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Energy efficiency of a dynamic glazing system

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Abstract

The reduction of air-conditioning energy consumptions is one of the main indicators to act on when improving the energy efficiency in buildings.

In the case of advanced technological buildings, a meaningful contribution to the thermal loads and the energy consumptions reduction could depend on the correct configuration and management of the envelope systems. In recent years, the architectural trend toward highly transparent all-glass buildings presents a unique challenge and opportunity to advance the market for emerging, smart, dynamic window and dimmable daylighting control technologies (Lee et al., 2004).

A prototype dynamic glazing system was developed and tested at ITC-CNR; it is aimed at actively responding to the external environmental loads. Both an experimental campaign and analyses by theoretical models were carried out, aimed at evaluating the possible configurations depending on different weather conditions in several possible places. Therefore, the analytical models of the building-plant system were defined by using a dynamic energy simulation software (EnergyPlus).

The variables that determine the system performance, also influenced by the boundary conditions, were analysed, such as *U*- and *g*-value; they concern both the morphology of the envelope system, such as dimensions, shading and glazing type, gap airflow thickness, in-gap airflow rate, and management, in terms of control algorithm parameters tuning fan and shading systems, as a function of the weather conditions.

The configuration able to provide the best performances was finally identified by also assessing such performances, integrating the dynamic system in several building types and under different weather conditions.

The dynamic envelope system prototype has become a commercial product with some applications in façade systems, curtain walls and windows.

The paper describes the methodological approach to prototype development and the main results obtained, including simulations of possible applications on real buildings.

Keywords: Dynamic envelope; Energy efficiency; Ventilated window

1. Introduction

The building energy efficiency improvement should be pursued, first of all, by reducing the building net energy demand. This can be achieved through suitable architectural and constructive choices in order to control the energy fluxes induced by the weather conditions and building operation. A good building envelope allows the systems size to be reduced, regarding both the HVAC and lighting ones. In particular, for commercial and retail building design, where wide transparent surfaces are used, the request for high performance components boosted the façade market towards technologically improved products, often without actual performances that could justify the high prices.

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The phases of design, development, realization, commissioning and the management of a dynamic envelope component should be carried out by focusing on the needs of building typologies, not defining a close system, but an open one, able to be tailored to the specific building where it will be installed.

A dynamic glazing system prototype was studied at ITC-CNR to evaluate the performance and the capability of the system itself to fit all the possible working conditions.

2. System description

The analysed dynamic system, called "VetroVentilato" (http://www.vetroventilato.it), is a triple glazing. The system foresees a shading component in the outer gap and the possibility to mechanically ventilate the inner gap by a tangential fan (Fig. 1).

This glazing system can be applied to both simple windows and curtain walls. The gaps' sizes, the panes typology, the shading component characteristics and the management of the whole system are defined and set in the design and commissioning phases. Finally, the system can operate stand-alone or integrated with the HVAC plants.

The control system allows the main operational parameters to be monitored and to actively drive the tangential fan and the shading component, in order to optimise the passive gains and the indoor environmental comfort.

Such a versatility allows the designers a broad freedom to optimise the system integration with the other building components and to maximise the energy performance of the building-plant system.

3. Methodological approach and assumptions

The dynamic system performance was assessed in comparison with a reference glazing system, through both an experimental campaign, using the methodological approach of the outdoor test cells (Fig. 2) (http://www.paslink.org/), and analytically, using EnergyPlus[1] (http://www.eere.energy.gov/buildings/energyplus/) and DesignBuider[2] (http://www.designbuilder.co.uk) in order to generalise the experimental results.

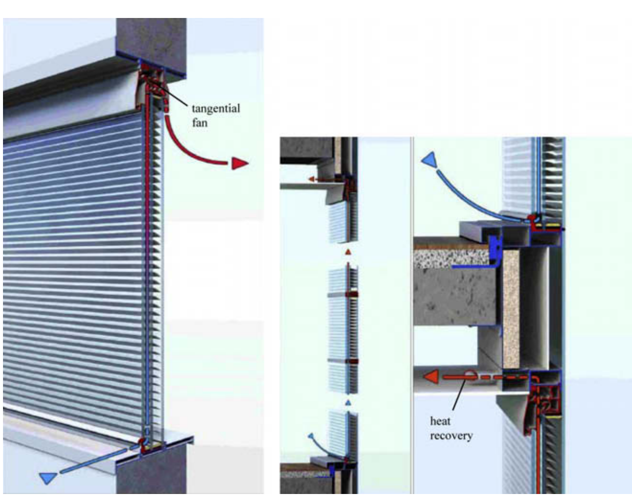


Fig. 1. To the left: the dynamic system operating in heat push out mode (airflow internal/external); to the right: the dynamic system integrated in a curtain wall (airflow internal/internal).

Fig. 2. Experimental arrangement used at ITC-CNR.

The best system configuration and operation of the envelope system were pursued initially through static calculation tools, without doubt easier to use and less time consuming. That was very important for the first stage of the work.

Afterwards, the optimisation process foresaw short term experimental campaigns, when the performances of the dynamic system were assessed in comparison with a reference window, both installed on similar outdoor test cells.

The subsequent stage of the analysis was aimed at generalising the experimental results, obviously dependent from some boundary conditions which were not controlled (e.g. weather conditions). For this stage, EnergyPlus, a dynamic simulation tool, was used.

As stated above, different software tools were used considering their particular capabilities and limitations, starting with the static to the dynamic ones: in the following there is a brief description of each of them.

The measurement results were not directly compared with simulation, because the aim of the theoretical analysis through modelling was the generalisation of the experimental results applying the system to different kinds of buildings and weather conditions.

3.1. Independent and dependent variables

A correct experimental campaign foresees the analysis of the dynamic system and every characteristic of his to purpose of individualize the independent and dependent variables.

[1] EnergyPlus is a software for dynamic energy simulations developed by the U.S. Department of Energy in agreement with the University of Illinois and the University of California.

[2] DesignBuider interface has been assessed using the EnergyPlus simulation.

Independent variables are:

- specific fan power;
- Venetian blind position;
- kind of glazing system;
- difference between the air gap and the indoor air temperature.

Dependent variables are:

- *U*-value, *g*-value, energy consumption;
- predicted percentage of dissatisfied (PPD);
- air change;
- daylighting factor (the analysis of these last two not reported in this paper).

In particular, the dependent variables affect the cooling need of the building where the system is installed.

Some of the above variables were considered in the experimental campaign, but it was not possible to test all the possible configurations. Then dynamic simulations were used, in order to generalise the experimental results, trying to apply the dynamic envelope system to a real building and in different climate conditions.

The process of optimisation envisages an experimental assessment with the system in different configurations and a direct verification of the contribution to the whole building performances by software tool.

3.2. Outdoor test cells

The test cells at ITC-CNR allowed to compare the energy efficiency of different glazing systems (ITC-CNR, 2005). Throughout the experimental campaign the system operative parameters were directly measured, and then used as an input for the simulation. This allowed the evaluations to be enlarged and generalised. In order to summarise the measures obtained from the sensors, two main parameters were used: energy consumption to maintain the set indoor comfort conditions and the air change rate (assessed through the tracer gas method).

