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Ventilation of buildings with heat recovery systems: Thorough energy and exergy analysis for indoor thermal wellness

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A B S T R A C T

This work analyses deeply and critically the behavior of a heat recovery device of the ventilation system, in a dwelling of the Basque Country, under the energy and the exergy point of view. The aim is to show the different results that come from both perspectives. Heating period was monitored and data of the velocities and temperatures of the extracted and renovation airflows have been registered. With the data recorded, the effectiveness, energy efficiency and exergy efficiency of the recovery system have been calculated. Later, energy savings, primary energy savings and economic savings have been evaluated. Besides, the minimum difference between the outdoor and the indoor temperatures, from which the operation of the recovery system achieves a primary energy saving, an economic saving or an exergy saving were calculated. In addition to the exhaustive monitoring, the concentration of carbon dioxide in each room of the dwelling has been measured. The results obtained show the convenience of using ventilation systems with heat recovery from an energy point of view (with an energy efficiency of 89%), but not so if an exergy analysis is performed (with an exergy efficiency of 4%). After all, Second Law perspective penalizes a lot the electricity consumption for heating purposes, requiring a temperature differences (between the indoor and outdoor temperatures) higher than 32 °C in order to obtain exergy savings (not so under the energy perspective, where a difference of 1.6 °C is enough for having savings). The indoor air quality analysis confirms the adequacy in terms of CO_2 concentration. This work is pioneer in terms of deep exergy application for ventilation systems.

1. Introduction

Indoor temperature and thermal environment control are essential factors to maintain comfortable conditions in our homes; even more so if we remain all day inside the dwelling, as is the case for some elderly people or the general public right now in the current circumstances of Covid-19, where the government has established such requirements to avoid spreading the virus.

1.1. Ventilation in buildings

Ventilation is the mechanism through which clean air, in a controlled manner, is provided inside the buildings, Ref. [1]. Ventilation is needed to eliminate the contamination emitted by indoor sources and to maintain minimum conditions of healthiness. As a result, there is an increase in energy demand, as indoor air (thermally conditioned but polluted) is replaced by clean outdoor, unconditioned air. However, based on the review of Ref. [2], although there have been considerable advances in ventilation in the last two decades, there is not a clear answer as to what extent today's control strategies for ventilation can be improved.

To evaluate the energy consumption of mechanical ventilation systems, in addition to the one that thermally conditions the air, we need to add the consumption of the operational fans that need to be installed. In Ref. [3], for example, simulations evaluate the impact of aggregating ventilation systems in cold climates. The experiments show how much power can be reduced without compromising indoor conditions. Ventilation demands in moderate climates are, otherwise, studied in Ref. [4] where the minimum airflow rates in offices and schools are analyzed for proper inside air quality. A literature review of ventilation strategies in warm climates, where the cooling demand is more remarkable and outdoor air at night can be useful, appears in Ref. [5].

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It is clear that energy consumption increases with the increase in the demand for ventilation and depends mainly on the severity of the climate in which the building is located and the type of the installed system. In Ref. [6] the usage of different ventilation types across five different climate zones is investigated to check the user trends and requirements. According to the outcomes, as the climate became warmer, the operating time of the natural ventilation increased, while the operating time of the mechanical ventilation decreased. Summer was the season with the longest natural ventilation run time and shortest mechanical ventilation run time, while the winter trend was reversed. In cold climate regions, probably due to the resulting thermal discomfort, the use of supply mechanical ventilation systems was much lower than that of energy recovery ventilation systems.

An analysis of air quality and energy cost in each housing block should be performed to select the system that, fulfilling air quality requirements, operates at the lowest possible cost. Achieving air quality goals and limiting consumption depends on the correct operation of the ventilation system, and this correct operation depends on the suitable design and installation and the good insulation of the dwelling, Ref. [7]. It was proved that, without a properly designed ventilation system, CO_2 concentration can increase considerably in closed spaces, even to undesirable values higher than 1000 ppm, so controlled mechanical ventilation has to be installed to avoid health related diseases, Ref. [8]. Nevertheless, if the correct natural ventilation design is made, controlling the natural ventilation air supply, the pollutants can be reduced and heating and cooling loads can also be reduced [9]. According to Ref. [2] it does not make sense to reduce the energy requirement if it affects negatively people's comfort and health. As an example, super-insulated homes with natural and decentralized ventilation systems are examined in Ref. [10].

The need to guarantee a minimal flow of ventilation makes it necessary to install mechanical systems, since natural ventilation systems cannot guarantee the minimum required throughout the year by the legislation of the different countries, for example, in Spain there is the Building Technical Code (CTE), Ref. [11]. To refine such regulation, a proposal to determine the design ventilation rate introducing an indoor air quality criteria in CTE was proposed in Ref. [12].

There are different types of mechanical ventilation systems and a brief overview is given in Ref. [13]. According to this reference, the ventilation systems are classified as: mixing ventilation, displacement and personalized and hybrid air distribution. Another more general classification can be found in Ref. [14] where the systems are divided in the following groups: natural intake and mechanical extraction systems, mechanical supply and natural extraction, mechanical balanced, and on-demand-controlled ventilation systems. Besides, as remarked in Ref. [15], hybrid technologies for heat recovery are currently at the center of interest.

1.2. Recovery systems in ventilation

Heat recovery systems (HRS) are pieces of equipment that allow a part of the conditioned indoor air energy provided to be recovered with a system of mechanical ventilation. They have a heat exchanger that puts the indoor air that is extracted into thermal contact with the outdoor air for renewal. In winter, they preheat the cold outdoor air and, in summer, they cool it down. These systems have some filters to improve the quality of the outdoor air. In this way, it is possible to recover a high percentage of the energy used to heat or cool the indoor air, which would be completely lost without the HRS. According to Ref. [16], heat recovery technology can recover up to 90% of the ventilation heat losses, depending on air tightness and the insulation of the building. Ref. [17] gives a summary of heat recovery technologies for residential building applications, including the integration of heat recovery with some energy-saving systems.

According to one classification, there are three types of heat recovery systems: *cross flow*, in which hot and cold air circulate in orthogonal directions so that they cross each other, *parallel flow* when the flows are parallel and *rotary flow*, which has a rotor with high thermal inertia whose rotation is driven by an engine.

1.3. A research gap of exergy analysis in recovery systems

A great amount of papers deal with energy performances in heat recovery systems in buildings, but few of them go beyond and make an exergy analysis. The exergy analysis, in contrast to energy analysis, enables the comparison of the performances of the various components in the system. After all, it is based not only in energy quantity but also in its quality, so that all components are analyzed under the same baseline.

As said, papers dealing with exergy analysis of HRS in buildings are scarce, even if in the last years some work has arisen. On the one hand, Ref. [18] analyses heat recovery ventilation systems under different outdoor conditions, using exergy analysis and non-equilibrium thermodynamics. Results show that commonly used energy effectiveness parameters make it difficult to compare the different systems and relate them to each other and that exergy parameters should be used instead. Ref. [19] combines dimensionless indices to achieve universal data of exergy analysis of heat recovery exchangers for technological design or management. One of the outcomes of this work is that exergy efficiency values of heat transfer processes are at their lowest. The idea of Ref. [20], on the other hand, is to better utilize the energy in an air-handling unit through the exergy analysis. To do that, the usefulness of installing HRS is investigated under the Second Law point of view. Mechanically controlled ventilation systems are analyzed in Ref. [21] and, apart from the exergy analysis, the energy and finance viability of those systems are investigated in residential premises for different climates in Italy. As a result, the mechanically ventilated systems allow saving primary energy, and the financial payback time is fairly low, particularly in cold climates. The book of Ref. [22] introduces the passive and active systems for conditioning the indoor climate to deepen the principle of bio-climatic design. Air handling units were also exergetically analyzed in Ref. [23], but, in this case, a step forward was done and a thermoeconomic analysis was also carried out. As a whole, Ref. [24] provides an overview of the present state-of-the-art of exergy research over the last 3 decades.

