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Assessment of the Performance of a Ventilated Window Coupled with a Heat Recovery Unit through the Co-Heating Test

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Abstract: The aim of the article is to describe the results of an experimental campaign based on the assessment of a heat recovery unit coupled with a dynamic window. Two fully monitored and calibrated outdoor test cells are used, in order to evaluate the energy performance and the related thermal comfort. The former presents a traditional window with double-glazing, aluminum frame and indoor blind and a centrifugal extractor for the air circulation. The latter is equipped with a dynamic window with ventilated and blinded double-glazing provided with a heat exchanger. The connection of the dynamic window and heat recovery unit provides different actions: heat recovery; heat transfer reduction; pre-heating before the exchanger. Different operating configurations allowed the trends of the dynamic system to be assessed in different seasons in terms of energy saving, thermal comfort behavior and energy efficiency. The results showed an overall lower consumption of the innovative system, both in winter and summer, with 20% and 15% energy saving, respectively. In general, the dynamic system provided the best comfort conditions, even if it involves a worse behavior than expected, in the summer season.

Keywords: dynamic system; ventilation; heat recovery; co-heating; thermal comfort; energy efficiency

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1. Introduction

As consequence of the Energy Performance of Buildings Directive (EPBD) recast 2010/31/CE, more restricted requirements for energy saving in existing and new buildings have been imposed. New buildings have a limited impact on overall energy saving as they represent just a fraction of the whole building stock [1]. The existing buildings constitute, therefore, the greatest opportunity for energy efficiency improvements [2], even if the refurbishment process is still slow [3].

At the global scale, the energy consumption of buildings represents about the 40% of the overall consumption [4] with the largest share due to the residential buildings in European countries and quite equally divided between domestic and commercial buildings in the USA [5]. The improvement of the energy efficiency of the building stock is an important step in minimizing the environmental impact of modern society. In particular, an important role is played by the tertiary buildings, thanks to a major attitude toward changes related to a wide economic vision [6]. In this category, the office buildings are those with highest consumption and CO_2 emissions [7]; they represent a starting point to achieve energy improvement.

The achievement of nearly zero energy balance of existing office buildings should be pursued, first of all, by reducing the energy losses and maximizing energy saving. This can be achieved through suitable architectural and constructive choices in order to control the energy fluxes induced by weather conditions and building operations. A performant building envelope allows the energy consumption to be reduced [8]. Different actions may be fielded to achieve this purpose and, among them, the interventions on the glazing systems play a key role [9].

The potential benefits of glazing systems on energy balance are still debated, above all from the near-zero energy buildings perspective [10,11]. The glazing systems should be designed as components that gain more energy than they lose in winter and just the opposite in summer in order to positively contribute to the energy balance of a building. Moreover, the glazing system should reduce the losses by infiltration and exfiltration, ensuring a reasonable air change, thanks to an efficient heat recovery unit [12].

Starting from this assumption, different transparent components have been developed, including the ventilated glazing systems. In a previous work, the authors demonstrated the variability of the thermal transmittance of a prototypal ventilated window equipped with a suction fan to generate an airflow in the gap between the glazing and an internal blind [13]. The total heat transfer of the ventilated window is directly proportional and inversely proportional with the flow rate increase in summer and in winter, respectively.

The article describes the results of an experimental campaign carried out on a dynamic window consisting of a ventilated window coupled with a heat recovery unit installed on an external test cell, following the guidelines of the co-heating test method [14]. The authors intend to test the performance of the coupled system, with respect to a traditional window installed in a similar test cell where the same airflow rate is assured by a forced air change. Other physical implications on the use of the ventilated window are not analyzed in this article but they will be the topics of other studies considering the installation in real buildings.

The performance was analyzed in terms of energy saving achieved by the system and indoor thermal comfort. The former is assessed in terms of cumulated consumption and the Energy Signature method [15] has been applied, aimed at assessing the overall energy behavior in different climatic conditions. For the latter purpose, the psychrometric analysis is applied to better understand the complex heat fluxes management [16].

2. Experimental Section

The experimental campaign, carried out on dedicated outdoor test cells located at the ITC-CNR headquarters in San Giuliano Milanese near Milan, involved two phases: the former aimed at analyzing the energy saving due to the installation of the dynamic system, the latter aimed at assessing the indoor thermo-hygrometric comfort.

2.1. Description of the Test Cells

The test cells, called C2 and C3, respectively, have the same geometric, constructive and thermo-physical characteristics. Their dimensions are 2.80 m × 2.80 m × 5 m and they are realized in lightweight concrete blocks with external insulation. The thermal transmittance of walls, floor and ceiling are equal to 0.20, 0.20 and 0.31 W/m^{2}K, respectively. The thermal capacity of each cell is equal to 2261 kJ/K. Both cells are equipped with a thermostat aimed at maintaining a constant indoor air temperature equal to 20 °C for the entire experiment. Both cells are also equipped with a ceiling fan to ensure the homogenization of the internal air temperature and to prevent vertical temperature stratification. The cells are completely monitored with temperature and relative humidity indoor sensors and with an electrical energy meter (Figure 1).

