TEMA

Technologies
Engineering
Materials
Architecture

Journal Director: R. Gulli

e-ISSN 2421-4574
DOI: 10.30682/tema0801

Vol. 8, No. 1 (2022)

Issue edited by Editor in Chief: R. Gulli

Cover illustration: Tokyo International Forum by Rafael Viñoly, interior view.
© Riccardo Gulli, 2018

Editorial Assistants: C. Mazzoli, D. Prati

TEMA
Technologies
Engineering
Materials
Architecture

e-ISSN 2421-4574
ISBN online 979-12-5477-084-9
DOI: 10.30682/tema0801

Vol. 8, No. 1 (2022)

Year 2022 (Issues per year: 2)

Editor in chief
Riccardo Gulli, Università di Bologna

Assistant Editors
Annarita Ferrante – Università di Bologna
Enrico Quagliarini – Università Politecnica delle Marche
Giuseppe Margani – Università degli Studi di Catania
Fabio Fatiguso – Università Politecnica di Bari
Rossano Albatici – Università di Trento

Special Editors
Luca Guardigli – Università di Bologna
Emanuele Zamperini – Università degli Studi di Firenze

Associated Editors
İhsan Engin Bal, Hanze University of Applied Sciences – Groningen
Antonio Becchi, Max Planck Institute – Berlin
Maurizio Brocato, Paris – Malaquais School of Architecture
Marco D’Orazio, Università Politecnica delle Marche
Enrico Dassori, Università di Genova
Vasco Peixoto de Freitas, Universidade do Porto – FEUP
Stefano Della Torre, Politecnico di Milano
Marina Fumo, Università di Napoli Federico II
José Luis Gonzalez, UPC – Barcellona
Francisco Javier Neila Gonzalez, UPM Madrid
Alberto Grimoldi, Politecnico di Milano
Antonella Guida, Università della Basilicata
Santiago Huerta, ETS – Madrid
Richard Hyde, University of Sydney
Tullia Iori, Università di Roma Tor Vergata
Raffaella Lione, Università di Messina
John Richard Littlewood, Cardiff School of Art & Design
Camilla Mileto, Universidad Politecnica de Valencia UPV – Valencia
Renato Morganti, Università dell’Aquila
Francesco Polverino, Università di Napoli Federico II
Antonello Sanna, Università di Cagliari
Matheos Santamouris, University of Athens
Enrico Sicignano, Università di Salerno
Claudio Varagnoli, Università di Pescara

Editorial Assistants
Cecilia Mazzoli, Università di Bologna
Davide Prati, Università di Bologna

Journal director
Riccardo Gulli, Università di Bologna

Scientific Society Partner:
Ar.Tec. Associazione Scientifica per la Promozione dei Rapporti tra Architettura e Tecniche per l’Edilizia
c/o DA - Dipartimento di Architettura, Università degli Studi di Bologna
Viale del Risorgimento, 2
40136 Bologna - Italy
Phone: +39 051 2093155
Email: info@artecweb.org - tema@artecweb.org

Media Partner:
Edicom Edizioni
Via I Maggio 117
34074 Monfalcone (GO) - Italy
Phone: +39 0481 484488

TEMA: Technologies Engineering Materials Architecture
Vol. 8, No. 1 (2022)
e-ISSN 2421-4574

CONSTRUCTION HISTORY AND PRESERVATION

CONSTRUCTION AND BUILDING PERFORMANCE

BUILDING AND DESIGN TECHNOLOGIES

METHODOLOGICAL APPROACH AND COMPARATIVE ANALYSES FOR SMART ENVELOPES ASSESSMENT IN THREE DIFFERENT TEMPERATE CLIMATES

TEMA
Technologies
Engineering
Materials
Architecture

e-ISSN 2421-4574
Vol. 8, No. 1 - (2022)

Francesco Carlucci, Francesco Fiorito

DOI: 10.30682/tema080m

Abstract

Recently, innovative and responsive technologies applied to building envelopes have drawn the attention of researchers to reduce energy consumption and improve indoor environmental quality. The main feature of these systems is to react to external environmental stimuli and adapt themselves to improve the overall building performance. The spread of these technologies has promptly led to a wide range of very different new devices that have added a further degree of complexity in the energy efficiency field. This study is part of this research topic and proposes a comparison of four different responsive technologies applied to glazed surfaces of an office model located in three different Italian cities to compare their advantages and disadvantages in different contexts. This comparison is conducted from both technological and energy points of view on the following selected technologies: i) electrochromic windows, ii) Phase Change Material windows, iii) dynamic automated external shadings, and iv) windows with variable thermal transmittance. The first part of this study focuses on the technology comparison – with reference to users' control, building integration, cost, and maintenance – to highlight the main strengths and disadvantages of these systems. Hence, starting from an office reference model located in Brindisi, Rome, and Milan, dynamic energy analyses are conducted in EnergyPlus to compare the responsive systems with reference static envelopes obtaining as the final output the savings comparison between different technologies, exposures, and climates.

Keywords

Smart façades, Electrochromic, Phase Change Material, Dynamic shadings, Variable thermal transmittance.

Francesco Carlucci*
DICATECH - Dipartimento di Ingegneria Civile, Ambientale, del Territorio, Edile e di Chimica, Politecnico di Bari, Bari (Italy)

Francesco Fiorito
DICATECH - Dipartimento di Ingegneria Civile, Ambientale, del Territorio, Edile e di Chimica, Politecnico di Bari, Bari (Italy)

**Corresponding author:
e-mail: francesco.carlucci@poliba.it*

1. INTRODUCTION

In the last years, the high impact of the building field on global energy consumption has led researchers and policymakers to focus their attention on building decarbonisation with the aim to meet the international goals defined by the United Nations Sustainable Development Goals and the Paris Agreement Commitment. Despite these efforts, we are still far from these goals; for example, in 2018, the energy intensity improvement rate was reduced to 1.2%, but the trend has still not been reversed [1]. When comparing 2020 and 2010, the space heating consumption has registered a significant reduction (-20%), followed by a strong lighting reduction (-17%), while cooling consumption has registered a decrease of nearly 7% [2]. This gap between different consumption sources can be explained considering the energy conservation approach that has spread in the last years in building design. The main outcome of this approach is the increase of the building's insulation that has led, on the one hand, to a reduction in the heating consumption and, on the other hand, to an increase in the building overheating, especially in hot climates.

Recently, this approach has been questioned by researchers who are trying to shift this strategy from the static maximisation of the insulation to a responsive approach that better suits the dynamism of environmental conditions. Therefore, the Responsive Building Elements (RBEs) are spreading in the last years, thanks to their capability to react in a controlled way – managing the transfer and storage of heat, air, light, and water [3] – according to external/internal changes and/or to users' interaction.

Responsive systems can be applied to several building elements and are characterised by different physical domains (thermal, optical, etc.), controls (intrinsic, extrinsic), response time (minutes, hours, seasons), and adaptation scale (micro, macro) [4]. All these characteristics make the prediction and comparison of these technologies more challenging. In the case of responsive systems applied to transparent envelopes, the level of complexity increases because – due to their multi-domain nature – they concurrently affect solar gains, daylighting, and heat transfers.

This paper fits into this research scene, proposing a comparison of four smart technologies implemented on the glazed surfaces of an office model located in three different Italian cities – Brindisi, Rome, Milan – to highlight the advantages and disadvantages of each system. The comparisons are conducted for i) electrochromic (EC) windows, ii) Phase Change Material (PCM) windows, iii) dynamic automated shadings, and iv) variable thermal transmittance (U) windows. PCM and U-variable materials can be implemented on both transparent and opaque surfaces; nevertheless, in this study, they are considered applied only on windows to conduct reliable comparisons with EC glazing and dynamic shadings. Before reporting the methodology adopted, the following subsections describe the state-of-the-art of these systems to better understand their functioning criteria, advantages, and disadvantages.

1.1. EC WINDOWS

Among active switchable glazing systems, EC windows are one of the most developed technologies, as confirmed by many commercial products already available. Their main feature is the capability to switch between bleached, dark, and intermediate states changing their optical and solar properties thanks to the application of an external electrical bias. This properties' switch is triggered by reversible oxidation-reduction reactions in the EC film that change the window solar and light transmittance. From a technological point of view, the EC glazing is composed of two EC films deposited on conductive layers (cathodic and anodic) separated by an electrolyte interlayer [5]. To avoid interferences between layers and to trigger simultaneous bleaching or colouration of both EC films, the most used chromogenic materials are the WO3 for the cathodic layer and the NiO for the anodic layer [6].

