Energy Reports 13 (2025) 5281–5289

Contents lists available at ScienceDirect

Energy Reports

journal homepage: www.elsevier.com/locate/egyr

Research paper

On the use of dynamic film to improve the thermal and solar performance of multiple glazing units. Preliminary testing and assessment

Michele Zinzi [a,*], Carlo Romeo [b], Stefano Agnoli [c], Luca Papaiz [d]

[a] Energy Technologies Department and Renewable Energy Sources, ENEA, Rome, Italy
[b] Energy Efficiency Department, ENEA, Rome, Italy
[c] Infrastructure and Services Management, ENEA, Rome, Italy
[d] R&D Management, Pellini spa, Codogno, LO, Italy

ARTICLE INFO

Keywords:
Moveable film
Glazing system
Dynamic envelope
Building energy performance
Transient simulation

ABSTRACT

Transparent systems play a crucial role in modern buildings affecting energy performance, visual and thermal comfort and interrelation between external and indoor environments. Due to the highly daily and seasonal variations in outdoor conditions and indoor requirements, dynamic façades represent a viable solution for optimizing overall building performance. This paper explores the potential of moveable transparent/opaque films placed within the gap of double glazing units. A selection of transparent and opaque polyester films was screened, and the optical properties and thermal emissivity of the selected samples were measured using laboratory equipment compliant with relevant international standards. Depending on the films, the solar transmittance ranged from 0 % to 75 % while the solar reflectance varied from 7 % to 89 %; the emissivity values were within the 0.10–0.80 range. When applied to double glazing units, the thermal transmittance decreased by up to 1.2 W/m^2K in conventional glazing systems and by up to 0.3 W/m^2K in low emissivity glazing systems, respectively. The solar properties, namely the solar factor, of the assembled units were extremely scattered, depending on the characteristics of both the glazing unit and the film, as reported in the results. The numerical analyses carried out at building scale on a reference residential case study, demonstrate that this technology can achieve up to 8 % energy savings for space heating and over 80 % for space cooling, depending on the glazing unit characteristics, the activation strategy and the climatic conditions within the Italian context.

1. Introduction

The transparent systems play a crucial role in shaping energy use and environmental comfort in the built environment (Graf and Albani, 2011; Hee et al., 2015), particularly in modern buildings with highly glazed facades (Quesada et al., 2012). Over the past decades significant research and technology developments have been dedicated to this sector (Grynning et al., 2013), especially because windows traditionally represented the weakest element of the building envelope in terms of thermal insulation (Wang et al., 2017). The development of multiple glazing units significantly improved the thermal performance of windows (Arıcı, Kan, 2015), primarily due to the insulating properties of the cavity and the gases used to fill it (Manz, 2008). In this contest, the use and analysis of air layer behaviour have been key research objectives (Zhang and Yang, 2019). The impact of multi-cell configurations in glazing units on the thermal insulation performance has been explored and discussed (Tiwari, Kim, 2022).

Thermal insulation can also be enhanced using low emissivity glass coatings (Karlsson and Roos, 2001), which can additionally improve the solar control capabilities of glazing unit (Teixeira et al., 2020). Due to the technology innovations, glass coatings for architectural glazing systems now allow to pursue enhanced performance across multiple functions of the building envelope (Khaled and Berardi, 2021).

Dynamic glazing solutions, which can passively and actively adapt transparent façades in response to different stimuli, represent a step forward in the decarbonization of the building sector and, at the same time, introduce new paradigms in modern architecture (Jamilu et al., 2024). Moreover, dynamic windows will be able to respond to future climatic conditions (De Masi et al., 2022).

The dynamic properties of glazing systems can be achieved using coatings able switching between transparent and coloured states, thus regulating the amount of transmitted and reflected solar irradiation by the system. Typical examples include thermochromic and

* Correspondence to: ENEA Energy Technologues and Renewable Energy Sources Department, Via Anguillarese 301, Rome 00123, Italy.
E-mail addresses: michele.zinzi@enea.it (M. Zinzi), carlo.romeo@enea.it (C. Romeo), stefano.agnoli@enea.it (S. Agnoli), lpapaiz@pellini.net (L. Papaiz).

https://doi.org/10.1016/j.egyr.2025.04.064
Received 30 December 2024; Received in revised form 28 April 2025; Accepted 29 April 2025
Available online 5 May 2025

Nomenclature

Symbols

ε	emissivity (-)
ρ	reflectance (%)
τ	transmittance (%)
g	solar factor (%)
H	horizontal solar irradiation (kWh/ m^2)
k	internal areal heat capacity (kJ/m^2K)
R	thermal resistance (m^2K/W)
T	air temperature (°C)
U	thermal transmittance (W/m^2K)

Subscripts

b	back
e	solar
f	front
v	visible

electrochromic materials (Wu et al., 2023; Liu et al., 2023). Another promising example of dynamic glazing is polymer-dispersed liquid crystal technology, in which liquid crystals are embedded between two glass panes (Zhang et a., 2022). The dynamic behaviour of transparent façades can also be achieved by coupling glazing systems with solar protection devices (Shum and Zhong, 2023). The review highlights the significant advancements in the design of these devices, including improvements in materials, automation levels, and their integration into multi-layer glazing units, enhancing solar and daylight control. All these dynamic solutions capable of modifying thermal, solar, and luminous performance in response to specific boundary conditions, can offer higher performance compared to static configurations (Shafaghat and Keyvanfar, 2022).

Another approach to enhance glazing systems performance involves utilizing the air gap to implement high-efficiency solutions such as fluid circulation (air or water) or high-performance materials (e.g., aerogel). Further improvements can also be achieved by optimizing the gap size between glass panes in multiple glazing units (Huang et al., 2021).

A major challenge associated with innovative systems is not only the additional cost, but also the extra weight of such solutions (e.g., multiple glass configurations, solar shading, more complex frames) which may compromise both the structural stability and operability of windows and façade elements. Consequently, there is a growing interest in thin and lightweight materials and components able to offer similar performance to conventional and advanced solutions without imposing a significant additional load on the building structure. A notable example is the application of transparent membranes and cushion as façades and roofs envelope elements (Hu et al., 2020). In such applications the main advantage lies in exploiting the potential of air layers behaviour as insulating material (Zhang et al., 2016).