Although some work has emerged, exergy research in heat recovery systems of buildings are still required, since the information obtained from the Second Law analysis gives essential information on the proper use of energy, which cannot be acquired with a common energy analysis.

1.4. Aim of the research

This work was carried out to make a step forward, beyond the classical energy analysis, in order to deeply and critically analyze of the performance of ventilation systems with heat recovery. Because of this, from the data obtained during the completely heating period of a dwelling (running from October to March), this work analyses a mechanical ventilation system with heat recovery. To begin with, the energy efficiency of the HRS and the primary energy savings are calculated. Later comes the calculation of exergy efficiency and the primary exergy savings. The results show the different conclusions obtained when the analysis is performed from the point of view of the First Law with respect to an analysis with the Second Law perspective.

After this Introduction, Section 2 deduces the expressions to calculate the seasonal average effectiveness of a HRS, and the seasonal energy and exergy efficiencies, as well as energy and exergy savings and primary energy and exergy savings of the ventilation system. The next step is to define the threshold values of the outdoor temperatures from which there is no energy, or exergy, or economic savings. Section 3 describes shortly the ventilation and monitoring system analyzed. Section 4 contains the real data obtained by the monitoring system and presents the corresponding graphs and tables. With the expressions from Section 2 and the data from Section 3, the results obtained appear in Section 4.

Section 5 contains the discussion and, finally, Section 6 gets the conclusions of this work.

2. Metodology to deeply analize the operation of a ventilation system

This section deals with the methodology followed along the work in order to carry out a deep energy and exergy analysis of ventilation with recovery systems. The expressions to be used along the calculations to characterize the performance of a ventilation system are here developed.

2.1. Effectiveness, energy and exergy efficiency of a ventilation system with heat recovery

Let us consider a heat recovery system in which the subscripts 0 and 1 correspond to the states of the outdoor air at the inlet and outlet of the recovery system, respectively. Likewise, 2 and 3 correspond to the extracted indoor air at the inlet and outlet of the recovery system, see Fig. 1.

Using $\dot{V}$ for the air flow rate introduced into the building, and assuming that it is the same as the extracted one (the ventilation system is balanced); using ρ_0, ρ_2 for the densities of the outdoor and indoor air respectively; and supposing, for example, some winter conditions, from the energy balance, we can write the equation, Ref. [25]:

$$\dot{V}\rho_2(h_2 - h_3) + \dot{W}_f = \dot{V}\rho_0(h_1 - h_0) + \dot{Q}_l \tag{1}$$

where $\dot{W}_f$ is the power of the two fans to overcome the load losses and $\dot{Q}_l$ is the rate of heat losses, which is approximately negligible.

Effectiveness characterizes the operation of the HRS, Ref. [26], which, as we know, is the heat exchanged with respect to the maximum heat that ideally been exchanged. Supposing that the ratio of the thermal capacity for the two airflows is the same, the effectiveness of the heat recovery exchanger is

$$\varepsilon = \frac{T_1 - T_0}{T_2 - T_0} \tag{2}$$

The effectiveness varies from 1 h to another, because the outdoor temperature changes, so it is better to define an average effectiveness

$$\overline{\varepsilon} = \frac{\sum_{i=1}^{H} \varepsilon_i h_i}{H} \tag{3}$$

where h_i is the number of hours in which the effectiveness is ε_i and H is the total number of hours in the period, for example, of heating.

Referring to the energy efficiency of the HRS, it can be defined as its output (the enthalpy increase of the ventilation supply air) divided by the enthalpy decrease of the exhaust air plus the fan energy input, and then

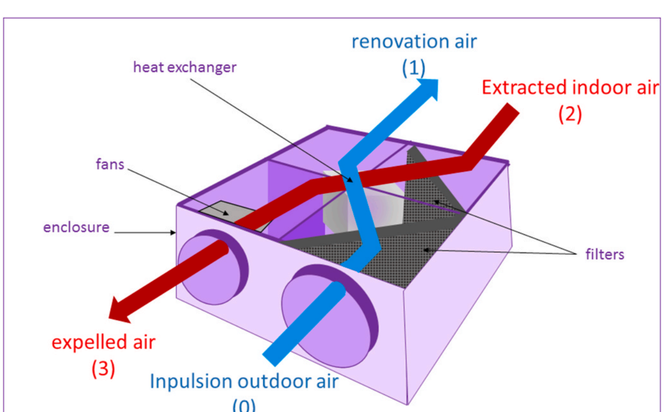

Fig. 1. Schematic of a heat recovery exchanger.

$$\eta_1 = \frac{\dot{V}\rho_0(h_1 - h_0)}{\dot{V}\rho_2(h_2 - h_3) + \dot{W}_f} = 1 - \frac{\dot{Q}_l}{\dot{V}\rho_2(h_2 - h_3) + \dot{W}_f} \tag{4}$$

If the HRS were adiabatic (the rate of heat losses is negligible and then, approximately, the decrease of enthalpy of the extraction air coincides with the increase of enthalpy of the renovation air), therefore its energy efficiency is near unity. Nevertheless, we can also define the efficiency supposing the indoor air enthalpy as the only one available, since the enthalpy in state 3 is part of the losses; that is

$$\eta_2 = \frac{\dot{V}\rho_0(h_1 - h_0)}{\dot{V}\rho_2 h_2 + \dot{W}_f} = 1 - \frac{\dot{V}\rho_2 h_3 + \dot{Q}_l}{\dot{V}\rho_2 h_2 + \dot{W}_f} \tag{5}$$

In the same way as for effectiveness, the average efficiency is a more interesting parameter.

We can also define the energy performance of the HRS as the enthalpy increase of the ventilation supply air divided by the fan energy input. The heat input from the exhaust air is disregarded in this indicator in a similar way as it is done when evaluating the COP of a heat pump; we then have

$$\eta_3 = \frac{\dot{V}\rho_0(h_1 - h_0)}{\dot{W}_f} \tag{6}$$

On the other hand, with an exergy balance in the recovery system we have

$$\dot{V}\rho_2(b_2 - b_3) + \dot{W}_f = \dot{V}\rho_0(b_1 - b_0) + \dot{I}_{rec} \tag{7}$$

where the term $\dot{I}_{rec}$ encompasses the exergy associated with the heat lost and the internal exergy destruction, due to the thermal and mechanical irreversibilities and b_i is exergy of the i-th flow. Indeed, since the exergy of air in state 3 is finally destroyed, it must be included in the term of irreversibilities ($\dot{I}_{T,rec}$) and since state 0 is ambient air, the exergy balance gives

$$\dot{V}\rho_2 b_2 + \dot{W}_f = \dot{V}\rho_0 b_1 + \dot{I}_{T,rec} \tag{8}$$

being the exergy efficiency[1]

$$\phi_2 = \frac{\dot{V}\rho_0 b_1}{\dot{V}\rho_2 b_2 + \dot{W}_f} = 1 - \frac{\dot{I}_{T,rec}}{\dot{V}\rho_2 b_2 + \dot{W}_f} \tag{9}$$

Similarly to what has been said for the energy, we can define an exergy performance indicator disregarding the exergy input from the exhaust air and then we have

$$\phi_3 = \frac{\dot{V}\rho_0 b_1}{\dot{W}_f} \tag{10}$$

As for the effectiveness and energy efficiency, we will obtain the average seasonal exergy efficiency of the equipment in a similar way.

The energy and exergy efficiencies of the HRS depend mainly on the outdoor temperature, since the amount and quality of the heat transferred to the ventilation air supply depends on that temperature.

2.2. Energy and exergy savings of a ventilation system with heat recovery

Now let us turn to a mechanical ventilation system with heat recovery for a dwelling. The objective is to evaluate the primary energy savings, comparing a ventilation system with heat recovery versus a mechanical system without recovery. After the energy analysis, in a second phase, we evaluate the exergy savings in order to highlight the interest of this type of analysis and to obtain additional information.

