ARCHITECTURE CIVIL ENGINEERING ENVIRONMENT
The Silesian University of Technology
No. 3/2021

doi: 10.21307/ACEE-2021-020

STUDY OF ELECTROCHROMIC (EC) AND GASOCHROMIC (GC) GLAZING FOR BUILDINGS IN ASPECT OF ENERGY EFFICIENCY

Janusz MARCHWIŃSKI *

*PhD Eng. Arch.; University of Ecology and Management in Warsaw, Faculty of Architecture,
Olszewska street 12, 00-792 Warsaw, Poland
ORCID ID: 0000-0003-3897-3580
E-mail address: *j.marchwinski@wseiz.pl*

Received: 22.02.2021; Revised: 14.06.2021; Accepted: 7.09.2021

Abstract
The paper analyzes the impact of switchable glazing: electrochromic (EC) and gasochromic (GC) on the energy efficiency of the building. Using the analytical and comparative method, the energy-relevant EC and GC glazing features were defined. Secondly, experimental studies on the energy-saving role of EC and GC glazing in various climatic zones were analyzed. The paper aims to define this role. The analyzes were referred to the thermal and lighting aspects. Comparisons were made between the EC and GC technologies, as well as with traditional – "static" types of glazing. The analysis showed differences in the technical characteristics of both technologies. Despite the differences, the results prove a beneficial effect of EC and GC glazing on the reduction of usable energy consumption in the building. The impact is most significant in terms of relieving the cooling and air conditioning systems. In this field, EC glazing was determined a more favorable technology. Further detailed research is required, focusing mainly on the lighting aspect for moderate and cold climate zones. The research was summarized with a collective evaluation of the energy-related role of EC and GC glazing.

Keywords: **Electrochromic (EC) glass; Energy-efficient buildings; Gasochromic (GC) glass; Smart windows; Solar façades; Solar architecture; Switchable glazing.**

1. INTRODUCTION

In the search for façade solutions that meet the goals of energy efficiency with simultaneous possibility of creating comfortable thermal and visual conditions by means of windows, switchable glazing technologies appear to be promising. This group includes glasses of variable optical parameters that can be activated in a controlled manner. These comprise electrochromic (EC) and gasochromic (GC) glazing technologies.

The analysis of the EC and GC technologies as façade glazing in the context of their impact on the energy efficiency of the building provides the subject of the paper.

The present paper is aimed at assessing the impact of these technologies on the energy consumption of a building. The research was conducted based on the analysis of the currently feasible technical parameters of EC and GC glazing as external building partitions. The study is also founded on the analysis of selected experimental studies conducted worldwide. The observations made in the discussion section of the paper are related to the comparison between the energy-saving role of both technologies and the state of research. The analytical and comparative methods are the leading study methods.

2. OPERATION AND STRUCTURE OF THE EC AND GC GLAZING

The EC and GC glass technologies differ significantly, despite the similar appearance of the glazing.

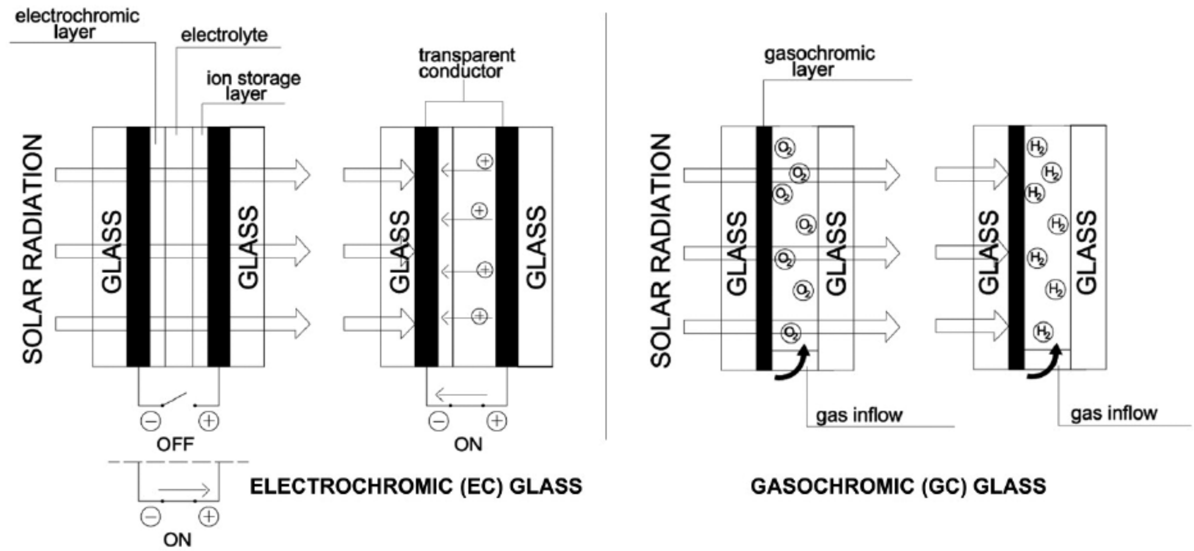

Figure 1.
General structure and principle of operation of electrochromic (EC) and gasochromic glass (GC) [5]

The operation of EC glazing is based on the use of electrochromic materials that change their optical properties due to the operation of an electric field. They may acquire and donate ions, whose factor determines their optical features. This means that the glazing changes its degree of transparency due to the operation of electric current. Activation of the electrochromic systems can be manual or automatic, may depend on the insolation of the façade or the room temperature. Stepless control is also possible.

The structure of EC glazing is complex. The ion storage layer (passive electrode), electrolyte (material ensuring the ion flow) and electrochromic layer (active electrode) are placed between two outer panes of glazing or translucent plastic panes with transparent conductors. The chemical reaction takes place with the flow of ions due to the voltage applied. The flow of ions from the electochromic layer to the ion storage layer results in darkening the former layer. By reversing the direction of the electric field, the ions return to the active layer, making the glazing transparent again. As the layers remain electrically charged for some time, the application of voltage is only required during the ion flow process (Fig. 1 left).