The improvement of transparent surface performance, while adding limited or negligible additional weight, can also be pursued through the application of thin transparent plastic films on the glazing systems. The basic option is the application of such films directly onto the glass unit, with the objective of improving the solar control (Wang et al., 2024) or enhancing the radiative cooling of the building envelope (Yi et al., 2021). Few studies investigated the application of thin plastic layers, also known as suspended films, to create multi-layer glazing units. For instance, a six-millimetre-thick polymeric four-layer configuration, placed on the internal side of a glass pane, allowed to reduce the thermal transmittance (U-value) from 5.8 to 2.9 W/m^2K (Kou et al., 2021). Additionally, a multi-layer thermal insulating glazing system incorporating polycarbonate films as intermediate layers achieved thermal and optical performances comparable to those of low emissivity glazing units. Conversely the use of films also presents several restraints, particularly regarding material durability and initial performance maintenance throughout the whole expected service life. (Li et al., 2023). The growing interest in this technology can be inferred by several patents existing on the topic over the past decade (Regan et al., 2011; Meng, 2016). However, the impressive improvement in static multi-chamber glazing units' technology negatively hindered the further development of suspended films technology (Fang et al., 2015).

The present study starts from the above premises and conducts a preliminary assessment of movable films integrated into the air gap of multiple glazing units. By combining the lightweight nature of the films with the ability to overcome the intrinsic limitations of static solutions, this approach enables adaptive windows and façade configurations to meet multiple objectives, including thermal insulation, solar and visual control and privacy, while minimizing structural loads and ensuring façade reversibility based on boundary conditions such as user preferences, building performance requirements, and local climatic conditions. This approach introduces a significant innovation compared to the current state of the art in glazing technology.

The objective of this paper is to identify and experimentally characterize opaque and transparent films suitable for glazing integration and to provide a preliminary evaluation of their impact on both glazing and building-level performance.

2. Materials and method

The present study combines experimental measurements and numerical analyses to assess how moveable films within the cavity of multiple glazing units can provide a viable solution for enhancing building envelope performance. The study follows a methodological approach beginning with the basic material characterization and leading to the full-scale building integration.

To achieve this objective the following methodological framework is implemented:

- Identification and selection of films suitable for integration within the glazing cavity;
- Measurement of the relevant radiative properties of the films, detailed in the Experimental section;
- Definition of reference glazing units and calculation of their thermal and solar properties, both with and without the inclusion of the films in the cavity;
- Evaluation of the energy performance of a reference residential building equipped with these glazing units under different climatic conditions.

This approach allows an assessment of the impact of these dynamic elements in enhancing the performance of building components and the overall building energy response, compared to conventional construction systems.

As this is an initial study, certain limitations apply. The analysis focuses exclusively on thermal and solar properties, as these factors significantly affect the space heating and cooling performance of buildings. The study is primarily concerned with dwellings; future works will be extended to commercial and institutional buildings as well. The crucial issues of daylighting and visual comfort will be explored in further analyses, focusing on the integration of these dynamic glazing solutions at multiple levels within the built environment.

2.1. Sample description and selection criteria

The identification of films for glazing integration presents a significant challenge, as such materials were seldom used for this purpose until now. Moreover, previous applications were limited to fixed films, while this study focuses on moveable solutions. A wide range of commercially available products was screened, and polyester was selected as the most suitable material given its widespread use in shading devices, particularly for outdoor screens and indoor blinds. The novelty of this approach lies in the requirement for the film to be extremely thin, because, once rolled up, it must have a diameter smaller than the cavity of a double-glazing unit. For such reason, the products' screening focused on foils with a maximum thickness of 25 microns.

Concerning film characteristics, several options were categorized, and the selection process was guided by the following key criteria:

- Thermal insulation enhancement: The activation of the film creates multiple gas chambers within the glazing cavity, as opposed to a single one when the film is retracted. The double air gap improves insulation performance by reducing convective and radiative heat transfer.
- Low-emissivity treatment: Performance can be further enhanced if one or both side of the films are coated with low-emissivity materials (e.g., aluminium or other metallic coatings), which effectively reduce radiative heat losses.
- Privacy control: Dark-coloured films offer an additional privacy function. They typically, should be activated at night during winter, when the heat loss increases due to greater temperature differences between indoor and outdoor environments.
- Solar control: Transparent films can also be used for solar control. Their activation is particularly beneficial during summer to limit solar heat gains, while in winter, they can be retracted to maximize passive solar heating.

The selected products are presented in Table 1. To be noted that thickness information for certain samples is incomplete due to manufacturer data limitations.

2.2. Integration of moveable films in multiple glazing system

The proposed system integrates a movable film mechanism within an insulating glass unit in functioning similarly to conventional shading systems. Given the size of the film, the total thickness of the unit can range from 30 to 32 mm depending on the internal and external glass panes used and the cavity size. The film operation is controlled by means of an internal motor which can be powered either via hard wiring or through a rechargeable battery module. The layout and functional scheme of the system are presented in Fig. 1.

The system provides several technical advantages compared to conventional solutions. The absence of an external head rail, a typical component of roller shutters, prevents potential thermal and acoustic bridges. The film is fully enclosed within the cavity, protecting it from dirt, atmospheric agents, and mechanical impacts. This configuration reduces the need for regular cleaning or maintenance and makes it windproof. The prototypical glazing systems were tested against functional performance decay. The film scrolling and packing up was successfully run for more than 20,000 operation cycles.

2.3. Reference glazing systems and variants' configurations

Two reference glazing systems were selected to evaluate the performance benefits of the movable films. Both systems consist of two glass panes: a conventional float glass pane (normal emissivity: 0.89) and a low-emissivity pane (emissivity: 0.03). The two glazing configurations are as follows:

Table 1
Selected films for radiative characterization.

Code	Thickness (μm)	Colour Side 1 Inward	Colour Side 2 Outward	Transparent
1	25	Black	Aluminium	NO
2	25	Black	Black	NO
7	23	White	Aluminium	NO
9	-	Aluminium	Aluminium	NO
11	-	White	White	YES
14	-	Pearl grey	Pearl grey	YES

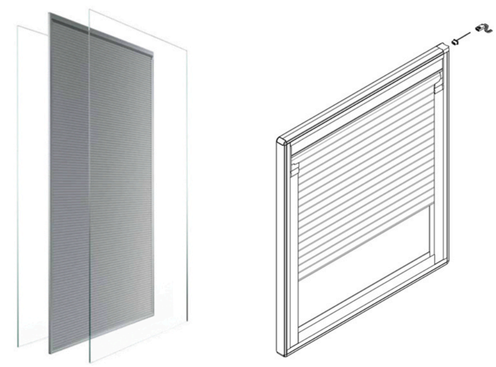

Fig. 1. Functional scheme of the moveable film integrated into the glazing unit.