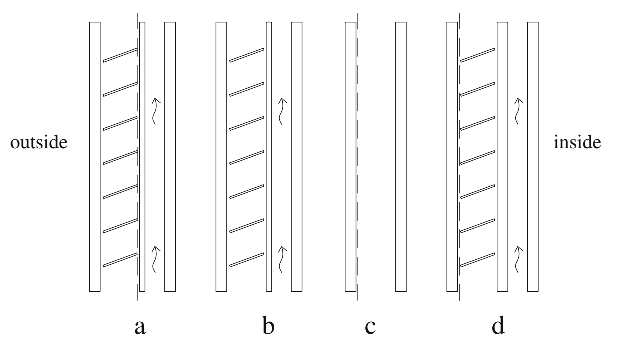


Fig. 3. (a) Dynamic system, (b) dynamic system no low-*E*, (c) double pane low-*E* and (d) dynamic system low-*E* on side 2.

3.3. Static software tools

The assessment of the thermal and energy performance of the studied glazing system is carried out, according to standard conditions, by specific tools such as THERM 5.2 (http://windows.lbl.gov/software/therm/therm.html), used for the calculation of the frame thermal transmittance in a steady state heat transfer, and WIS 3.0, (http://www.windat.org/wis/html/) used to assess the performance of the glazing system with a given airflow inside the gap. The heat transfer coefficients were calculated by the software in compliance with ISO 15099 (2003).

3.4. Dynamic software tools

Finally, the methodological approach foresaw the use of a building energy dynamic simulation tool: EnergyPlus through DesignBuilder interface. Through this simulation tool, a dynamic envelope system can be evaluated in its operating conditions, in the building where it is going to be installed, with the weather file of the location. Then its influence on the energy performance of the whole building can be assessed. One of the most important features of this kind of software is the possibility to set the best schedule for the active components, such as blinds and fans (that force the airflow in the window gap), in order to optimise the energy savings.

3.5. The glazing systems

Four kinds of transparent modules (Fig. 3) were considered.

Regarding the dynamic system, the air is drawn from the indoor environment by a tangential fan placed at the top of the internal gap and ejected in different ways in summer and winter:

Table 1
Glazing considered in the analysis. They are made of clear glasses ($\varepsilon = 0.84$) possibly with a low emission layer.

Glazing elements	a	b	c	d
Outside	Clear glass Air gap: 22 mm Venetian blind Glass low-*E* Air gap: 11 mm	Clear glass Air gap: 22 mm Venetian blind Clear glass Air gap: 11 mm	Glass low-*E* Air gap: 22 mm	Glass low-*E* Air gap: 22 mm Venetian blind Clear glass Air gap: 11 mm
Inside	Clear glass	Clear glass	Clear glass	Clear glass

- in the summer period it is ejected outside;
- in the winter period, the warm air in the gap is conveyed to the plant and re-used for heating purposes (Table 1).

3.6. The experimental assessment of the system

The laboratory test allowed energy and environmental assessments in actual working conditions of the system to be carried out. Analyses were carried out both in summer and in winter, with and without the use of cooling and heating.

Experimental settings, weather conditions and internal environmental conditions were monitored throughout the test, with an adequate distribution of sensors managed by a data acquisition software.

Standard EN ISO 7730 (2005) was assumed as reference in order to assess the thermal–hygrometric comfort of the indoor environment where the dynamic system was installed. In particular, an air temperature sensor, a humidity sensor and a radiative temperature sensor were placed at the centre of the test cell, other four air temperature sensors were positioned aloft and at the bottom of the test-cells median axle.

The PPD index (predicted percentage of dissatisfied) was calculated, to get information about thermal discomfort, or thermal uneasiness, foreseeing the percentage of people that would feel discomfort in a certain indoor environment.

The management system allowed the fan to switch on when the temperature difference between the air gap and the indoor air overcame a fixed threshold settable by the user (ΔT).

3.7. The assessment of the system through dynamic simulations

For the analytical assessment some buildings were modelled where the dynamic envelope system could be installed. The simulations were carried out on building samples, whose standard schedules and loads were defined. In particular, a small restaurant and two office buildings with different shapes, named “block” and “tower” (Fig. 4) were outlined.

3.7.1. Case of the restaurant building

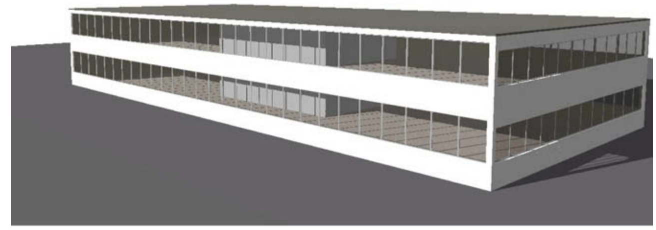
It was characterised by two glazing façades, south and west facing, the other orientations being closed by opaque adiabatic walls, in order not to introduce further variables. In this way it was possible to analyse the performance indicators only as a function of the glazing envelope.

The total glazing surface is 44 m^2 for south-facing exposure and of 68 m^2 for the west-facing one.

With regard to the internal loads and the thermal set-point for heating and cooling, standard conditions of use for a restaurant were taken into account.

The variables used to assess the different experimental arrangements are:

- *Fan activation:* the fan is always available (able to be activated) in all the analysed configurations. The temperature difference in the summer season, which causes the fan to switch on, is set at 2 °C or 4 °C. The air speed in the ventilated gap is 0.55 m/s, corresponding to a gap airflow of 21.6 m^3/h per linear meter.
- *Lowering of the Venetian blinds:* in the summer period the control of the blinds is active when the irradiance on the vertical surface reaches 50 W/m^2. In the winter period the Venetian blind is active when the internal temperature is >22 °C and the irradiance on the vertical surface is >350 W/m^2; these values were adopted with the aim to optimise the solar gains without triggering an excessive overheating of the indoor environments.



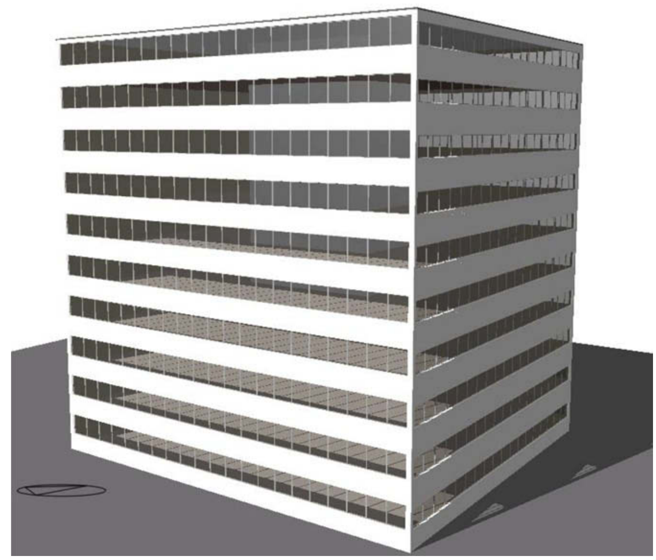


Fig. 4. The block (up) and tower (down) building samples analysed.