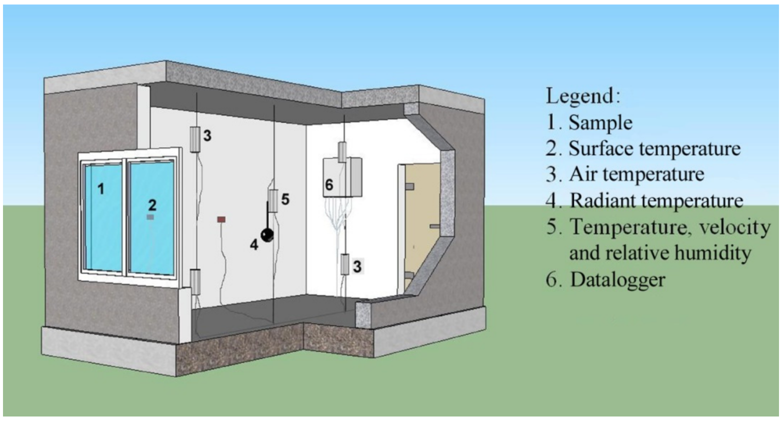

Figure 1. Section of the test cell and position of the internal sensors.

In C2, a traditional window with a south-exposed low emission double-glazing (3.3-16-3), aluminum frame (overall thermal transmittance equal to 1.7 W/m^{2}K) and micro-drilled blind were installed with a centrifugal extractor for the air circulation placed on the north wall, on the opposite side of the window, as shown in Figure 3a. The C3 was equipped with a south-exposed dynamic system made with a double-glazing window and internal blind with the same characteristics of C2, in which the ventilated air gap, between the glass and the blind, is directly connected to a heat exchanger (Figure 1b), ensuring the required airflow rate. The nominal performance of the heat recovery unit is about 90%. The average ventilation losses represent about 28% of the total of the test cells. In both the cells, the air conditioning system consisted of an electric heater and a heat pump, for winter and summer, respectively. The internal gains are negligible.

In the first prototype of the dynamic window, the ventilation was ensured by a fan located in the top of the window frame, drawing air through the gap placed between the blind and the innermost glass sheet [13]. The air suction created a vacuum in the cavity, thus triggering convective circulation within the room. The inlet air was then expelled to the outdoor environment both in summer and in winter. The goal is to remove the heat accumulated behind the glass and reduce the thermal transmittance. The operation of the system was controlled by sensors, detecting the temperature of the glass and the environment. A device remotely controlled the fan speed and adjusted its ignition time.

In the current experimental campaign, the dynamic system is built without active integrated systems, such as the fan, and the above section of the gap is directly connected to a heat recovery unit so as to exploit the preheating of the air through the system (Figure 2). The structure of the heat exchanger is made of foamed polypropylene; it is equipped with a bypass system that turns off the recovery in specific environmental conditions defined by the manufacturer.

Figure 2. (**a**) Outside view of the test cells: C2 on the right side, C3 on the left side; (**b**) Internal view of C3.

The indoor air is forced to pass through the air gap due to the depression produced by the heat exchanger. The airflow rate is fixed equal to 45 m^3/h. The air through the gap warms due to the solar radiation effect; the exchanger allows the recovery of this load with a pre-heating action on the inlet air from the outside, as shown in Figure 3.

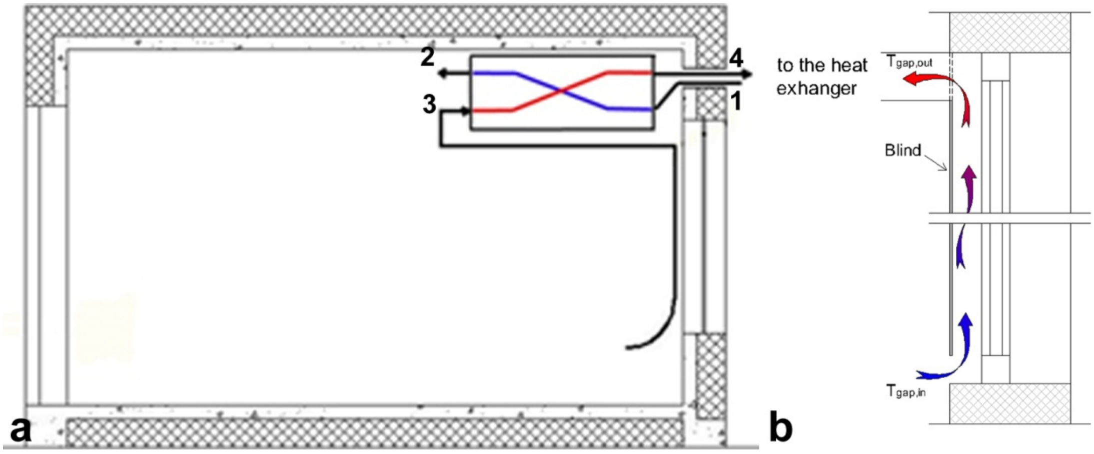

Figure 3. (**a**) Section of the overall system; (**b**) Section of the air flow through the air gap.