Fig. 2 a) represents schematically the simple exhaust ventilation

[1] subscript 2 and 3 were deliberately used in order to follow the analogy with the previous energy efficiency definitions.

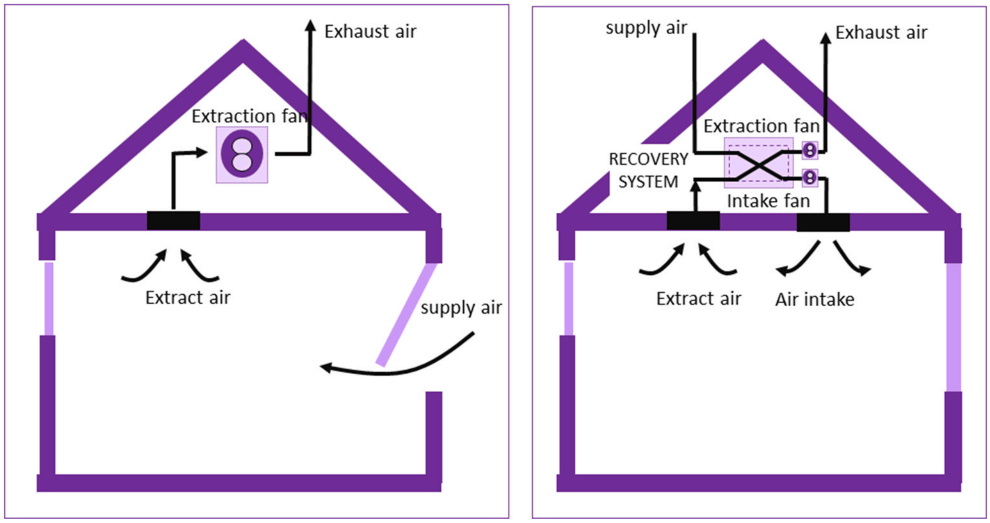

Fig. 2. Mechanical ventilation a) without recovery b) with heat recovery (as in the case study).

system (without HRS and only one extraction fan), compared to the system with HRS in Fig. 2 b). Infiltration airflows, which may differ according to the ventilation system, are not taken into account in this analysis.

In winter conditions, the heat contributing to warm up that airflow from the external conditions to the indoor temperature T_2 of the apartment is

$$\dot{Q} = \rho_0 \dot{V}\left(c_{p,a} + \omega_0 c_{p,v}\right)(T_2 - T_0) \tag{11}$$

being $c_{p,a}$ and $c_{p,v}$ the specific heat of dry air and vapor respectively, and ω_0 the absolute humidity of outdoor air. Assuming that the flow is the same for the extracted air as for the renovation air (as what occurs in a well-balanced system), the temperature at the outlet of the HRS is

$$T_1 = T_0 + \varepsilon(T_2 - T_0) \tag{12}$$

Therefore, the rate of thermal energy savings ($\dot{ES}$) due to this heat recovery is

$$\dot{ES} = \rho_0 \dot{V}\left(c_{p,a} + \omega_0 c_{p,v}\right)\varepsilon(T_2 - T_0) \tag{13}$$

Now, the electricity consumption of the fan in the supply air duct ($\dot{W}_{f,s}$) needs to be subtracted from these savings (since it is not needed in the system without heat recovery) in addition to the electricity consumption of the fan in the extraction duct needed to overcome the pressure losses in the HRS.

Being Δp these pressure losses, we have

$$\Delta p = C\dot{V}^2 \tag{14}$$

where C is a coefficient, supplied by the equipment manufacturer. Then the electricity consumption due to the pressure losses in the recuperator is

$$\dot{W}_{f,e\Delta p} = \frac{1}{\eta_{el,m}}\dot{V}\Delta p \tag{15}$$

where $\eta_{el,m}$ is the electrical efficiency of the drive motor. Then the surplus of electricity consumption due to the HRS is

$$\dot{W}_f^{su} = \dot{W}_{f,s} + \dot{W}_{f,e\Delta p} \tag{16}$$

Hence, the rate of net energy savings is

$$\dot{ES}_n = \rho_0 \dot{V}\left(c_{p,a} + \omega_0 c_{p,v}\right)\varepsilon(T_2 - T_0) - \dot{W}_f^{su} \tag{17}$$

According to this expression, there will be an environmental temperature threshold above which $\dot{ES}_n < 0$ will take place. Then, from the perspective of the First Law, the recovery ceases to be viable when there are no net energy savings; that is, when

$$\dot{ES}_n = \rho_0 \dot{V}\left(c_{p,a} + \omega_0 c_{p,v}\right)\varepsilon(T_2 - T_0) - \dot{W}_f^{su} = 0 \tag{18}$$

Supposing that the effectiveness of the recovery heat exchanger remains constant, the threshold value of the outside temperature from which there are no energy savings is

$$T_0 = T_2 + \frac{\dot{W}_f^{su}}{\varepsilon \dot{m}_a\left(c_{p,a} + \omega_0 c_{p,v}\right)} \tag{19}$$

More interesting than the $\dot{ES}_n$, is the *Primary Energy Saving*. For this, it is necessary to translate the consumption of electricity to Primary Energy (*PE*), depending on the energy mix of the country. Regarding the thermal energy, to translate it to *PE,* we will have to take into account the efficiency of the generation and distribution of the heating system in the building, since if that thermal energy were not recovered, it would have to be supplied by the heating system. Therefore, if η_{el} is the energy efficiency of the electrical system at a national level and η_g is the generation and distribution energy efficiency of heating, the net savings of primary energy is

$$P\dot{ES}_n = \frac{\rho_0 \dot{V}\left(c_{p,a} + \omega_0 c_{p,v}\right)\varepsilon(T_2 - T_0)}{\eta_g} - \frac{\dot{W}_f^{su}}{\eta_{el}} \tag{20}$$

Now, considering the great difference in quality between the energy saved in the recovery system (low temperature thermal energy) and the energy consumption (electricity), it is obvious that it is very convenient to analyze the true benefit of the recovery system through an exergy analysis. In fact, due to the high thermodynamic quality of electricity, we find that although heat recovery can save energy, it may have higher consumption in exergy, so it might be not recommended to recover heat from the perspective of Second Law. It is worth noting that by using exergy for the analysis, the threshold temperature from which no savings are achieved is much lower than the threshold temperature obtained with energy analysis.

Using exergy analysis, the rate of exergy savings of the HRS is

$$E\dot{x}S = \rho_0 \dot{V}\left(c_{p,a} + \omega_0 c_{p,v}\right)\left[T_1 - T_0 - T_0 ln\frac{T_1}{T_0}\right] \tag{21}$$

where T_1 is calculated in Eq. (12), so that the rate of *Net Exergy Saving* gives

$$\dot{ExS}_n = \rho_0 \dot{V} (c_{p,a} + \omega_0 c_{p,v}) \left[\varepsilon (T_2 - T_0) - T_0 ln \left(1 + \frac{\varepsilon (T_2 - T_0)}{T_0} \right) \right] - \dot{W}_f^{su} \quad (22)$$

Then, from the Second Law perspective, the recovery is no longer feasible when there are no exergy savings, this is $\dot{ExS}_n = 0$. If we consider that the heat exchanger effectiveness remains constant, the temperature threshold from which the recovery ceases to be interesting appears by solving this following equation

$$T_0 \left[\varepsilon + ln \left(1 + \varepsilon \left(\frac{T_2}{T_0} - 1 \right) \right) \right] = \varepsilon T_2 - \frac{\dot{W}_f^{su}}{\rho_0 \dot{V} (c_{p,a} + \omega_0 c_{p,v})} \quad (23)$$

Using this expression, we can calculate the threshold value of T_0 above which $\dot{ExS}_n$ is negative. On the other hand, in the same way as the energy analysis has been done evaluating the Primary Energy Savings, exergy analysis can be referred to Primary Exergy (*PEx*). In this case, the exergy efficiency of electricity generation at the national level ϕ_g, as well as the exergy efficiency of heating production and distribution ϕ_g in the building, are considered. Therefore, the savings of primary exergy is

$$P\dot{ExS}_n = \frac{\rho_0 \dot{V} (c_{p,a} + \omega_0 c_{p,v}) \left[T_1 - T_0 - T_0 ln \frac{T_1}{T_0} \right]}{\phi_g} - \frac{\dot{W}_f^{su}}{\phi_{el}} \quad (24)$$