The configurations of the dynamic envelope system and of the double panes that were tested are listed in Table 2.

3.7.2. Cases of the office buildings

The analyses were carried out comparing the same building where the dynamic system and a double glazing window without shadings were installed.

Table 2
Tested configurations.

ID	Name	Summer set-point of the fan
1	Dynamic system $\Delta T4$	ON if $\Delta T = 4$
2	Dynamic system $\Delta T2$	ON if $\Delta T = 2$
3	Dynamic system no low-*E*	ON if $\Delta T = 4$
4	Dynamic system low-*E* on side 2	ON if $\Delta T = 4$
5	Double pane with internal blinds	–
6	Double pane with external blinds	–

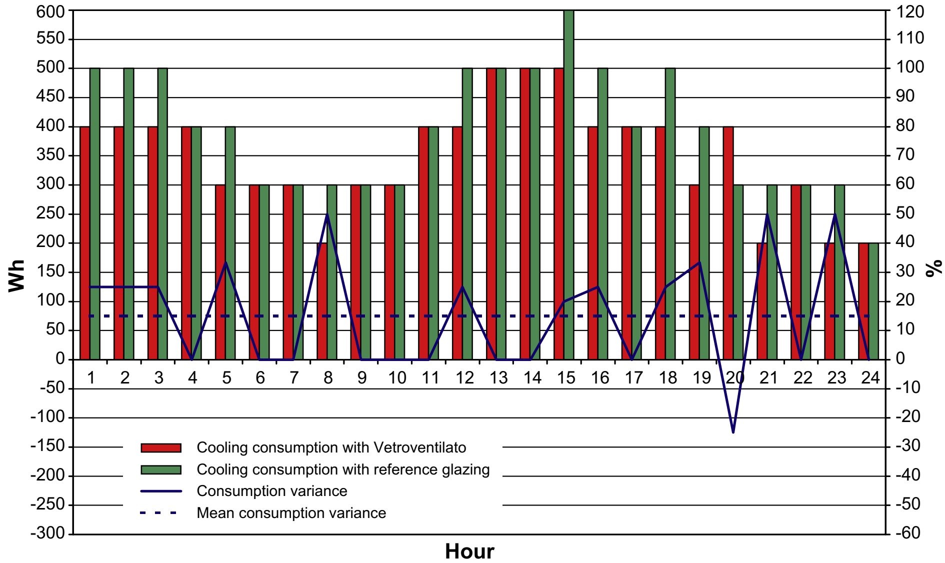


Fig. 5. Electrical consumption in a typical summer day.

The management system of the fan allowed it to be switched on when the air temperature difference between the internal environment and the gap was more than the defined ΔT both in summer and in winter. The Venetian blinds were controlled to optimise the solar gains, avoiding the overheating of the indoor environment.

4. Results

The results of both the experimental campaign and the simulations are illustrated below. The former show quite good energy and comfort performances, even if with a small difference in comparison with a reference case. Unfortunately the prototype and test rig arrangement did not allow further configurations to be tested. For this reason a long series of simulations was carried out with the aim of generalising the experimental results and study the behaviour of the dynamic system in several working conditions.

4.1. Experimental campaign and comparison with cavity static analysis

Energy consumptions were measured in active conditions by a thermostatic control of the two cells at 26 °C, and comparing the respective consumptions on equal

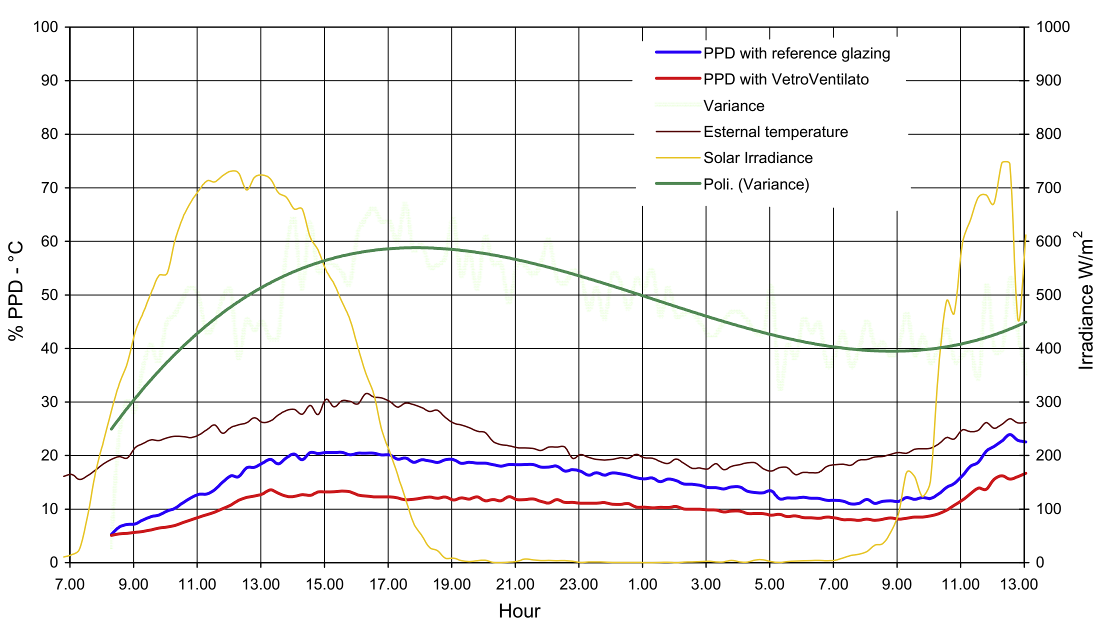


Fig. 6. PPD comparison in a typical summer day – slat angle of the shading component $\alpha = 60°$ and $\Delta T = 2$ °C.