The switching time of these systems ranges from 7 to 20 minutes, and once the EC glazing changes its state, it can keep that specific state without applying any voltage depending on its optical or open circuit memory. This parameter usually ranges between 2 and 12 hours and affects the durability of the system that is related to a certain number of cycles that corresponds to a service life of nearly 20-30 years [7].

Sibilio et al. [8] proposed a wide analysis of the commercial EC devices useful to define the modulation range of this technology. This analysis reports that the Solar Heat Gain Coefficient (SHGC) can range from 0.29 to 0.49 in the window bleached state and from 0.04 to 0.13 in the fully dark state, while the Visible Light Transmittance (VLT) ranges from 0.43 to 0.69 for the bleached state and between 0.01 and 0.10 in the dark state.

Starting from these conventional EC devices, different systems can be realised depending on the EC films applied. EC films can act differently on the spectrum wavelengths and, depending on their behaviour, are classified into three macro groups: Conventional EC (CEC), Near-infrared radiation switching EC (NEC), and Dual-Band EC (DBEC) [9].

Hence, the key advantages of the EC devices are the extrinsic control system coupled with a customisable sensing/control algorithm and the high retrofitting suitability. Moreover, the low switching voltage (1-5 V), the power absorption during the switching phase, the good open circuit memory, the minimal polarisation, and distortion are functioning features that increase the potential of these devices [10, 11].

On the other hand, the high investment cost and aesthetical drawbacks of a changing colour system are the main disadvantages of this technology.

1.2. PCM WINDOWS

The main feature of PCMs is the capability to change their phase autonomously and reversibly with a resulting storage/release of a high amount of latent heat in low volume elements; for this reason, they are classified as intrinsically controlled with a gradual micro-scale adaptability.

Thanks to this behaviour, PCMs have been recently considered as a possible solution for the low thermal inertia of glazed surfaces. Clearly, not every PCM can be considered suitable for windows applications due to their lack of transparency. Nevertheless, paraffin-based PCMs show a translucent behaviour in the solid state and fully transparent behaviour in the liquid state that allow these applications.

An example of PCM window is the 8-15-6 mm Double Glazing Unit (DGU) developed by Goia et al. [12]; in this case, the cavity is filled with a paraffin wax with a melting temperature of 35°C and a heat storage capacity of 170 J/g. The implementation of PCM in the DGU led to improvements in the energy performance in summer behaviour in a temperate climate. Instead, from the daylighting point of view, Giovannini et al. [13] found that this technology leads to improvements in the illuminance and Daylight Glare Probability only for low overall sky luminance.

The complexity of PCM windows is very high due to their multi-domain nature as they couple the heat storage/release with the change of optical properties. This behaviour can lead to concurrent improvements – e.g., the increase of the summer heat storage – and worsening, such as the higher SHGC of the liquid phase.

To sum up, the key feature of this system is to shift the summer heat load peaks improving the heat storage capacity; this leads to higher comfort thanks to a reduction of the surface temperature. Other advantages are the low maintenance cost and the low glare risk in the solid phase, thanks to the PCM scattering effect [14].

The spread of this technology could be slowed down by the technological limitations – low fire safety, no external controls allowed, high SHGC in the liquid state, reduction of daylight and external view in the solid state – and due to aesthetic inhomogeneity during the transition phase [14].

1.3. DYNAMIC AUTOMATED EXTERNAL SHADINGS

One of the oldest strategies to control incoming solar radiation is the use of shading systems. Starting from simple static shadings, the evolution of this technology has led to the development of intelligent and adaptive systems that can move or change their shape through automated or autonomous adjustments.

The shading movement can rely on different functioning, and a plethora of new technologies have spread in the last years. For example, one of the latest and most promising approaches is based on phytomimetic [15] and considers the capability of generating movement through proper distribution and orientation of the material's fibres. This functioning can be coupled with shape-memory materials to develop a new class of plant-inspired shading systems. The shape memory wires are characterised by a stress-strain hysteresis that allows modifying the wires' shape depending on their temperature; this feature is extremely useful to consider these wires as embedded actuators. If the wire temperature is increased by using an electrical current, the shading can be considered automated and extrinsically controlled; on the contrary, if the transition is triggered by solar radiation, the device is classified as autonomous or intrinsically controlled.

This brief example aims only to show the wide range of possible dynamic shading systems highlighting a faceted scenario where specific pros and cons should be referred to each system. However, narrowing the field to automated or extrinsically controlled shadings, the main advantages are the extrinsic control system coupled with a customisable sensing/control algorithm and the wide range of possible geometries allowed.

On the other hand, the high maintenance costs of the mechanical systems and the high architectural integration needed – for both aesthetical reasons and the reduction of external view – are the main weak points of these devices.

1.4. VARIABLE THERMAL TRANSMITTANCE WINDOWS

The energy efficiency of highly insulated buildings is widely recognised during winter and the summer air conditioning period. Nonetheless, buildings with super-insulated envelopes can be affected by overheating when the cooling system is off and can lose the benefits related to the summer night heat flow. The concept behind variable U building elements is to find a balance between summer and winter behaviours controlling the heat exchange through the envelope. Currently, these systems are based on the use of variable air or liquid convection, variable gas pressure, variable surface interaction, or movable insulation to change their thermal properties [16].

Narrowing the field to the variable U windows, the main prototypes available are based on the variable convection or the movable insulation technologies. The former is based on a movable insulating pane in a closed module that can move between its middle and top position. The pane is in the top position for the insulating state, as no convection around the panel is allowed. In contrast, when the insulation switches to its middle position, the temperature difference triggers large-scale convection around it [17] (Fig. 1). These systems can be implemented in glazed elements only using translucent materials – such as open-pore melamine foam (λ=0.035 W/mK) or aerogel materials (λ=0.013 W/mK) – to allow the light transmission.

Another movable insulation technology is based on the use of a series of air cavities separated by rollable opaque films [18]. When the films are rolled out, the U values are lower thanks to the creation of a series of thin air cavities; while, when the films are rolled up, the resulting larger single air cavity eases the heat exchanges.

The main benefits of the described devices are the possibility to extrinsically control the device and couple the activation with a customisable sensing/control system with low activation energy.

On the other hand, the main drawbacks of the implementation of this technology are the difficult maintenance, the low VLT, and the partial reduction of the external view.

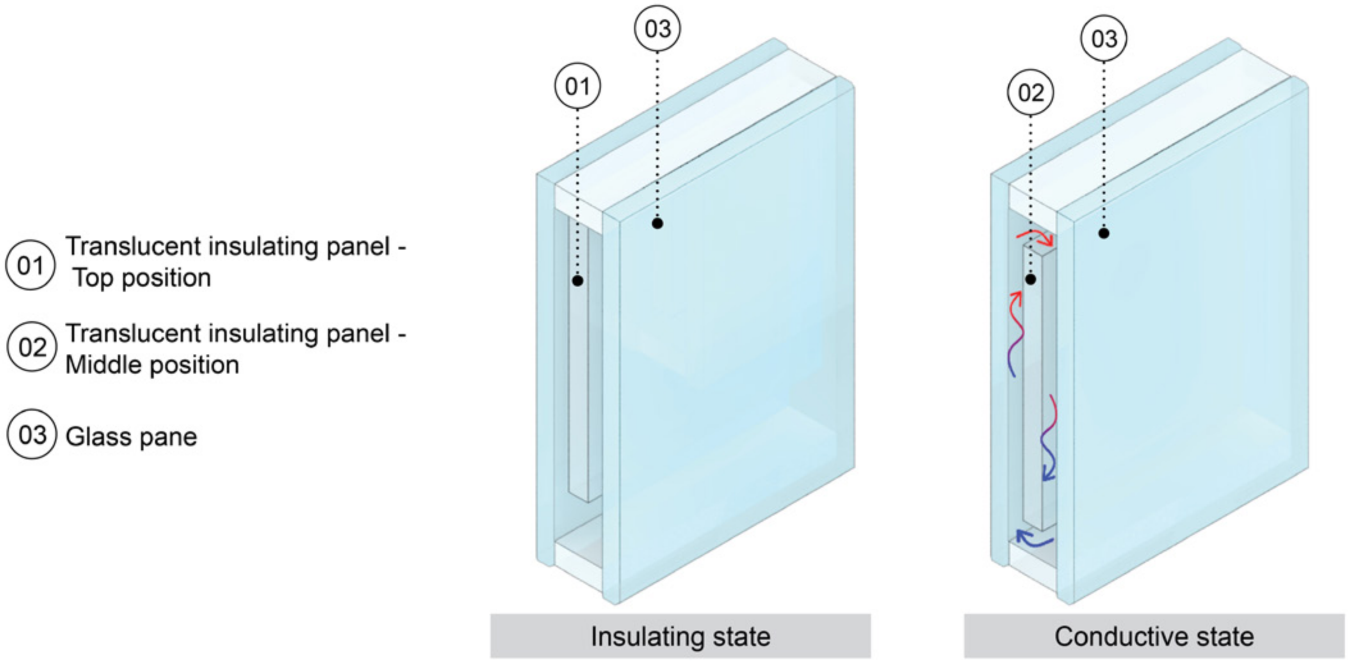


Fig. 1. *Functioning of a variable U window based on variable air convection [19].*

