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Energy flexibility potential of transparent responsive building envelope elements

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Abstract

Enhancing energy flexibility in buildings is crucial as they are evolving into active energy prosumers, capable of consuming, producing, and managing their energy demand. A key yet under-explored aspect is the potential of responsive building envelopes, particularly transparent ones, in contributing to the building energy flexibility. This study addresses this gap by introducing a simulation framework designed to assess the energy flexibility of responsive building envelope technologies, with a particular focus on double skin façade systems. Through a case study of a reference office located in a temperate climate, the framework evaluates the impact of double skin façades on different key performance indicators measuring building energy flexibility. The results demonstrate the efficacy of these systems in maintaining indoor comfort conditions during demand response events and lowering rebound energy. In winter, the double skin facade can completely eliminate the rebound energy required after the event, while in summer, integrating blinds into the cavity reduces rebound energy by up to 99% compared to a triple glazing unit with blinds.

Key Innovations

- Assessment of energy flexibility potential of transparent responsive building envelope elements.
- Simulation framework to analyse effects on indoor temperature and rebound effect when the HVAC system is turned off for two hours (DR event)

Practical Implications

This study demostrate the considerable potential of double-skin façades (DSFs) in enhancing energy flexibility within buildings, particularly during demand response (DR) events.

Introduction

In recent decades, the rising challenge of reducing CO_2 emissions in buildings has driven the European Union (EU) to adopt ambitious goals and policies aimed at tackling climate change. With an objective to reduce emissions by 55% by 2030 and to achieve climate neutrality by 2050, the EU is implementing policies with a strong emphasis on reducing energy consumption, particularly in the building sector, which is responsible for 40% of global energy use and 36% of related greenhouse gas emissions (European Parliament And The Council, 2023). Transparent building envelope components are a significant contributor to the building energy demand, primarily through heat transfer and ventilation (Desideri & Asdrubali, 2018) and typically provides the largest potential for energy saving (Jin & Overend, 2014). As buildings are increasingly relying on electricity for HVAC systems and other services, the need for greater energy flexibility has become more pressing (Pedram et al., 2023). In this context, the development and implementation of demand response (DR) strategies have emerged as imperative for enhancing the flexibility and reliability of the electricity grid, particularly in the context of the growing integration of renewable distributed energy resources (DER). From the perspective of building management, this flexibility can be achieved through the integration of responsive systems that are capable of dynamically adapting to grid demands (Orikpete et al., 2023). The concept of energy-flexible buildings, introduced by the International Energy Agency's Energy in Buildings and Communities (IEA EBC) Annex 67, identifies building that can actively regulate their energy generation and consumption in response to weather conditions, user needs, and grid requirements (Jensen et al., 2017). In recent years, a range of strategies have been developed with this objective while minimising occupant thermal discomfort. These strategies include the use of thermal mass within the building envelope and the integration of external Thermal Energy Storage (TES) systems into HVAC systems. The effectiveness of these strategies as part of Demand-Side Management (DSM) has been well documented (Fop et al., 2024; Li et al., 2022). Building on these approaches, transparent responsive building envelope elements could offer opportunities to enhance energy flexibility, in fact by actively managing heat exchange, these components can assist in maintaining indoor comfort conditions during flexibility events, thereby reducing reliance on active HVAC operation while enhancing the overall responsiveness of buildings to dynamic energy demands. While previous studies have focused primarily on improving energy efficiency, fewer have explored their potential in grid-responsive strategies. For instance, electrochromic (EC) glazing has been shown to support demand response (DR) by dynamically modulating solar gains and reducing peak energy loads when integrated

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with HVAC systems (Gehbauer et al., 2023). However, a substantial research gap persists regarding the broader impact of responsive building envelope technologies on energy flexibility at the building level.

Within these, double-skin facades (DSF) could have great potential in supporting DR strategies, as they can actively regulate heat transfer within the glazed façade. This depends on the cavity ventilation strategy adopted and the management of solar gains through integrated solar shading, reducing thermal loads and contributing to more stable indoor conditions. At the same time, DSFs help reduce reliance on HVAC power needed to restore set point conditions after the demand response event. This mitigates temperature deviations and limits the reduction of indoor environmental quality during the DR event. This capability is particularly relevant in addressing the rebound effect, a phenomenon in which energy demand surges after a DR event due to the intensified operation of HVAC systems (Kathirgamanathan et al., 2020) in order to restore the environmental conditions.

