am, Aw, BWh, BSh, Csa, Csb, Cwa, Cwb, Cfa, Cfb, Dsa, Dfa		
2-Photovoltachromic	Energy Efficiency improvement	2–41%	• High energy efficiency • Energy production	• Not transparent in all stages of implemented PV cells
	Visual Comfort	40–45.5%		
	Colors	Purple Yellow		
	Best Performing Climates	Af, Am, Aw, BWh, BSh, Csa, Cwa, Cfa		
3-Gasochromic	Energy Efficiency improvement	25–84%	• Low-cost layer configuration • High solar transmittance • Doe does not require transparent conductors • It can be cast directly on glass • Large-scale production • Fast switching time	• Requires three kinds of different gasses • Active system • It relies on ion and electron • Low energy efficiency
	Visual Comfort	NA		
	Colors	Blue		
	Best Performing Climates	Af, Am, Aw, BWh, BSh, Csa, Csb, Cwa, Cwb, Cfa, Cfb, Dsa, Dfa		

Table 4. *Cont.*

Type			Pros	Cons
4-Thermochromic	Energy Efficiency improvement	3–57.1%	• Passive • Single coating layer • Low cost	• Low visible transmittance (VT) • High transition temperature • Limited solar modulation • Limited material types
	Visual Comfort	15.5–43%		
	Colors	Blue		
	Best Performing Climates	Af, Am, Aw, BWh, BSh, Csa, Cwa, Cfa		
5-Photochromic	Energy Efficiency improvement	20–92.7%	• Passive • Thin coating • Single coating • Small amount of material • Low-emission casting process • Multiple colors • Various materials	• Low durability • Large-size production difficulties • Performance dependent on material
	Visual Comfort	Up to 41%		
	Colors	All colors		
	Best Performing Climates	BWk, BSk, Csc, Cwc, Cfc, Dsa, Dsb, Dsc, Dsd, Dwa, Dwb, Dwc, Dwd, Dfa, Dfb, Dfc, Dfd, ET, EF		
6-Hydrochromic	Energy Efficiency improvement	Further research required in that area	• Passive • Requires marginal water to be activated • Low weight	• Undeveloped • Highly opaque in tinted stage
	Visual Comfort	Further research required in that area		
	Colors	White		
	Best Performing Climates	Af, Cwa, Cfa, Cfb, Cfc, Dwa, Dwb, Dfa, Dfb, Dfc, Dfd		
7-Low-E	Energy Efficiency improvement	2.7–20%	• Passive • High energy efficiency • Applicable to all climates • Transparent in all stages	• Expensive casting • Complex casting • Dependent on the casting position
	Visual Comfort	Up to 5%		
	Colors	Transparent		
	Best Performing Climates	All climates (depends on the coating's position on the window)		

6. Conclusions

In response to the lack of practical recommendations for smart windows' implementation over various climate zones, a comparative study has been presented to explore and recommend the most efficient smart windows across different climate zones. By reviewing more than 50 articles published between 2013–2022, the properties of smart window types, including thermal transmittance rate, solar heat gain coefficient, light-to-solar gain ratio, shading coefficient, visible transmittance ratio, solar transmittance ratio, visible transmittance, and reflectance have been identified and presented. The comparison of properties with their advantages and shortcomings for each smart window type and reasons for utilizing them in specific climate zones have also been provided in this study.

Due to limited studies on the positive effects of photochromic windows in improving energy efficiency in buildings located in cold regions, this study recommends additional studies on this topic in the future. In addition, future investigations could measure the potential of multi-pane windows with two layers of smart windows on energy efficiency and users' comfort.

Finally, this paper could navigate researchers through possible future research areas in the intersection of material science, interior architecture, and building performance simulation, where innovation arises in interdisciplinary efforts.