Let us now make some economic considerations. If c_E and c_F are the unit cost of electricity and fuel respectively (both in €/kWh units), from an economic point of view, the recovery ceases being viable when

$$E\dot{coS}_n = \frac{\rho_0 \dot{V} (c_{p,a} + \omega_0 c_{p,v}) \varepsilon (T_2 - T_0)}{\eta_g} c_F - \dot{W}_f^{su} c_E = 0 \quad (25)$$

And then, if the recovery system effectiveness is considered to remain constant, the threshold value of the outdoor temperature from which there are no cost savings is

$$T_0 = T_2 + \frac{\dot{W}_f^{su} \eta_g}{\varepsilon \rho_0 \dot{V} (c_{p,a} + \omega_0 c_{p,v})} \frac{c_E}{c_F} \quad (26)$$

These energy, exergy and economic analyses refer to winter conditions, in which the recovery system preheats the outdoor air. Summer conditions require similar analyses, but, conversely, the recovery system pre-cools the outdoor air that enters the room.

3. Description of the ventilation and the monitoring system

A measurement campaign was done in two ventilation systems with HRS. They correspond to two dwellings of a block of dwellings located in Vitoria (Basque Country) but we only present the results of one of them. The data used to represent the graphics correspond to the period between 20th of February and March 21, 2017, even if the campaign was carried out during the six-month heating period. Fig. 3 a) shows the typical configuration of all the building's portals and Fig. 3 b) a floor plan with the schematic of the balanced ventilation system with heat recovery. The dwelling corresponds to the south-facing configuration, with the recovery system just in front of the access door. The other dwelling has a north configuration, with the recovery system away from its door, at the opposite end of the corridor.

Table 1 shows the surface and volume of each room of the dwelling; a young couple with two young children occupy this dwelling.

The ventilation system has a maximum airflow of 150 m^3/h. Depending on their needs, the airflow rate can be modified manually or by programming a schedule. Besides, the ventilation system is always in operation, so that an automatic bypass system avoids overheating or super-cooling. Fig. 4 shows the placement of the sensors. The following measurements were made:

- Air temperature in the supply duct at the inlet (T_0), and at the outlet of the recovery system (T_1) and air temperature in the extraction duct at the inlet (T_2) and outlet (T_3) of the HRS.
  For that four-wire Pt100, class 1/10 DIN (±0.03 °C to 0 °C, ±0.08 °C) at 100 °C have been used.
- Air velocity was measured in the straight section of the ducts, between the outside and the HRS; at the inlet of the recovery system for the supply air (V_0) and at the outlet of the recovery system for the extraction air (V_2).
  A Produal thermoanemometer, model IVL20 (Range 0–50 m/s ± 7% at 25 °C, 0–50 °C ± 0.5 °C at 25 °C) has been used.
- An AR-485 single-phase network analyzer has measured the active power of the fans.
- In addition, for assessing the indoor air quality of rooms, the CO_2 concentration in the living rooms and in the bedrooms has been measured with a Producer HDH CO_2 Controller (±40 ppm, ±3% of the actual value).

3.1. Data obtained

Fig. 5 a) shows the supply air temperature at the inlet and outlet of the recovery system, without considering the bypass periods; a remarkable preheating of ~ 7.0 °C is observed (with a range of variation of ~± 3.5 °C). Besides, the minimum intake air temperature is 16 °C. To complete the overall behavior of the system, Fig. 5 b) shows the temperatures including the periods in which the recovery system operates in bypass mode.

The air velocity in the extract and supply ducts appear in Fig. 6 a), where two different speeds of the ventilation system are distinguished and, in addition, the operating schedule is also included in Fig. 6 b). This scheduled timetable covers the periods of maximum occupancy and activity for the highest speed regime, while the lowest speed is set for the period of absence of occupants and low metabolic and domestic activity. From an energy point of view, this is a strategy to increase energy efficiency and that has no negative consequences on indoor air quality. The relationship between the velocity of the supply and the extraction air is approximately unity, since the flow rates are virtually equal. However, the mass flow rate of extraction air is slightly lower than that of supply, so the dwelling has a small exfiltration.

Fig. 7 shows the active power consumed by the fans. Accordingly, the consumed power ranges between two levels, corresponding to the two speeds of the ventilators; for the lower level the power is 35.6 W and around 56.6 W for the higher one.

During the measurement period, the condition of the filters was examined to check the accumulated dirt, see Fig. 8. Hence, in order to make the ventilation system work in optimal conditions, it is necessary to clean or replace periodically the filters, since dirt causes additional pressure losses and influences the indoor air quality.

During the selected period, the total electricity consumption was 29.3 kWh, so the average value of the specific energy consumption of the fans in the period considered was 0.23 kWh/m^3.

3.2. Indoor air quality

In addition to the exhaustive monitoring of the HRS, the indoor air quality (IAQ) was analyzed in terms of CO_2 concentration, using the requirements defined by the Basic Document of Healthiness of the Buildings Technical Code (HS3 DB of the CTE) [27] and the classification based on IDAs defined by EN ISO 15665 as references, see Table 2.

As already mentioned, two adults share room 1, and two minors (4 years old and a newborn) are in NW and SE facing bedrooms. The data presented in Fig. 9 correspond to the dry zones (bedrooms and living room).

Fig. 9 a) presents the evolution of the CO_2 concentration during a working day in each of the rooms, while Fig. 9 b) shows the case of the

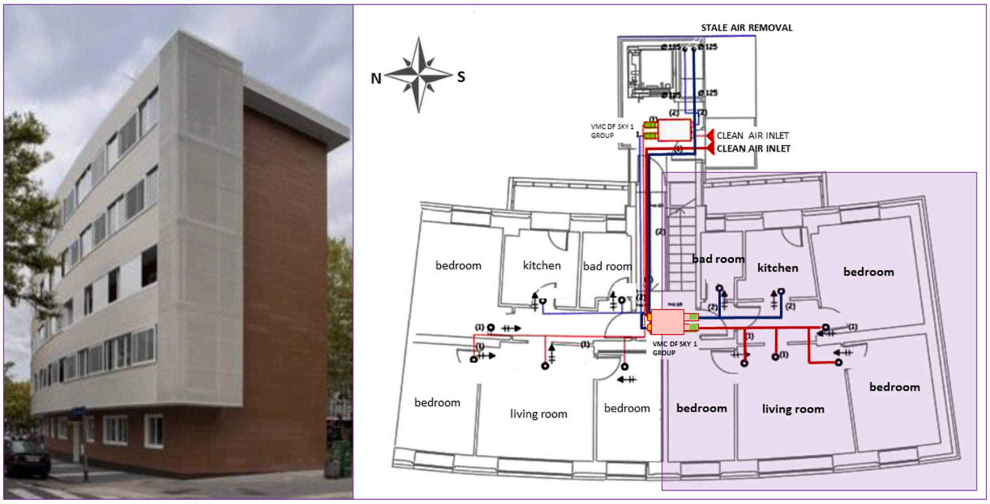

Fig. 3. a) Photograph of the building b) Floor plan with the schematic of the ventilation system.

Table 1
Surface and volume of the dwelling's rooms.