Building on this premises, the present study aims to develop a preliminary approach to assess the role of responsive building envelope systems, and particularly DSFs in DR strategies. By analysing how DSFs influence heat transfer and indoor temperature recovery, the work provides an initial insight into their potential to enhance building energy flexibility and support grid-responsive strategies.

Methods

This study aims to evaluate the energy flexibility potential of responsive façade systems by analyzing their capacity to modulate thermal loads and dynamically interact with building energy systems. To achieve this, a double-skin façade (DSF) was selected as the representative technology due to its high architectural adaptability and its ability to harness solar radiation, converting it into thermal energy that is subsequently transferred to the cavity airflow (Favoino et al., 2021). The analysis follows a progressive approach, introducing increasing levels of flexibility and integration with the HVAC system, starting from a triple-glazing unit (TGU) as a baseline and advancing to a DSF with an integrated shading device. To assess the flexibility potential of this component, key performance indicators (KPIs) were identified based on existing literature on both façade systems and HVAC performance metrics. These KPIs were selected to effectively capture the capacity of the façade to enhance energy flexibility and its interaction with the building's energy system. The evaluation was conducted across multiple scenarios, including winter and summer peak conditions as well as average days, ensuring a comprehensive assessment of the behavior of these technologies. To achieve this, a simulation model was developed in EnergyPlus, representing a simplified office room case, which allows for the systematic analysis of the façade's dynamic behavior under varying boundary conditions.

Case study

The case study employed in this work consists in a double skin façade (DSF), which is a glazing envelope component consisting of at least two glass layers with an intermediate air cavity, where air can circulate either naturally or through mechanical ventilation. While normally DSF presents only two opening, a more flexible concept of DSF with four opening (two at the bottom and two at the top) was chosen. This adaptability allows for the modulation of heat exchange between the indoor and outdoor environments, making the façade a more climate-responsive element (Catto Lucchino et al., 2022). The system operates in three modes, which are depicted in Figure 1. Supply Air (SA), where outdoor air is pre-heated in the cavity, and is delivered indoors to maximize energy harvesting in winter; Outdoor Air Curtain (OAC), where air circulates between the cavity and outdoors to limit solar heat gains; Exhaust Air (EA), where air from indoor passes the cavity and is expelled outdoor; and Thermal Buffer (TB), where the cavity is sealed to preserve indoor conditions and minimize thermal losses.

In addition to ventilation control, the DSF can also provide solar modulation when venetian blinds are installed within the air cavity.

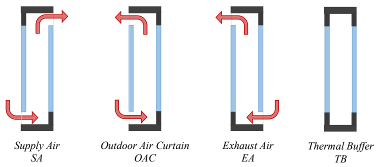

Figure 1: DSF ventilation modes

To analyse the flexibility potential of the DSF component, the chosen approach involves comparing its different operational modes against a static benchmark. The benchmark selected is a Triple Glazing Unit (TGU) with the same thermo-optical properties as the DSF. From an energy perspective, this represents a high-performance reference, allowing for a like-for-like comparison of the DSF ability to enhance energy flexibility compared to a static façade system.

The thermal behaviour of a dynamic façade is crucial for understanding the heat transfer mechanisms, depending on the ventilation strategy and boundary conditions. To quantify the total heat gains or losses through the advanced glazing system for advanced control purposes, Gennaro et al. (Gennaro et al., 2021, 2023) introduced the Façade Total Heat Transfer (FTHT) indicator showed in Figure 2.

Specifically, FTHT consists of the following components:

- Convective and radiative heat transfer, denoted as $Q_{\Delta T}$, resulting from the temperature difference between the inner skin of the façade and the indoor space, including the solar heat gain absorbed by the façade system and re-emitted towards the indoor environment;
- Short-wave solar radiation, denoted as $Q_{s,dir}$, which is directly transmitted into the indoor environment;

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- Ventilation heat gain or loss introduced in the indoor environment, denoted as Q_v, Q_{v_dsf} or Q_{v_hr}, based on the ventilation strategy.