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Abbreviations

HVAC	Heating ventilation and air conditioning system
SW	Smart Window
EC	Electrochromic
PVC	Photovoltachromic
GC	Gasochromic
TC	Thermochromic
PC	Photochromic
HC	Hydrochromic
Low-E	Low emission
DGP	Double glazing pane
SGP	Single glazing pane
U-value	Thermal Transmittance
SHGC	Solar Heat Gain Coefficient
LSG	Light to solar gain ratio
SC	Shading coefficient
T_{vis}	Visible light transmittance ratio
T_{sol}	Solar light transmittance ratio
VT	Visible transmittance

References

1. Sharma, A.; Saxena, A.; Sethi, M.; Shree, V. Varun Life cycle assessment of buildings: A review. *Renew. Sustain. Energy Rev.* **2011**, *15*, 871–875. [CrossRef]
2. Webb, M. Biomimetic building facades demonstrate potential to reduce energy consumption for different building typologies in different climate zones. *Clean Technol. Environ. Policy* **2022**, *24*, 493–518. [CrossRef] [PubMed]
3. Heidari Matin, N.; Eydgahi, A. Technologies used in responsive facade systems: A comparative study. *Intell. Build. Int.* **2019**, *14*, 54–73. [CrossRef]
4. Aelenei, D.; Aelenei, L.; Pacheco, C. Adaptive Façade: Concept, applications, research questions. *Energy Procedia* **2016**, *91*, 269–275. [CrossRef]
5. Morteza, S.; Mohammadi, M.; Rosemann, A.; Schröder, T. A morphological approach for kinetic façade design process to improve visual and thermal comfort: Review A morphological approach for kinetic façade design process to improve visual and thermal comfort: Review. *Build. Environ.* **2019**, *153*, 186–204.
6. Dewidar, K.; Mahmoud, A.H.; Magdy, N.; Ahmed, S. The role of intelligent façades in energy conservation. In Proceedings of the International Conference on Sustainability and the Future: Future Intermediate Sustainable Cities (FISC 2010), Elshourouq, Egypt, 23–25 November 2010; Volume 1.
7. Carlucci, F. A review of smart and responsive building technologies and their classifications. *Future Cities Environ.* **2021**, *7*, 10. [CrossRef]
8. Su, M.; Song, Y. Printable Smart Materials and Devices: Strategies and Applications. *Chem. Rev.* **2022**, *122*, 5144–5164. [CrossRef]
9. U.S. Department of Energy. Chapter 5: Increasing Efficiency of Building Systems and Technologies. In *An Assessment of Energy Technologies and Research Opportunities*; U.S. Department of Energy: Washington, DC, USA, 2015.
10. Casini, M. Smart windows for energy efficiency of buildings. In Proceedings of the Second International Conference on Advances in Civil, Structural and Environmental Engineering–ACSEE, Zurich, Switzerland, 25–26 October 2014.
11. Granqvist, C.G.; Azens, A.; Hjelm, A.; Kullman, L.; Niklasson, G.A.; Rönnow, D.; Strømme Mattsson, M.; Veszelei, M.; Vaivars, G. Recent advances in electrochromics for smart windows applications. *Sol. Energy* **2017**, *63*, 199–216. [CrossRef]
12. Feng, W.; Zou, L.; Gao, G.; Wu, G.; Shen, J.; Li, W. Gasochromic smart window: Optical and thermal properties, energy simulation and feasibility analysis. *Sol. Energy Mater. Sol. Cells* **2016**, *144*, 316–323. [CrossRef]
13. Malara, F.; Cannavale, A.; Carallo, S.; Gigli, G. Smart windows for building integration: A new architecture for photovoltachromic devices. *ACS Appl. Mater. Interfaces* **2014**, *6*, 9290–9297. [CrossRef]
14. Tällberg, R.; Jelle, B.P.; Loonen, R.; Gao, T.; Hamdy, M. Comparison of the energy saving potential of adaptive and controllable smart windows: A state-of-the-art review and simulation studies of thermochromic, photochromic and electrochromic technologies. *Sol. Energy Mater. Sol. Cells* **2019**, *200*, 109828. [CrossRef]