The flows through the heat exchanger are represented as follows:

- point 1 is the inlet airflow from the outside;
- point 2 is the heat recovery unit airflow to the inside;
- point 3 is the intake airflow of the heat recovery unit from the inside, after passing through the ventilated gap of the window;
- point 4 represents the heat recovery unit airflow to the outside.

The experiment was carried out with different configurations, as shown in Table 1.

Table 1. Configurations.

Code	Heating	Cooling	Heat Exchanger
Heating	On	Off	On
Cooling	Off	On	On
Comfort	Off	Off	On

2.2. Calibration of the Test Cells

A preliminary step of calibration of the thermal losses of the cells was required to correctly proceed with the experimental campaign, aimed at verifying their thermo-physical behavior. The calibration was made before the glazing systems were mounted and the south faces of the cells were made by opaque walls with the same characteristics. Figure 4 shows the results of the calibration phase in terms of cumulated consumption to the cumulated degree-hours.

The almost perfect overlap of the graphs of energy consumption implies an identical energy behavior between the cells.

Once verified, the analogy of the energy behavior, the related test windows and the heat recovery unit in the C3 were then mounted. The calculation of the flow rate for each cell, in accordance with EN ISO 12569 [17], was carried out by linearizing the logarithm of the concentration difference of the sulfur hexafluoride (SF_6) gas between the end and the beginning of the sampling. Figure 5 shows the trend of the decay of the SF_6 over a period of 7 h: in blue, the cyclical activation of the extractor

(15 min per hour), in red the almost constant performance given by the heat recovery, and the slope of the line represents the flow rate per hour.

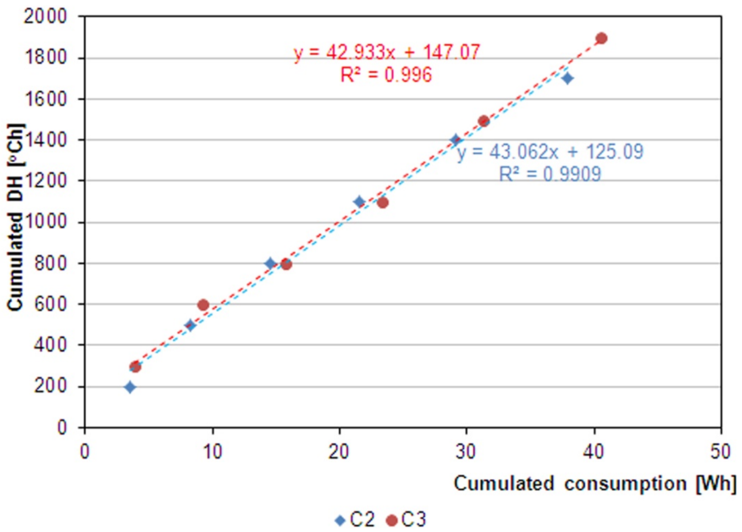

Figure 4. Calibration of energy consumption.

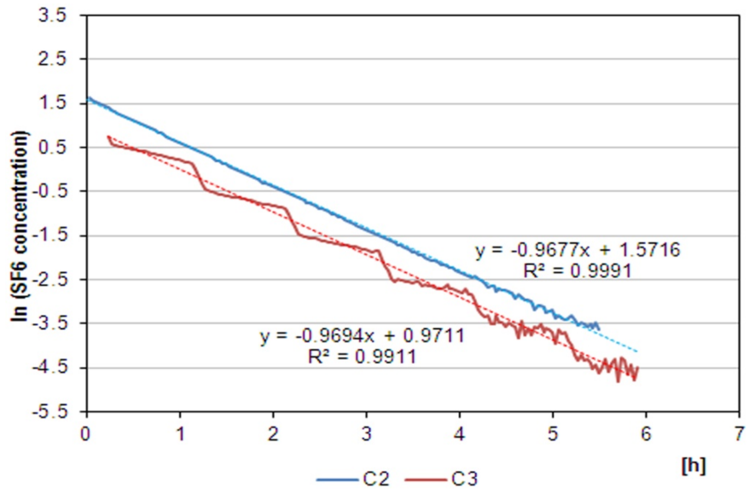

Figure 5. Flow rate per hour.

3. Results and Discussion

3.1. Assessment of the Energy Consumption

The first phase of the test consists of the analysis of the energy consumption of the cells aimed at assessing the energy performance of the dynamic system compared to the traditional sample. In particular, the energy consumption was analyzed following two different methodological approaches:

- Cumulated consumption;
- Energy Signature method.

The Energy Signature (ES) method, described in Annex B of the international standard EN 15603:2008 [18], is traditionally applied to assess the overall energy behavior of a building [19–21]. In the present work the method is used as an indirect empirical tool to assess the energy performance of the dynamic system [22]. The ES of buildings is an assessment method in which energy consumption is correlated with climatic variables; it represents the actual energy behavior of the building. It consists of a graphical representation of the power or energy consumption of a building (heating, cooling, hot water, *etc.*) as a function of external parameters (usually the outdoor air temperature). In an outdoor temperature-power graph, the slope of the curve represents the overall heat loss coefficient of the building. The ES is also used to evaluate the thermal performance of building components in operational conditions [22], based on the assumption that in the same outdoor conditions the difference in energy performance is due to the physical characteristics of the elements under evaluation.