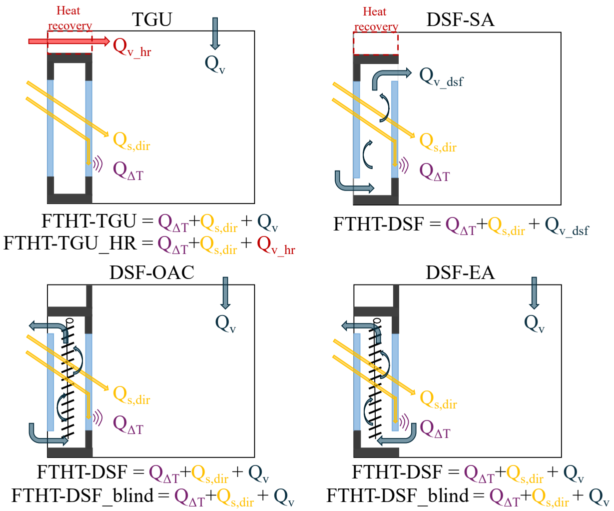

Figure 2: Schematic representation of the Façade Total Heat Transfer (FTHT) indicator

The FTHT varies depending on the different configurations of the DSF system. Figure 2 illustrates the different possible configurations, and their related FTHT.

The ventilation heat gain or loss term depends on the ventilation method, and can be written as:

- Q_v ,the air moves directly from the outside into the indoor environment

$$Q_v = m \cdot c_p \cdot (\dot{T}_{outdoor})$$

- Q_{v_dsf}, the air moved from the outdoor environment into the DSF and then into the indoor space.

$$Q_{v\_dsf} = m \cdot c_p \cdot (\dot{T}_{outlet} - T_{outdoor})$$

- Q_{v_hr}, the air moved from the outdoor environment into the heat recovery system and then into the indoor space.

$$Q_{v\_hr} = m \cdot c_p \cdot (\dot{T}_{outdoor}) \cdot (1 - \eta_{hr})$$

Where m is the mass flow rate [kg/s], c_p is the air specific heat [J/kgK], $T_{outdoor}$ is the outdoor temperature, T_{outlet} is the air temperature exiting the DSF cavity and η_{hr} is the heat recovery system efficiency (in this study it is considered for simplicity constant and equal to 75 %).

Boundary Conditions

The boundary conditions of this work regard the comfort band during the DR event, the climatic data employed, the DR start and ending time, and the simulation matrix employed.

The simulations are carried out for the city of Turin in Italy. Regarding thermal comfort limits, the acceptable temperature range is set between 19°C and 21°C during the heating season and between 25°C and 27°C during the cooling season.

To accurately model the dynamic behaviour of the building under variable environmental conditions, a climatic dataset is required. In this work, a Typical Meteorological Year (TMY) file was used, incorporating meteorological data collected between 2007 and 2021 (*Climate.Onebuilding.Org*, n.d.).

In this study, the flexibility potential of the different technologies is evaluated on typical days, which are representative of both seasonal average and seasonal peak conditions. To achieve this, the Italian standard UNI 10349-1 (Italian Organisation for Stardardisation (UNI), 2016) was employed, which provides the necessary climatic data to assess peak and average daily temperatures as well as solar radiation levels for each month. Based on the climatic conditions of Turin, two representative days were selected for each season: one corresponding to the peak (lower peak for winter and upper peak for summer) and one to the average daily. The characteristics of these days for the city of Turin are summarized in Table 1.

Table 1: Turin typical days data

Typical day type	T Max [°C]	T Mean [°C]	T Min [°C]	Solar Rad [Wh/m^2]
Winter average	7.58	3.50	0.74	3115.76
Winter peak	1.05	-0.24	-1.91	407.41
Summer average	29.00	23.70	17.583	2969.51
Summer peak	30.58	23.7	17.3	3610.32

Once the reference days are established, the starting time of the DR event needs to be defined. A common practice is to align this selection with the peak electricity demand periods for the country where the building is located. To determine these periods, data from the "Gestore dei Servizi Energetici" (GSE) website (GSE, 2025) were analysed. In Italy, electricity demand typically exhibits two peak periods: one in the morning and another in the evening. In winter, the first peak occurs between 8:00 and 10:00 AM, while the second occurs between 6:00 and 8:00 PM. In summer, the primary peak is observed between 7:00 and 9:00 PM. However, to also assess the building's response during the daytime, an additional morning event from 8:00 to 10:00 AM was considered.

As previously introduced, the analysis follows a methodological approach that employs progressively advanced design technologies. Each simulation incorporates a specific ventilation operating mode, determined by both the season and the façade technology under consideration. Table 2 presents the simulation matrix adopted in this study, outlining the different technologies and corresponding ventilation strategies for each season. Specifically, the term *alwayson* indicates that ventilation operates continuously, with the airflow path depending on the configuration previously illustrated in Figure 2. In contrast, *startdrevent* denotes a mode in

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which outdoor ventilation remains active at all times, but air is directed through the DSF only when the demand response (DR) event begins.