- Glazing Unit A: 6 mm float glass – 20 mm air gap – 6 mm float glass
- Glazing Unit B: 6 mm float glass – 20 mm air gap – 4 mm low-e glass (coated side facing the gap)

The characteristics of the two glazing units are reported in Table 5 in the Results section to ensure consistency and homogeneity in data presentation.

2.4. Reference building and climates

The building selected for the numerical analysis corresponds to one of the typical Italian residential buildings used for the national implementation of the energy performance code (Ministry of Economic Development. 2015). The building consists of three levels with two apartments per floor, each of them has a net floor area of 89 m^2 and an internal volume of 242 m^3. The total windows area is 17 m^2 for each apartment, distributed across three different orientations, as illustrated in the typical floor layout in Fig. 2.

Two building configurations were implemented: one not-insulated (representative of existing buildings stock) and one insulated (exemplary for new constructions or energy-retrofitted buildings). The main thermo-physical properties of the reference buildings taken into account include the thermal transmittance, the thermal resistance, and the internal areal heat capacity. These properties are summarized in Table 2. The insulated configuration of the building has been further structured into three distinct envelope models, each with different levels of thermal insulation, corresponding to three characteristic climatic zones (B, D and E) of the Italian territory, in compliance with current national standards.

The energy performance calculations were conducted in compliance

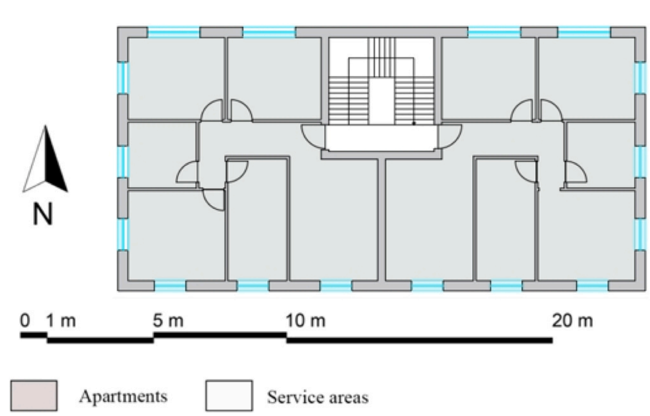

Fig. 2. Plan of the typical floor of the reference building.

Table 2
Thermo-physical properties of the building envelope components.

Envelope component	Zone	U W/m²K	R m²K/W	k kJ/m²K	U W/m²K	R m²K/W	k kJ/m²K
		Insulated			Not insulated		
Vertical wall	B	0.40	2.50	101.0	1.66	0.60	361.2
	D	0.32	3.14				
	E	0.28	3.60				
Roof	B	0.32	3.13	104.7	0.95	1.05	101.0
	D	0.26	3.85				
	E	0.24	4.17				
Ground floor	B	0.42	2.38	77.3	1.20	0.83	149.1
	D	0.32	3.13				
	E	0.28	3.57				

with relevant national standards (UNI – Italian Standards Body, 2014). Accordingly, the following operational settings and internal heat gains were defined for the building model:

- Internal sensible heat gains: 5 W/m^2;
- Internal latent heat gains: 2.5 W/m^2;
- Natural ventilation rate: 0.5 h^{-1} Air Change per Hour (ACH).

According to the national regulation, the indoor temperature set points were set at 20°C for heating and 26°C for cooling. Additionally, a relative humidity set point of 55 % was applied during the summer period.

The building performance analysis was carried out for three representative localities: Turin, Rome, and Palermo corresponding to the northern, central and southern Italian climatic conditions (Zone E, D, and B, respectively). As an exemplary representation of the average climatic conditions Table 3 reports the average ambient temperature and cumulated solar irradiation for the three warmest (June, July, and August) and coldest (December, January, and February) months. The climatic data are sourced from an international weather database commonly used in energy performance simulations (Meteonorm 8 8 2020). The data highlight a progressive increase in air temperature and solar irradiation from north to south, in both seasons. Significant temperature differences were observed especially in winter, with seasonal variations exceeding 10°C between Turin and Palermo. In general differences are more accentuated between Turin and Rome than between Rome and Palermo as the latter two cities share a Mediterranean climate.

The key performance indicators used in this analysis are the net space cooling and heating energy demand. The term net refers to the amount of energy required to maintain indoor conditions at the prescribed set-points, assuming ideal energy systems with 100 % efficiency, without considering actual system efficiencies.

3. Experimental

The experimental work consisted in the characterisation of the selected films by measuring their optical and radiative properties on both sides of each sample. The products were supplied in different size and next cut into 10 x10cm specimens suitable for testing.

The spectral reflectance (ρ) and transmittance (τ) of the films were measured using a PerkinElmer Lambda 950 spectrophotometer equipped with an integrating sphere of 150 mm diameter, coated with Spectralon. The instrument is equipped with a halogen light source for the visible/near-infrared range and a deuterium light source for the ultraviolet range. The light beam has an approximate cross-section of 1 cm^2, and the reflectance measurements were performed using a calibrated Spectralon reference target. The spectrophotometer slit width was set to 2 nm in the visible range and operated in servo mode in the near infrared-range, allowing slit adjustment at each wavelength to optimise the gain at a given wavelength. The integration time is one second across the entire measurement range. Measurements were performed over the 300–2500 nm spectral range with a 5 nm resolution at ambient temperature. The measurement uncertainty was ± 1 % in the 0–100 scale. The broad band parameters were calculated in accordance to the relevant European standard (CEN – European Committee for Standardization 2011a).

The thermal emissivity (ε) was measured using a customized emissometer, built in accordance with the specification of the relevant European standard (CEN – European Committee for Standardization 2011b). This was a broad-band measurement over the 3–40 micron range, performed against two calibrated reference targets: low-emissivity (ε=0.05) and high emissivity (ε=0.88). The measurement was conducted at ambient temperature, with the heat source set to 80°C. Each sample was measured 3 times, and the results were averaged. The measurement uncertainty was ± 0.2 in the 0–1 scale.