The cumulated consumption and the ES of the test cells have been evaluated in the periods shown in Table 2.

Table 2. Heating and cooling periods and weather data. The period of diurnal average of solar radiation is: (a) from 11 a.m. to 4 p.m.; (b) from 8 a.m. to 6 p.m.; (c) from 8 a.m. to 9 p.m.

Configuration	Period	External Temperature (°C)			Solar Radiation (W/m^2)	
		Min	Max	Avg	Max	Avg
(a) Heating	7 January–11 February	−3.91	12.87	2.88	552	192
(b) Heating	4–30 April	0.9	29.16	14.51	915	371
(c) Cooling	1–21 July	10.97	34.88	24.51	955	491

3.1.1. Heating Configuration

Figure 6 shows the cumulated consumption of the test cells detected in configuration (a) and (b) of Table 2. The overall energy consumption of C3 is constantly lower than C2 in both periods. In particular, in configuration (a) the consumption of C3 is, on average, 20% lower than C2, with a cumulated difference equal to 109 kWh. In configuration (b), characterized by higher external temperatures, the energy behavior of the test cells diverges to a greater extent and the mean percentage difference increases up to about 30% with peaks exceeding 40%.

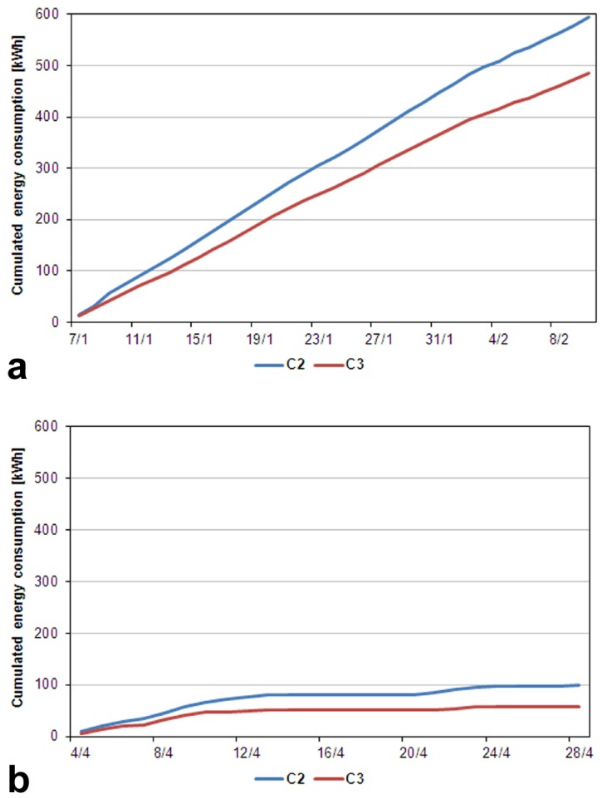

Figure 6. Cumulated consumption: (**a**) configuration "a" of Table 2; (**b**) configuration "b" of Table 2.

This trend is better explained by observing in more detail the cells' consumption in absolute terms: the greatest energy savings and the lowest percentage difference are detected in the first period, which is much cooler, and vice versa, the lowest energy savings, in absolute value, and the greatest percentage difference are detected in the second period, which is much warmer.

The dynamic system allows a lower utilization of the heating plant, especially in the warmer period.

The combined system is compared with individual operations, ventilated windows or the heat recovery unit alone. In the former (Figure 7), the system aims at saving about 13% of the energy compared to C2.

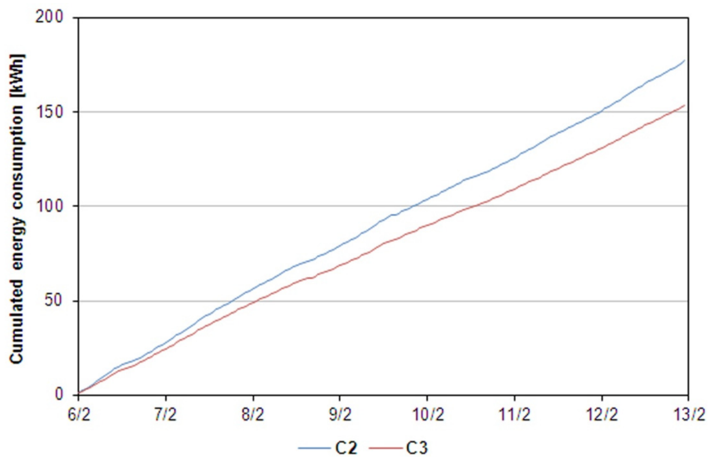

Figure 7. Energy consumption referring to the operation of the ventilated window alone, in winter.

In the latter (Figure 8), the overall consumption of C3 is lower than that detected for C2, which is about 20%. The heat recovery unit alone would seem to achieve the same energy savings obtained by the combined system. This condition occurs only for certain ranges of external temperature, as is specified in more detail in the paragraph on the efficiency of the system.