Tungsten trioxide (WO_3) is a popular material used to create electrochromic coatings. The material is characterized by a relatively large range of light transmittance parameters. In the colored phase, the glazing acquires a dark blue color. The use of other materials makes it possible to obtain alternative glazing colors in the darkened mode, e.g. bronze (NiO), black (IrO_2) or changing colors, such as red-blue (CoOx) or yellow-green (Rh_2O_3) [1, 2].

In a way, the GC glazing technology was created as a response to the complex structure of EC glass. In GC glazing, the darkening and bleaching process takes place thanks to the use of a gas mixture. This eliminates the need for electric current, as is the case with EC glazing, and thus the application of transparent electrodes and an ion-conducting layer is not required.

The color of the glazing is determined by the active gas that flows through the void between the layers of the glazing. The gas reacts with the WO_3 gasochromic layer deposited on the glazing surface, causing it to turn blue (darkening) or return to a neutral color (decolorization). This effect is associated with a change in the physical properties of light transmittance and solar energy. Diluted hydrogen (below 3% of the combustion limit) is used for coloring. The return to the transparency stage occurs as a result of the introduction of oxygen that acts on the gasochromic layer (Fig. 1 right) [3, 4].

3. ANALYSIS OF TECHNICAL PARAMETERS OF EC AND GC GLAZING IN TERMS OF ENERGY EFFICIENCY

3.1. Thermal characteristics

Thermal protection of the glazing technologies can be defined by:

- solar heat gain coefficient (SHGC), also described as g-value is a value of energy transmittance as a result of solar radiation. It is determined by the solar transmittance/energy absorbed by window materials and reemitted inwards. This factor is used to quantify the solar shading capabilities of these transparent components to the short-wave radiation and it is important for reducing the use of heating loads in winter [6];
- U-value of the glazing, also known as the total heat transfer coefficient or total thermal transmittance, is used to measure its effectiveness as a thermal insulator. Measured in W/(m^{2}K), the U-value is evaluated based on the air to air heat transfer through the glazing. The heat transfer is mainly due to the heat conduction [6].

3.1.1. g- value (SHGC)

Both technologies considered in the paper exert an impact on reduction of total solar energy transmittance while in their activated mode.

On the basis of the referenced sources [7–10], typical g-values for the technologies can be estimated. For EC, the value is 0.05 to 0.6 for bleached and darken mode respectively. For GC, g-values range between 0.14 to 0.75.

3.1.2. U-value

Single EC and GC panes have unsatisfactory thermal insulation properties to be applied within facades [11]. Furthermore, in both EC and GC glass, switching occurs through absorption rather than through reflection. This means that such windows are susceptible to heating, which heat is transmitted into room interiors and, consequently, may cause their overheating.

For the above reasons, EC and GC glazing is produced as combined glazing: double glazed units (DGU) and triple-glazed units (TGU).

In DGU systems, EC and GC coatings are applied on the inside to the outer pane, usually of tempered glass. In EC glazing, the coating may be located between two layers of laminated glass [12].

The same applies to TGU systems, but adding a third pane causes additional thermal insulation layer to be created by the gap between the 2nd and 3rd pane.

In GC glazing, the space (8 mm as standard) between the outer and inner (DGU) or middle (TGU) panes creates a void for the flow of active gas.

Also, a low-emission (low-e) coating is often added to the outer surface of the pane that faces the room [3].

Manufactured glazing units with the use of EC glazing are currently characterized by a greater range of U coefficients than GC glazing systems (Fig. 2). They also reach lower values of this coefficient: 0.5–1.7W/(m^{2}K) [13], compared to 0.9–1.3W/(m^{2}K) for GC glazing [6].

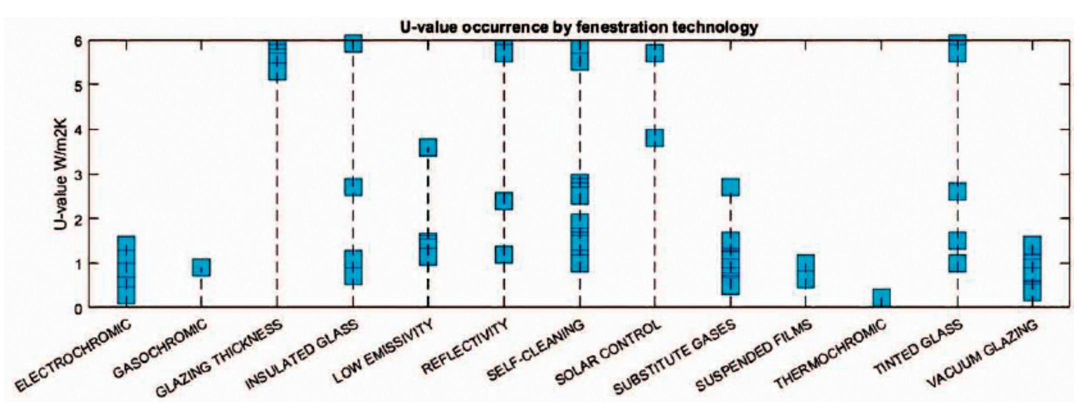

Figure 2.
Average U-value comparison of commercial glass including EC and GC technology [6]

3.2. Optical characteristics

In terms of energy efficiency, the optical characteristics of EC and GC glazing is determined by the visual (visible) light transmittance factor (Tv) as well as the relationship between Tv and g-value.

- the visual (visible) light transmittance factor (Tv) defines optical property of the glass by comprising the visible portion of the light spectrum that passes through a given glazing material. It typically amounts to 0.9 for clear glazing. This factor is determined by the type of glazing, the number of panes and the presence of coatings that can affect transparency. A high visible transmittance means more daylight presence in a given space and, usually, a reduction in electric lighting and heating loads [6].
- Tv to g-value relation: in terms of energy efficiency, it can be regarded as a more reliable indicator, because this relation determines the change in optical properties (light transmittance) against the changes in the solar protection properties expressed by the g-value.

3.2.1. Tv-value

Both technologies noticeably change their Tv values according to the mode they are in.

The visible light transmittance largely depends on the glazing structure. For EC DGU and TGU insulation systems, it is possible to achieve practically impermeable surfaces (Tv = 0.01) in the dimmed mode. On the other hand, in the bleached state, the threshold is currently Tv = 0.7, with the most common value being in the range of 0.5-0.6. The detailed optical properties of the Tv value of EC glazing are given in the graph (Fig. 3).