2. METHODOLOGY

To understand the energy behaviour of these technologies, EnergyPlus v.9.4 was used as a simulation engine. This software allows a good multi-domain integration and is one of the most complete tools for the dynamic simulation of responsive façades [20]. Moreover, the U.S. Department of Energy provides 16 validated EnergyPlus models that can be used as a reference for energy efficiency-oriented research.

In particular, the medium office was considered a starting point for this study and a reference model was created according to the Italian energy code [21]. Then, a set of models implementing responsive façade elements were considered for the analyses. Southern, western, and eastern façades were implemented with EC windows, PCM windows, automated blinds, and variable U windows defining four responsive models. The functioning criteria considered for each responsive and reference model depend on the technology, and details are provided in the following subparagraphs; instead, all other opaque building elements were designed in accordance with current Italian law.

Three different Italian cities – Brindisi, Rome, Milan – were selected to understand the behaviour of each technology in different climates. The climatic variables of the considered cities are described in Figure 2.

Moreover, to improve the results reliability, systems availability and schedules of the reference and responsive models were considered in accordance with the Italian law for heating availability (D.P.R. n. 412, 1993 [22]) and with common values for cooling availability as reported in Table 1. The dimmable lighting system was connected to a daylighting sensor with a 500 lux setpoint, placed in the middle of each zone in order to account for lighting change. Regarding the internal gains, the main internal loads were changed according to local and more recent standards [23, 24]; particularly, 6.5 W/m^2, 5.5 W/m^2, and 13.9 m^2/person were considered, respectively, as light power density, equipment power density, and zone floor area per person.

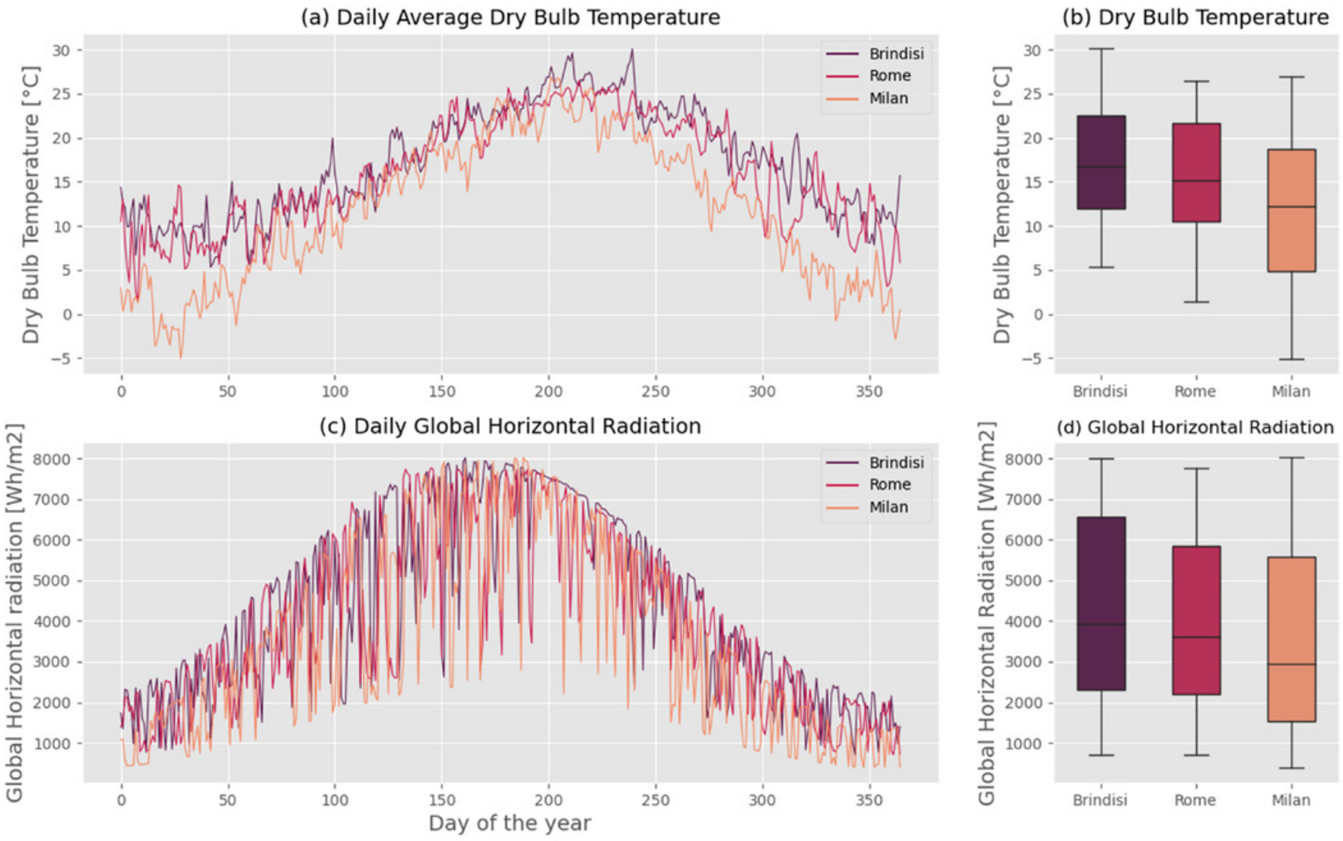


Fig. 2. *Weather data: (a) daily average and (b) statistical distribution of the dry bulb temperatures, (c) daily cumulative global horizontal radiation, (d) statistical distribution of the global horizontal radiation.*

City	Climate characteristics		System availability schedule		
	Köppen–Geiger classification	HDD $_{18°C}$	Source	Period	Hours
Brindisi	Csa	1151	Heating	11/15 – 03/31	08:00 – 17:00*
			Cooling	06/01 – 09/30	08:00 – 17:00*
Rome	Csa	1444	Heating	11/01 – 04/15	08:00 – 17:00*
			Cooling	06/01 – 09/30	08:00 – 17:00*
Milan	Cfa	2639	Heating	10/15 – 04/15	08:00 – 17:00*
			Cooling	06/01 – 09/30	08:00 – 17:00*

* Saturday 08:00 – 14:00, on Sunday and Holidays systems are off

Tab. 1. *Climate characteristics of the cities considered and the system availability schedule.*

2.1. RESPONSIVE TECHNOLOGY MODELLING

The transmittance parameters considered to guarantee good results reliability were all deducted from experimental studies or commercial products, and the responsive technologies were modelled as follows.

2.1.1. EC WINDOWS

The parameters of the EC windows were deducted from the commercial low-e DGU manufactured by Sage Glass, whose solar and optical properties were analysed by Sibilio et al. [8] and are reported in Table 2. Regarding the thermal transmittance, the values change according to the climate zones as described in the Italian Ministerial Decree 26/06/2015 [21]. The EC windows modelled switch between a clear and a dark configuration according to the incident solar radiation and the outdoor air temperature. The radiation threshold was defined by running a preliminary daylighting analysis to predict the minimum incident solar radiation that allows an illuminance of 2000 lux within 50 cm from the windows. The resulting minima (120 W/m^2 for southern/western façade and 230 W/m^2 for eastern exposure) were selected as activation thresholds for the EC device to reduce the cooling loads and to guarantee a good amount of natural light. Regarding the temperature threshold, the windows can switch to the coloured state only if the radiation criterion is met and the outdoor air temperature exceeds 18°C; in this way, negative effects of the coloured state on lighting and heating during winter are minimised.