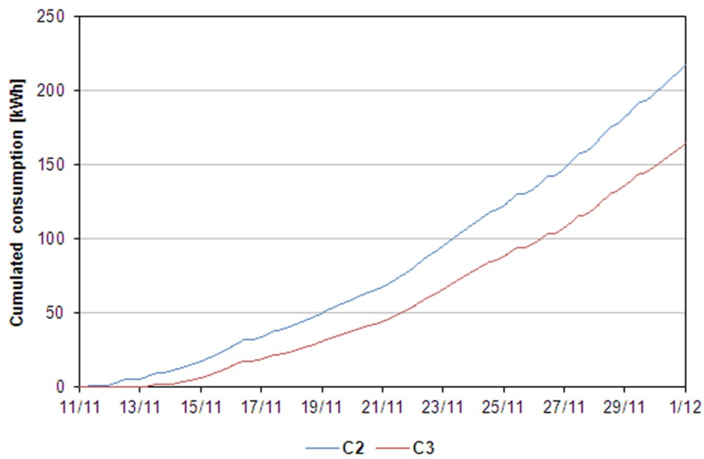

Figure 8. Energy consumption referring to the operation of the heat recovery unit alone, in winter.

The comparison of the ES of the cells (Figure 9a) shows a better energy behavior of C3 than C2, confirming the performance of the dynamic system both in terms of heat losses (related to the slope of the straight lines) and of switch-off temperature of the heating system (intersection of the straight line with the x-axis). The slope and the switch-off temperature of C3 are about 3.5 W/K and 2 °C lower than those of C2, respectively. These results demonstrate that the combined system reduces the heat losses of the window. In fact, the surface temperature of the inner glass is maintained as close as possible to the temperature of the indoor environment. This action involves a reduction of the thermal transmittance of the component as a function of the increasing flux in the air gap [13]. Moreover, the heat exchanger works at more favorable temperatures as shown in the following psychrometric analyses.

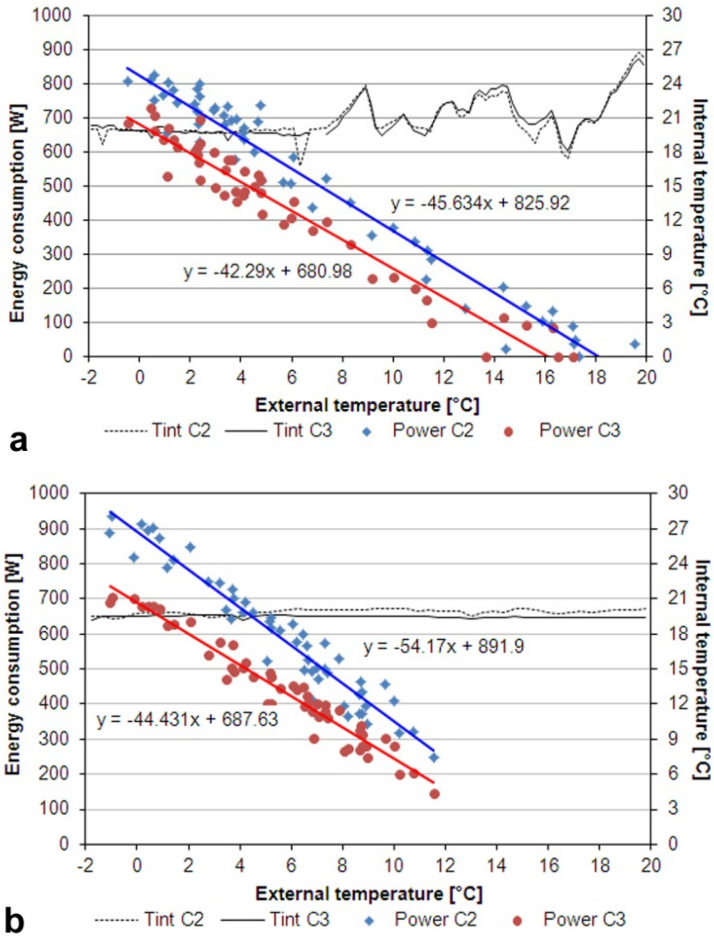

Figure 9. Energy Signature of heating configuration: (**a**) ventilation rate equal to 45 m^3/h; (**b**) ventilation rate equal to 60 m^3/h.

An increase of the ventilation rate (Figure 9b) determines the increase of the percentage difference of the two test cells. The energy behavior of C3 is further improved than that of C2. This is due to the performance of the two single components, the glazing system and heat recovery unit, which are more efficient with the increasing of the airflow rate [8]. In C3, the increasing of the airflow rate, which involves greater ventilation losses, is balanced by the combined action of the dynamic system. In C2, the ventilation losses are not recovered, with a consequent increase of the overall consumption.

3.1.2. Cooling Configuration

Figure 10 shows the trend of the cumulated consumption of the test cells in configuration (c). C3 has the best energy behavior and the lowest consumption, both in percentage (about 13%) and in absolute terms (about 25 kWh) compared to C2. However, in the cooling phase, the combination of the dynamic glazing and the heat recovery unit does not allow the flux to be optimally managed, because the exhaust air that comes into the exchanger from the indoor environment transfers heat to the inlet air, warming it. The following psychrometric analyses show the behavior of the coupled system from a physical-technical point of view.