Table 3
Seasonal average air temperature (T) and cumulative global horizontal solar irradiation (H) for the three selected localities.

Locality	Winter H (kWh/m²)	Summer H (kWh/m²)	Winter T (°C)	Summer T (°C)
Turin	144	507	2.9	21.5
Rome	181	607	8.8	23.0
Palermo	207	633	13.3	23.8

4. Calculation

4.1. Glazing units' properties

The thermal and solar properties of the glazing units, both with and without the film in the cavity, were estimated using a calculation tool capable to simulating glazing systems and shading devices in compliance with the relevant international standards (Winshelter 3 3,0 2023; ISO – International Organization for Standardization, 2017). The solar properties were calculated using the reference spectral data for glasses and measured spectral data for the selected films.

The calculation procedure was carried out as follows:

1. The film is positioned parallel to the two glass panes in the midpoint of the air gap. Due to the limitation in minimum thickness accepted by the software the film was assumed to be 1 mm thick;
2. In a first set of calculations, the film was modelled as a conventional blind according to the procedure defined in (ISO – International Organization for Standardization, 2017);
3. In a next phase, the film was modelled as an additional glass pane, effectively transforming the double-glazing unit into a triple-glazing unit. This approach accounts for the special guides rails along which the film scrolls, minimizing the airflow between the two separated volumes within the glazing gap according to the procedures defined in (ISO – International Organization for Standardization, 2017).
4. For films with different surface finishes, the properties of the glazing systems were calculated twice: once with the film with the exposed surfaces facing inward and once facing outward with respect to the air cavity.

The lighting, solar and thermal properties were calculated for both reference glazing units in combination with all the selected films, including the variations described in point 4.

4.2. Building energy performance

The energy performances of the reference building were calculated using TRNSYS 18, a widely recognized and validated simulation tool for transient thermal analysis of buildings and solar energy systems. A TRNSYS project consists of several routines (*types*), each performing a specific calculation task and linked together to simulate complex energy interactions.

The project implemented in this study includes the following routines: a) Weather Data Processor: reads data at regular time intervals from an external weather data file (Meteonorm: TM2 format) and interpolates the data (including solar radiation on tilted surfaces). The city of Turin, Rome and Palermo (Italy) were selected as representative locations for the present study; b) the Generic Data Files Reader: used to input additional specific weather data; c) the Solar Radiation Processor: calculates solar insolation based on the position of the sun on a number of surfaces with either fixed or variable orientation according to the input global horizontal solar irradiation; d) the Psychometrics: calculates the moist air properties; e) the Effective Sky Temperature: calculates the long-wave radiation exchange between an arbitrary external surface and the atmosphere; f) the Multi-Zone Building Model: imports the building description from a preprocessor program called TRNBuild and simulates the thermal behaviour of a building divided into different thermal zones; g) the Soil Temperature Profile: models the heat transfer between the building and the soil below.

TRNSYS uses the Z-transform method to calculate the heat transfer through the building structure and uses a single node approach for each thermal zone for the building thermal analysis. One hour was the time resolution step selected for this calculation exercise, suitable to simulate the massive structures of Italian buildings.

The thermal and solar properties of Glazing Units A and B, including the measured spectral data of the films, were also modelled in (Berkeley Lab WINDOW Version, 2024). The broad-band thermal and solar quantities at different incidence angles were then directly called by the TRNSYS Multi-Zone building model.

The energy performance simulations were calculated for the following configurations:

n.2 building configurations: (insulated and not-insulated);

n.3 localities: (Turin, Rome, Palermo);

n.2 reference glazing unit configurations (type A and B);

n.3 film types: 1, 2 and 11 plus the reference case with no-film in the gap.

Films 1 and 2 were tested to assess their impact on heating performance when dark films function as nighttime shutters. The use of a conventional film and a low-emissivity coating allows comparing the impact of more advanced materials. The Film 11 was used to investigate the effect of seasonal solar control strategies on cooling energy demand. To accurately simulate the dynamic behaviour of these configurations, a specific set of equations was integrated into the TRNSYS project.

The following conditions were set to activate the films within the glazing unit gap:

1. 08:00–20:00 Glazing A – 20:00–08:00 Glazing A plus Film 1 (aluminium inward)
2. 08:00–20:00 Glazing A – 20:00–08:00 Glazing A plus Film 2
3. 08:00–20:00 Glazing A plus Film 11 – 20:00–08:00 Glazing A

The calculations were carried out for both the heating and cooling seasons. The same calculation set was carried out for Glazing B with and without the plastic film in the gap. The calculation procedure was based on a multi-zone modelling approach (6 apartments and an unconditioned stairwell). The energy performance results are expressed as aggregated values for the entire building. As already indicated in the methodology section, the outputs of the simulation consist in the net energy demand for space cooling and heating, assuming that the thermal load was calculated 24 hours per day throughout the entire winter and summer simulation periods.

5. Results

5.1. Films characterization

The broad-band properties of the selected films are shown in Table 4. The results include the reflectance (ρ) and the transmittance (τ) values in the solar (*e*) and visible (*v*) ranges and refer to both sides of each film: front (*f*) refers to the side facing inward, while and back (*b*) to the outward-facing side. This distinction is purely conventional as no specific applications guidelines are provided for these films.

The results show that the first 5 samples in the table are opaque to solar radiation across both the visible and solar spectral range, while their reflectance properties are influenced by the colour (black/white) and the surface finishing (aluminium coating) of the films. These samples do not exhibit spectral selectivity, as their visible and solar reflectance values are similar.

The metallic surface treatment ensures a low-e response with emissivity values ranging from 0.07 to 0.11 for samples (1. 5. 7. 9). In contrast, the non-treated polyester surfaces exhibit emissivity values between 0.77 and 0.80, which is consistent with the expected behaviour of polyester foils. An anomalous lower emissivity value (0.61) was measured for the sample 11, which was unexpected being the material of the same nature of the previous ones. Two issues should be considered: 1. eventual surface treatment might enhance the diffuse properties of the films although no specific information about such treatment is available to the authors; 2. the sample might exhibit infrared transmittance effects, which could influence the emissivity of the material. The latter behaviour will be further investigated in the next steps of the research.