2 PORTAL. N°2. 1° L		
Room	Surface [m^2]	Volume [m^3]
NO bedroom	6.70	17.15
SE bedroom	9.99	25.67
SO bedroom	8.24	21.34
Living room	18.27	43.75
Kitchen	4.78	12.24
Bad room	2.62	6.34

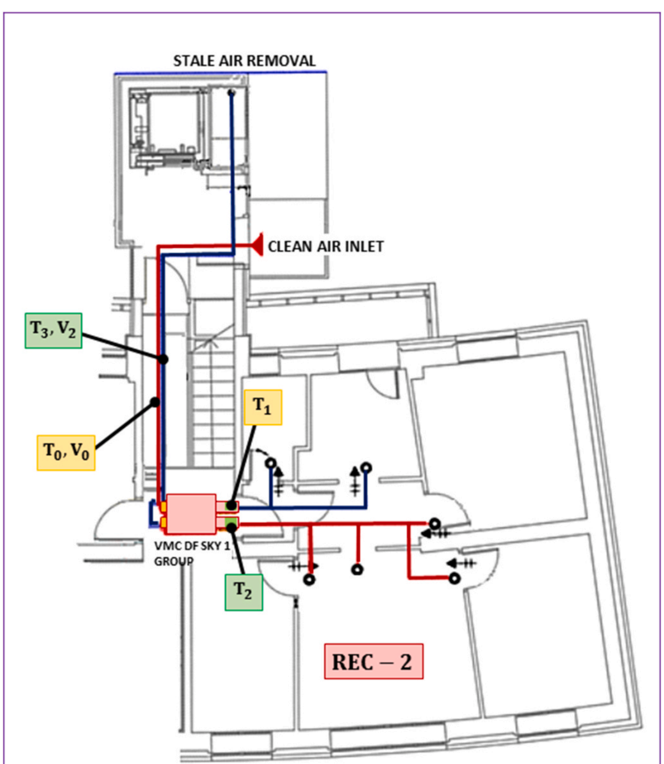

Fig. 4. Measuring point.

family on a weekend. Both profiles are very similar, but this is because both adults work during the weekend. The increases and decreases in the CO_2 concentration reflect the occupation and non-occupation periods respectively.

Fig. 10 presents the percentage of time in which the CO_2 concentration corresponds to a certain category. When analyzing the results, it is important to consider the periods when the rooms are occupied and not occupied.

According to Fig. 10, the indoor air quality is good, since as we can see, the percentage of time in which the indoor air quality pertains to the IDA IV category (CO_2 concentration greater than 1000 ppm) is very low in all rooms. To complete the indoor air quality analysis, the values corresponding to the CO_2 average and maximum concentrations during the period considered are also presented.

4. Calculations

This section deals with the case study's numerical results: the first part analyses the energy and economic savings at the current situation. Then, a thermodynamic study of the HRS was done in energy and exergy terms and, in the last sections, the threshold temperatures for obtaining advantageous operating conditions are calculated.

4.1. Energy saving analysis

During the measurement period, if a simple exhaust ventilation system were used instead, the heating demand associated with such air renewal would have been $\dot{m}(c_{p,a} + \omega_0 c_{p,v})(T_2 - T_0)\cdot\Delta t = 170\,kWh$. However, the ventilation is performed with a heat recovery system, so the demand calculated from the recorded data is $\dot{m}(c_{p,a} + \omega_i c_{p,v})(T_2 - T_1)\cdot\Delta t = 63\,kWh$. Therefore, the reduction in heating demand due to air renewal is around 63%. Keep in mind that the study-period corresponds to the end of winter and beginning of spring, so that temperatures begin to increase; therefore, the full potential of HRS is not attained, so that more energy would be recovered in the coldest months.

The energy consumption of the additional supply fan plus the consumption in the extraction fan due to pressure losses in the HRS ($\dot{W}_f^{su}$, from Eq. (16)) is estimated as half of the total electricity consumption (which includes the supply fan and the extract fan), so that it corresponds to 14.6 kWh for the period considered. Besides, the heating system of the dwelling consists of a natural gas boiler with an energy efficiency equal to 92%. Then, the energy savings in heating fuel consumption, Eq. (18), is 117 kWh during the defined period.

The heating season in Vitoria-Gasteiz runs from the last Saturday of

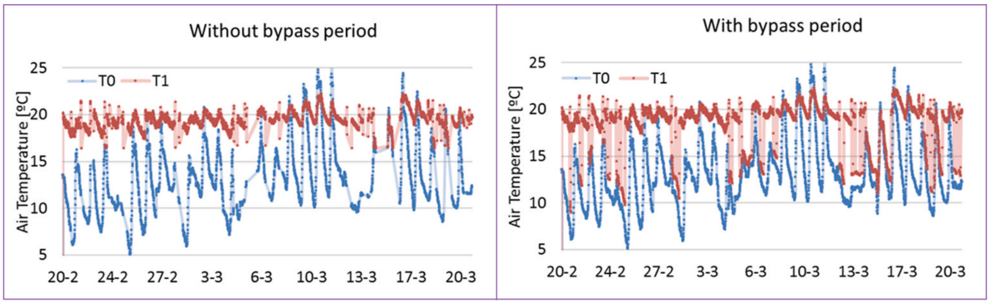

Fig. 5. Supply air temperature, outdoor (T_0) and intake (T_1) a) without bypass periods b) including bypass periods.

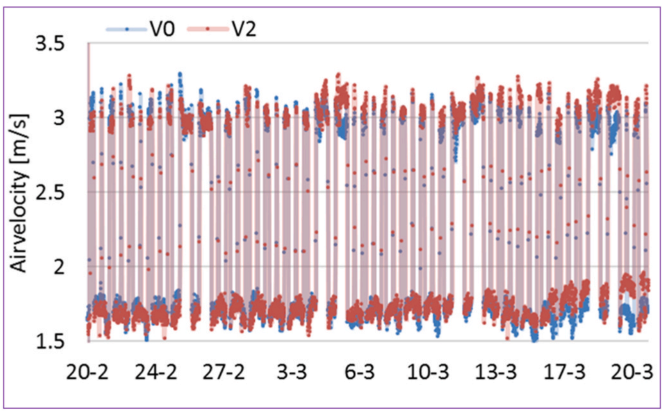

Fig. 6. a) Air velocity at the supply duct (V_0) and at the extraction duct (V_2) b) Operation schedule.

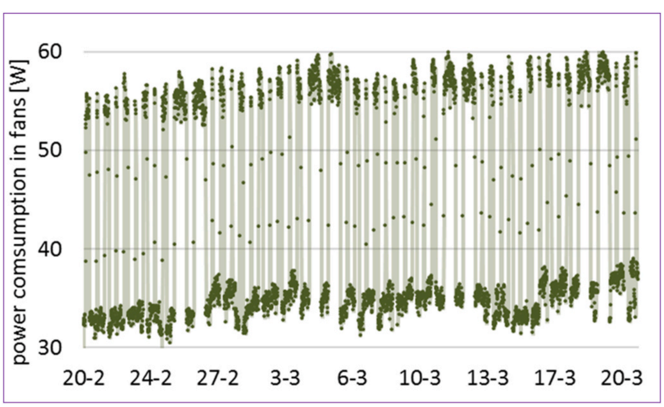

Fig. 7. Electric power consumed by the ventilation system.

October to the last Sunday of March. Table 3 contains the heating demands ratio for the other heating months in relation to the measurement period, based on the degree-days methodology [28] and the registered data in the year2017.[2] This is a simple and approximate methodology based on the idea that heating demand is proportional to the number of degrees in which the average daily outdoor temperature falls below an indoor temperature threshold (so-called degree-days), during the heating period (or above it, during the cooling period).

In accordance with this proportionality, the fuel energy savings in heating totals a value of 561 kWh. In such period, the electricity consumption due to the additional supply fan and the consumption in the extraction fan due to the pressure losses in the HRS is 70 kWh so that the recovered fuel consumption is 8 times higher than the electricity consumption in the heating period.

As the indoor recommended temperature in dwellings for the summer months is in the range of 23–26 °C, we have chosen a value of 25 °C. According to the registered meteorological data in Vitoria-Gasteiz, 31% of the time, the outdoor temperature is above 25 °C and therefore, in such hours, the HRS precools the outdoor air. During the remainder time, the HRS works in bypass mode so fans continue working throughout the year. Consequently, outside the heating season the electricity extra consumption is 108 kWh.