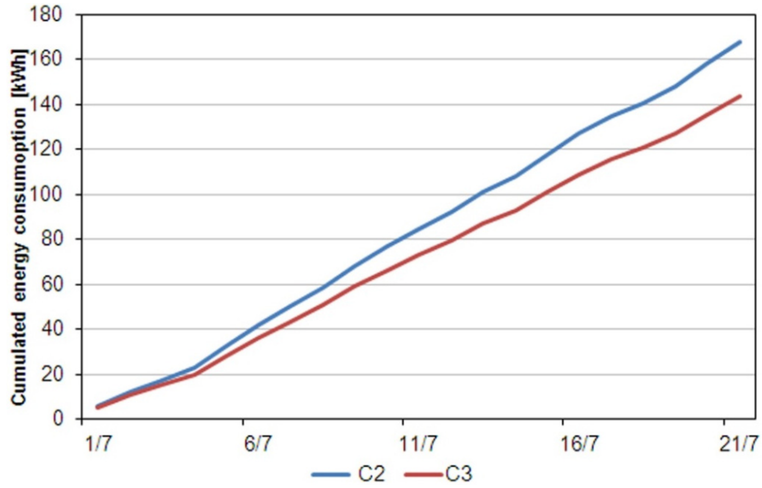

Figure 10. Cumulated consumption of cooling configuration (c) of Table 2.

In the cooling season, the reduction of the consumption is due only to the dynamic glazing (Figure 10).

On the contrary, the combined system is less efficient when compared with the summer operation of the ventilated window with the activation of the bypass (Figure 11). In this case, C3 saves about 33% of energy compared to C2.

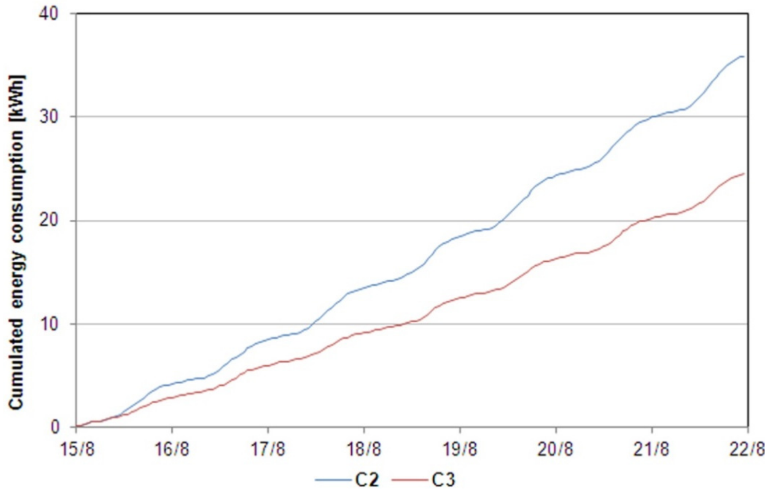

Figure 11. Energy consumption referring to the operation of the ventilated window alone, in summer.

Similarly to the heating configuration, it is possible to analyze the behavior of the dynamic system through the Energy Signature method.

The outcome of the cumulative consumption analysis is confirmed by the assessment of the Energy Signature. The comparison, in fact, shows both a lower slope and a downward translation of the Energy Signature of C3 with respect to C2, due to a better management of the thermal loads of the combined system compared to the reference one (Figure 12).

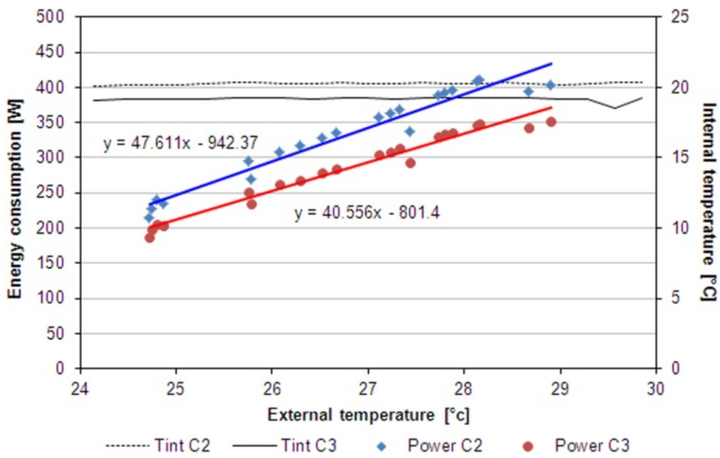

Figure 12. Energy Signature of cooling configuration.

3.2. Thermal Comfort Evaluation

The psychrometric analyses [23], particularly focused on the environment line and the straight patterns of the transforms, allow the evaluation and the interpretation of the results from a thermal efficiency and comfort perspective.

During the winter testing period, the indoor environmental monitoring data show the positive synergy between the dynamic system and the heat recovery unit, which confirms the above energy consumption data.