In the case of GC glazing, visible light transmittance values are respectively slightly higher and usually reach the range of 0,1 in the darkened and 0.75 in the neutral mode [7, 9]. Baetens et al. [8] provides a greater range of 0.06-0.77, whereas these values depend, albeit to a small extent so, on the thickness of the gasochromic coating and on gas concentration in the glazing unit [8]. As in EC glazing, the number of panes matters as well. DGU systems are characterized by a higher Tv value compared to comparable TGUs, that is up to approx. 10% [3, 13].

3.2.2 Tv to g-value

When analyzing Tv to g-value in the bleached and tinted states, this relationship is proportional for EC and GC. This means that as the g-value decreases, the Tv-value goes down proportionally, and vice versa. For EC glazing, the curve that defines the discussed relation is marked lower on the graph than the curve for GC glazing, i.e. EC glazing is generally a stronger barrier in terms of both heat and sunlight transmittance. The shape of both charts is similar, so the change in the characteristics of the thermal and optical parameters takes place in a similar proportion for both technologies.

The comparison of the Tv to g-value relationship for exemplary EC (DGU) and GC (DGU) glazing is

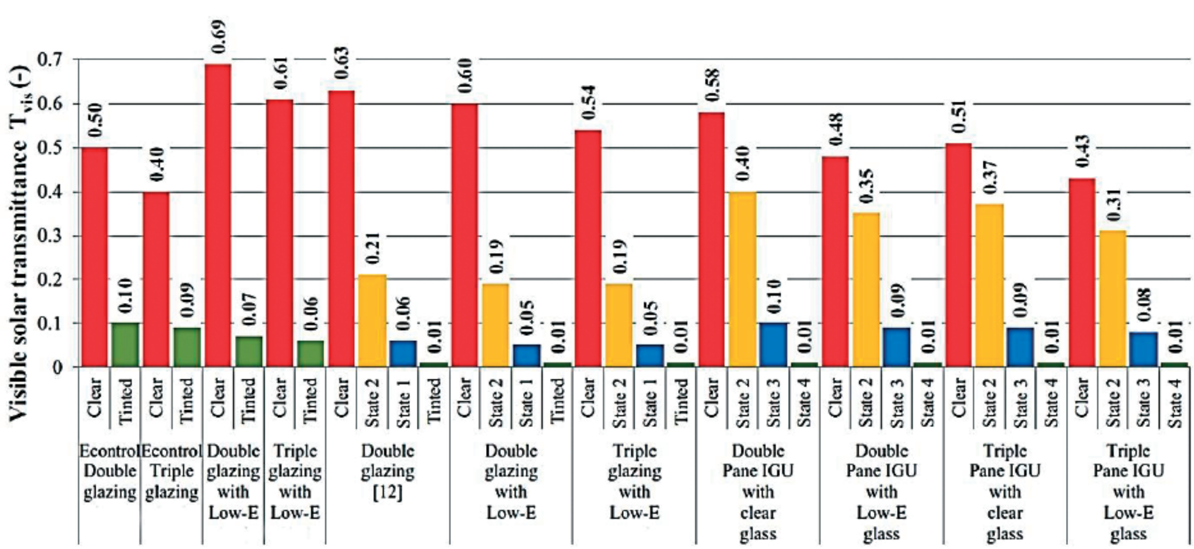

Figure 3.
Values of visible solar transmittance for EC products at different modes they are in [13]

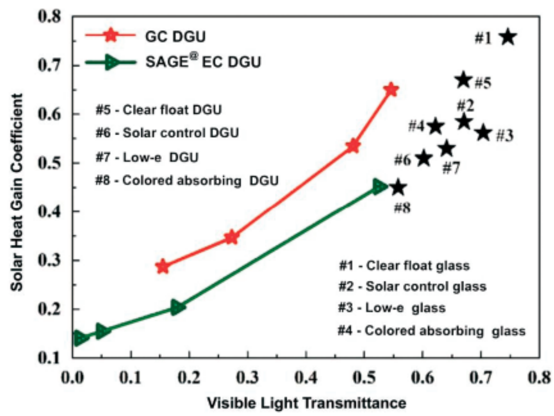

Figure 4.
Tv to g-value (SHGC) relationship of selected glazing technologies including EC and GC [14]

shown in diagram 1 (Fig. 4). The characteristics of traditional (static) glazing were also marked on it, thus highlighting the advantages of the discussed switchable technologies as solar control glazing.

In graph 2 (Fig. 5) an analogous comparison is presented between EC glazing and conventional glazing technologies with a larger Tv and g-vlaue span compared to the technology illustrated in graph 1 (Fig. 4). The comparison was made, for cases such as glazing with high solar protection properties (reflective glazing) and – for contrast – highly transparent low-e glazing. The graph for EC glazing shows that this technology may be seen as a bridge between the compared technologies of static glass, as it combines their mutually exclusive advantages.

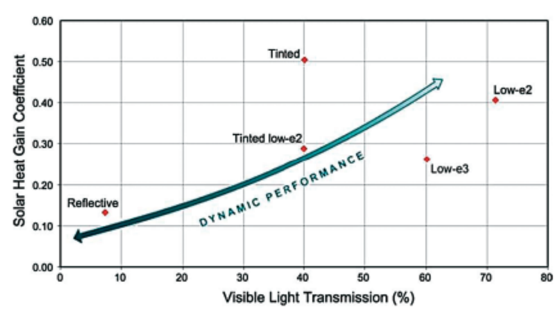

Figure 5.
Tv to g-value (SHGC) relationship of EC and selected solar/thermal protective static glazing technologies [15]

3.3. Shift in thermal and optical characteristics – phase transition period

In the case of switchable glazing, apart from the thermal and optical parameters, switching time is another important element of assessment of glazing in terms of energy efficiency. This aspect has a potential impact on the effectiveness of solar protection. Therefore, switching time may ultimately translate into the energy balance of the building related to shaping of the thermal and lighting environment.

In this aspect, there are fundamental differences between the discussed technologies. In the case of GC, switching speeds are 20 seconds to color and less than a minute to bleach the glazing [5].