2.1.2. PCM WINDOWS

To overcome the impossibility of applying PCM to a cavity or glazing unit in EnergyPlus, the effect of the optical properties change was split from the latent heat storage phenomenon. The former is addressed by temperature-driven switchable glazing, while the latter is considered absorbing or releasing a certain heat amount in each thermal zone. Table 2 reports the characteristics of the equivalent solid/liquid switchable glazing in accordance with the experimental measurements proposed in specific studies [13, 25].

Concurrently, starting from the temperature of the windows, the partial enthalpy of the PCM – with a 35°C melting point – was evaluated with reference to the enthalpy curve of a commercial material (Rubitherm RT35HC, https://www.rubitherm.eu/, accessed on Feb 28, 2022) in the range of 27°-42°C (Fig. 3) to obtain the latent heat absorbed or released in each thermal zone.

2.1.3. EXTERNAL AUTOMATED BLINDS

The automated blind considered is an opaque external venetian blind with horizontal slats 10 cm wide, 0.5 cm thick, and separated by 10 cm, controlled by a radiation/temperature sensor similar to those described for the EC

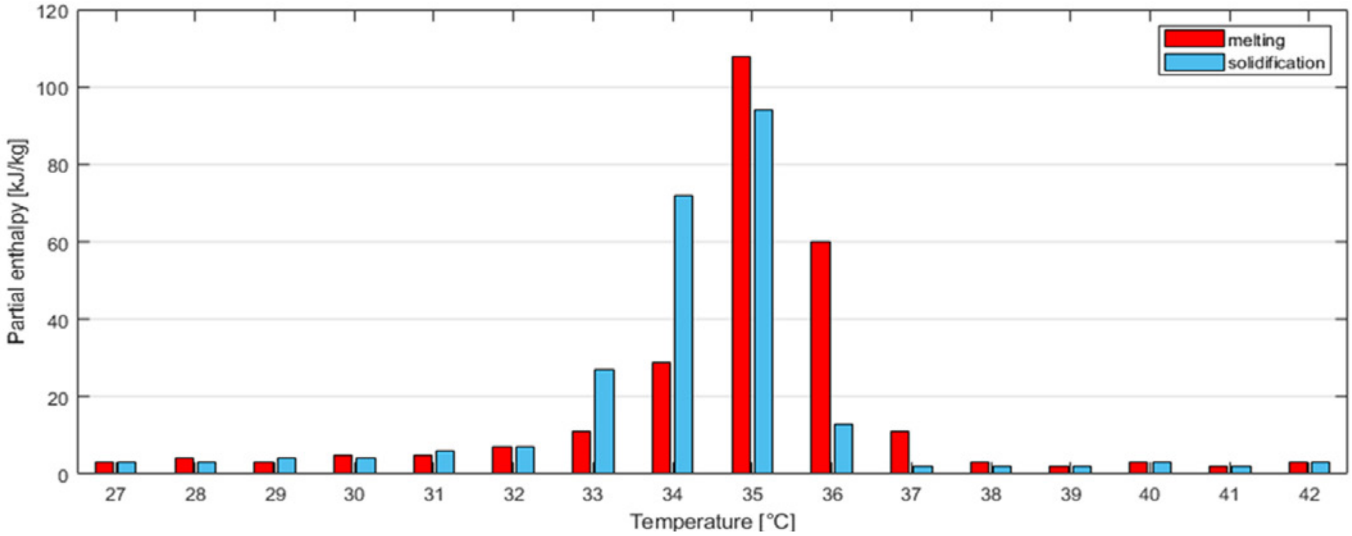


Fig. 3. *Partial enthalpy chart of the selected PCM [19].*

window. When the incident radiation exceeds the radiation threshold (120 W/m^2 for southern/western exposure, 230 W/m^2 for eastern façade) and the temperature exceeds 21°C, the blinds shade the glazing. The use of different temperature thresholds – according to preliminary analyses – for EC and automated blinds is due to their different behaviours; since EC acts on both heating and cooling, a lower activation temperature allows benefits also in the heating period. Moreover, to improve the sunlight protection, the slat angle – set at 0° by default – is automatically changed to block the direct solar beam.

2.1.4. VARIABLE U WINDOWS

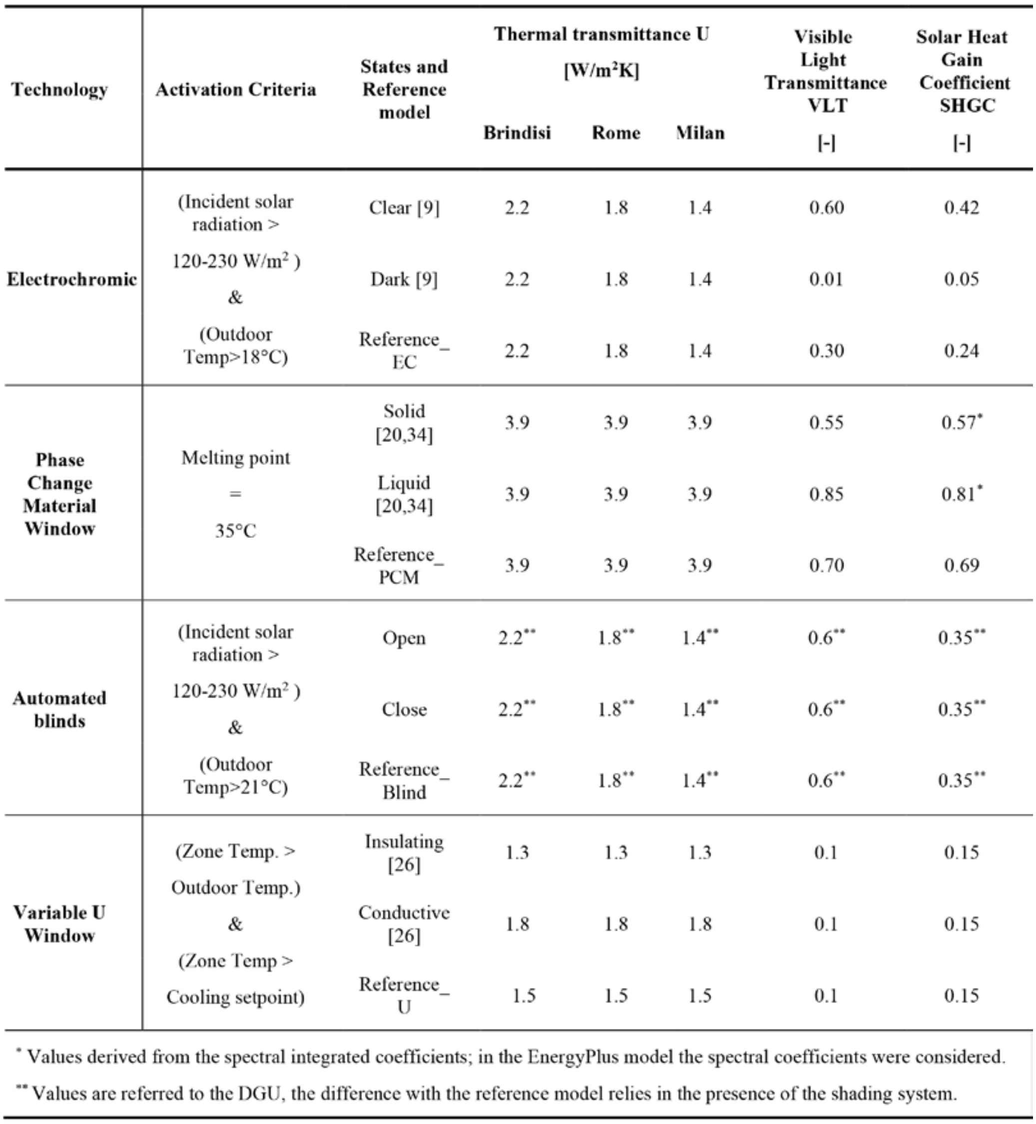
In this study, the variable convection system studied by Pflug et al. [17] was considered as the variable U window device. This system varies the U value according to the insulating pane position (top or middle configurations) with a consequent change in the air convection around the panel. Specifically, a 10 mm top air cavity and 17.5 mm lateral cavities were considered for this study; Table 2 reports the thermal and optical data obtained by the measurements conducted in the abovementioned study used to model the switchable glazing in EnergyPlus. Regarding the activation, the device is in its insulating state when the indoor air temperature is simultaneously lower than the outdoor air temperature and higher than the cooling setpoint; in this way, the heat exchanges are reduced in the heating period and fostered in the cooling period.