Table 2: Simulation matrix

Season	Technology	Ventilation
Winter	TGU	alwayson
	TGU hr	alwayson
	DSF	alwayson
	DSF	startdrvent
Summer	TGU	alwayson
	TGU blind	alwayson
	DSF	OACalwayson
	DSF	EAalwayson
	DSF blind	OACalwayson
	DSF blind	EAalwayson

Simulation model

The case study considers a single enclosed, south-facing room based on the BESTEST case 600 model (Struck et al., 2009), located in Turin, Italy (45° 7′ N, 7° 43′ E), within climatic zone E (2617 degree days). The room has dimensions of 6 m in width, 8 m in length, and 2.7 m in height. Adiabatic boundary conditions are applied to all surfaces except for the south-facing wall, simulating its integration within a larger building maintained at the same indoor temperature. This approach allows for the isolation of the thermal behaviour of the south-facing wall. This wall measures 6 m by 2.7 m and incorporates two windows, each 3 m wide and 2 m high (WWR of 74%). Building constructions comply with local standards for Turin's climate zones, aiming for a thermal transmittance (U-value) of 0.26 W/m^2K and an infiltration rate of 0.001 m^3/s with equipment loads set at 12 W/m^2 and lighting at 10.55 W/m^2 constant during the entire day. Ventilation is ensured in every simulation, whether through direct mechanical supply from the outside, via the DSF, or through the heat recovery system. The airflow rates are identical in all cases, set at 1.86 ACH, in accordance with the Italian standard (Italian Organization for Standardisation (UNI), 2019) .When using the Double Skin Façade (DSF) in SA, the airflow is mechanically supplied through the DSF cavity. In all other configurations, airflow is directly supplied from the outdoor environment. The mass flow rate remains consistent across all cases for comparability . The DSF is modelled using the "Airflow Window" component embedded in EnergyPlus. The DSF and TGU have the same stratigraphy, with identical thermos-optical properties, as shown in Figure 4. In the case of the DSF, the ventilated cavity is on the exterior side.

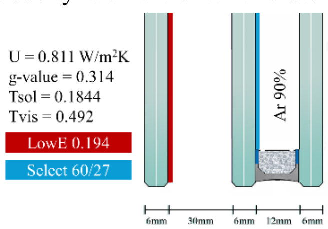

Figure 3: DSF and TGU thermo-optical properties

Since the focus of this analysis is the energy flexibility provided to the electricity grid, heat pumps are considered as the generation system for building heating and cooling. The heating systems were sized based on the buildings maximum thermal load under steady-state conditions, using the minimum winter temperature for the selected locations, as recommended by UNI EN 10349-2 (Italian Organisation for Stardardisation (UNI), n.d.). In this study, the heating demand was estimated at 4.1 kW, with a design outdoor temperature of -8°C and an indoor setpoint of 21°C. The simulations were conducted using the EnergyPlus software, with the Demand Response (DR) event implemented through the Energy Management System (EMS) of EnergyPlus. The DR event was simulated by defining an input that triggers the deactivation of the HVAC system during the designated period.

Metrics

To evaluate in a compact manner the flexibility potential of transparent responsive building envelope elements, this study employs two main metrics, which are the rebound energy and the Cumulative Temperature Deviation (CTD).

Rebound energy

The rebound energy (E_{rb}) captures the change in energy consumption following or before a DR event compared to the reference case (Kathirgamanathan et al., 2020). In this case study there are no preconditioning strategies applied therefore there is no pre-rebound, so the rebound effect can be expressed as:

$$E_{rb} = \int_{I_{DR,end}}^{+\infty} \left(P_{DR} - P_{Ref}\right) dt$$

The $+\infty$ denotes the rebound horizon. When calculating E_{rb} ,the horizon can be several hours or longer depending on the system response of the control strategy. In this case study normally after one hour condition are restored, but to be sure to include all cases a *three hours horizon* after the event was considered.