As representative cases of the tested samples Fig. 3 presents the spectral reflectance curves of samples 1 and 2, whose transmittance is zero throughout the entire solar range. The plots show that the black colour and the polyester composition results in very low reflectance for sample 2, as well as for the front side of sample 1, which, conversely, has a very high reflectance across the 300–2500 nm range. To be noted that the reflectance remains high in the infrared region as inferred from the low measured emissivity value. These solutions could be particularly suitable for applications where traditional shutters need to be replaced with lighter façades solutions simultaneously enhancing the insulation properties of the façade by creating multiple gap glazing units.

Fig. 4 shows the spectral transmittance and reflectance of the sample 11. This material highlights a moderately low transmittance in the visible range (300–800 nm), that progressively increases in the near-infrared region. A symmetrical behaviour is observed for the reflectance curves (front and back surfaces show practically identical trends). An interesting issue lies here in the fluorescence of the material within the 300–400 ultraviolet region, which results in a very high reflectance values (>110 %), a phenomenon that deserves further investigation to make the material suitable for building applications. Despite this effect, such samples could be promising for solar and glare control under high solar irradiation conditions. Lastly, sample 14 could be interesting in applications where increased thermal insulation of glazing units is required while maintaining high levels of solar gains and daylighting.

Table 4
Optical properties and emissivity of the selected films.

Film Code	τ_e [%]	τ_v [%]	ρ_{e_f} [%]	ρ_{e_b} [%]	ρ_{v_f} [%]	ρ_{v_b} [%]	ε_f [-]	ε_b [-]
1	0	0	7	87	7	87	0.77	0.11
2	0	0	7	7	7	7	0.80	0.80
7	0	0	84	88	84	88	0.60	0.10
9	0	0	85	89	86	89	0.07	0.07
11	24	18	72	73	77	78	0.61	0.61
14	75	73	20	20	22	21	0.78	0.78

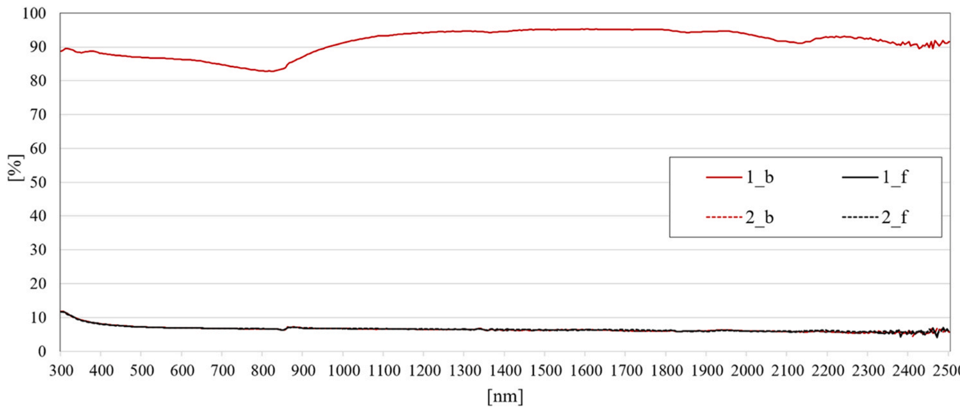

Fig. 3. Front and back spectral reflectance of sample 1 and 2.

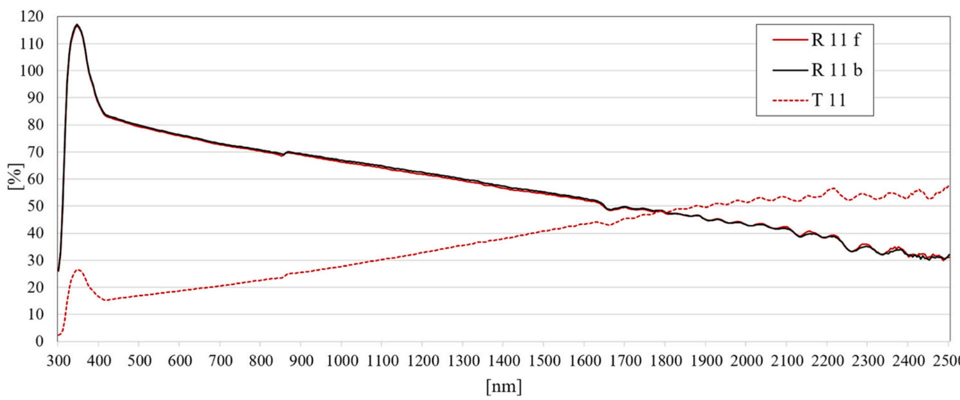

Fig. 4. Spectral reflectance and transmittance of sample 11.

5.2. *Glazing units' performance*

Table 5 and Table 6 show the main thermo-physical parameters of the glazing units for all the relevant configurations: direct transmittance values in the visible (τ_v) and solar (τ_e) range, solar factor (*g*) and thermal transmittance (*U*). Preliminary results were aimed at comparing the performance of the glazing unit with the movable film modelled either as a shading element or as glass panes. Given the calculation procedure prescribed by the mentioned standard, the differences between the two modelling approaches resulted to be negligible. For such reason, only the results referring to the film as a shading element are reported in the following tables.

Table 5 presents the results for the films in combination with Glazing A. The thermal transmittance (U) is reduced by approximately 40 % (around 1.0 W/m^{2}k**)** when low-emissivity films are applied to a double float glazing-unit (configuration 1). It can also be noted that placing the low-e side of the film facing the indoor side results in a 0.1 W/m^{2}k reduction compared to the opposite side (see sample 1 and 5) as the low-e coating provides a barrier to heat transmission within the warm internal gap. The effect of the low-e treatment accounts for approximately 0.4 W/m^{2}k as inferred by comparing the results of Glazing 1 equipped with Films 1 and 2. The intrinsic lower emissivity of sample 11 results in an improved insulation performance of 0.1 W/m^{2}k compared to sample 2 and 14, which exhibit higher emissivity. Concerning the solar gains, the opaque films obviously significantly reduce the glazing units' g-values (g). It is interesting observing the effect of the secondary heat transfer (i.e., the amount of radiation absorbed by the glazing systems and transmitted to the indoor as infrared radiation). When the black side of the films is exposed, the g-values range from 25 % to 33 % (the transmitted solar energy is reduced by up to two-thirds with respect to the glazing unit without film). In contrast, when aluminium and white sides are exposed, the glazing unit's g-value is reduced by 90 % or more

Table 5
Solar and thermal properties of the assembled glazing systems in configuration 1.