EC technology speed is inversely proportional to the glazing area – for façade glazing, full coloration is achieved typically in 5-10 minutes [5], although it may require up to 20 minutes [13].

EC glazing is the slowest switchable glazing technology available today. The graph (Fig. 6) shows the transition period of EC and GC glazing, as well as of other switchable glass technologies: liquid crystal devices (LCD), micro blinds (MB) and suspended particle devices (SPD).

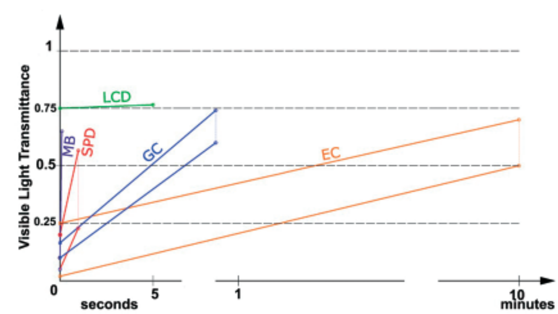

Figure 6.
Transition period for various switchable glazing technologies, including EC and GC glazing – visible transmittance as a time variable [5]

3.4. Electricity consumption

The EC and GC technologies typically require small amount or no power, respectively.

The GC glazing is not powered by electricity. The switching process is stimulated by gas (hydrogen/oxygen) that can be generated at the window wall with an electrolyzer and a distribution system integrated into the façade [5].

EC glazing requires low-voltage power, up to 10 V DC, to change the mode they are in. For some EC types (polymer laminate), the device is switched to its desired mode and then no power is needed to maintain the state. This type of device has a long memory once switched (power is not required for three to five days to maintain a given switched mode) [16].

When no voltage is applied, EC glass remains in the clear (off) mode.

It is also possible to completely eliminate electricity consumption by integrating the glazing with photovoltaic (PV) technology, which generates electric current for, among other purposes, the supply of EC glazing.

PV-EC technologies, including photoelectrochromic (PEC) glazing, are passive devices that do not require external power for operation. They can work both as free electricity generators, as well as a semitransparent solar window [17]. When integrated in building application, they provide enormous energy savings. As reported by NREL [18] , 1 kW_p of PV power can remove approximately 3 W_p of heat from a building envelope, while the same 1 kW_p of PV used to activate a PV-EC window can avert 110 kW_p. To color the window in 5 minutes requires only about 0.1 mA/cm^2 current density from the PV device [19].

4. ANALYSIS OF EXPERIMENTAL STUDIES ON THE USE OF EC AND GC GLAZING IN TERMS OF ENERGY EFFICIENCY

4.1. The influence of EC and GC glazing on energy use for heating and cooling

Simulation studies were conducted under Task 27 of the Solar Heating & Cooling Programme at the Fraunhofer Institute of Solar Energy in Freiburg [20]. As the subject matter of the study, typical cell offices with a northern and southern orientation, covering the same area and with the façade glazing share of 30% were adopted. The tests were conducted for windows equipped with EC and GC glazing, as well as traditional (static) solar control glazing with a low-emission (low-e) and reflective “mirror” coating (the parameters of the tested glazing are presented in Table 1). The research was conducted for three locations: Stockholm, Brussels and Rome, each representing the zones of cool, moderate and warm Mediterranean climate in Europe, respectively.

Research has shown that switchable windows are energy-efficient compared to traditional windows with low-e and solar control glazing (Tab. 1).

The main energy savings result from a significant reduction in the need for cooling and air-conditioning of rooms with such glazing. This applies to all climatic zones. In this aspect, the GC glazing is slightly inferior to the EC glazing tested in the simulation, which fact results from its higher g-value. This fact, however, translates into a more favorable result in terms of savings on demand for heating. GC glazing is more successful at fulfills its role of a passive solar heating element.

Low demand for cooling caused by the application of switchable glazing enables maintaining thermal comfort with the use of passive cooling methods only. The night-time ventilation strategy applied in the case of Brussels and Stockholm significantly reduced the number of overheat hours (only a few hours above 27°C, while for low-e glazing, approximately 700 hours).

However, it should be emphasized that passive cooling, if implemented as the only strategy to maintain a comfortable indoor microclimate, is in practice possible in cold climates only. It is unsuitable for locations such as Rome, where the air temperature is high in extreme periods, even at night. According to the present study, in conditions of long-lasting high air temperature outside the building, greater usefulness should be attributed to the GC glazing as it is characterized by a lower U-value. Such glazing may prove more effective in protecting the building not only against thermal energy loses in winter, but also against overheating in summer.

Table 1.
Energy demand for heating and cooling in three different climatic conditions in Europe using four different types of glazing, including EC and GC [20]

Heating Energy (kWh/m^2a)				
	Low-e DGU $U=1.3W/(m^2K)$ $g=0.60$	Solar-control DGU $U=1.1W/(m^2K)$ $g=0.33$	EC TGU $U=1.1W/(m^2K)$ $g=0.15$-0.40	GC TGU $U=0.9W/(m^2K)$ $g=0.18$-0.48
Rome	3.7	5.5	5.8	4.9
Brussels	16.6	20.3	19.9	17.2
Stockholm	33.8	39.4	37.9	33.1
Cooling Energy (kWh/m^2a)				
Rome	45.5	24.2	14.1	15.2
Brussels	16.3	6.8	3.0	3.4
Stockholm	18.8	7.3	2.6	3.1

The above mentioned studies present average results for the north and south oriented windows. More detailed results were presented in the research [21] conducted for the same office rooms and locations, but with slightly different glazing parameters. Two types of switchable glazing and static glazing with improved thermal insulation properties with a low-e coating were analyzed. Even though the study did not distinguish between the EC and GC technologies, it can be assumed that the parameters of glazing A correspond more to EC, and glazing B – GC (the parameters of the tested glazing are discussed below the graphs in Fig. 7).

The results confirmed the usefulness of switchable glazing as solar protection, i.e. their major contribution to protection against room overheating and, consequently, to relieving cooling and air conditioning systems. In the tinted mode, both A and B glazing types show a significant advantage over static glazing in all discussed locations, both for the northern and southern orientations. In terms of impact on heating needs, the simulations point to advantages of switchable glazing only in the case of high thermal insulation properties and high solar energy transmittance in the neutral mode (g-vale). However, the studies confirm that the main importance of switchable glazing for the energy efficiency of a building stems from its influence as a protection against overheating, regardless of the windows orientation.