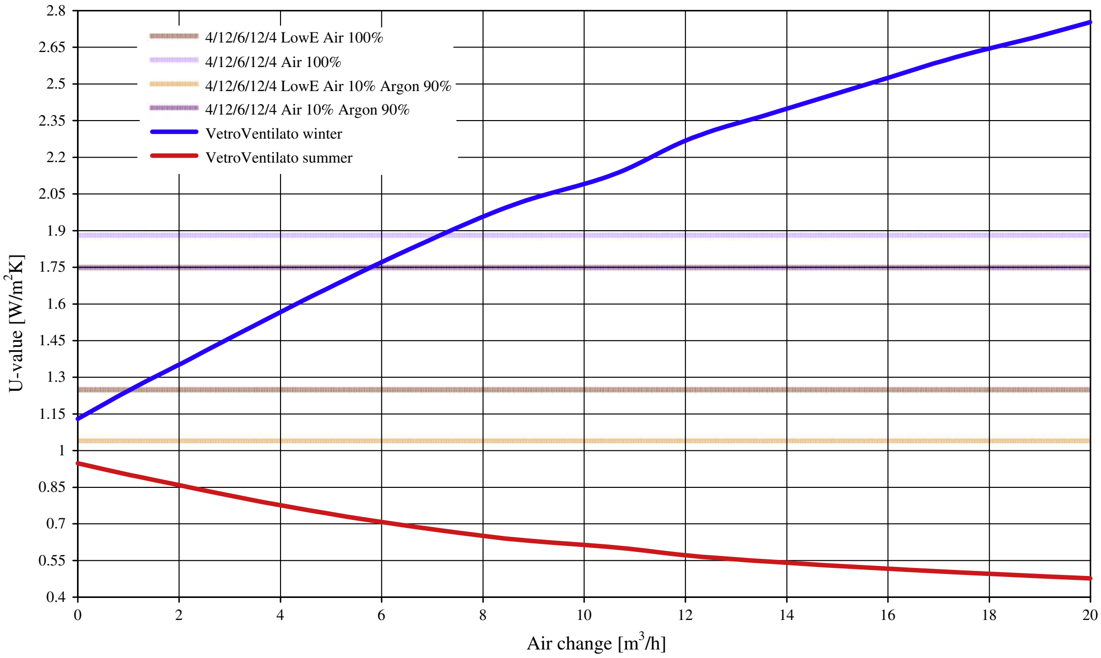


Fig. 7. *U*-value pattern depending on the air change per hour.

indoor microclimate (measured through the PPD index). Such a comparison (Fig. 5) allowed the estimation of a mean energy saving for the cell where the dynamic system was set up of about 15%. Concerning the consumption of the tangential fan, a value of about 0.4 kW h/day was measured.

In a steady operational mode, the dynamic system ensures (Fig. 6) a better comfort ($\Delta \approx 60\%$) when the external temperature reaches the maximum value ($T \approx 30$ °C).

The experimental results agree with static calculations carried out through WIS software, whose boundary conditions and forced ventilation in cavities equations are in compliance with ISO 15099 (2003).

The *U*-value of a transparent system with ventilated gaps is the sum of three parts:

$$U = U_{conv} + U_{ir} + U_{vent}$$

where U_{conv} is convective losses through the window system, U_{ir} is irradiative losses through the window system, and U_{vent} is ventilation losses through the window system.

In the case of ventilated gaps (from lower/in to upper/in in winter conditions and from lower/in to upper/out in summer conditions), short-cuts (pathways) are also created for energy flows that would not be present in the case of non-ventilated gaps. Again, this will influence the *U*-value, but less strongly than with gaps ventilated from outdoor to indoor.

Fig. 7 reports the curve fitting, in winter and summer conditions, describing the relationship between *U*-value and ventilation airflow rate; on the same graph are presented the mean *U*-values of some triple pane glass (calculated in compliance with EN 673) between 1 and 1.9 W/m^2 K. In summer conditions: the asymptotic curve decreases as ventilation increases, starting from a *U*-value of about 1.0 W/m^2 K (no ventilation), it goes down to 0.45 W/m^2 K, obtained with a ventilation rate of 20 m^3/h, (the asymptote is around 0.3 W/m^2 K with an hypothetic ventilation rate of 70 m^3/h).

In winter conditions *U*-value pattern is given by following polynomial:

$$U_{win} = -0.0016 \cdot ach^2 + 0.1137 \cdot ach + 1.1352$$

where U_{win} is the dynamic system *U*-value in the winter configuration and *ach* is air change per hour, in m^3/h.

While in summer conditions:

$$U_{sum} = 1 \times 10^{-7} \cdot ach^4 - 2 \times 10^{-5} \cdot ach^3 + 0.0014 \cdot ach^2 - 0.0444 \cdot ach + 0.938$$

where U_{sum} is the dynamic system *U*-value in the summer configuration.

In winter conditions (the blue curve) *U*-value increases as ventilation increases, starting from a *U*-value of about 1.15 W/m^2 K (no ventilation) it goes up to 2.8 W/m^2 K, obtained with a ventilation rate of 20 m^3/h. *g*-value follows the *U*-value trend, but in quantitative terms the variation is lower than the *U*-value one (see Fig. 8).

The tested dynamic system's configurations envisaged an airflow path into the gap from lower/in to upper/out in summer and from lower/in to upper/in in winter. In these configurations, in all weather conditions, the more the gap airflow rate increases, the lower both convective and radiation contributions become; moreover, in summer conditions, the heat transmission factor due to ventilation becomes null and that is the reason why the *U*-value decreases as the airflow increases. *g*-value follows the *U*-

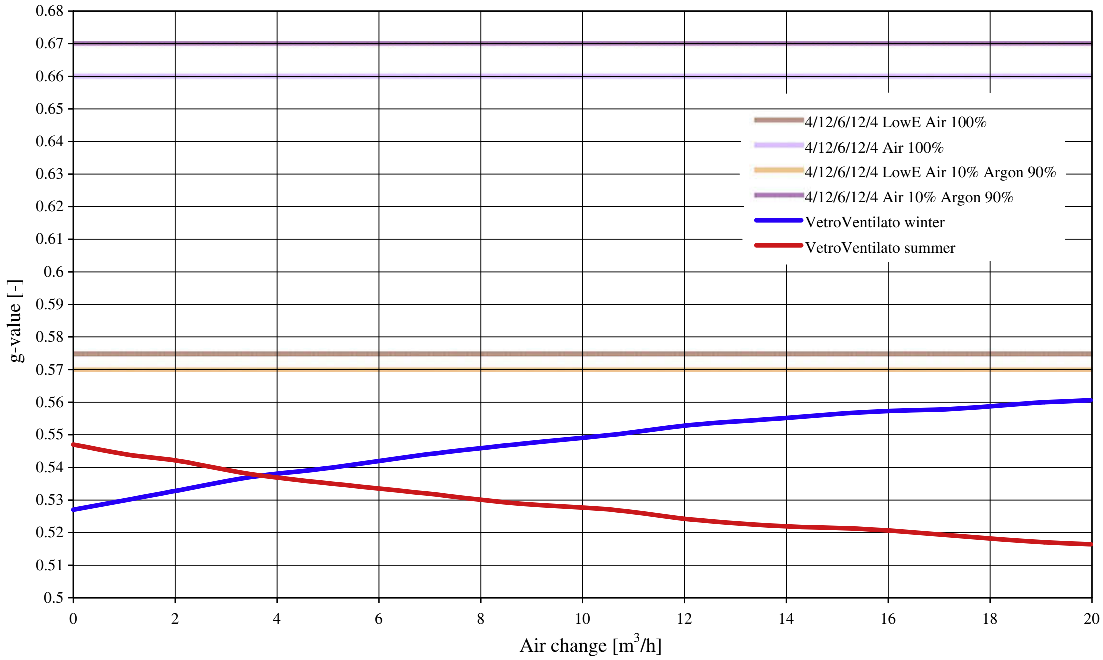


Fig. 8. g-value pattern depending on the air change per hour.

value trend, but with a lower variation rate than the U-value curve (see Fig. 8).