Cumulative Temperature Deviation

The Cumulative Temperature Deviation (CTD) quantifies the total deviation from thermal comfort conditions during a demand response (DR) event. It is computed as the cumulative sum of the absolute temperature differences between the indoor air temperature and a predefined comfort threshold over an extended DR period, including the time required to restore comfort conditions after the event ends. This post-event recovery phase is essential, as it contributes to the overall thermal experience of occupants and influences perceived comfort levels.

$$CTD = \sum_{i=1}^{N} \left|\left(T_{indoor,i} - T_{threshold}\right)\right| \cdot \Delta t$$

N is the number of time steps considered during the extended DR period (including the recovery phase). $T_{indoor,i}$ is the indoor air temperature measured at time step

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i. $T_{threshold}$ is the comfort threshold, set to 19°C in winter and 27°C in summer. Δt denotes the time step duration in hours.

The CTD is expressed in Kelvin-hours (K·h), capturing both the intensity and duration of discomfort. Only deviations beyond the threshold contribute to the CTD; periods where the temperature remains within the comfort range are excluded. In winter, CTD values indicate overcooling when indoor temperatures fall below 19 °C, while in summer, they reflect overheating when temperatures exceed 27 °C. A CTD of zero signifies uninterrupted thermal comfort during the entire evaluation period.

Results

To provide insights into the flexibility potential of the DSF compared to its benchmarks, this section analyses the dynamic behaviour of the simulated room during DR events, focusing on both indoor temperature trends and the metrics during and after the DR events. For a more detailed analysis, these results are organized in two main parts, i.e. summer typical days and winter typical days, deepening the most interesting cases.

Winter typical days

To compare the flexibility potential of the different technologies investigated in this study, Figure 4 reports the metrics developed for both the peak and the average winter day, considering each technology and ventilation strategy during DR events occurring at AM and PM hours.

Time	Technology	Ventilation strategy	Rebound Energy [Wh]	CTD [Kh]
Winter average day				
AM	DSF	alwayson	0	0
	DSF	startdrevent	0	0
	TGUhr	alwayson	0	0
	TGU	alwayson	15266.6	0.48
PM	DSF	alwayson	93.7	0
	DSF	startdrevent	5783.7	0
	TGUhr	alwayson	0	0
	TGU	alwayson	19349.2	0.09
Winter peak day				
AM	DSF	alwayson	19043.7	0.34
	DSF	startdrevent	19033.3	0.33
	TGUrec	alwayson	7232.3	0
	TGU	alwayson	27218.4	3.53
PM	DSF	alwayson	20131.2	0.4
	DSF	startdrevent	20099.8	0.38
	TGUrec	alwayson	6604.1	0
	TGU	alwayson	25860.7	3.21

Figure 4: KPIs for winter typical days. The green color represents a good performance (low rebound energy and low CTD) while the red a worst performance (high rebound energy and high CTD)

As can be seen from Figure 4, during the average winter day, the DSF both with "alwayson" and "startdrevent" ventilation strategies demonstrates significantly better performance than the TGU in terms of rebound energy and CTD. It also exhibits a performance comparable to the TGUhr configuration, which serves as the highest-performance benchmark considered in this study. In particular, during DR events occurring in AM hours, the high availability of solar radiation enables the DSF to completely eliminate rebound energy and achieve CTD values of 0, meaning full comfort in both cases (alwayson, startdrevent). This means the DSF is able to maintain thermal comfort more effectively while also avoiding post-DR energy spikes, particularly under moderate winter conditions. In contrast, the TGU system, despite delivering similar thermal insulation, demonstrates higher sensitivity to DR interruptions, resulting in measurable discomfort (CTD = 0.48) and rebound energy exceeding 15,000 Wh. During DR events occurring in PM hours, when no solar radiation is present, the DSF exhibits lower performance than in AM hours, but still performs significantly better than the TGU, particularly in maintaining indoor temperature above the threshold (CTD=0).

On the winter peak day, due to the limited solar radiation in both the AM and PM hours, the DSF is unable to introduce a positive Q_v. However, it still outperforms the TGU by reducing heat loss through the glazed façade, thanks to the circulation of air within the cavity. During the AM hours the DSF is able to decrease rebound energy of 30 % compared to a TGU, while during PM hours it decreases rebound energy of almost 22% compared to a TGU.

Moreover, while the TGUhr is included as a high-performance benchmark, it is important to emphasize the fundamental distinction between the DSF and a heat recovery (HR) system. The DSF is a building envelope component that manages both ventilation and heat transfer, whereas an HR system is an active, energy-dependent HVAC component. The fact that the DSF can achieve performance levels comparable to an HR system, on average, is particularly noteworthy.