Film	Low-e side	τ_e [%]	τ_v [%]	g [%]	U [W/m^{2}k]
0	0	72	82	76	2.4
1	internal	0	0	25	1.4
1	external	0	0	7	1.5
2	—	0	0	33	1.8
7	internal	0	0	5	1.3
7	external	0	0	7	1.5
9	both	0	0	5	1.1
11	—	20	17	22	1.7
14	—	56	62	61	1.8

Table 6
Solar and thermal properties of the assembled glazing systems in configuration 2.

Film	Low-e side	τ_e [%]	τ_v [%]	g [%]	U [W/m^{2}k]
0	0	56	82	64	1.3
1	internal	0	0	23	1.2
1	external	0	0	5	1.1
2	—	0	0	23	1.2
7	internal	0	0	5	1.2
7	external	0	0	5	1.1
9	both	0	0	5	1.0
11	—	17	16	21	1.2
14	—	44	61	52	1.3

(to 5–7 %). It is worth noting that black films performed worse than the transparent diffusing film in terms of g-value (22 %). The Film 14, which is highly transparent, provides limited solar protection, but ensures high transparency and improved thermal performance compared to the base case.

The differences become less pronounced in the case of Glazing B (configuration 2) as the unit is already equipped with a low-emissivity glass pane. The maximum observed U-value reduction is 0.2 W/m^2k achieved when the low-e side of the film faces the external pane. This represents a significant behavioural difference in comparison with the previous case, which can be explained by the fact that the internal gap of the unit has a low radiation loss due to the low-emissivity coating of the glass. Consequently, the low-e side of the film becomes more effective in the external gap, where radiative heat losses are higher. In relative terms, the improvement in thermal insulation falls within the 8–15 % range. The response to solar gains is consistent with the previous case, with only minor differences in relative terms.

5.3. Building energy performance

The technology positively impacts the energy performance of the reference building in both winter and summer, as shown in Fig. 5, which presents the energy loads for three typical days, one in summer (mid-July) and one in winter (mid-January) for the not-insulated building configuration in the city of Rome. The left graph illustrates the heating loads for the building equipped with windows with glazing A, with and without the Film 1. A moderate effect of the extra insulation during nighttime hours can be observed. The right graph shows the cooling load profiles for the same glazing, with and without the Film 11. The impact of solar control is more evident as daytime peaks are more than halved.

Tables 7 and 8 present the net energy demand for space heating and cooling (expressed in megawatt-hours) for the not-insulated and insulated configurations, respectively. The results refer to the various glazing combinations described in the Calculation section.

The not-insulated energy performance of the reference building shows a strong predominance of space heating demand in Turin and Rome, while in Palermo, cooling and heating demands are balanced for both Glazing A and B. The dark films applied to the double float glazing provides energy savings in the 3–8 % range, depending on the film type and the locality. The highest absolute savings (3.6 MWh) are achieved with Film 1 in Turin, while the highest relative savings (8 %) are recorded in Palermo. The maximum energy savings achievable with the low-emissivity film amount to 1.3MWh compared to an equivalent conventional polyester film. It must be noted that these films cause a slight increase in cooling demand during summer, as the extra insulation limits the nighttime heat dissipation. The impact of the solar control Film (11) in summer is highly beneficial, with absolute peak savings greater than 7.9MWh and relative savings in the 74–85 % range across the three localities. Conversely, a static window with the same characteristics would have resulted in a significant increase in the heating demand (higher than 10MWh) due to the reduction in solar gains during winter. The impact of the dark films applied to the Glazing B is less pronounced, with peak energy savings close to 1MWh, achieved only for the low-e film in Turin. However, solar control film still provides substantial energy savings in summer, ranging from 5 to 7.6MWh in Turin and Palermo, respectively. In contrast, the impact of the solar filter if applied in winter remains negative, with a magnitude very similar to that observed in the previous case.

For the reference insulated building, it can be observed that heating loads still predominate in Turin, while the opposite occurs in Palermo; the two energy demands are balanced in Rome. Space heating demands are much lower compared to the not-insulated configuration, and consequently, the potential energy savings are also reduced. The impact of the technology differs in insulated buildings, with the highest energy savings recorded in Turin, as expected, reaching 3.7 MWh for Glazing A equipped with the low-e Film 1. Savings above 1MWh are calculated for the same glazing unit in Rome, while in all the other cases, heating savings are negligible. Conversely, cooling energy savings achieved with Film 11 during summer are significant. Cooling demands lower than 2.5MWh are calculated for Glazing A and B in Turin and Rome, with an absolute reduction in the 6.2–9.7MWh range. Even higher savings are achieved in Palermo, with absolute reductions of up to 13.4MWh and relative savings in the 71–74 % range.

6. Conclusion

This paper presented the first findings on the performance achievable by glazing units equipped with moveable plastic films in the air gap, as well as their impact on the global energy performance of buildings.

The radiative properties of selected films were characterised through laboratory measurements. The polyester films exhibited a wide range of luminous and solar properties, ranging from high transparency to a completely opaque behaviour. High reflectance (>85 %) and low-emissivity (≅ 0.10) were reached by aluminium coatings. The thermal transmittance of double-glazing units was reduced by 10–40 %, depending on the glazing and film characteristics: the lower the baseline performance of the glazing, the greater the thermal insulation improvement. Even larger variations were observed in the solar properties, highly dependent on the film characteristics. For opaque films, the solar gains ranged from 5 % (with white and/or aluminium finishing) up to 25 % for black films, while values exceeded 60 % in case of transparent films.