2.2. REFERENCE MODEL AND COMPARISON TABLE

After the definition of technologies and responsive models, a set of four static reference models was considered for each selected location. To understand the specific benefit of each technology, each reference model considers intermediate values between the two extreme states of the selected responsive devices. Table 2 sums up the properties and the activation criteria considered for the above-described set of models.

3. RESULTS

Energy consumption analyses were performed for all the building zones in all the considered locations for each selected technology. By comparing different exposures and cities, the yearly trends are similar, while the main differences involve the magnitude of the consumption variations and their relative balance. Based on these outcomes, the following subparagraphs report the yearly distribution of the consumption variations for a sample exposure. The sample simulation is referred to an intermediate climate (Rome) for the eastern exposure, which is the most affected by thermal and visual discomfort conditions caused by direct solar radiation. However, the results from other exposures and cities are provided in the discussion, and the final comparison graph is provided in the conclusion section.



Technology	Activation Criteria	States and Reference model	Thermal transmittance U [W/m^2K]			Visible Light Transmittance VLT [-]	Solar Heat Gain Coefficient SHGC [-]
			Brindisi	Rome	Milan		
Electrochromic	(Incident solar radiation > 120-230 W/m^2) & (Outdoor Temp>18°C)	Clear [9]	2.2	1.8	1.4	0.60	0.42
		Dark [9]	2.2	1.8	1.4	0.01	0.05
		Reference_EC	2.2	1.8	1.4	0.30	0.24
Phase Change Material Window	Melting point = 35°C	Solid [20,34]	3.9	3.9	3.9	0.55	0.57*
		Liquid [20,34]	3.9	3.9	3.9	0.85	0.81*
		Reference_PCM	3.9	3.9	3.9	0.70	0.69
Automated blinds	(Incident solar radiation > 120-230 W/m^2) & (Outdoor Temp>21°C)	Open	2.2**	1.8**	1.4**	0.6**	0.35**
		Close	2.2**	1.8**	1.4**	0.6**	0.35**
		Reference_Blind	2.2**	1.8**	1.4**	0.6**	0.35**
Variable U Window	(Zone Temp. > Outdoor Temp.) & (Zone Temp > Cooling setpoint)	Insulating [26]	1.3	1.3	1.3	0.1	0.15
		Conductive [26]	1.8	1.8	1.8	0.1	0.15
		Reference_U	1.5	1.5	1.5	0.1	0.15

* Values derived from the spectral integrated coefficients; in the EnergyPlus model the spectral coefficients were considered.

** Values are referred to the DGU, the difference with the reference model relies in the presence of the shading system.

Tab. 2. *Thermal, optical and activation criteria considered in the responsive and reference models.*

3.1. EC WINDOWS

The results obtained for the EC technology show an overall beneficial effect for the eastern exposure on the energy consumption, thanks to a significant reduction of the cooling loads and a decrease of the heating loads, that is counterbalanced by a slight increase in lighting consumption. Figure 4 shows the yearly analyses of consumption for the Eastern zone of the city of Rome, where a cooling-dominated scenario can clearly be identified.

The implementation of EC windows in the Rome eastern zones leads to significant summer benefits thanks to the reduction of the solar loads with a robust reduction of cooling consumption (-14%). Instead, considering the lighting consumption, different trends can be identified during summer (+81%) and during winter and mid-seasons (-17%), with an overall yearly variation of lighting consumption of +7%. Finally, considering the heating consumptions, values in the responsive model are significantly lower (-35%) but are less relevant in the overall balance due to their low magnitude. All these variations lead to a reduction of the total consumption of 10% for the eastern thermal zones.

On the contrary, considering the western and southern exposures, despite a trend similar to the eastern façade, the lighting consumptions increases are nearly equal to the benefits of the cooling and heating. This behaviour can be explained considering the number and position

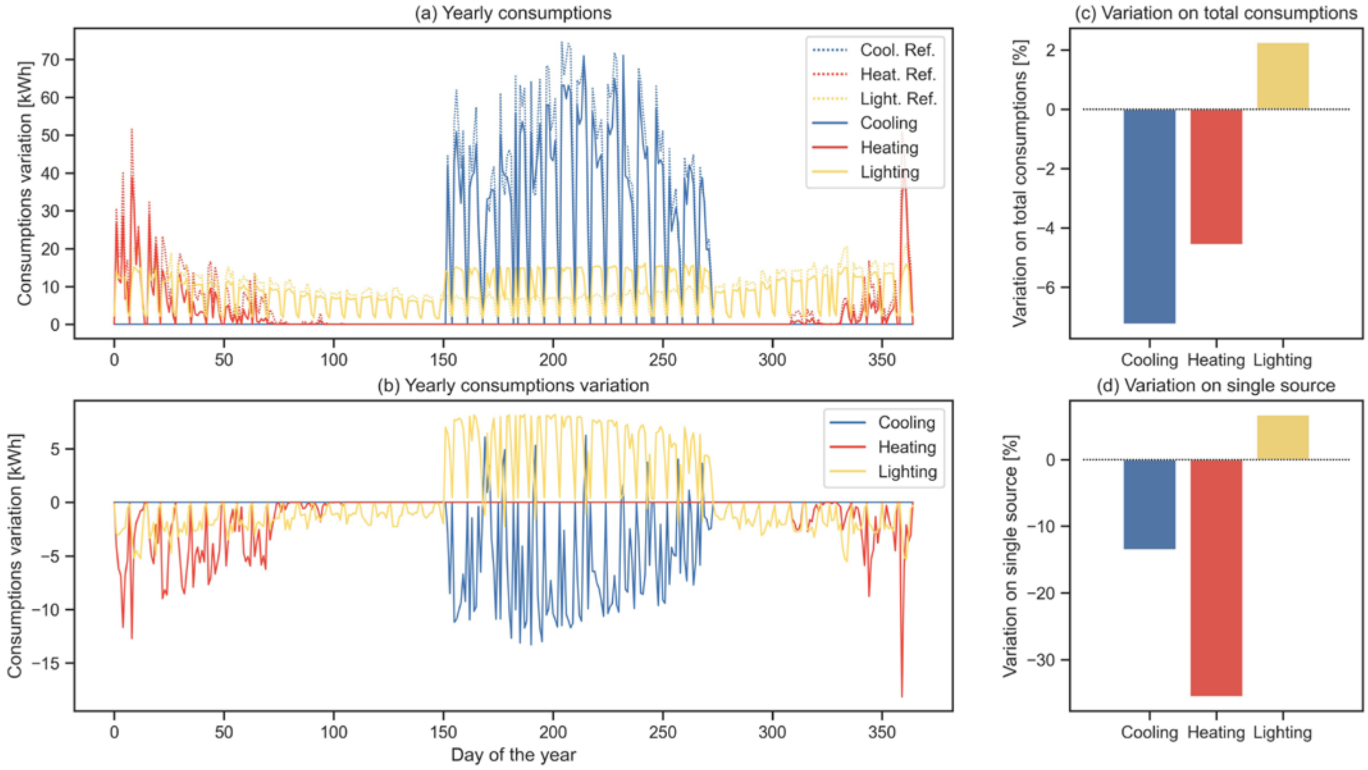


Fig. 4. *Consumption results for the EC technology (Eastern zone, Rome): a) consumption curves and b) consumption differences (responsive – reference), c) percentage variation on total consumption, d) percentage variation of each source.*

of the daylighting sensors (one for each thermal zone placed in the middle of the zone) and the different solar radiation values. Comparing different exposures, the different incidence angle of the solar beam varies the sunlight penetration leading to higher illuminance values on the sensor, reducing the lighting consumption. A way to improve the behaviour of this technology is to increase the number of daylighting sensors to have different lighting areas that can account for the different sunlight penetration in the zones. In this way, the part of the zone closer to the windows would not be affected by the lighting consumption increase, thanks to higher illuminance values on its controller.