The g-value is composed of four components:

$$\tau_s = \tau_{dir} + \tau_{conv} + \tau_{ir} + \tau_{vent}$$

where τ_{dir} is the direct transmission (direct and diffuse solar radiation) through the system, and τ_{conv}, τ_{ir} and τ_{vent} are the indirect transmission components (Fig. 8).

In winter conditions g-value pattern is given by following polynomial:

$$\tau_{s,win} = -6 \times 10^{-5} \cdot ach^2 + 0.0028 \cdot ach + 0.5274$$

where $\tau_{s,win}$ is the dynamic system g-value in the winter configuration and ach is air change per hour, in m^3/h.

While in summer conditions:

$$\tau_{s,sum} = 5 \times 10^{-9} \cdot ach^4 - 9 \times 10^{-7} \cdot ach^3 - 5 \times 10^{-5} \cdot ach^2 + 0.0024 \cdot ach + 0.5464$$

where $\tau_{s,sum}$ is the dynamic system g-value in the summer configuration.

4.2. Energy dynamic simulations

4.2.1. Case of the restaurant building

This case study was aimed at comparing several configurations of the dynamic system with regard to a reference case. The first comparison was made in terms of annual energy demand, both for cooling and heating; such data were analysed better sharing the whole data in the monthly demand. Finally, the daily trends of specific variables dependent on the dynamic system and determining the energy demand stated above, are reported.

Data reported in Table 3 indicate the restaurant building energy amount needed to maintain the set-point temperature, as a function of weather conditions. The obtained results provide accurate hints in order to choose the best configurations from the energy point of view, leading to immediate cost effective conditions as for the expenses to be borne (Table 3).

Fig. 9 illustrates the monthly cooling energy needs, then excluding the electrical energy needs for lighting and equipment.

Table 3
Predicted energy need for restaurant case study in MJ.

Glazing system	Summer (1/5 to 30/9)		Winter (15/10 to 15/4)	
	Cooling	Δ%	Heating	Δ%
Dynamic system $\Delta T4$	11,052	–	78,002	–
Dynamic system $\Delta T2$	10,980	−0.65	78,002	+0.00
Dynamic system no low-E	10,757	−2.67	88,539	+13.51
Dynamic system low-E on side 2	10,849	−1.84	84,398	+8.20
Double pane with internal blinds	35,727	+223.26	88,925	+14.00
Double pane with external blinds	11,022	−0.27	90,488	+16.01

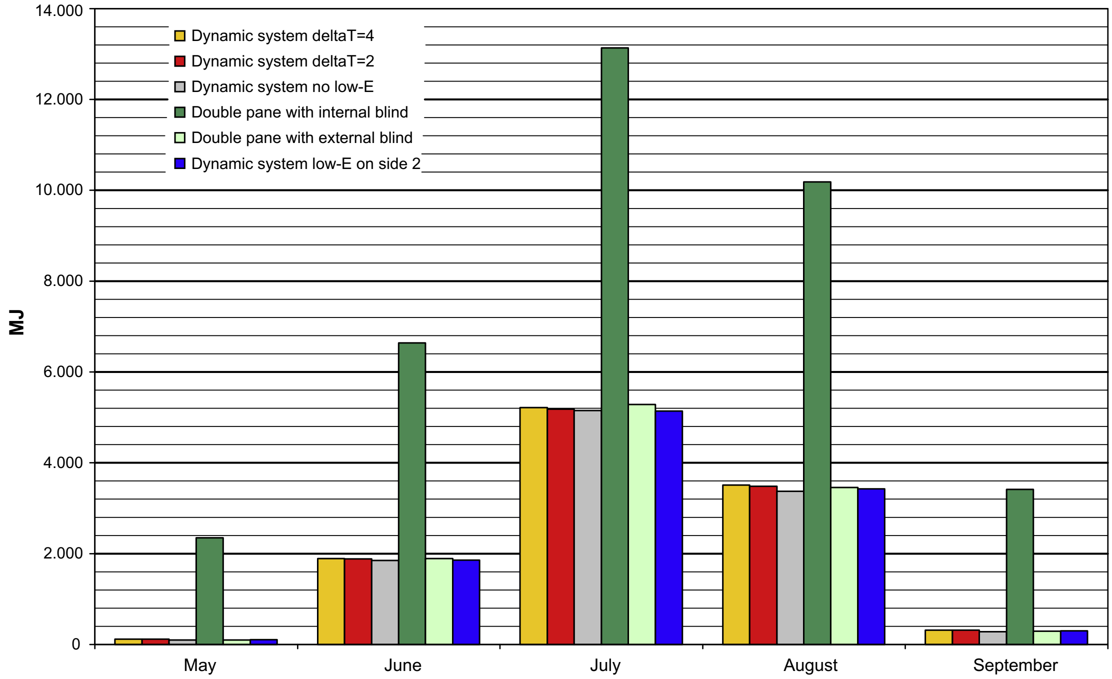


Fig. 9. Predicted monthly cooling energy need for the restaurant case study.

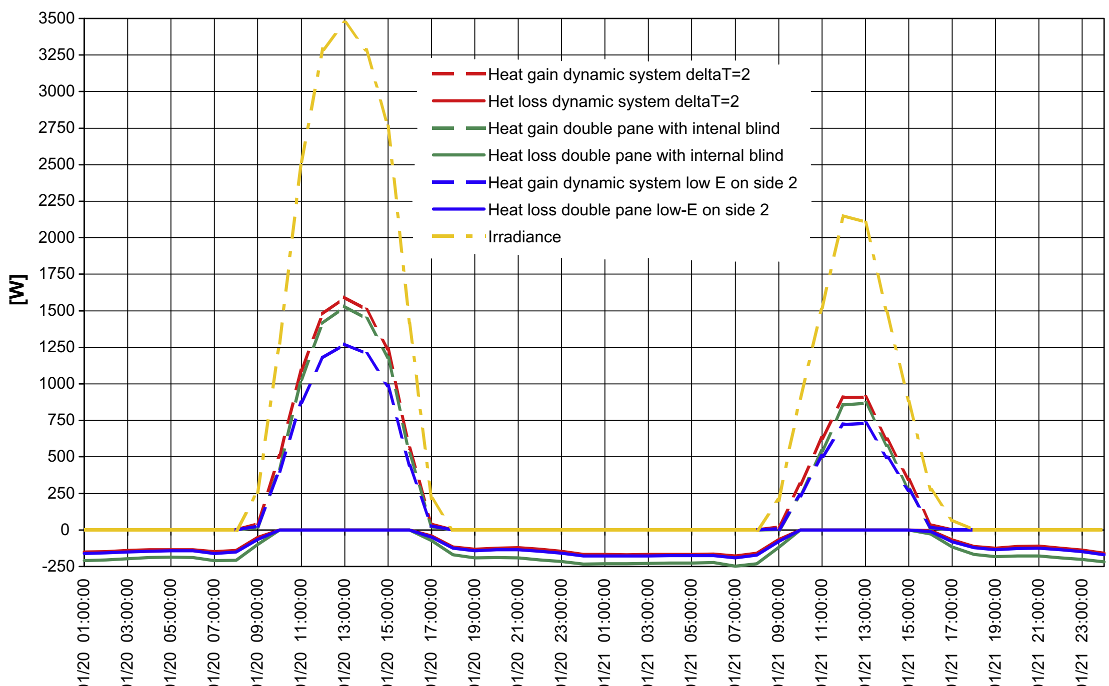


Fig. 10. Hourly winter heat gain and loss – south facing of the restaurant case study.