To further detail the results obtained, Figure 5 shows the indoor temperature trends for the different configurations investigated in this study during the AM hours for the winter average day. The first noticeable aspect is that not only the DSF (both always on or started at the beginning of the DR event) does perform better than the TGU in maintaining comfort conditions, but it is also able to increase the indoor temperature up to 1 degree during the two hours in which the HVAC is turned off. The incorporation of heat recovery enhance the performance of the TGU, which behave similarly to the DSF.

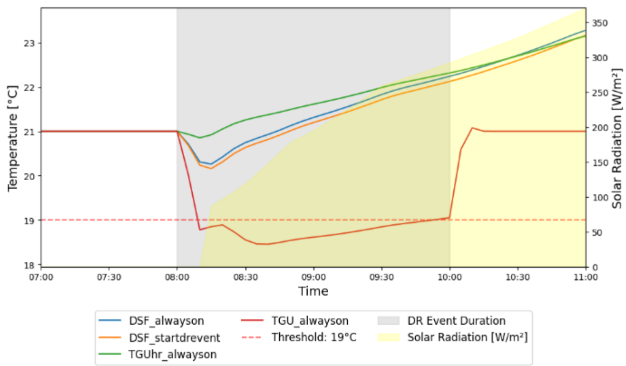

Figure 5: Winter average day temperature trend during DR events occurring at AM hours

The behavior differs during the DR event occurring at PM hours, showed in Figure 6, where the DSF, when kept continuously on, maintains an indoor temperature

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consistently above 21°C. Even when used statically and activated only at the start of the DR event (DSF_startdrevent), the DSF is still able to keep the indoor temperature just 0.5°C below the set point, effectively maintaining conditions above the threshold.

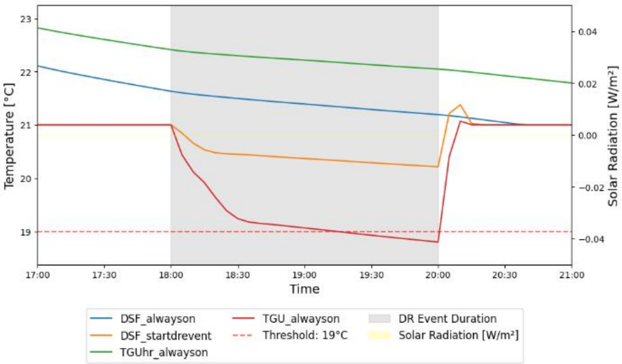

Figure 6: Winter average day temperature trend during DR events occurring at PM hours

As explained, the DSF and the TGU share identical thermal and optical characteristics. In fact, when the DSF is used statically ("DSF_startdrevent"), its behavior mirrors that of the TGU, as demonstrated by the power trends in Figure 7, before the DR event. However, since the DSF is an active component, once it is activated at the start of the DR event at 18:00 pm, it not only helps maintain the indoor temperature near the set point, as seen in Figure 6, but also reduces the rebound effect after the DR event ends, as shown in Figure 7 (orange line). This is achieved by lowering the energy required to restore the set point conditions in the indoor environment. This effect is due to the fact that activating the DSF increases the FTHT by increasing the ventilation Q_v gains. Specifically, the air introduced by the DSF is at a temperature higher than the indoor environment, thus Q_v represents a gain. In contrast, for the case with the TGU, where Q_v is a loss because the inlet air temperature is lower than the indoor temperature.

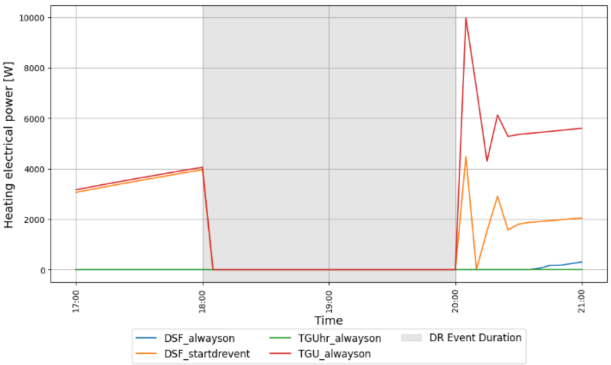

Figure 7: Winter average day power trends during the DR event occurring at PM hours.

Summer typical days

The metrics obtained during summer typical days are shown in Figure 8.