Similar trends can be found for Brindisi and Milan, with differences in the magnitude of the consumption variations. The only exception is related to the eastern exposure in Milan, where the lighting consumptions are lower in the responsive model. This behaviour is related to the lower solar height in Milan that improves the sunlight penetration increasing the illuminance on the sensor. In this case, the additional summer consumption is lower than the winter and mid-season savings leading to lower yearly consumption.

3.2. PCM WINDOWS

When comparing the PCM and the reference model, no significant differences can be found, as the responsive and reference consumptions are almost overlapped for all the simulations. For the eastern zone in the city of Rome (Fig. 5), the heating and lighting are slightly lower in the reference model; the resulting overall consumptions of the responsive model are thus slightly higher (+1.2%) than the reference model. This behaviour can be explained by the low SHGC of the solid state of the windows during winter, which leads to a reduction of the winter solar gains and a consequent increase in the heating consumption. On the contrary, during the cooling period, the benefits of the latent heat storage are offset by the increase of the summer loads related to the high SHGC of the liquid state.

The western zone shows similar trends and values; on the contrary, considering the southern exposure, the main differences rely on the higher cooling consumption in the summer period, which leads to a higher variation of the total consumption (+2.2%). Regarding the different climates, the trends described are similar to those ob-

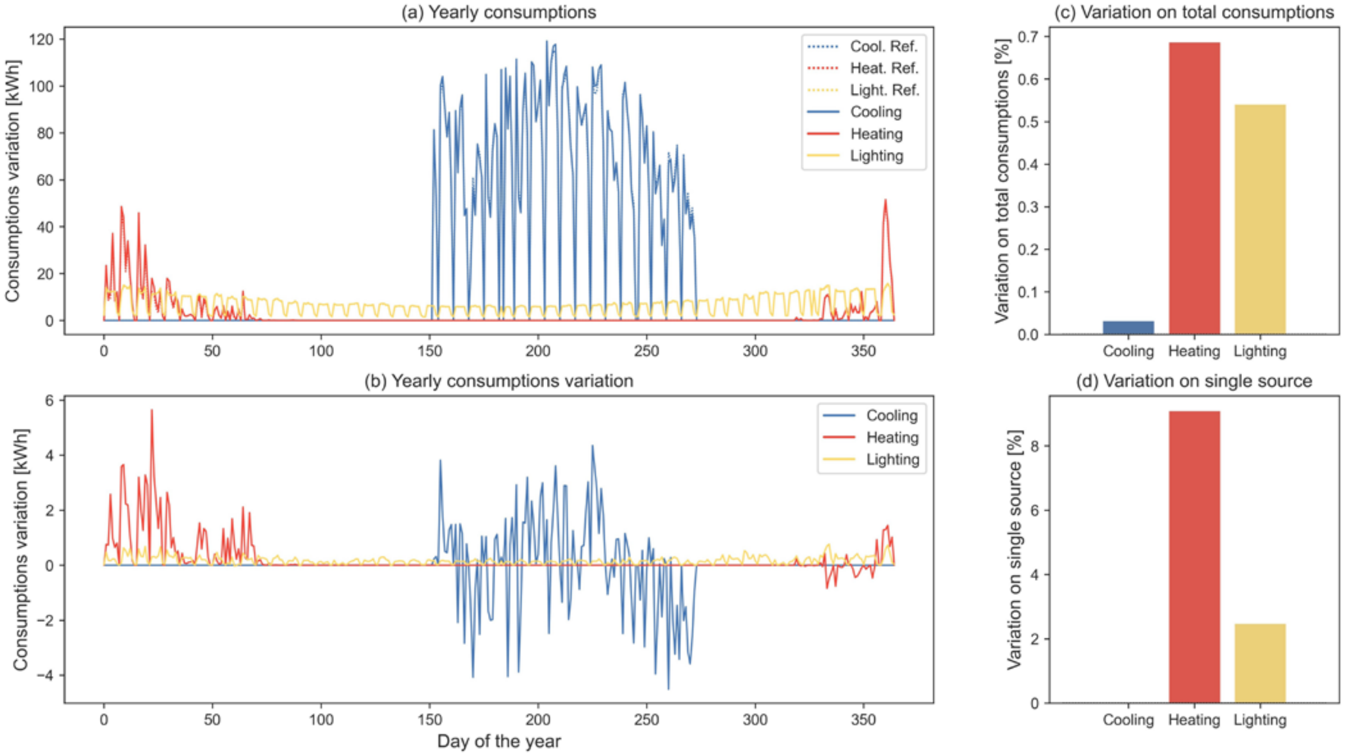


Fig. 5. *Consumption results for the PCM windows (Eastern zone, Rome): a) consumption curves and b) consumption differences (responsive – reference), c) percentage variation on total consumption, d) percentage variation of each source.*

tained for Milan and Brindisi, with the only exceptions of a different magnitude of the cooling differences and a slight heating reduction during the winter period in the eastern and western zones. These differences are due to the lower solar height in Milan that reduces the beam incidence angle, increasing the glazing temperature; hence, the higher temperature increases the number of timesteps when the PCM is in its liquid phase, increasing the SHGC and the solar gains.

3.3. AUTOMATED BLINDS

Similarly to the EC models, the shading effect of the automated blinds leads to a considerable reduction of the cooling loads counterbalanced by an increase in the lighting consumption. Considering the eastern thermal zone for the city of Rome (Fig. 6), the implementation of automated external blinds contributes positively to the energy reduction with a decrease in cooling consumption of nearly 14%. These benefits are partly limited by a slight increase in lighting consumption (+0.75%), while heating consumption is the same and does not contribute to the consumption balance. Overall, a total energy reduction of 8% is achieved for the eastern thermal zones.

Also in this case, the number and the positions of the daylighting sensors increase the lighting consumption in the western and southern zones thwarting the cooling benefits. Therefore, it follows that the benefits for these zones are lower, with a total consumption variation of -4% for the southern zone and +3% for the western exposure.

The yearly trends found for the other cities are similar to those described for the city of Rome; the only differences regard the magnitude of the variation of each energy source. Clearly, considering that the blinds act only on the cooling consumption, benefits are lower in colder climates.

3.4. VARIABLE U WINDOWS

The implementation of variable U windows does not act on solar radiation but works only on managing the heat fluxes. The results obtained show that this behaviour does not affect consumption in temperate climates. Con-