15. Cui, Y.; Ke, Y.; Liu, C.; Chen, Z.; Wang, N.; Zhang, L.; Zhou, Y.; Wang, S.; Gao, Y.; Long, Y. Thermochromic VO_2 for Energy-Efficient Smart Windows. *Joule* **2018**, *2*, 1707–1746. [CrossRef]
16. Ke, Y.; Chen, J.; Lin, G.; Wang, S.; Zhou, Y.; Yin, J.; Lee, P.S.; Long, Y. Smart Windows: Electro-, Thermo-, Mechano-, Photochromics, and Beyond. *Adv. Energy Mater.* **2019**, *9*, 1902066. [CrossRef]
17. Cannavale, A.; Zampini, G.; Carlucci, F.; Pugliese, M.; Martellotta, F.; Ayr, U.; Maiorano, V.; Ortica, F.; Fiorito, F.; Latterini, L. Energy and daylighting performance of building integrated spirooxazine photochromic films. *Sol. Energy* **2021**, *242*, 424–434. [CrossRef]
18. Pyun, S.B.; Song, J.E.; Kim, J.Y.; Cho, E.C. Hydrochromic Smart Windows to Remove Harmful Substances by Mimicking Medieval European Stained Glasses. *ACS Appl. Mater. Interfaces* **2020**, *12*, 16937–16945. [CrossRef]
19. Addonizio, M.L.; Ferrara, M.; Castaldo, A.; Antonaia, A. Air-stable low-emissive AlN-Ag based coatings for energy-efficient retrofitting of existing windows. *Energy Build.* **2021**, *250*, 111259. [CrossRef]
20. Brzezicki, M. A systematic review of the most recent concepts in smart windows technologies with a focus on electrochromics. *Sustainability* **2021**, *13*, 9604. [CrossRef]
21. Marchwiński, J. Study of Electrochromic (Ec) and Gasochromic (Gc) Glazing for Buildings in Aspect of Energy Efficiency. *Archit. Civ. Eng. Environ.* **2021**, *14*, 27–38. [CrossRef]
22. Amirkhani, S.; Bahadori-Jahromi, A.; Mylona, A.; Godfrey, P.; Cook, D. Impact of Low-E window films on energy consumption and CO_2 emissions of an existing UK hotel building. *Sustainability* **2019**, *11*, 4265. [CrossRef]
23. Zhou, Y.; Dong, X.; Mi, Y.; Fan, F.; Xu, Q.; Zhao, H.; Wang, S.; Long, Y. Hydrogel smart windows. *J. Mater. Chem. A Mater.* **2020**, *8*, 10007–10025. [CrossRef]
24. Cao, D.; Xu, C.; Lu, W.; Qin, C.; Cheng, S. Sunlight-Driven Photo-Thermochromic Smart Windows. *Sol. RRL* **2018**, *2*, 1870163. [CrossRef]
25. Chan, Y.C.; Tzempelikos, A.; Konstantzos, I. A systematic method for selecting roller shade properties for glare protection. *Energy Build.* **2015**, *92*, 81–94. [CrossRef]
26. Yu, J.H.; Nam, S.H.; Lee, J.W.; Boo, J.H. Enhanced visible transmittance of thermochromic VO_2 thin films by SiO_2 passivation layer and their optical characterization. *Materials* **2016**, *9*, 556. [CrossRef] [PubMed]
27. Sadhukhan, D.; Peri, S.; Sugunaraj, N.; Biswas, A.; Selvaraj, D.F.; Koiner, K.; Rosener, A.; Dunlevy, M.; Goveas, N.; Flynn, D.; et al. Estimating Surface Temperature from Thermal Imagery of Buildings for Accurate Thermal Transmittance (U-Value): A Machine Learning Perspective. *J. Build. Eng.* **2020**, *32*, 101637. [CrossRef]
28. Zhang, Y.; Yang, Y.; Zhang, L.; Zhao, C.; Yan, J.; Liu, M.; Zhao, L. Seasonal variation in leaf area index and its impact on the shading effects of vertical green facades in subtropical areas. *Build. Environ.* **2022**, *225*, 109629. [CrossRef]
29. Villalba, A.; Correa, E.; Pattini, A.; Vicare, D. Hot-cool box calorimetric determination of the solar heat gain coefficient and the U-value of internal shading devices. *Energy Effic.* **2017**, *10*, 1553–1571. [CrossRef]
30. Mahdieh, M.H.; Sohrabi, M. Precise design of VO_2 thin films for smart windows by employing thickness dependent refractive index. *arXiv* **2021**, arXiv:2112.04582.
31. Lee, J.W.; Jung, H.J.; Park, J.Y.; Lee, J.B.; Yoon, Y. Optimization of building window system in Asian regions by analyzing solar heat gain and daylighting elements. *Renew. Energy* **2013**, *50*, 522–531. [CrossRef]
32. Davis, J.; Mengersen, K.; Bennett, S.; Mazerolle, L. Viewing systematic reviews and meta-analysis in social research through different lenses. *Springerplus* **2014**, *3*, 511. [CrossRef]
33. Beck, H.E.; Zimmermann, N.E.; McVicar, T.R.; Vergopolan, N.; Berg, A.; Wood, E.F. Present and future köppen-geiger climate classification maps at 1-km resolution. *Sci. Data* **2018**, *5*, 180214. [CrossRef]
34. Belda, M.; Holtanová, E.; Halenka, T.; Kalvová, J. Climate classification revisited: From Köppen to Trewartha. *Clim. Res.* **2014**, *59*, 1–13. [CrossRef]
35. Peel, M.C.; Finlayson, B.L.; Mcmahon, T.A. Hydrology and Earth System Sciences Updated world map of the Köppen-Geiger climate classification. *Hydrol. Earth Syst. Sci.* **2007**, *11*, 1633–1644. [CrossRef]
36. Kottek, M.; Grieser, J.; Beck, C.; Rudolf, B.; Rubel, F. World map of the Köppen-Geiger climate classification updated. *Meteorol. Z.* **2006**, *15*, 259–263. [CrossRef] [PubMed]
37. Baetens, R.; Petter, B.; Gustavsen, A. Solar Energy Materials & Solar Cells Properties, requirements and possibilities of smart windows for dynamic daylight and solar energy control in buildings: A state-of-the-art review. *Sol. Energy Mater. Sol. Cells* **2010**, *94*, 87–105.
38. Granqvist, C.G. Electrochromics for smart windows: Oxide-based thin films and devices. *Thin Solid Film.* **2014**, *564*, 1–38. [CrossRef]
39. Casini, M. Active dynamic windows for buildings: A review. *Renew. Energy* **2018**, *119*, 923–934. [CrossRef]
40. Kamalisarvestani, M.; Saidur, R.; Mekhilef, S.; Javadi, F.S. Performance, materials and coating technologies of thermochromic thin films on smart windows. *Renew. Sustain. Energy Rev.* **2013**, *26*, 353–364. [CrossRef]
41. Wang, Y.; Runnerstrom, E.L.; Milliron, D.J. Switchable Materials for Smart Windows. *Annu. Rev. Chem. Biomol. Eng.* **2016**, *7*, 283–304. [CrossRef]
42. Aburas, M.; Soebarto, V.; Williamson, T.; Liang, R. Thermochromic smart window technologies for building application: A review. *Appl. Energy* **2019**, *255*, 113522. [CrossRef]