Let us suppose that a cooling system, with a chiller of COP = 3, maintains the dwelling at 25 °C in the warmest months.[3] According to the outdoor temperature distribution, we have found that the recovered energy obtained by precooling the outdoor air in the HRS is equal to 6 kWh, so that the savings in electricity consumption in the chiller would be equal to 2 kWh. As expected, in the no-heating period, the electricity consumption savings (2 kWh) are much lower than the electricity consumption in the fans (108 kWh). Summer is mild in Vitoria-Gasteiz and, as said, there are very few hours where the temperatures are high.

Accordingly, it is necessary to check, referring to primary energy (PE, Eq. (20)), if the energy savings on preheating (561 kWh of fuel) and precooling (2 kWh of electricity) compensates for this additional electricity consumption during the whole year (178 kWh). Therefore, since the electricity conversion factor is 2.403 [29], the surplus in electrical energy consumption in the fans during the whole year, referred to primary energy, is 428 kWh_{PE}. Conversely, the conversion factor for natural gas is 1.195 [29] so the primary energy savings in heating due to the recovered heat are equal to 670 kWh_{PE} and the primary energy savings in no-heating period are 4 kWh_{PE}, making a total of 674 kWh_{PE}.

Therefore, when referring to primary energy, the additional yearly electricity consumption in the fans of the ventilation system is fully offset by simply recovering heat in winter.

All the above results are summarized in Fig. 11. Fig. 11 a) shows the yearly distribution of heating and no-heating period (which includes both, mid and cool season) with the corresponding energy savings and the extra electricity consumption in the fans. Fig. 11 b) compares the savings and the surplus in electricity consumption over the year in energy and primary energy terms; net savings are also remarked. The results obtained justify the lack of cooling systems in Vitoria-Gasteiz.

4.2. Economic savings analysis

In addition to energy savings, economic analysis must be done to measure the advantage of ventilation systems with heat recovery in relation to a system without recovery.

To make this analysis, it is taken into account that the unit cost of electricity is 12.4 c€/kWh, and that of natural gas is 5.09 c€/kWh. Therefore, for the whole year, the additional consumption of electrical

[2] HDD of Vitoria- Gasteiz according to Eurostat are equal to 2273.

[3] In the cold climate of Vitoria-Gasteiz, the Spanish energy legislation does not require a specific cooling system.

Fig. 8. Photos of the supply and extraction filters after the operating period.

Table 2
Classification of indoor air quality.

Category	CO_2 concentration [ppm]
IDA I	≥400
IDA II	400–600
IDA III	600 - 1000
IDA IV	1000 ≤

energy implies an additional cost of 22.1 €, and the savings in natural gas costs are equal to 28.5 €, so that 6.4 € are saved yearly.

According to the economic data supplied by the installer, a double flow ventilation system with recovery for a 3-bedroom dwelling costs 2300 € and without recovery 1250 €, so the cost increment is 1050 €. Therefore, the payback time for the HRS is 164 years, which suggests that this system is not economically viable for the climatic conditions and economic environment of the case.

4.3. *Effectiveness of the heat recovery system*

The effectiveness of the HRS was calculated every 10 min using Eq. (2) and the results for the entire considered period are represented in Fig. 12 a). The intervals for when the system operates in bypass mode can be seen, as well as the inertia of the system, when it goes from bypass mode to exchange mode.

Fig. 12 b) shows the effectiveness of the HRS only in the periods in which the system operates in exchange mode. To obtain this operation mode, the effectiveness values above 50% are filtered. The values in exchange mode represent around 70% of the total period considered and, as already mentioned, the ventilation system has been programmed to operate at two speeds.

The average effectiveness of the HRS, when the system works at low speed, is 87.3%, while it is equal to 86.1% when working at high speed.

4.4. *Energy efficiency*

If we calculate the η_1 energy efficiency in the common way, that is, as the ratio between the enthalpy increment in outdoor air flow $(\dot{V}\rho_0(h_1 - h_0))$ and the sum of enthalpy increment of the extracted air flow and fan consumption $(\dot{V}\rho_i(h_2 - h_3) + \dot{W}_f)$, the average value of the HRS efficiency is $\eta_1 = 89\%$, Eq. (4); therefore, it is close to an adiabatic system.

However, if we calculate the energy efficiency by using Eq. (5), where the indoor air enthalpy is considered as the only available and the enthalpy in state 3 is taken as part of the losses, the efficiency is the ratio between the recovered enthalpy $(\dot{V}\rho_0(h_1 - h_0))$ and the sum of exhaust air enthalpy and electricity consumption $(\dot{V}\rho_i h_2 + \dot{W}_f)$. In such case, the average efficiency is equal to $\eta_2 = 31\%$, Eq. (5).

If the enthalpy from the exhaust air is disregarded, similarly to what is done when evaluating the COP of a heat pump, then Eq. (6) is used to calculate the energy efficiency.

Fig. 13 shows the values of these three efficiencies of the HRS only in the periods in which the system operates in exchange mode. As can be seen in Fig. 13, the energy input of the fans is very small in comparison to the energy output and, thus, the values of the energy efficiency η_3 is very high, with an average value of 3.17 and a maximum value of 8.85.

4.5. *Exergy efficiency*

By using Eq. (9), the average exergy efficiency for the period has been calculated, resulting $\phi_2 = 4.0\%$. The dynamic values for the exchange mode calculated every 10 min are in Fig. 14. Similarly, by using Eq. (10), we found that by disregarding the exergy of the exhaust air, the

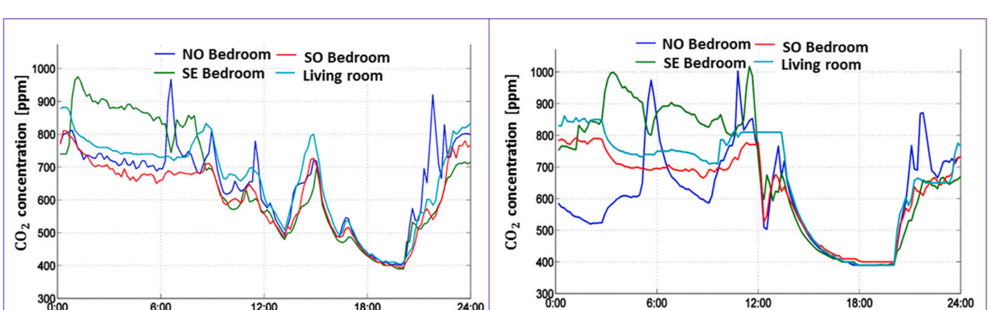

Fig. 9. Evolution of CO_2 concentration in a) a working day b) weekend.

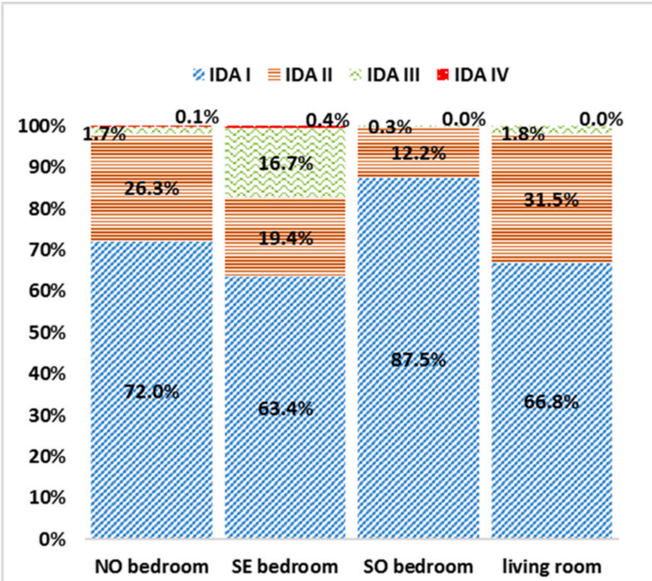

Fig. 10. a) Percentage of time for each indoor air category and b) average and maximum CO_2 concentration (ppm).