Time	Technology	Ventilation strategy	Rebound Energy [Wh]	CTD [Kh]
Summer average day				
AM	DSFblind	EAalwayson	84.70	0.85
	DSFblind	OACalwayson	778.55	0.71
	DSF	EAalwayson	15383.52	1.34
	DSF	OACalwayson	20350.19	1.18
	TGUblind	alwayson	15254.69	1.22
	TGU	alwayson	24932.47	1.69
PM	DSFblind	EAalwayson	13563.60	2.12
	DSFblind	OACalwayson	13941.00	2.07
	DSF	EAalwayson	15797.96	2.56
	DSF	OACalwayson	15084.71	2.39
	TGUblind	alwayson	18963.00	2.13
	TGU	alwayson	20195.64	2.38
Summer peak day				
AM	DSFblind	EAalwayson	3052.40	1.22
	DSFblind	OACalwayson	1643.22	1.10
	DSF	EAalwayson	23352.55	1.70
	DSF	OACalwayson	22241.17	1.47
	TGUblind	alwayson	10355.84	2.52
	TGU	alwayson	27130.42	2.54
PM	DSFblind	EAalwayson	19569.35	2.56
	DSFblind	OACalwayson	19293.70	2.49
	DSF	EAalwayson	22029.94	3.10
	DSF	OACalwayson	21562.33	3.01
	TGUblind	alwayson	27189.95	2.58
	TGU	alwayson	30455.29	3.30

Figure 8: KPIs for summer typical days. The green color represents a good performance (low rebound energy and low CTD) while the red a worst performance (high rebound energy and high CTD)

During summer days, the analysis includes the integration of blinds within the DSF cavity, requiring a consistent comparison between DSF and TGU, as well as DSFblind and TGUblind. In both the OAC and EA configurations, DSF consistently outperforms TGU in terms of rebound energy and CTD, a trend also observed for DSFblind compared to TGUblind. This effect is particularly pronounced during DR events occurring in AM hours, when the ventilated cavity effectively reduces FTHT due to solar radiation. During the summer average day, when the DR event happens during AM hours the integration of blinds in the DSF reach a rebound energy of 778.55 Wh and 84.70 Wh for EA and OAC respectively, meaning they decrese the rebound energy of 94% and 99% compared to a TGUblind.

During DR events occurring in PM hours, its impact is less significant, as heat transfer is driven solely by the indoor-outdoor temperature difference, which the ventilated cavity alone cannot fully mitigate.

The addition of blinds further enhances performance by reducing heat transfer, though the effect remains moderate. In terms of CTD, the low values observed in the morning for DSFblind (0.85-0.71) indicate improved temperature stability following DR events, whereas in the afternoon, all configurations show quite high CTD values, showing overheating.

To provide a more in-depth analysis of the results obtained, Figure 9 shows the evolution of the indoor temperature during a peak summer day. There is a significant difference between the different components, both in terms of the peak temperature reached and the rate at which the indoor temperature rises. With a TGU, the indoor temperature rises by around 3°C in the two hours when the HVAC system is switched off. The use of a DSF with exhaust air and OAC helps to achieve lower temperatures, but for a more advantageous effect on heat gain modulation, blinds should be installed in the cavity.

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This would allow the temperature to remain just two degree above the comfort threshold at the end of the DR event and also slow the rate of temperature increase. More importantly, when the HVAC system is reactivated at 10:00, the indoor setpoint conditions are restored promptly with the use of the double-skin façade with blinds. The double-skin façade without blinds also restores conditions shortly after, whereas the TGU requires more than an hour to reach the setpoint.

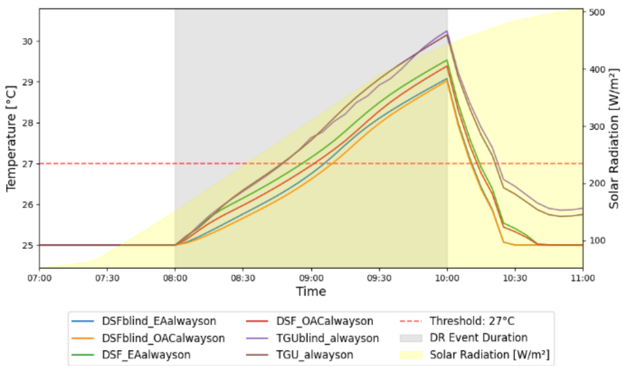

Figure 9: Summer peak day temperature trend during DR events occurring at AM hours

Unfortunately, during the PM hours in summer, the DSF is less effective in maintaining comfort conditions. This is primarily due to the fact that the main source of heat gain is no longer solar radiation, which is no longer present, but rather the temperature difference between the indoor and outdoor environment. In fact, the only strategy in which an improvement can be observed is the use of blinds, which enhance thermal insulation. From Figure 10, it can be observed that as long as solar radiation is present, FTHT is reduced by using blinds, which modulate solar gains. Once the DR event begins, FTHT decreases in all cases due to the rise in indoor temperature. By the end of the solar radiation period, all components exhibit similar performance.