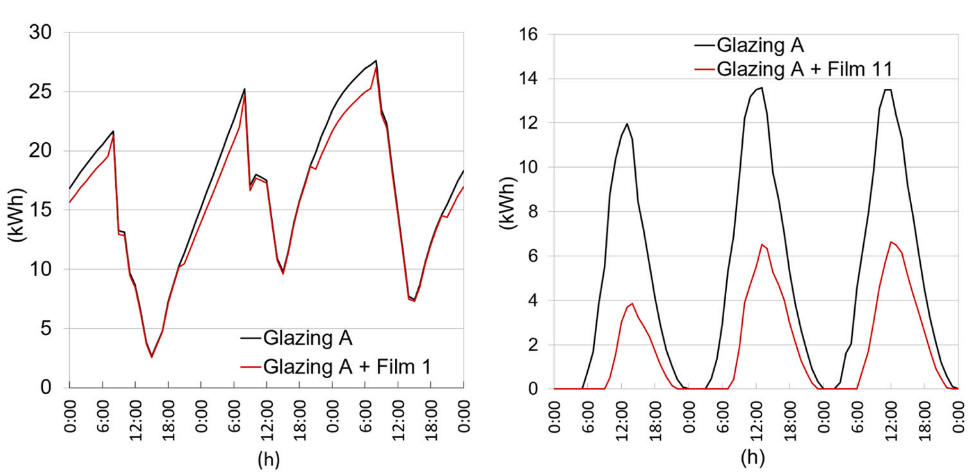

Fig. 5. Energy needs for two glazing combinations for heating (left) and cooling during three typical days in winter and summer, respectively.

Table 7
Energy performance of the not insulated buildings for all the glazing unit variants.

Glazing+Film	Turin		Rome		Palermo	
	Cooling (MWh)	Heating (MWh)	Cooling (MWh)	Heating (MWh)	Cooling (MWh)	Heating (MWh)
GA_0	5.6	70.2	9.4	36.6	16.5	14.6
GA_1	5.8	66.6	9.7	34.3	16.7	13.4
GA_2	5.7	67.9	9.6	35.1	16.7	13.8
GA_11	1.5	80.4	3.5	46.5	7.7	22.5
GB_0	4.8	66.3	8.2	34.6	14.6	13.7
GB_1	4.7	65.5	8.1	34.3	14.4	13.8
GB_2	4.6	66.1	8.0	34.7	14.4	14.0
GB_11	1.3	77.0	3.3	44.5	7.2	21.5

Table 8
Energy performance of the insulated buildings for all the glazing units' variants.

Glazing+Film	Turin		Rome		Palermo	
	Cooling (MWh)	Heating (MWh)	Cooling (MWh)	Heating (MWh)	Cooling (MWh)	Heating (MWh)
GA_0	8.0	31.8	12.1	13.9	18.1	3.9
GA_1	8.5	28.1	12.8	11.7	18.5	2.9
GA_2	8.3	29.4	12.5	12.5	18.3	3.3
GA_11	1.2	33.9	2.4	19.0	4.7	8.6
GB_0	7.1	27.8	10.7	11.8	15.9	3.1
GB_1	6.9	26.8	10.4	11.5	15.5	3.1
GB_2	6.8	27.5	10.3	11.9	15.5	3.2
GB_11	0.9	31.0	2.2	17.3	4.6	7.7

Opaque films can improve the building energy performance up to 8 % corresponding to absolute savings of 3.7MWh in a residential building, when used as night shutters. However, their performances are strongly influenced by climate conditions and the glazing characteristics. Transparent films used as solar filters during daytime in summer can reduce cooling demand by up to 13.4MWh with relative reduction reaching 80 % in Turin, where the cooling demand becomes almost negligible.

The outcome of the study stressed the importance of the moveable film approach. The benefits of dynamic transparent films were demonstrated by the increased space heating demand in winter when the film was considered static, due to the reduction of solar gains through the transparent systems. The opaque systems also offer promising potentials, as they optimise the energy performance at night, when outside vision is not required. Several limitations apply to this study. The analysis was based on a limited number of products and does not cover all the potential performances beyond the energy savings, such as thermal comfort and daylighting, which could also benefit from this technology, but were not analysed in the study. Additionally, the research focused exclusively on dwellings, whereas the technology deserves evaluation also in not-residential buildings, where the dynamic behaviour of the envelope could offer relevant advantages during both cooling and heating seasons.

These preliminary findings underline the need for further developments. Future experimental activities will include the direct measurements of the thermal properties of glazing units assembled with films in the air gap to assess their insulation performance under real operating conditions, as well as an evaluation of the impact of semi-transparent films in dynamically modulating solar gains modes. The numerical simulations will be expanded to include additional glazing system configurations and building typologies, particularly offices and schools. A crucial direction for future research will also involve a comprehensive assessment of building response taking into account lighting energy demand and daylighting performances.

CRediT authorship contribution statement

Papaiz Luca: Supervision, Investigation, Conceptualization. **Agnoli Stefano:** Software, Formal analysis, Data curation. **Romeo Carlo:** Writing – original draft, Validation, Software, Formal analysis. **Zinzi Michele:** Writing – original draft, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: M. Zinzi, C. Romeo, S. Agnoli reports financial support was provided by Italian Ministry of Environment and Energy Security. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

This study was funded in the Program Agreement between the Italian National Agency for New Technologies. Energy and Sustainable Economic Development (ENEA) and the Ministry of Environment and Energy Security (MASE) in the framework of "Ricerca di Sistema Elettrico".

Data availability

Data will be made available on request.

References

Arıcı, M., Kan, M., 2015. An investigation of flow and conjugate heat transfer in multiple pane windows with respect to gap width, emissivity and gas filling. Renew. Energy 75, 249–256. https://doi.org/10.1016/j.renene.2014.10.004.
Berkeley Lab WINDOW Version (2024), ⟨https://windows.lbl.gov/window-software-downloads⟩.
Graf, F., Albani, F. (Eds.), 2011. Glass in the 20th Century Architecture: Preservation and Restoration. Mendrisio Academy Press, Mendriso.
CEN – European Committee for Standardization (2011a) EN 410:2011 - Glass in Building - Determination of Luminous and Solar Characteristics of Glazing.
CEN – European Committee for Standardization (2011b) EN 15976:2011 - Flexible Sheets for Waterproofing, Determination of Emissivity.
De Masi, R.F., Festa, V., Gigante, A., Ruggiero, S., Vanoli, G.P., 2022. The incidence of smart windows in building energy saving and future climate projections. Energy Rep. 8 (ement 16), 283–289. https://doi.org/10.1016/j.egyr.2022.10.222.

Fang, Y., Hyde, T.J., Arya, F., Hewitt, N., Wang, R., Dai, Y., 2015. Enhancing the thermal performance of triple vacuum glazing with low emittance coatings. Energy Build. 97, 186–195. https://doi.org/10.1016/j.enbuild.2015.04.006.

Grynning, S., Gustavsen, A., Time, B., et al., 2013. Windows in the buildings of tomorrow: energy losers or energy gainers? Energy Build. 61 (3), 185–192. https://doi.org/10.1016/j.enbuild.2013.02.029.