Similar simulative studies were conducted for different climates in five locations across eastern China [14]. Harbin and Chonguing represent cool climate zones characterized by severe winters and relatively mild summers. Beijing is located in moderate climate. Shanghai is a city with mild winters and hot summers, while Guangzhou is set in a hot climate. Contrary to the presented studies based in Europe, all cities are located in a zone characterized with similar annual irradiation amounting to approx. 1.300 kWh /m^2 [22]

Table 2.
Climatic characteristics (annual values of outside air temperature and irradiation) for Chinese cities covered by simulation studies [23]

	Average lowest temperature values (°C)	Average highest temperature values (°C)	Irradiation (kWh/m^2)
Beijing	-4	+26	1300
Chonguing	-15	+23	
Guangzhou	+14	+29	
Harbin	-18	+23	
Shanghai	+5	+28	

(the equivalent of central France and Hungary). Detailed data on average temperatures are presented in Table 2.

The research was conducted for open space offices located around the perimeter of the building. In offices with a northern and southern exposure, the share of windows in the elevation was 45%, and in the east-west exposure – 30%. The height of the rooms was set at 3 m. The HVAC system was a split heat pump with a DX coil system. The heating set point was established at 21°C and cooling set point at 26°C.

Comparative studies were conducted for windows with EC and GC DGU systems and for eight types of static glass (Table 3).

The research proved the advantage of EC and GC glazing in terms of reducing energy consumption by HVAC systems in all tested locations. Compared to the reference single clear float glass, EC and GC glazing can reduce energy requirements of the building by 25–35% and 27–31%, respectively.

Table 3.
EC and GC glazing as well as various types of static glazing studied with reference to the impact on energy efficiency of a virtual office building for 5 different climatic conditions in China [14]

Glazing system types	ID	g (SHGC)	Tv
#1: Clear Float glass	8205	0.758	0.746
#2: Solar Control glass	8253	0.585	0.671
#3: Low-E glass	8307	0.562	0.704
#4: Colored absorbing glass (Green)	8209	0.575	0.622
#5: Clear Float+Clear float DGU	8205+8205	0.670	0.670
#6: Solar Control+Clear float glass DGU	8253+8205	0.510	0.602
#7: Low-E+Clear float glass DGU	8307+8205	0.530	0.641
#8: Colored absorbing +Clear float glass DGU	8209+8205	0.450	0.558
#9: SAGE@EC+ Clear float glass DGU	Bleached state Colored state	0.452 0.141	0.525 0.013
#10: GC+Clear float glass DGU	Bleached state Colored state	0.650 0.287	0.546 0.155

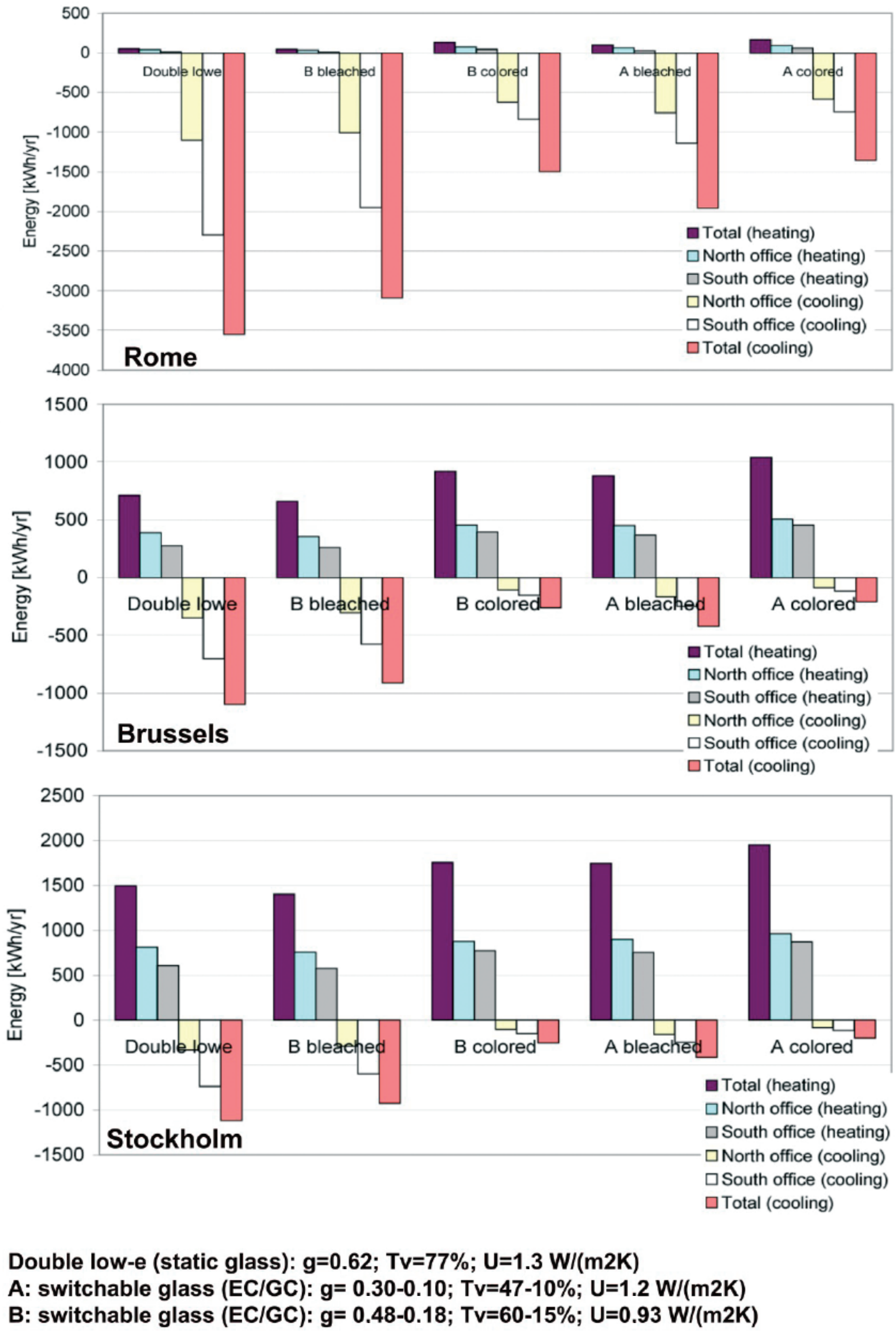

Figure 7.
Energy demand for heating and cooling of office spaces in three different locations across Europe, depending on the technology and parameters of window glazing, including switchable glazing (EC/GC) [21]

The advantage of switchable glazing over static glazing, however, applies to the annual balance sheet. Certain types of traditional glazing offer an advantage in individual months. For example, in Shanghai, the most energy-efficient type of glazing in winter is low -e DGU (#7).