Since both the energy need and the conditions which determine the environmental comfort perform better with $\Delta T = 2$ than with $\Delta T = 4$, only this value is shown for a better reading of the graphs (Figs. 10 and 11).

The use of the dynamic system allows for a better energy performance of the building, considering both the heating and cooling needs and allowing a very significant saving with respect to the use of a low emissive double glazing (side 2) with an external shading element. These results are determined by the action of the internal gap ventilation and the Venetian blind in the external gap. Besides, the ventilation determines a sensible decrease of summer gains and a reduction of the surface temperature of the internal glass, then improving the thermal comfort next to the glazing.

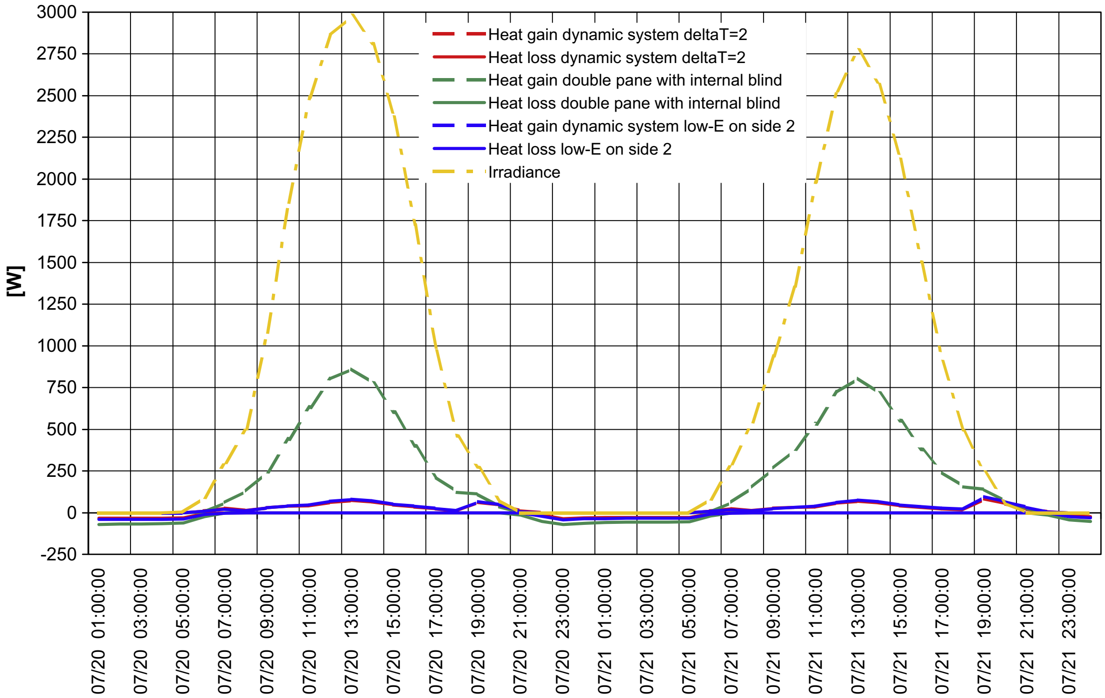


Fig. 11. Hourly summer heat gain and loss – south facing of the restaurant case study.

Table 4
Annual net energy demand with dynamic system (MJ) for the office building case study.

City	"Tower" building		"Block" building	
	Cooling	Heating	Cooling	Heating
Milan	333,869	635,931	49,328	157,673
Paris	108,455	616,760	13,382	156,984
Sevilla	637,378	–	104,868	–
Abu Dabi	2,603,203	–	456,035	–

4.2.2. Cases of the office buildings

Regarding the office building samples, the dynamic system was compared with a reference glazing system (clear double glass as stated above) in different climatic contexts; i.e. in the following tables a part of the results are reported. The cooling and heating demand depends on the thermostat temperatures set at 26 °C and 20 °C without any specific summer and winter season length.

The first comparison was made in terms of annual energy demand, both for cooling and heating, such data were analysed better sharing the whole data in the monthly demand. Then, the daily trends of specific variables dependent on the dynamic system and determining the energy demand stated above and indoor comfort, are reported (Tables 4 and 5).

Further than the global demand calculation, the simulation allowed very detailed analyses for the assessment of the dynamic system thermal-energy performances and functional characteristics to be carried out. In particular, graphs are presented concerning the energy demand, both in winter and summer season (Figs. 12 and 13), the trend of the solar gains through the system during typical summer days (Fig. 14), the trend of the indoor surface temperatures of the glazing and of the indoor air temperature (Figs. 15 and 16).

The indoor surface temperatures of the glazing are significantly different in the two glazing systems. With the dynamic system, the local comfort conditions show a remarkable improvement due to the rise of the temperatures close to the glazing during the coldest season and their cooling down in the summer season. It allows the

Table 5
Annual net energy demand with reference glazing (MJ) for the office building case study and difference (as %) in comparison to the same building with the studied dynamic system.

City	"Tower" building		"Block" building	
	Cooling	Heating	Cooling	Heating
Milan	957,769 (+187%)	712,330 (+12%)	180,326 (+266%)	179,795 (+14%)
Paris	496,651 (+358%)	736,997 (+19%)	90,177 (+574%)	186,791 (+19%)
Sevilla	1,428,992 (+124%)	–	275,565 (+163%)	–
Abu Dabi	4,326,850 (+66%)	–	825,145 (+81%)	–