43. Allen, K.; Connelly, K.; Rutherford, P.; Wu, Y. Smart windows—Dynamic control of building energy performance. *Energy Build.* **2017**, *139*, 535–546. [CrossRef]
44. Tavares, P.F.; Gaspar, A.R.; Martins, A.G.; Frontini, F. Evaluation of electrochromic windows impact in the energy performance of buildings in mediterranean climates. *Energy Policy* **2014**, *67*, 68–81. [CrossRef]
45. Reynisson, H.E.; Guðmundsson, K. Energy Performance of Dynamic Windows in Different Climates. Master's Thesis, KTH, School of Architecture and the Built Environment (ABE), Civil and Architectural Engineering, Building Technology, Stockholm, Sweden, 2015.
46. Sibilio, S.; Rosato, A.; Scorpio, M.; Iuliano, G.; Ciampi, G.; Vanoli, G.P.; de Rossi, F. A review of electrochromic windows for residential applications. *Int. J. Heat Technol.* **2016**, *34*, S481–S488. [CrossRef]
47. Dussault, J.M.; Gosselin, L. Office buildings with electrochromic windows: A sensitivity analysis of design parameters on energy performance, and thermal and visual comfort. *Energy Build.* **2017**, *153*, 50–62. [CrossRef]
48. Granqvist, C.G.; Pehlivan, İ.B.; Niklasson, G.A. Electrochromics on a roll: Web-coating and lamination for smart windows. *Surf. Coat. Technol.* **2018**, *336*, 133–138. [CrossRef]
49. Cannavale, A.; Ayr, U.; Fiorito, F.; Martellotta, F. Smart electrochromic windows to enhance building energy efficiency and visual comfort. *Energies* **2020**, *13*, 1449. [CrossRef]
50. Bui, D.K.; Nguyen, T.N.; Ghazlan, A.; Ngo, T.D. Biomimetic adaptive electrochromic windows for enhancing building energy efficiency. *Appl. Energy* **2021**, *300*, 117341. [CrossRef]
51. Favoino, F.; Fiorito, F.; Cannavale, A.; Ranzi, G.; Overend, M. Optimal control and performance of photovoltachromic switchable glazing for building integration in temperate climates. *Appl. Energy* **2016**, *178*, 943–961. [CrossRef]
52. Pierucci, A.; Cannavale, A.; Martellotta, F.; Fiorito, F. Smart windows for carbon neutral buildings: A life cycle approach. *Energy Build.* **2018**, *165*, 160–171. [CrossRef]
53. Fiorito, F.; Cannavale, A.; Santamouris, M. Development, testing and evaluation of energy savings potentials of photovoltachromic windows in office buildings. A perspective study for Australian climates. *Sol. Energy* **2020**, *205*, 358–371. [CrossRef]
54. Pugliese, M.; Bisconti, F.; Rizzo, A.; Colella, S.; Prontera, C.T.; Gigli, G.; Maiorano, V.; Cossari, P. Highly efficient all-solid-state WO3-perovskite photovoltachromic cells for single-glass smart windows. *ACS Appl. Energy Mater.* **2020**, *3*, 10453–10462. [CrossRef]
55. Liang, R.; Liu, D.; Sun, Y.; Luo, X.; Grant, D.; Walker, G.; Wu, Y. Investigation of Mg-Y coated gasochromic smart windows for building applications. *Build. Simul.* **2019**, *12*, 99–112. [CrossRef]
56. Gao, G.; Xue, S.; Wang, H.; Zhang, Z.; Wu, G.; Debela, T.T.; Kang, H.S. Highly Thermally Stable and Transparent WO_3-SiO_2 Gasochromic Films Obtained by an Automated Printing Method. *ACS Sustain. Chem. Eng.* **2021**, *9*, 17319–17329. [CrossRef]