According to the simulation data, the most energy efficient type of static window varies in different regions. Solar control DGU, colored absorbing DGU, low-e DGU, solar control DGU and colored absorbing DGU seem the best choice for Beijing, Guangzhou, Harbin, Changchun and Shanghai respectively.

This derives from the fact that heating contributes the largest proportion of HVAC loads in cold regions, while the opposite is true in Guangzhou. Thus, in this region, a lower U-value is desired to offset major heat loss through direct conduction due to extreme cold temperature, whereas a high SHGC is desired to help passively heat the building. Nevertheless, a low SHGC is required to attenuate the intense sun and limit solar gain in warm climates.

In terms of the annual energy balance, a comparison of switchable glazing with most energy-efficient static glazing technologies for a given location shows the greatest advantage, of EC glazing in warm climates (Shanghai and Guangzhou), and the lowest benefit in cold climates (Harbin). In the case of GC glazing, this advantage is opposite – i.e. the greatest advantages of GC glazing in terms of energy saving are revealed in the cold (Harbin), while the least beneficial situation was observed in the hot climate (Fig. 8 right).

This is confirmed by simulation calculations of annual energy outlay on HVAC for the tested locations. Compared to both switchable technologies, GC glazing proves a more energy-efficient technology per year only for the Harbin conditions. In turn, the greatest advantage of EC glazing is noted in hot climates (Guangzhou) (Fig. 8 left). This may suggest that high transparency of the glazing during the heating period is similar to the low transparency during hot periods. It may also be predicted that if the proportion between cooling needs and heating load of buildings is closer to 50%, smart windows will provide more energy saving potential.

4.2. The influence of EC and GC on energy use on cooling and lighting

In the simulation study [24], EC and GC windows together with termochromic (TR) and static tinted type of glazing have been compared in order to define which of the above offers a better balance between reducing energy consumption on cooling and saving daylight. The simulation was conducted for an office building in southern Egypt for all orientations and various window area-to-floor ratios (WFR): 8%, 16%, 24% and 32%.

The research showed the greatest efficiency of switchable glazing in terms of saving energy, which results from the relief of air conditioning systems. The EC glazing has an advantage over the GC glazing for each orientations and for each WFR tested.

With regard to traditional clear glass (Tv = 0.78, g = 0.86), the greatest savings for both technologies concern the southern and western orientations at WFR 32%, while the lowest amount of energy saving was noted for the north and east for WFR 8–16%. As an optically dynamic but non-switchable technology,

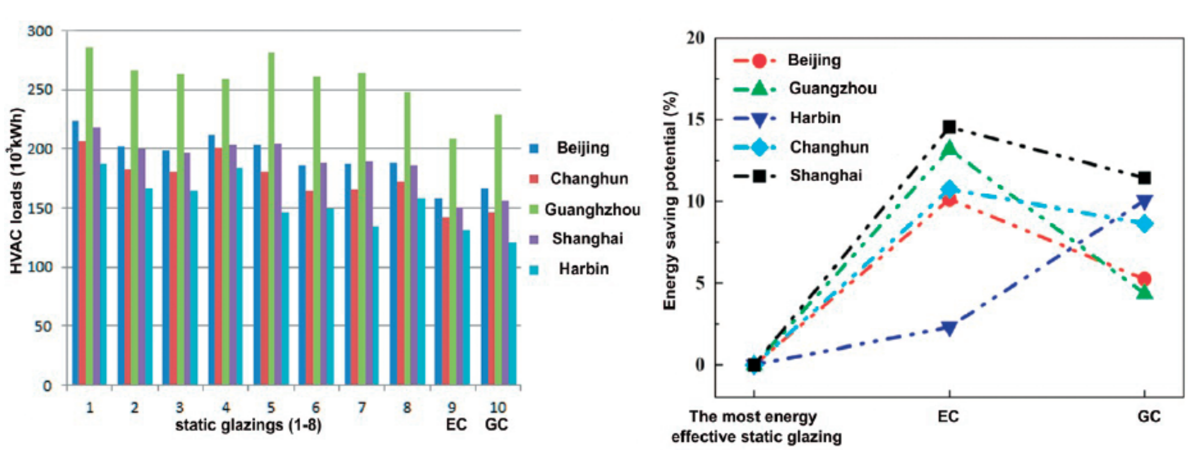

Figure 8.
HVAC loads of different glazing systems, including EC and GC, in 5 different regions across China (left) (by the author, on the basis of [14]). Energy saving potential of EC and GC glazing for the studied locations

TR glazing ranks in the discussed aspect between EC/GC glazing and traditional (static tinted) solar protection glazing. This fact proves the effectiveness of dynamic glazing as a solar protection with the superiority of switchable technology (EC and GC).

In terms of lighting aspect, the differences between the tested glazing are insignificant. EC reduced glare in the eastern and western orientations by 64%. Moreover EC reduced consumption of lighting energy by 60%, 61% and 57% in eastern, southern and western orientation, respectively. The performance of GC glass was similar to that of EC glass in providing daylight. Tinted blue glass achieved similar performance as did GC glass in the northern, eastern and western orientations, but GC glass is superior in the southern orientation. For daylighting availability, all types of smart glazing and tinted color glass are used to reduce the glare of daylight in the morning hours in the eastern orientation and the afternoon hours of the day for the western exposure.