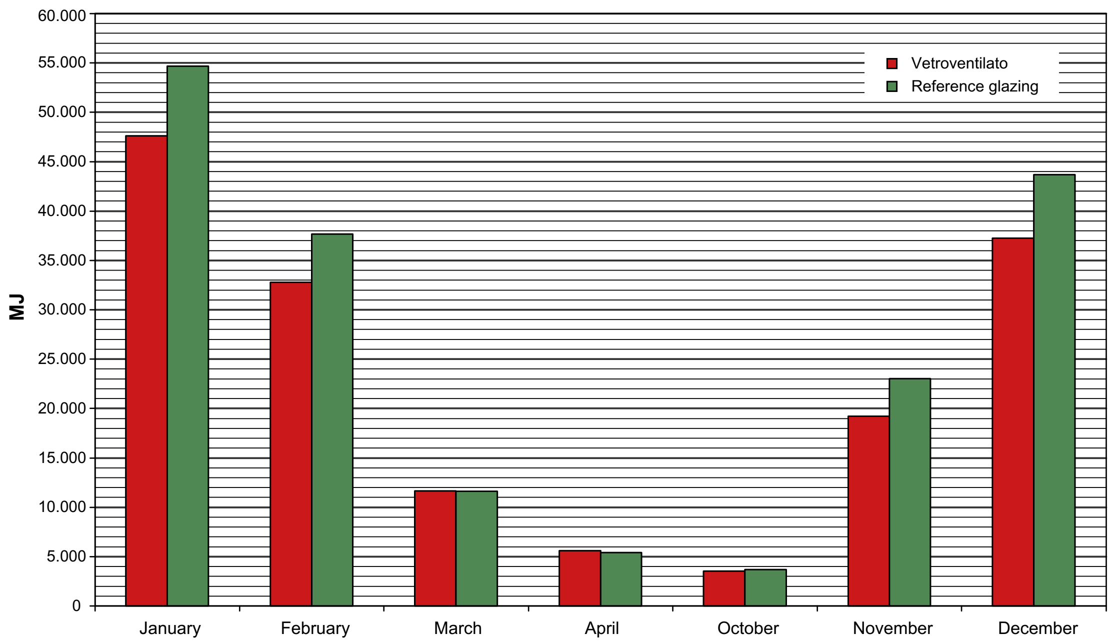


Fig. 12. Monthly net heating energy demand for the case study concerning the office building located in Milan.

comfort area to be extended, that is the available surface used for the normal activities foreseen in the building, even very close to the glazing.

The use of the dynamic system compared to a double glazing has given overall advantages in all of the analysed cases. The shading of direct solar radiation, the extraction of hot air through the gap in the summer season and the reuse of the pre-heated internal air in winter, produces economic benefits as a consequence of the reduced primary energy demand, also improving the built environment thermal comfort.

In some of the quoted cases, the performance of the analysed dynamic system can be significantly improved through an adjustment of its functioning related to the external environmental conditions. However, the "commissioning" procedure should be carried out, specifically by analysing the physical–technical characteristics of the building where the dynamic system is installed, in order to obtain the best performances, also in relation to the constructive typology, the thermal properties of the used materials, the utilization patterns, the choice of the plant's layout and the management and control systems. Having

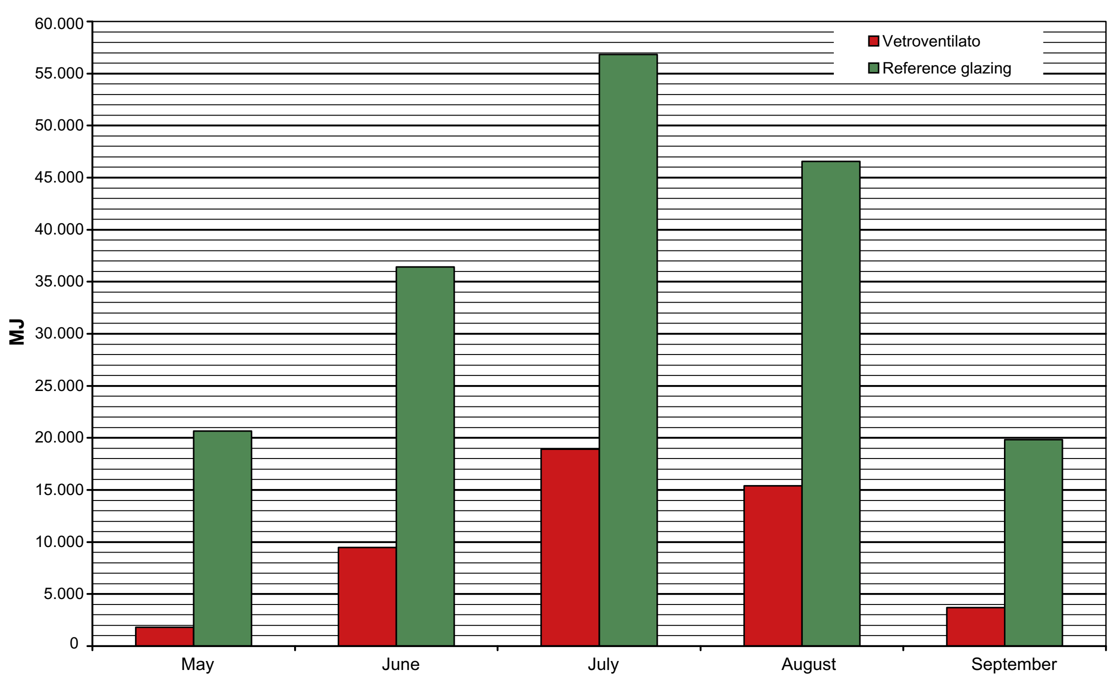


Fig. 13. Monthly net cooling energy demand for the case study concerning the office building located in Milan.

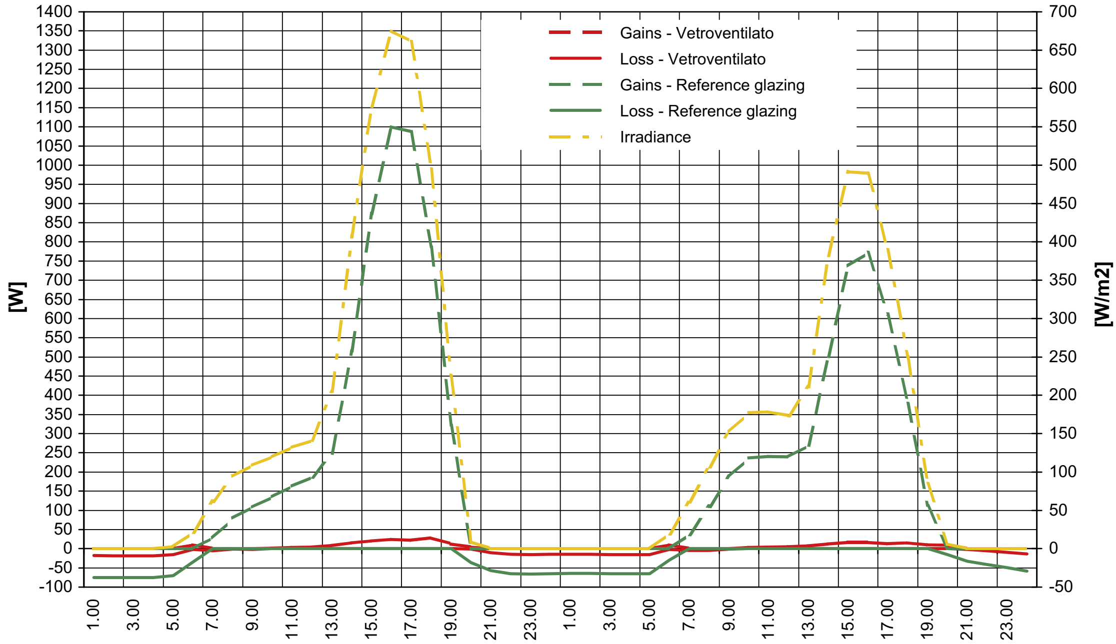


Fig. 14. Hourly solar gains vs loss for the west front of the case study concerning the office building located in Milan.