Table 3
Ratio of heating demands.

PERIOD	HEAT RATIO
21/10–20/11	0.64
21/11–20/12	1.00
21/12–20/01	1.07
21/01–20/02	1.09
21/02–20/03	1.00

average exergy efficiency is $\phi_3 = 4.4\%$ and the values in 10-min intervals are also represented in Fig. 14. As we can observe, in exergy terms, the efficiency of the HRS is much lower due to the low-quality of the energy recovered versus the high-quality of the electricity input into the fans.

4.6. Threshold temperatures for energy savings in the heating period

Given a fixed indoor set temperature, the heat recovered depends on the outdoor temperature, so, the lower it is, the more heat is recovered. This is the same as saying that the recovery system is more effective when the difference between the indoor and outdoor temperatures are greater. The electric power consumption of the fan, however, does not depend on the environmental conditions, because in operation, the consumption is fixed. The following calculations are related to the heating period when the recovery system is functioning.

As previously stated and represented in Fig. 7, when working at speed 1, the average fan power consumption is equal to 35.6 W, and when working at speed 2, it is 56.6 W. The indoor comfort temperature is considered to be at 20 °C, the average air mass flows in each regime are 0.0244 kg/s and 0.041 kg/s, and the average effectiveness are equal to 86.7% and 86.5% respectively. Therefore, using Eq. (19) and EES solver Ref. [31], the threshold temperatures, i.e. the limit values of outdoor temperature above which there are no energy savings ($\dot{ES}_n = 0$), are 18.4 °C and 18.5 °C in respect to each speed.

To calculate threshold temperatures in relation to the consumption of primary energy, one must use Eq. (20) and equal it to zero ($\dot{PES}_n = 0$), which now incorporates the conversion factors of final to primary energy for electricity and thermal energy. In this case, the threshold temperatures are 16.8 °C and 17.0 °C for speed 1 and speed 2, respectively.

Table 4 gathers all the above results. Therefore, if the outdoor temperature is lower than those indicated in Table 4, the use of the HRS for ventilation is advantageous (during the heating period) compared to a simple exhaust ventilation system.

Fig. 16 a) shows the cumulative frequency of the outdoor air temperature in Vitoria-Gasteiz for the heating period. Accordingly, for the typical meteorological year, the temperature of the outdoor air is below 18 °C during most of the winter, more specifically during 99.8% of the heating period.

The accumulated frequency curves are also given for the other two capitals of the Basque Country, Bilbao and San Sebastian, see Fig. 16 b). During the heating period, in the case of Bilbao, the outdoor air temperature is lower than the calculated threshold temperature 97% of the time. In the case of San Sebastian, the percentage is close to 93%.

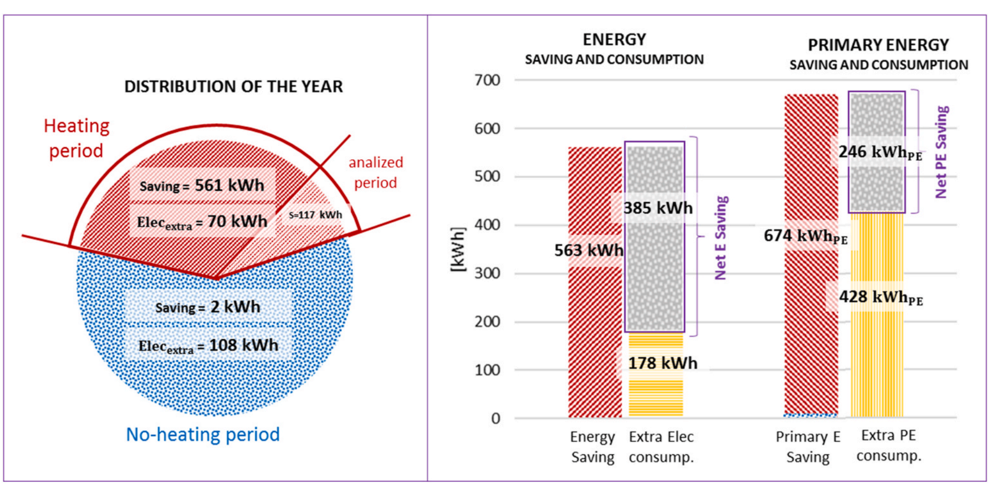

Fig. 11. a) Heating and no-heating periods along the year and b) energy saving, extra electricity consumption and primary energy saving.

The energy η_3 and exergy ϕ_3 efficiencies of the HRS as a function of the outdoor T_0 temperature are represented in Fig. 15. Note the different scales for the energy efficiency (left y-axis) and exergy efficiency (right y-axis).

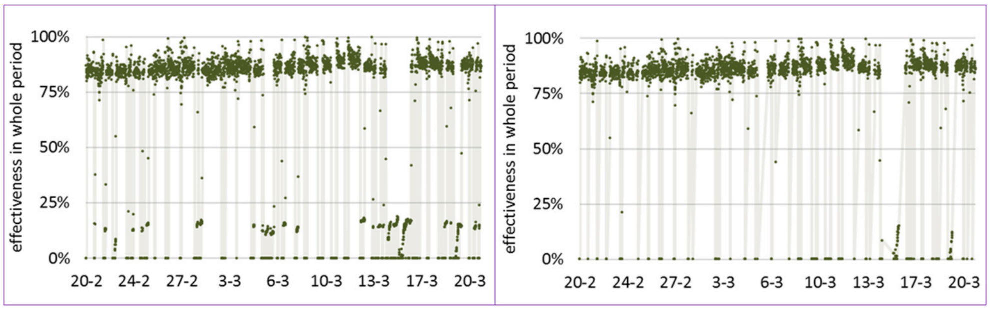

Fig. 12. Recovery system effectiveness a) in the whole period b) in the exchange period.

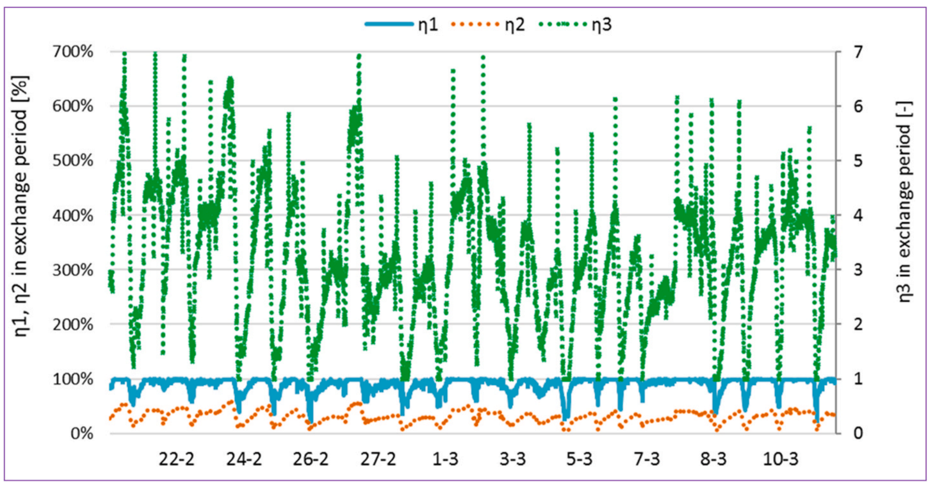

Fig. 13. Recovery system efficiency (η_1, η_2 and η_3).