Figure 13 shows the points of the transform of the thermal cycle of the heat exchanger:

- segments 1–2 represent the process of the heat exchange from outside to inside by the recovery unit that exchanges heat with outgoing airflow;
- segment 2–3′ show the process of heating or cooling of the internal ambient by the plant;
- segment 3′–3 are the overheating of the ambient air passing through the ventilated gap of the window;
- segment 3–4 indicate the process of the heat exchange of the air from the inlet airflow in the recovery unit to outside giving heat incoming airflow.

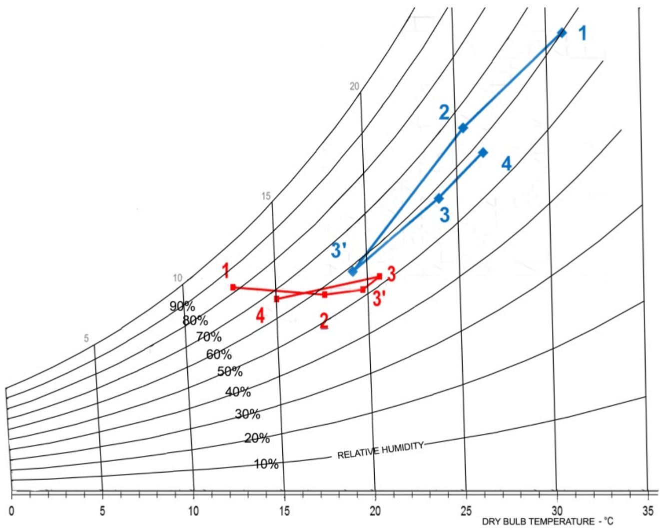

Figure 13. Psychrometric chart—thermodynamic transforms: (red lines) "Heating"—22 April at 12 p.m.—and (blue lines) "Cooling"—3 July at 12 p.m.

During the tests in winter (Figure 13, red lines), besides the energy advantage generated by the heat recovery operation, the air passing through the gap of the ventilated window overheats (3′–3) by increasing the heat exchange of the outgoing airflow with the incoming one. The higher temperature difference between the airflows (3′–3) increases the energy efficiency of the overall system with respect to the theoretical operation of the heat recovery alone (2–3), allowing the achievement of the set point conditions with a reduced energy expenditure by the heating system.

The considerations in the summer season are different (Figure 13, blue lines). The operation of the ventilated window involves a daily overheating of the pre-treated air through the gap (3′–3), reducing the heat recovery unit efficiency. In fact, the ventilated window defines a smaller difference of temperature (3–4) than the difference of temperature that would obtain with the exchanger alone (theoretical 3′–4).

3.3. Efficiency of the Coupled System

In this section, the improvement of the performance of the energy recovery unit is shown as a result of the pre-heating of the air through the gap of the ventilated window. The nominal efficiency of the heat exchanger, declared by the manufacturer, is a function of the variable airflow rate. The flow rate limit for experimentation is equal to 45 m^3/h with an efficiency between 94% and 95%.

The coupled system takes an important role in the heat flow management by developing three actions, the last of which is dependent on the previous, as in following:

- heat recovery;
- heat exchange reduction;
- integrated action of pre-heating in the dynamic windows before the heat recovery unit.

The first action takes place in the heat recovery unit: in winter, the exhaust hot air, outgoing from the air conditioner, exchanges heat with the cold air inlet.

The two next actions take place at the level of the ventilated window. The passing of the air through the ventilated air gap allows the surface temperature of the inner glass to be maintained as close as possible to the internal air temperature; the thermal transmittance of the glass is reduced, increasing the air flow in the gap [12]. The solar radiation through the transparent component preheats the air that crosses the air gap even before it can reach the heat recovery unit [24].

As is known, the performance of the integrated system varies depending on weather conditions; therefore, the following charts show the trends of energy efficiency of the dynamic system.

The performance cannot reportable through the single formulation of the efficiency of the exchanger but it was used for the broader definition of energy efficiency of the coupled system (Equation (1)), as follows:

$$\eta = \frac{(T_{air,in} - T_{ext})}{(T_{int} - T_{ext})} \tag{1}$$

where:

$T_{air,in}$ is the temperature of inlet air in the recovery system (point 3 in Figure 3);
T_{ext} is the external temperature (point 1 in Figure 3);
T_{int} is the internal temperature of the cell.

The dynamic system performance is heavily dependent on the external temperature trend and the internal air temperature incoming to the heat recovery unit, preheated from the ventilated window.

As can be seen for external temperatures between about 10 °C and 22 °C (Figure 14a), the combined action of the exchanger and the ventilated window increases the efficiency of the system with increasing external temperature and intake flow temperature, starting from an efficiency of 0.9 until about 3. When the external temperature goes below 10 °C, the benefit of the ventilated window is irrelevant because the efficiency of the coupled system is similar to the efficiency of the heat recovery unit alone. Above 22 °C, instead, the yield is opposite, decreasing with increasing temperatures (Figure 14b).