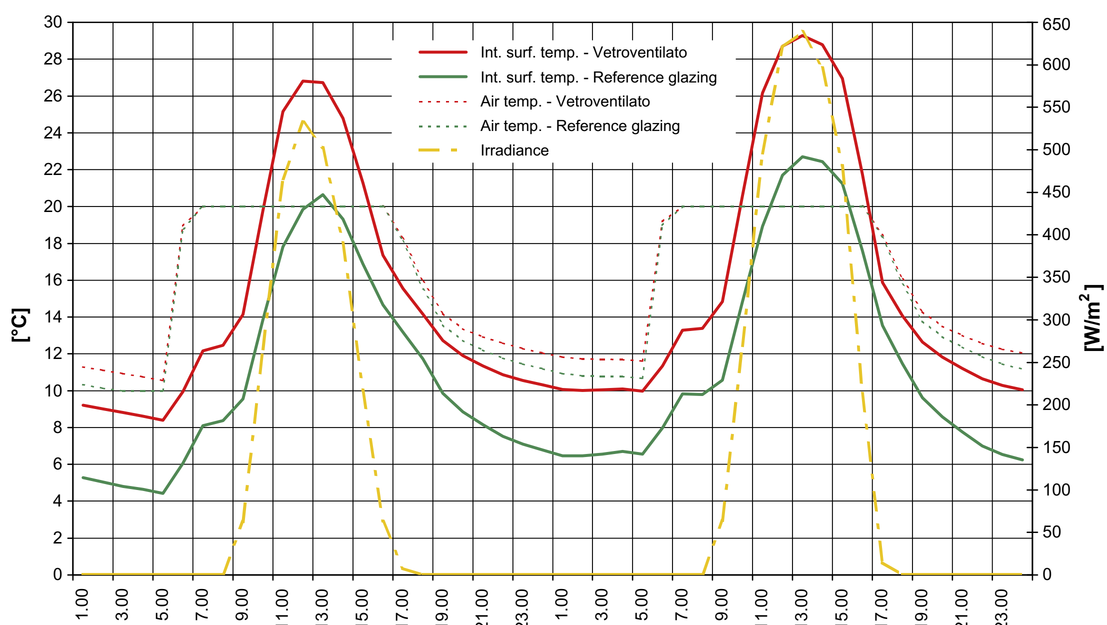


Fig. 15. Hourly surface temperatures for the south front and indoor air (temperature) in winter conditions for the office building case study located in Milan.

stated the flexibility of the system, it is important to introduce the stage of system configuration definition and realization into an integrated design procedure, which involves all the building process actors, allowing continuous feedbacks in order to increase the energy performance of the whole building, working on all the possible factors at play.

5. Discussion

The analysis of the heat fluxes, and subsequently of the temperatures, allows the detection of a significant improvement of the internal environmental conditions between a double glazing and the analysed dynamic system, with more or less relevant variances according to the configurations. It is shown that the best thermal comfort condition is when the fan is activated with $\Delta T = 2$ and the low-E coating is on side 3. In fact, even if in the summer period the low-E coating on side 2 provides better performance, in the winter season the placement of the low-E coating on side 3 allows, in addition to the reduction of heat losses, the heating of the blinds and of the air in the external gap.

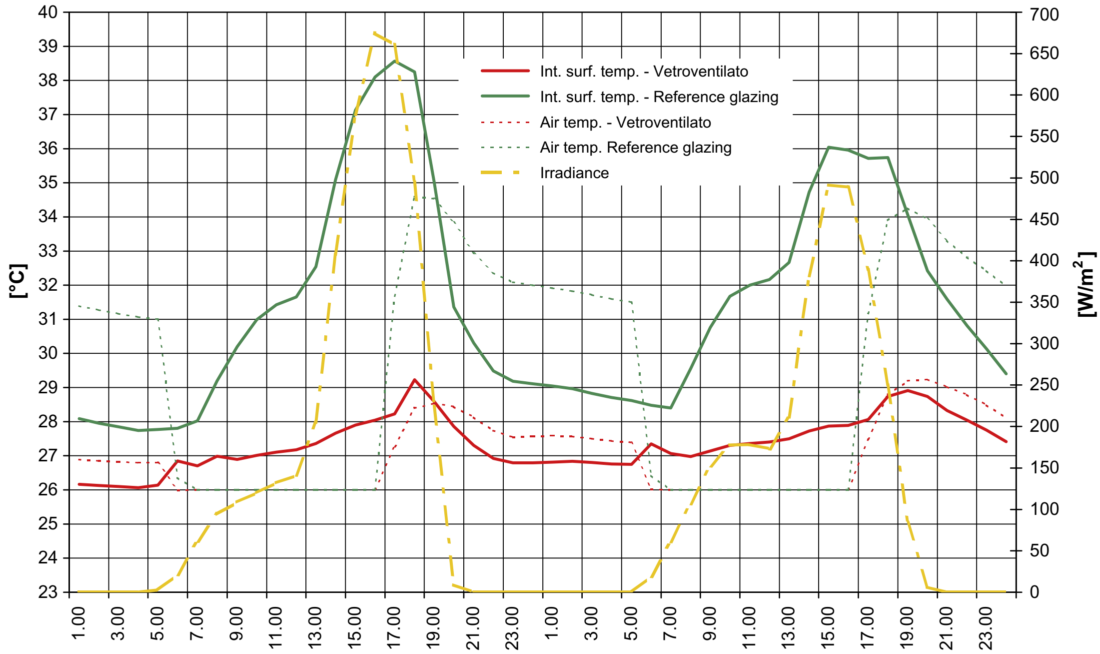


Fig. 16. Hourly surface temperatures for the south front and the internal air temperature in summer conditions for the case study concerning the office building located in Milan.

A further consequence of these evaluations is that the software is not only useful in the design phase to find out the best product configuration, but also in the definition of the control algorithms of the dynamic components such as the Venetian blinds, which could be lifted and lowered and the slats oriented as a consequence of several input data, and for what concerns the fan, for which, in addition to the activation ΔT, it would be possible to define variable a flow rate or particular switching on configurations.

Following the used methodological approach it is possible to handle a complete assessment of the component. In this way the choice of the best configuration of the dynamic system, in relation with planning requirements, can be carried out with full knowledge of all its capabilities and the requirements it can satisfy.

The dynamic system analysed in this report shows its suitability to different building typologies as for size, use, exposure. Further analyses are being carried out; the next essential phase of the study is the assessment of the performance of the system on site, as can be measured during the building occupancy. Such a measurement is not considered to be the last stage of the research project, but a step which will allow the performance of the system and its suitability to the different building typologies and uses to be improved and optimised.

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