57. Nageib, A.; Elzafarany, A.M.; Elhefnawy, M.H.; Mohamed, F.O. Using smart glazing for reducing energy consumption on existing office building in hot dry climate. *HBRC J.* **2020**, *16*, 157–177. [CrossRef]
58. Liang, R.; Wu, Y.; Wilson, R. Thermal and Visual Comfort Analysis of an Office with Thermochromic Smart Windows Applied. In Proceedings of the International Conference CISBAT 2015 Future Buildings and Districts Sustainability from Nano to Urban Scale, Lausanne, Switzerland, 9–11 September 2015.
59. Liang, R.; Sun, Y.; Aburas, M.; Wilson, R.; Wu, Y. Evaluation of the thermal and optical performance of thermochromic windows for office buildings in China. *Energy Build.* **2018**, *176*, 216–231. [CrossRef]
60. Ke, Y.; Yin, Y.; Zhang, Q.; Tan, Y.; Hu, P.; Wang, S.; Tang, Y.; Zhou, Y.; Wen, X.; Wu, S.; et al. Adaptive Thermochromic Windows from Active Plasmonic Elastomers. *Joule* **2019**, *3*, 858–871. [CrossRef]
61. Li, X.H.; Liu, C.; Feng, S.P.; Fang, N.X. Broadband Light Management with Thermochromic Hydrogel Microparticles for Smart Windows. *Joule* **2019**, *3*, 290–302. [CrossRef]
62. Ke, Y.; Zhang, Q.; Wang, T.; Wang, S.; Li, N.; Lin, G.; Liu, X.; Dai, Z.; Yan, J.; Yin, J.; et al. Cephalopod-inspired versatile design based on plasmonic VO_2 nanoparticle for energy-efficient mechano-thermochromic windows. *Nano Energy* **2020**, *73*, 104785. [CrossRef]
63. Liang, R.; Kent, M.; Wilson, R.; Wu, Y. The effect of thermochromic windows on visual performance and sustained attention. *Energy Build.* **2021**, *236*, 110778. [CrossRef]
64. Arnaoutakis, G.E.; Katsaprakakis, D.A. Energy performance of buildings with thermochromic windows in mediterranean climates. *Energies* **2021**, *14*, 6977. [CrossRef]
65. Lin, C.; Hur, J.; H Chao, C.Y.; Liu, G.; Yao, S.; Li, W.; Huang, B. All-weather thermochromic windows for synchronous solar and thermal radiation regulation. *Sci. Adv.* **2022**, *8*, eabn7359. [CrossRef]
66. Ke, Y.; Tan, Y.; Feng, C.; Chen, C.; Lu, Q.; Xu, Q.; Wang, T.; Liu, H.; Liu, X.; Peng, J.; et al. Tetra-Fish-Inspired aesthetic thermochromic windows toward Energy-Saving buildings. *Appl. Energy* **2022**, *315*, 119053. [CrossRef]
67. Zou, X.; Ji, H.; Zhao, Y.; Lu, M.; Tao, J.; Tang, P.; Liu, B.; Yu, X.; Mao, Y. Research progress of photo-/electro-driven thermochromic smart windows. *Nanomaterials* **2021**, *11*, 3335. [CrossRef] [PubMed]
68. Zeng, R.; Chini, A.; Srinivasan, R.S.; Jiang, P. Energy efficiency of smart windows made of photonic crystal. *Int. J. Constr. Manag.* **2017**, *17*, 100–112. [CrossRef]
69. Miyazaki, H.; Ishigaki, T.; Ota, T. Photochromic Smart Windows Employing WO_3-Based Composite Films. *J. Mater. Sci. Res.* **2017**, *6*, 62. [CrossRef]
70. Hočevar, M.; Opara Krašovec, U. A photochromic single glass pane. *Sol. Energy Mater. Sol. Cells* **2018**, *186*, 111–114. [CrossRef]
71. Kang, M.J.; Santoro, E.G.; Kang, Y.S. Enhanced Efficiency of Functional Smart Window with Solar Wavelength Conversion Phosphor-Photochromic Hybrid Film. *ACS Omega* **2018**, *3*, 9505–9512. [CrossRef]