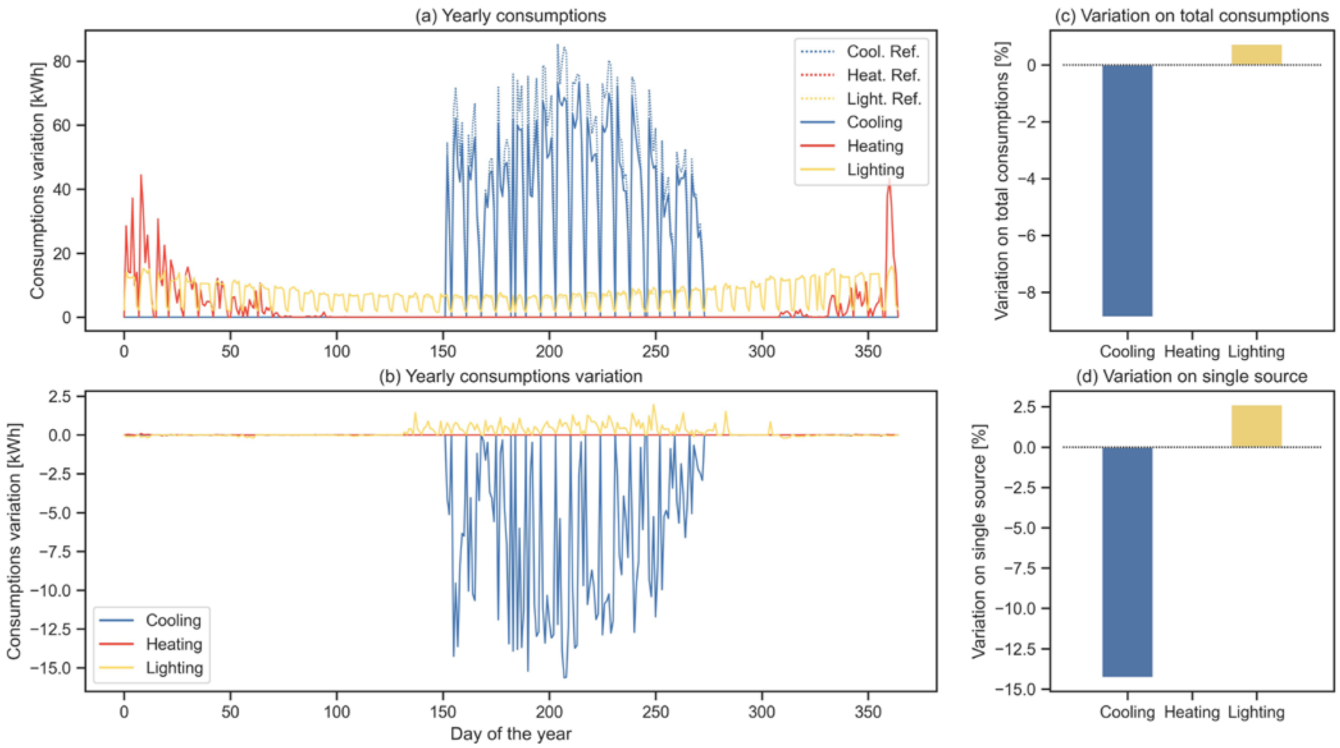


Fig. 6. *Consumption results for the automated blinds (Eastern zone, Rome): a) consumption curves and b) consumption differences (responsive – reference), c) percentage variation on total consumption, d) percentage variation of each source.*

sidering the eastern zones of the city of Rome, total consumptions decrease by 0.6%. The main contribution is the reduction of the heating consumption (-7%), which is, though, characterised by a low incidence in this climate (Fig. 7). A minimal difference can be identified regarding cooling consumption, while no differences can be found for lighting as the VLT values are the same in the responsive and reference models. Moreover, in the southern and western zones, the consumptions variations are very similar, with a total variation of -0.4% and -0.5%, respectively.

Trends overlap in the other analysed locations with total benefits that increase in colder climates, confirming that this technology works better in very cold climates due to its benefits on heating consumption.

4. CONCLUSION

The outcome of this study is described in Figure 8, which includes a comparison of the benefits of smart envelopes for different locations and exposures.

Among the considered systems, the potential highest benefits are related to the implementation of EC windows, thanks to their capability of acting on both heating and cooling. However, the main disadvantage of this technology is a significant increase in summer lighting, which the cooling reduction can sharply set off. It is worth highlighting that a detailed study and optimisation of the activation thresholds and the lighting sensing system are required for each exposure and location. The comparison graph clearly shows that with the considered daylighting sensor and activation criterion, this technology can be highly recommended for the eastern exposure, while for the other ones, the implementation could be unaffordable due to its high lighting consumption. However, by implementing a diffuse sensing system, this technology can allow good daylighting comfort guaranteeing a minimum natural illuminance reducing the glaring risk. Undoubtedly, the high investment cost and the uneven aesthetical change of the external façade could be considered a weak point in the spread of this technology.

Similar conclusions can be drawn for the automated blinds, where a significant cooling reduction overcomes the negative effects on lighting consumption. With respect to the EC windows, in this case, the energy benefits

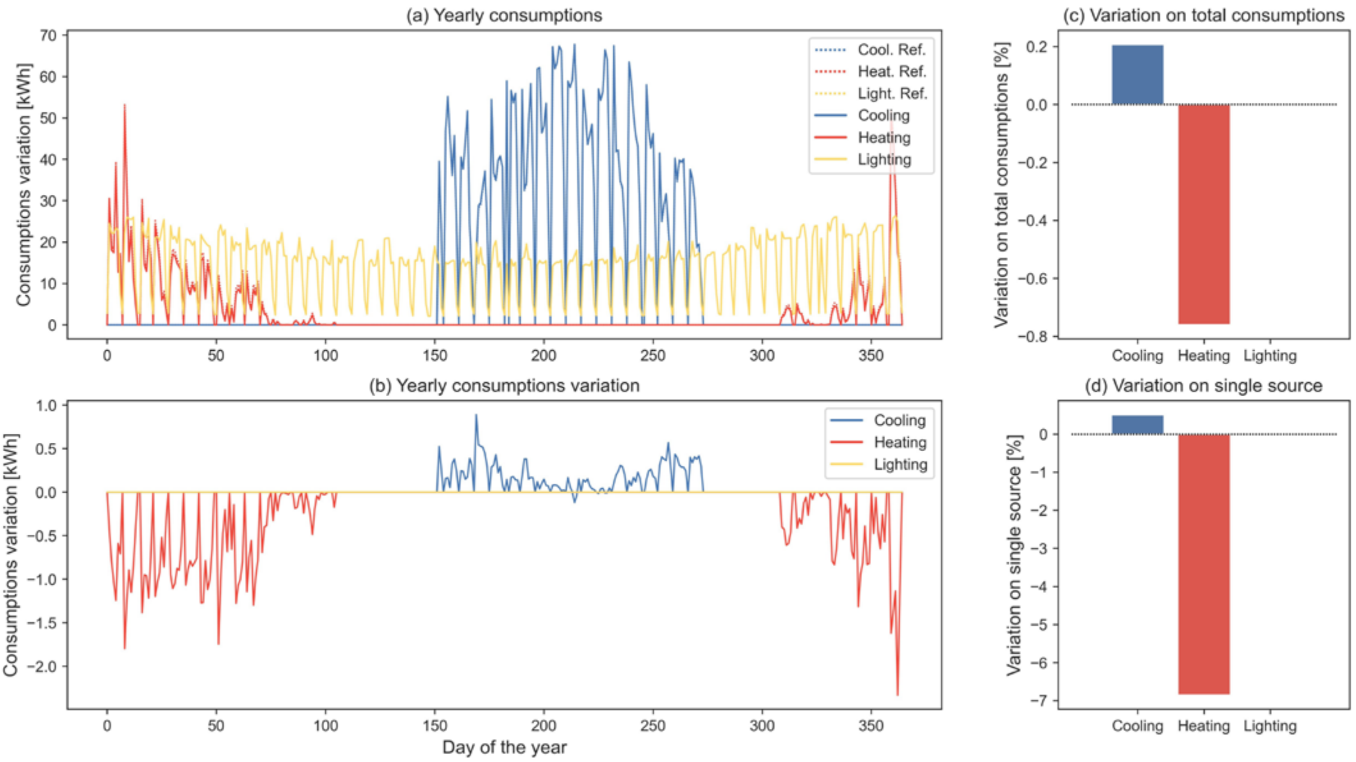


Fig. 7. *Consumption results for the variable U window (Eastern zone, Rome): a) consumption curves and b) consumption differences (responsive – reference), c) percentage variation on total consumption, d) percentage variation of each source.*