Simulation proved that static glazing systems are unable to adapt to the changing environment in the hot dry climate of Egypt. EC glass proves the most favorable solution and its significance increases along with the rise of WFR value. It can save cooling energy by 40%, and light energy by 43% at 8% WFR in southern orientation, whilst at 32% WFR by 46%, and 61% respectively. In both cases it is better than other glass types.

5. DISCUSSION AND CONCLUSIONS

Technical parameters of the EC and GC glazing (U, g, Tv) in the DGU and TGU systems are satisfactory in the view of construction requirements, so that both the EC and GC glazing can be treated as fully adapted to use within the building envelope in this aspect. Such solutions offer an attractive alternative to traditional glazing technology – solar control and low-emission. Their advantage lies in the possibility of adjusting thermal and optical parameters to the environmental conditions, thanks to which they merge

Table 4.
Percentage of reduced cooling and lighting energy of EC, GC glazing and solar protective static glazing for different ratios of window to floor (WFR) area in offices in hot climate (southern Egypt) [24]

	North		East		South		West	
	Cooling Energy	Light Energy	Cooling Energy	Light Energy	Cooling Energy	Light Energy	Cooling Energy	Light Energy
8% WFR								
EC	38	20	30	35	40	42	32	30
GC	22	20	25	34	32	41	27	30
TC	15	19	21	30	26	37	24	26
Blue	11	30	18	31	19	38	21	26
Green	11	16	17	41	18	48	21	35
Brown	9	25	16	36	16	43	19	31
16% WFR								
EC	28	41	32	52	36	56	35	47
GC	26	41	28	52	31	55	30	45
TC	22	33	22	47	25	53	24	40
Blue	19	33	18	47	15	52	20	40
Green	19	48	18	56	15	57	19	49
Brown	17	41	16	52	12	55	16	45
24% WFR								
EC	31	54	40	52	40	59	43	51
GC	25	54	34	52	34	58	36	57
TC	20	48	26	47	27	57	29	54
Blue	16	50	22	47	19	58	25	54
Green	16	57	21	56	18	59	25	53
Brown	13	55	19	52	15	59	23	50
32 WFR								
EC	35	57	43	60	46	61	45	57
GC	30	57	38	60	40	60	41	57
TC	25	54	30	58	32	59	33	54
Blue	19	55	23	59	21	59	25	54
Green	19	59	23	60	20	60	25	59
Brown	16	58	21	60	16	59	23	57

the advantages of solar protection, passive heating and natural lighting of rooms, which factors are mutually exclusive in the case of traditional (static) glazing technologies.

EC glazing is characterized by a wider selection of products – this advantage is particularly visible in terms of thermal insulation of glazing units. A comparative analysis of g- and Tv values shows that, in principle, EC glazing is a "darker" glazing than GC, i.e. adapted to stronger solar protection. Both technologies can be treated as passive ones, i.e. they do not require external power. Although electric power is required for the operation of EC glazing, it is negligible in the building scale, and the possibility of integration with PV technology makes it independent from an external power source.

The cited experimental studies prove the effectiveness of EC and GC glazing as energy-saving measures on an annual basis. Clear merits and advantages over static glazing are revealed in the aspect of solar protection, i.e. in relieving air conditioning systems operation. This advantage was confirmed in all tested climatic zones, regardless of the orientation, size and area share of the glazing. Generally, EC glazing achieved better results, which may lead to the conclusion that it should be particularly recommended in warm and sunny climatic zones, where the main problem results from overheating of buildings.

In terms of the impact on the energy efficiency of buildings related to relieving heating systems, the role of switchable glazing is less significant. Comparative analyzes with traditional glazing have shown that switchable glazing can be competitive only in case of a low U-value and relatively high translucency (Tv) in the natural mode. This result is confirmed by European studies. Basically, a greater role should be assigned to GC glazing, which in turn is confirmed by Chinese studies (GC proved more favorable than EC for Harbin, i.e., the coldest location).

An interesting aspect of research on the energy-saving role of EC and GC glazing is related to taking into account their impact on the lighting environment of the interior space, i.e. reducing the share of artificial lighting. Simulation studies have shown the particular advantages of EC glazing in the overall energy balance. This influence was considered together with the cooling needs. With regard to neutral glass, EC glazing exerted the greatest impact on reducing energy consumption, as compared to static solar control glazing, TC and GC glazing. The impact of this technology on the energy efficiency increases with the rise in the proportion of glazing in relation to the room area and is greatest at the southern exposure. However, should the lighting aspect be considered separately, the EC and GC technologies yielding a similar effect showed no significant advantages, regardless of the glazing to room ratio or the orientation. This aspect requires further research for locations with less sunlight.

The presented research leads to the conclusion that EC and GC glazing can exert positive effects on the energy balance of a building and, on an annual basis, offer an advantage over static glazing in all basic climate zones. In short-term analyzes of temporary weather conditions, however, EC and GC may not always be the best solution. This means that these technologies need to be further improved. In terms of energy efficiency, further research is needed, with as much as possible account to the "behavior" of the glazing in real use conditions, including switching between the off and on modes. Given the much longer transition period for EC glazing compared to GC glazing, the advantages of the former may be reduced, especially in "dynamic" climates where frequent glazing is required. Another research gap is noticeable in a comprehensive comparative analysis of EC and GC glasses with regards to the impact on heating, air-conditioning and lighting needs, conducted for moderate and cold climates with different irradiation characteristics.