72. Timmermans, G.H.; Saes, B.W.H.; Debije, M.G. Dual-responsive "smart" window and visually attractive coating based on a diarylethene photochromic dye. *Appl. Opt.* **2019**, *58*, 9823. [CrossRef]
73. Wang, L.; Liu, Y.; Zhan, X.; Luo, D.; Sun, X. Photochromic transparent wood for photo-switchable smart window applications. *J. Mater. Chem. C Mater.* **2019**, *7*, 8649–8654. [CrossRef]
74. You, C.C.; Karazhanov, S.Z. Effect of temperature and illumination conditions on the photochromic performance of yttrium oxyhydride thin films. *J. Appl. Phys.* **2020**, *128*, 013106. [CrossRef]
75. Al-Qahtani, S.D.; Binyaseen, A.M.; Aljuhani, E.; Aljohani, M.; Alzahrani, H.K.; Shah, R.; El-Metwaly, N.M. Production of smart nanocomposite for glass coating toward photochromic and long-persistent photoluminescent smart windows. *Ceram. Int.* **2022**, *48*, 903–912. [CrossRef]
76. Cai, G.; Wang, J.; Eh, A.L.S.; Chen, J.; Qian, K.; Xiong, J.; Thangavel, G.; Lee, P.S. Diphylleia grayi-Inspired Stretchable Hydrochromics with Large Optical Modulation in the Visible-Near-Infrared Region. *ACS Appl. Mater. Interfaces* **2018**, *10*, 37685–37693. [CrossRef] [PubMed]
77. Yoo, G.Y.; Lee, S.; Ko, M.; Kim, H.; Lee, K.N.; Kim, W.; Do, Y.R. Diphylleia grayi-Inspired Intelligent Hydrochromic Adhesive Film. *ACS Appl. Mater. Interfaces* **2020**, *12*, 49982–49991. [CrossRef] [PubMed]
78. Hedge, A.; MacNaughton, P.; Woo, M.; Guglielmetti, R.; Tinianov, B. Airport passenger experiences in concourses with either electrochromic or low-e glass windows. *Int. J. Aviat. Manag.* **2021**, *5*, 1. [CrossRef]
79. Lin, S.; Wang, H.; Zhang, X.; Wang, D.; Zu, D.; Song, J.; Liu, Z.; Huang, Y.; Huang, K.; Tao, N.; et al. Direct spray-coating of highly robust and transparent Ag nanowires for energy saving windows. *Nano Energy* **2019**, *62*, 111–116. [CrossRef]
80. Grosjean, A.; le Baron, E. Longtime solar performance estimations of low-E glass depending on local atmospheric conditions. *Sol. Energy Mater. Sol. Cells* **2022**, *240*, 111730. [CrossRef]
81. Granqvist, C.-G. Electrochromic Foil: A Case Study. In *Electrochromic Materials and Devices*; John Wiley & Sons, Ltd.: Hoboken, NJ, USA, 2013; pp. 525–544.
82. Cannavale, A.; Cossari, P.; Eperon, G.E.; Colella, S.; Fiorito, F.; Gigli, G.; Snaith, H.J.; Listorti, A. Forthcoming perspectives of photoelectrochromic devices: A critical review. *Energy Environ. Sci.* **2016**, *9*, 2682–2719. [CrossRef]
83. Gugliermetti, F.; Bisegna, F. Visual and energy management of electrochromic windows in Mediterranean climate. *Build. Environ.* **2003**, *38*, 479–492. [CrossRef]
84. Lee, E.S.; Dibartolomeo, D.L. LBNL-45841 OM-426 Application issues for large-area electrochromic windows in commercial buildings. *Sol. Energy Mater. Sol. Cells* **2002**, *71*, 465–491. [CrossRef]