Hee, W.J., Alghoul, M.A., Bakhtyar, B., Elayeb, Om.Kalthum, Shameri, M.A., Alrubaih, M.S., Sopian, K., 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.

Hu, J., Chen, W., Qu, Y., Yang, D., 2020. Safety and serviceability of membrane buildings: a critical review on architectural, material and structural performance. Eng. Struct. 210, 110292.

Huang, Y., El Mankibi, M., Cantin, R., Coillot, M., 2021. Application of fluids and promising materials as advanced inter-pane media in multi-glazing windows for thermal and energy performance improvement: a review. Energy Build. 253, 111458. https://doi.org/10.1016/j.enbuild.2021.111458.

ISO – International Organization for Standardization (2017) ISO 52022-3:2017 - Energy Performance of Buildings -Thermal, Solar and Daylight Properties of Building Components and Elements -Part 3: Detailed Calculation Method of the Solar and Daylight Characteristics for Solar Protection Devices Combined with Glazing.

Jamilu, G., Abdou, A., Asif, M., 2024. Dynamic façades for sustainable buildings: a review of classification, applications, prospects and challenges. Energy Rep. 11, 5999–6014. https://doi.org/10.1016/j.egyr.2024.05.047.

Karlsson, J., Roos, A., 2001. Annual energy window performance vs. glazing thermal emittance the relevance of very low emittance values. Thin Solid Films 392 (2), 345–348. https://doi.org/10.1016/S0040-6090(01)01055-0.

Khaled, K., Berardi, U., 2021. Current and future coating technologies for architectural glazing applications. Energy Build. 244, 111022. https://doi.org/10.1016/j.enbuild.2021.111022.

Kou, R., Zhong, Y., Wang, Q., Kim, J., Chen, R., Qiao, Y., 2021. Improved window energy efficiency with thermal insulating polymer-air multilayer. Appl., Therm. Eng. 191 (5), 116890. https://doi.org/10.1016/j.applthermaleng.2021.116890.

Li, N., Meng, Q., Zhao, L., Li, H., Wang, J., Zhang, N., Wang, P., Lu, S., 2023. Thermal performance study of multiple thermal insulating glazings with polycarbonate films as interval layers. J. Build. Eng. 76, 107159.

Liu, J., Yang, R., Zhang, J., Tao, Q., Li, A., Liu, Z., Su, Y., Liu, Y., 2023. Dual-function smart windows with dynamic and fast thermal response for building energy-saving/storage. Sol. Energy Mater. Sol. Cells 249, 112048. https://doi.org/10.1016/j.solmat.2022.112048.

Manz, H., 2008. On minimizing heat transport in architectural glazing. Renew. Energy 33 (1), 119–128. https://doi.org/10.1016/j.renene.2007.01.007.

Meng, Q. (2016) A multi cavity insulating glass, China Patent 7 (2016 -04 -08), 201620292429,

Meteonorm 8 (2020), https://meteonorm,com/en/.

Ministry of Economic Development (2015) Decree of June 26 2015 - Application of Energy Performance Calculation Methodologies and Definition of Prescriptions and Minimum Requirements for Buildings.

Quesada, G., Rousse, D., Dutil, Y.-, Badache, M., Hallé, S., 2012. A comprehensive review of solar façades, transparent and translucent solar façades. Renew. Sustain. Energy Rev. 16 (5), 2643–2651.

W.,R., Regan, A., Zettl, B.,J., Aleman, Suspended thin film structures, UnitedStates Patent (2011), US2011/0200787A1.

Shafaghat, A., Keyvanfar, A., 2022. Dynamic façades design typologies, technologies, measurement techniques, and physical performances across thermal, optical, ventilation, and electricity generation outlooks. Renew. Sustain. Energy Rev. 167, 112647.

Shum, C., Zhong, L., 2023. A review of smart solar shading systems and their applications: opportunities in cold climate zones. J. Build. Eng. 64, 105583.

Teixeira, Henriqueta, Gomes, M.Glória, Moret Rodrigues, A., Pereira, Júlia, 2020. Thermal and visual comfort, energy use and environmental performance of glazing systems with solar control films. Build. Environ. 168, 106474. https://doi.org/10.1016/j.buildenv.2019.106474.

Tiwari, R., Kim, J., 2022. Multi-cell, triple pane, vacuum insulated glazing. Sol. Energy 245, 340–352.

UNI – Italian Standards Body (2014) UNI/TS 11300-1:2014 - Energy performance of buildings - Part 1: Determination of the thermal energy requirement of the building for summer and winter air conditioning.

Wang, H., Hang, J., Yang, J., Gao, Z., Zhao, J., Xu, F., 2024. Reduced-scale experimental study on the cooling effect of solar control films and cool materials. Energy Build. 320, 114636. https://doi.org/10.1016/j.enbuild.2024.114636.

Wang, Y., Shukla, A., Liu, S., 2017. A state of art review on methodologies for heat transfer and energy flow characteristics of the active building envelopes. Renew. Sustain. Energy Rev. 78, 1102–1116. https://doi.org/10.1016/j.rser.2017.05.015.

Winshelter 3,0 (2023), www,winshelter,enea,it.

Wu, S., Sun, H., Duan, M., Duan, M., Mao, H., Wu, Y., Zhao, H., Lin, B., 2023. Applications of thermochromic and electrochromic smart windows: materials to buildings. Cell Rep. Phys. Sci. 4 (5), 101370. https://doi.org/10.1016/j.xcrp.2023.101370.

Yi, Z., lv, Y., Xu, D., Xu, J., Qian, H., Zhao, D., Yang, R., 2021. Energy saving analysis of a transparent radiative cooling film for buildings with roof glazing. Energy Built Environ. 2 (2), 214–222. https://doi.org/10.1016/j.enbenv.2020.07.003.

Zhang, T., Tan, Y., Yang, H., Zhang, X., 2016. The application of air layers in building envelopes: a review. Appl. Energy 165, 707–734. https://doi.org/10.1016/j.apenergy.2015.12.108.

Zhang, Tiantian, Yang, Hongxing, 2019. Heat transfer pattern judgment and thermal performance enhancement of insulation air layers in building envelopes. Appl. Energy 250, 834–845. https://doi.org/10.1016/j.apenergy.2019.05.070.