Among the presented analyzes, the outcomes obtained for Brussels and Beijing can be treated as the closest to the potential results for the climatic conditions in Poland. On the basis of these results, it can be concluded that in the thermal aspect, both EC and GC glazing have a positive effect on the energy efficiency of the building in terms of relieving HVAC systems. Thus, in this aspect, these solutions are more

Table 5.
Evaluation of EC and GC glazing in terms of their impact on the energy efficiency of the building [by the author]

<table>
<tr><td></td><td colspan="6">Climate</td></tr>
<tr><td></td><td colspan="2">Cold</td><td colspan="2">Moderate</td><td colspan="2">Hot</td></tr>
<tr><td></td><td>EC</td><td>GC</td><td>EC</td><td>GC</td><td>EC</td><td>GC</td></tr>
<tr><td>HVAC</td><td>+</td><td>++</td><td>++</td><td>+</td><td>++</td><td>+</td></tr>
<tr><td>- cooling,
- air conditioning</td><td>+</td><td>+</td><td>++</td><td>+</td><td>++</td><td>+</td></tr>
<tr><td>- heating</td><td>+/-</td><td>+</td><td>+/-</td><td>+</td><td>-</td><td>+/-</td></tr>
<tr><td rowspan="2">HVAC + lighting</td><td>+</td><td>++</td><td>+</td><td>+</td><td rowspan="2">++</td><td rowspan="2">+</td></tr>
<tr><td colspan="4">evaluation predicted:
further research required</td></tr>
</table>

Beneficial effect compared to static glazing with solar control and thermal insulation properties: ++: very high; +: large; +/-: comparable; - : lack beneficial than static glass technologies. Compared to the EC and GC technologies, it can be assumed that the EC glazing is more suitable. These benefits will increase with increasing needs for cooling the building space. On the other hand, in view of the lighting aspect, the GC glazing, being brighter and faster at reacting to dynamic weather changes, suggests greater energy savings in this regard.

REFERENCES

[1] Lampert C.M. (1995). Chromogenic Switchable Glazing: Towards the development of the Smart Window. Proceeding – window innovations'95. Toronto. Canada July 5-6th 1995.

[2] Marchwiński J. (2007). Szklenie elektrochromatyczne w budownictwie (Electrochromic glazing in buildings). *Świat Szkła, 2*(106), 18–19.

[3] Marchwiński J. (2007). Szklenie gazochromatyczne w budownictwie (Gasochromic glazing in buildings). *Świat Szkła, 6*(109), 20–21.

[4] Persson M.L. (2006). Windows of Opportunities. Uppsala University. Faculty of Science and Technology.

[5] Marchwiński J. (2014). Architectural evaluation of switchable glazing technologies as sun protection measure. *Energy Procedia*, 57, 1677–1686. doi:10.1016/j.egypro.2014.10.158.

[6] Aguilar-Santana J.S., Jarimi H., Velasco-Carrasco M., Riffat S. (2020). Review on window-glazing technologies and future prospects. *International Journal of Low-Carbon Technologies*, 15, 112–120. doi:10.1093/ijlct/ctz032.

[7] Addington M. & Schodek D. (2006). Smart Materials and Technologies. Elsevier.

[8] Baetens R., Jelle B.P. & Gustavsen A. (2010). Properties, Requirements and Possibilities of Smart Windows for Dynamic Daylight and Solar Energy Control in Buildings: State-of-the-Art. *Solar Energy Materials and Solar Cells, 94*(2), 87–105. doi: 10.1016/j.solmat.2009.08.021.

[9] Georg A. (2008). Switchable glazing with tungsten oxide. Elsevier.

[10] Hausladen G., Saldanha M. & Liedl P. (2006). Climate Skin, Building-skin Concepts that Can Do More with Less Energy. Birkhauser, Basel-Boston-Berlin.

[11] Platzer W.J. (2003). Handbook for the Use of Façade Technology. Architectural and technical guidelines. Fraunhofer ISE.

[12] Cannavale A., Ayr U., Fiorito F.& Martellotta F. (2020). Smart Electrochromic Windows to Enhance Building Energy Efficiency and Visual Comfort. *Energies*, 13, 1449. doi:10.3390/en13061449.

[13] Sibilio S., Rosato A., Scorpio M., Iuliano G., Ciampi G., Vanoli G.P.& de Rossi F. (2016). A Review of Electrochromic Windows for Residential Applications. *International Journal Of Heat And Technology, 34*(2), 481–488. doi:10.18280/ijht.34S241.

[14] Wei Feng, Liping Zou, Guohua Gao, Guangming Wu, Jun Shen & Wen Li. (2016). Gasochromic smart window: optical and thermal properties, energy simulation and feasibility analysis. *Solar Energy Materials & Solar Cells*, 144, 316–323. doi:10.1016/j.solmat.2015.09.029.

[15] Sbar N.L., Podbelski L., Yang H.M. & Pease B. (2012). Electrochromic dynamic windows for office buildings. *International Journal of Sustainable Built Environment*, 1, 125–139. doi:10.1016/j.ijsbe.2012.09.001.

[16] Carmody J., Selkowitz S., Lee E., Arasteh D. & Willmert T. (2004). Windows Systems for High Performance Buildings. WW Norton & Company, New York-London.

[17] Lefthieriotis G., Syrrokostas G., Yianoulis P. (2013). Photocoloration efficiency and stability of photoelectrochromic devices. *Solid State Ionics*, 231, 30–36. doi:10.1016/j.ssi.2012.10.024.

[18] Deb S.K., Se-Hee Lee, Tracy C.E., Pitts J.R., Gregg B.A. & Branz H.M. (2001). Stand-alone photovoltaic-powered electrochromic smart window. *Electrochimica Acta*, 46, 2125–2130] doi:10.1016/S0013-4686(01)00390-5.

[19] Deb S.K. (2000). Photovoltaic-Integrated Electrochromic Device for Smart-Window Applications. World Renewable Energy Congress VI Brighton, U.K. July 1–7, 2000.

[20] Platzer W.J. (2003). Switchable Façade Technology – Energy Efficient Office Building with Smart Façades, Solar World Congress. Proceedings. CD-ROM : Solar energy for a sustainable future; June 14–19, 2003, Göteborg, Sweden.

[21] Köhl M. (2006). Performance, durability and sustainability of advanced windows and solar components for building envelopes. International Energy Agency Solar Heating & Cooling Programme – Task 27 (Performance of Solar Façade Components). Subtask A: Performance. Projekt A2: Switchable glazing. Final Report. Fraunhofer ISE. March 2006.

[22] https://www.powermarket.uk/markets/china/ [2021-01-15].

[23] https://www.climate-data.org [2021-01-15].

[24] Nageib A., Elzafarany A.M., Elhefnawy M.H. & Mohamed F.O. (2020). Using smart glazing for reducing energy consumption on existing office building in hot dry climate. *HBRC Journal, 16*(1), 157–177. doi:10.1080/16874048.2020.1794226.