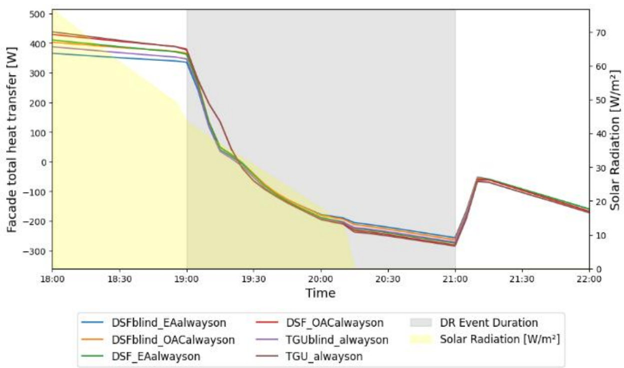

Figure *10: Summer peak day FTHT trend during DR events occurring at PM hours*

A similar trend is observed in the rebound energy shown in Figure 11. The use of blinds significantly reduces the need for electrical energy following the DR event, with the DSF without blinds showing a slightly higher demand. In contrast, the TGU requires the highest energy input for at least one hour after the event to restore indoor conditions.

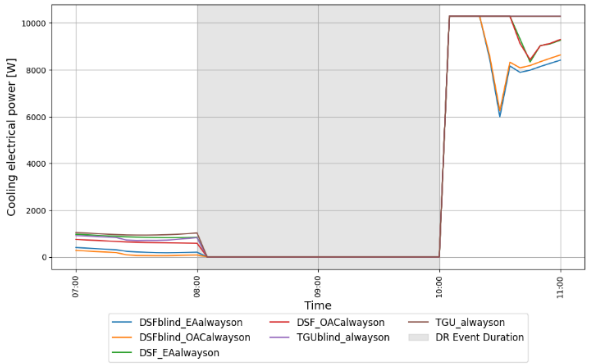

Figure 11: Summer peak day power trends during the DR event occurring at PM hours.

Conclusion

This study employs a simulation-based methodology to evaluate the potential of a double-skin façade (DSF) in enhancing energy flexibility, with a specific focus on its impact on rebound energy and thermal comfort. This study introduced a methodology that implies comparing progressive levels of technologies and high performance benchmark, that differ for winter and summer season. By analysing demand response (DR) events in both heating and cooling seasons, the study quantifies how DSFs influence energy rebound needs and indoor comfort. The DSF showed the ability to pre-heat indoor air during winter, even on days with low solar radiation. On days with higher solar radiation, the façade not only maintains the indoor temperature but can also increase it by introducing air at a temperature above the setpoint. This effectively reduces or even eliminates rebound energy compared to standard components, behaving similarly to more advanced HVAC components. During summer months, the flexibility of this component is shown to significantly reduce overheating during day hours, especially when integrated with between-glass blinds. The findings demonstrated that under these conditions, rebound energy could be reduced by up to 99% compared to a static benchmark. Conversely, the performance during nocturnal hours was less remarkable, because of the system limited capacity to modulate heat exchange in the absence of solar radiation.

This study serves as a starting point for understanding the behavior of double-skin façades (DSFs) without embedded control strategies. This choice was deliberate, with the aim being to isolate and quantify the intrinsic potential of the DSF system. Nevertheless, it is imperative to recognise that the absence of active control constitutes a limitation, as such strategies have been shown to significantly enhance performance. Furthermore, the modelling approach was based on the standard DSF module available in EnergyPlus, which does not account for thermal inertia. Consequently, the simulations may underestimate the effects of heat storage and delayed thermal response, both of which are crucial when evaluating the system role in energy flexibility.

Future work will address these limitations by integrating predictive control strategies and employing higher-resolution simulation models capable of capturing transient thermal dynamics and inertia. The research will also be expanded to encompass the entire building, and its application will be adapted to suit a range of climatic contexts. Furthermore, detailed models of HVAC systems will be incorporated to investigate the synergies between transparent envelope components and HVAC control in supporting demand response and improving building energy flexibility while maintaining occupant comfort.

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