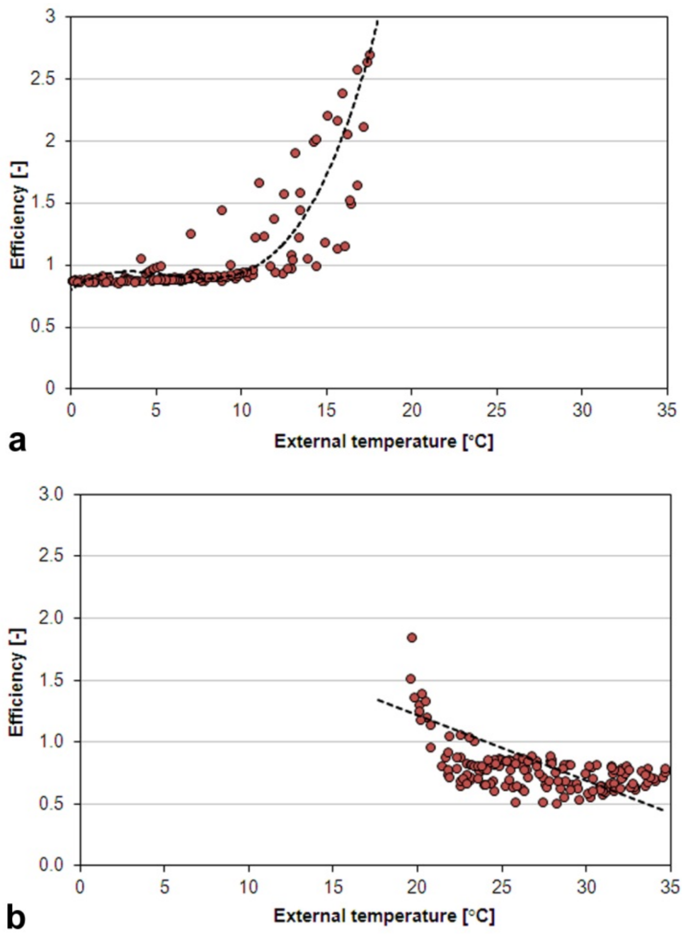

Figure 14. Behavior of energy efficiency of the system in function of: (**a**) external temperature below 20 °C; (**b**) external temperature above 20 °C.

In summer, the ventilated window alone would save up to 33% of the energy supplied by the heat pump (Figure 9), but with the activation of the heat recovery unit the energy saving decreases to 13% (Figure 8), due to the overheating of the outgoing air.

The system does not work in an optimal way for temperatures higher than 22 °C because the heat recovery unit is managed by algorithms optimized to work alone. The heat recovery unit integrates a system that allows the inlet air to bypass the heat exchanger under certain environmental conditions. Specifically, the bypass is activated when the outside temperature (T_1) is simultaneously less than the internal temperature (T_{int}), and greater than that of the setting (T_{set} = 20 °C) or when T_1 is greater than 18 °C and even greater than T_{int} and T_{int} is less than T_{set}.

In fact, the temperature of the inlet air to the unit (point 3 in Figure 7) is higher than the outlet air temperature. If there is no overheating (segment 3′–3), the recovery unit would work properly.

4. Conclusions

The improving effect of the ventilation on the total heat transfer of the dynamic window has been subject to analysis of a previous publication [13]. Starting from the achieved results, we proposed an upgrade of the system consisting of the ventilated window coupled with a heat recovery unit. This article analyzes the behavior of this dynamic system and the thermal comfort reachable in operating conditions, typically in an office.

The results of the experimentation show that the combined system provides good performance in terms of energy saving with respect to a traditional window, especially in winter. The improvement is visible both at outdoor temperatures less than about 10 °C (in January) and at warmer temperatures until about 22 °C (in April) with an energy saving of about 20% and 40%, respectively. This effect is due to both the pre-heating of the air through the air gap and the operation of the heat exchanger. In particular, in the warmest winter period, higher external temperature, between about 10° and 22 °C, allows the increase of the efficiency of the heat exchanger with a consequent higher energy saving.

The sum of the energy savings achieved in winter with the operation of the dynamic window alone from one side, and of only the heat recovery unit from the other side, should allow it to reach a 33% energy savings. The experimental results show that at certain periods of the year the efficiency of the energy saving improves. The experimental results show that in any period of the year the efficiency of the coupled unit is better than the single system, reaching about 40% energy savings.

Conversely, in summer, the energy savings of the combined system decreases to about 13%. This result is obtained thanks to the reduction of heat losses of the ventilated window that compensates the negative efficiency of the heat recovery unit. In fact, the energy savings of the ventilated window alone would be about 20%.

A new specific algorithm of operation should exclude the heat recovery for temperatures higher than 20°C in order to maintain high values of performance in any condition.

The good results obtained by the experimental campaign make the thus far analyzed dynamic system a good technology for energy saving in the office refurbishments sector.

The proposed system is easily employable in building renovation in the tertiary sector, especially in office buildings, and represents a good compromise between cost of intervention, invasiveness of construction and energy savings. In such intended use, the indoor environment is occupied during the day when the system ensures greater efficiency.

Analyses in real buildings are the future challenges both in terms of energy performance and architectural integration.

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Conflicts of Interest: The authors declare no conflict of interest.

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