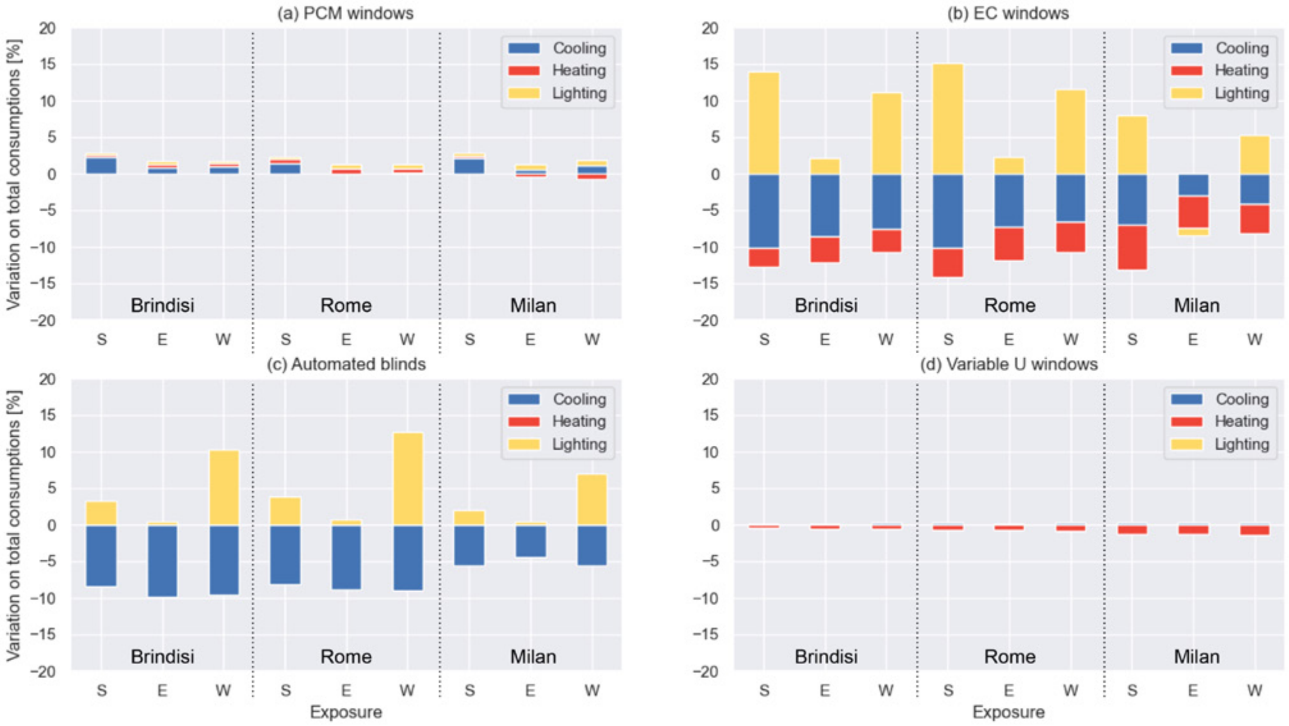


Fig. 8. *Total consumption variation for the technologies, locations, and exposures analysed.*

are lower due to a lack of advantages during the winter period but are partially offset by the lower increase in lighting consumption. Regarding the climate factor, the automated blinds are more suitable in hot climates as they work only on cooling consumption. Moreover, this technology boasts a lower investment cost and a wide range of possible architectural solutions. However, regarding the disadvantages, the high maintenance costs and the partial reduction of the external view should be considered the main drawbacks of this technology.

A different behaviour characterises the PCM windows due to their intrinsic control. In this case, an increase in the glazing temperature during summer leads to the PCM melting, with a resulting increase in the SHGC and the incoming solar radiation. This behaviour is diametrically opposed to the one described for the EC windows and affects the energy balance sensibly. The main advantage of this technology is the increased latent heat storage, but in these specific cases, the benefits related to this phenomenon are lower than the cooling consumption increase related to the higher SHGC, resulting in overall higher consumption.

Finally, the variable U windows show limited benefits in the investigated models. Indeed, the results show very low benefits on cooling and a good beneficial effect on the heating consumption in all the locations; nevertheless, the heating benefits are sensibly limited by the low incidence of heating on the overall energy balance. Probably, this technology could improve its performance in colder climates or, considering a wider U range, between the conductive and insulating state.

To sum up, the results obtained, for the technologies and locations selected, highlight the importance of considering each functioning criterion in strict relation to climate, exposures, and sensing systems. For example, the EC windows seem affordable, mainly for the eastern façade; nevertheless, simply changing the daylighting sensor position can overturn the technology behaviour leading to different considerations.

5. REFERENCES

[1] IEA (2019) 2019 Global Status Report for Buildings and Construction

[2] World Green Building Council (2020) WorldGBC Annual Report 2019/20. 42

[3] Van der Aa A, Heiselberg P, Perino M (2011) Designing with Responsive Building Elements. IEA-ECBCS Annex 44 Integr Environ Responsive Elem Build

[4] Loonen RCGM, Trčka M, Cóstola D, Hensen JLM (2013) Climate adaptive building shells: State-of-the-art and future challenges. Renew Sustain Energy Rev 25:483–493. https://doi.org/10.1016/j.rser.2013.04.016

[5] Granqvist CG, Bayrak Pehlivan İ, Niklasson GA (2018) Electrochromics on a roll: Web-coating and lamination for smart windows. Surf Coatings Technol. https://doi.org/10.1016/j.surfcoat.2017.08.006

[6] Cannavale A (2020) Chromogenic Technologies for Energy Saving. Clean Technol 2:462–475. https://doi.org/10.3390/cleantechnol2040029

[7] Cannavale A, Ayr U, Fiorito F, Martellotta F (2020) Smart electrochromic windows to enhance building energy efficiency and visual comfort. Energies 13:1–17. https://doi.org/10.3390/en13061449

[8] Sibilio S, Rosato A, Scorpio M, et al (2016) A review of electrochromic windows for residential applications. Int J Heat Technol. https://doi.org/10.18280/ijht.34S241

[9] DeForest N, Shehabi A, Selkowitz S, Milliron DJ (2017) A comparative energy analysis of three electrochromic glazing technologies in commercial and residential buildings. Appl Energy 192:95–109. https://doi.org/10.1016/j.apenergy.2017.02.007

[10] Hee WJ, Alghoul MA, Bakhtyar B, et al (2015) The role of window glazing on daylighting and energy saving in buildings. Renew Sustain Energy Rev 42:323–343. https://doi.org/10.1016/j.rser.2014.09.020

[11] Martin PM (2004) Optical Materials: Smart Optical Materials. In: Encyclopedia of Modern Optics, Five-Volume Set. Elsevier Inc., pp 9–16

[12] Goia F, Perino M, Serra V (2014) Experimental analysis of the energy performance of a full-scale PCM glazing prototype. Sol Energy 100:217–233. https://doi.org/10.1016/j.solener.2013.12.002

[13] Giovannini L, Goia F, Lo Verso VRM, Serra V (2017) Phase Change Materials in Glazing: Implications on Light Distribution and Visual Comfort. Preliminary Results. Energy Procedia 111:357–366. https://doi.org/10.1016/j.egypro.2017.03.197

[14] Vigna I, Bianco L, Goia F, Serra V (2018) Phase change materials in transparent building envelopes: A Strengths, Weakness, Opportunities and Threats (SWOT) analysis. Energies 11. https://doi.org/10.3390/en11010111

[15] Martone PT, Boiler M, Burgert I, et al (2010) Mechanics without Muscle: Biomechanical inspiration from the plant world. Integr Comp Biol 50:888–907. https://doi.org/10.1093/icb/icq122

[16] Koenders SJM, Loonen RCGM, Hensen JLM (2018) Investigating the potential of a closed-loop dynamic insulation system for opaque building elements. Energy Build 173:409–427. https://doi.org/10.1016/j.enbuild.2018.05.051

[17] Pflug T, Nestle N, E. Kuhn T, et al (2018) Modeling of facade elements with switchable U-value. Energy Build. https://doi.org/10.1016/j.enbuild.2017.12.044

[18] Pflug T, Bueno B, Siroux M, Kuhn TE (2017) Potential analysis of a new removable insulation system. Energy Build 154:391–403. https://doi.org/10.1016/j.enbuild.2017.08.033

[19] Carlucci F, Fiorito F (2021) Implementation of smart technologies in building envelopes: methodological approach and com-

parative analyses in a hot-summer Mediterranean climate. In: Sicignano E (ed) Colloqui.AT.e 2021 Design and construction Tradition and innovation in the practice of architecture. EdicomEdizioni, Monfalcone (GO)

[20] Loonen RCGM, Favoino F, Hensen JLM, Overend M (2017) Review of current status, requirements and opportunities for building performance simulation of adaptive facades. Journal of Building Performance Simulation 10(2):205–223. https://doi.org/10.1080/19401493.2016.115230

[21] Ministry of Economic Development (2015) Ministerial Decree 26/06/2015, Applicazione delle metodologie di calcolo delle prestazioni energetiche e definizione delle prescrizioni e dei requisiti minimi degli edifici

[22] Italian Decree (1993) DPR 412/93: Norme per la progettazione, l'installazione, l'esercizio e la manutenzione degli impianti termici degli edifici ai fini del contenimento dei consumi di energia. Italy

[23] Kim H, Park KS, Kim HY, Song YH (2018) Study on variation of internal heat gain in office buildings by chronology. Energies 11:1013. https://doi.org/10.3390/en11041013

[24] International Code Council (2021) 2021 International Energy Conservation Code

[25] Goia F, Zinzi M, Carnielo E, Serra V (2012) Characterisation of the optical properties of a PCM glazing system. Energy Procedia 30:428–437. https://doi.org/10.1016/j.egypro.2012.11.051