85. Lee, E.S.; Tavil, A. Energy and visual comfort performance of electrochromic windows with overhangs. *Build. Environ.* **2007**, *42*, 2439–2449. [CrossRef]
86. King, D.L.; Boyson, W.E.; Kratochvil, J.A. *Photovoltaic Array Performance Model*; U.S. Department of Energy: Washington, DC, USA, 2003.
87. Cannavale, A.; Hörantner, M.; Eperon, G.E.; Snaith, H.J.; Fiorito, F.; Ayr, U.; Martellotta, F. Building integration of semitransparent perovskite-based solar cells: Energy performance and visual comfort assessment. *Appl. Energy* **2017**, *194*, 94–107. [CrossRef]
88. Cannavale, A.; Fiorito, F.; Resta, D.; Gigli, G. Visual comfort assessment of smart photovoltachromic windows. *Energy Build.* **2013**, *65*, 137–145. [CrossRef]
89. Mirzaei, M.R.; Rostami, A.; Matloub, S.; Mirtaghizadeh, H. Ultra-high-efficiency luminescent solar concentrator using superimposed colloidal quantum dots. *Opt. Quantum Electron.* **2020**, *52*, 327. [CrossRef]
90. Rastkar Mirzaei, M.; Rostami, A.; Matloub, S.; Nazari, M. Design and optimization of graphene quantum dot-based luminescent solar concentrator using Monte-Carlo simulation. *Energy Built Environ.* **2021**, *4*, 140–147. [CrossRef]
91. Li, D.; Wu, G.; Gao, G.; Shen, J.; Huang, F. Ultrafast coloring-bleaching performance of nanoporous WO_3-SiO_2 gasochromic films doped with Pd catalyst. *ACS Appl. Mater. Interfaces* **2011**, *3*, 4573–4579. [CrossRef] [PubMed]
92. Delalat, F.; Ranjbar, M.; Salamati, H. Blue colloidal nanoparticles of molybdenum oxide by simple anodizing method: Decolorization by $PdCl_2$ and observation of in-liquid gasochromic coloration. *Sol. Energy Mater. Sol. Cells* **2016**, *144*, 165–172. [CrossRef]
93. Smith, G.B. Green nanotechnology. In *Nanostructured Thin Films IV, Proceedings of the SPIE Optics + Photonics, NanoScience + Engineering, San Diego, CA, USA, 21–25 August 2011*; SPIE: Bellingham, WA, USA, 2011; Volume 8104, p. 810402.
94. Ulaeto, S.B.; Pancrecious, J.K.; Rajan, T.P.D.; Pai, B.C. Smart Coatings. In *Noble Metal-Metal Oxide Hybrid Nanoparticles: Fundamentals and Applications*; Elsevier: Amsterdam, The Netherlands, 2018; pp. 341–372.
95. Heidari Matin, N.; Mirabedini, S.M.; Rashidzadeh, Z. Smart Colored Window Technology Improving Users' Comfort with an Interdisciplinary Approach. In Proceedings of the Facade Tectonics 2022 World Congress, Los Angeles, CA, USA, 12–13 October 2022.
96. Matin, N.H.; Eydgahi, A.; Gharipour, A.; Matin, P. A Novel Framework for Optimizing Indoor Illuminance and Discovering Association of Involved Variables. *Buildings* **2022**, *12*, 878. [CrossRef]
97. Heidari Matin, N.; Eydgahi, A.; Matin, P. The Effect of Smart Colored Windows on Visual Performance of Buildings. *Buildings* **2022**, *12*, 861. [CrossRef]
98. Duan, Q.; Zhao, Y.; Wang, J. Thermal performance and condensation risk of single-pane glazing with low emissivity coatings. *MRS Adv.* **2020**, *5*, 2555–2564. [CrossRef]