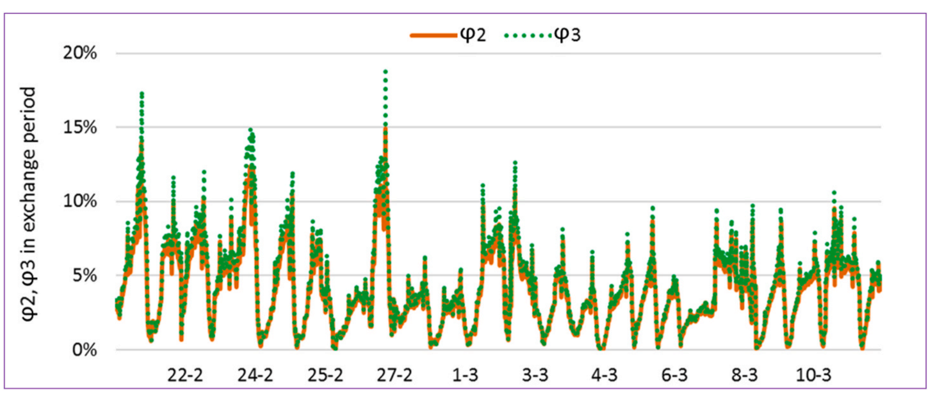

Fig. 14. Recovery system exergy efficiency (ϕ_2 and ϕ_3).

4.7. Threshold temperatures for exergy savings in the heating period

Likewise, similar calculations can be done from an exergy point of view ($\dot{ExS}_n = 0$, $P\dot{ExS}_n = 0$)[4] during the heating period and then the threshold temperatures from which the recovery system is not viable from an exergetic point of view can be calculated.

However, in this case, we encountered some difficulties, and to overcome them, we proceeded in the following way: instead of maintaining the indoor T_2 temperature at 20 °C, the outdoor T_0 temperature was set to a constant value and equal to the previously calculated threshold values. The reason for proceeding in this way was due to the mathematical difficulty encountered in the calculation process, since, if the outdoor temperature is below 0 °C (at atmospheric pressure), the water vapor in the air changes its phase to solid state and mathematical difficulties stops the program from running. However, this approach meets the practical objective of this study which is to evaluate the minimum temperature difference ΔT between T_2 and T_0 in order to obtain exergy savings.

Hence, Table 5 collects the outdoor threshold temperatures beyond which exergy savings are obtained for each parameter ($\dot{ExS}_n$, $P\dot{ExS}_n$) and for each speed of the fan. As it is observed, the difference between the indoor and outdoor temperatures should be greater than $\tilde{}32^{\circ}C$ to have

[4] Electricity primary exergy conversion factor is 2.403 and 1.243 for natural gas.

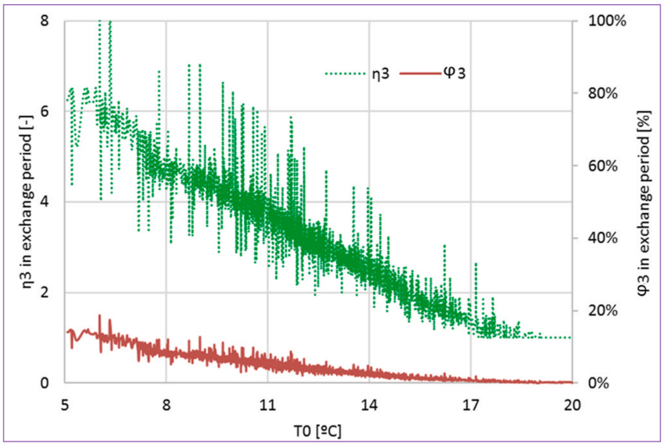

Fig. 15. Energy η3 and exergy ϕ3 efficiency as a function of T_0.

Table 4
Threshold temperatures in heating for energy savings.

Fan at Speed 1	T2v1 [°C]	T0v1 [°C]	ΔTv1 [°C]
ESn = 0	20	18.4	1.6
PESn = 0	20	16.8	3.2
Fan at Speed 2	**T2v2 [°C]**	**T0v2 [°C]**	**ΔTv [°C]**
ESn = 0	20	18.5	1.5
PESn = 0	20	17.0	3.0

exergy savings and greater than ~45°*C* for primary exergy savings.

4.8. *Threshold temperatures for economic savings in the heating period*

The analysis is completed calculating the threshold temperatures to obtain economic savings ($Ec\dot{o}S_n = 0$). Using Eq. (26),[5] the threshold temperatures for regime 1 and 2 are shown in Table 6.

5. Discussion

Before starting the discussion, all the results are summarized in Table 7. This work analyses an HRS which provides the indoor environmental quality as well as a part of the heating and the cooling demand (the rest is provided by a boiler with an efficiency of 92% and a chiller with COP = 3) of a 4 people dwelling. The results can be divided into three groups:

(1) energy, primary energy and economic saving (compared to the situation without HRS);
(2) energy and exergy effectiveness and efficiency of the HRS (comparing different definitions)
(3) minimum temperature difference between indoor and outdoor (T_2-T_0) for obtaining energy/exergy, primary energy/primary exergy and economic savings in the heating period.

According to the results, the following discussion can be extracted, for each of the groups. In relation to the 1st group:

(1.1) The fuel energy savings in the heating period are 8 times higher than the electricity extra consumption in fans; in no-heating period, conversely, the electricity consumption in the extra fans is 54 times higher. As a whole, during the year, the energy savings are 3 times higher than the extra energy consumption in fans.
(1.2) Referring to PE, the primary energy savings are 1.6 times higher than the extra primary energy consumed in fans.
(1.3) Therefore, the yearly electricity consumption in the fans of the HRS, either in energy terms either in primary energy terms, is fully offset by recovering heat in winter.
(1.4) However, considering the economic savings, the payback of 164 years shows the low economic viability of the system for those climatic conditions and economic environment.

Considering the 2nd group:

(2.1) The average effectiveness $\bar{\varepsilon}$ are similar in both speeds and close to 87%.
(2.2) We have shown three different definitions of the average energy efficiency with quite different values: $\bar{\eta}_1$ can arrive to the unity if the HRS is adiabatic, $\bar{\eta}_2$ considers the outdoor enthalpy as an additional loss, so it is always less than 1 and lower than $\bar{\eta}_1$ and $\bar{\eta}_3$ is similar to the COP of a heat pump so it is always higher than 1.
(2.3) The average exergy efficiency $\bar{\phi}$ is very low, compared to the energy efficiency, since electricity (high quality energy) is used to feed the HRS whose aim is to provide thermal energy (low quality). For example, the average energy efficiency defined as $\bar{\eta}_3$ is 79 times higher than the exergy efficiency $\bar{\phi}_3$.

Considering the 3rd group:

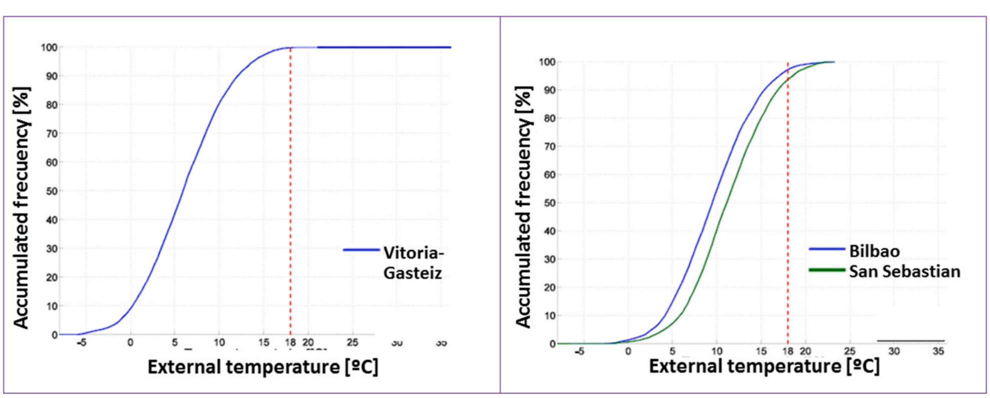

Fig. 16. Accumulated temperature frequency in the heating period a) Vitoria-Gasteiz b) Bilbao and San Sebastian.

[5] As said, c_E = 12.4 c€/kWh and c_F = 5.09 c€/kWh and speed 1 is turned on during 440 h, while speed 2 is turned on during 252 h during the studied period.

Table 5
Threshold temperatures in heating for exergy savings.

Fan at Speed 1	T0v1 [°C]	T2v1 [°C]	ΔTv1 [°C]
ExSn = 0	18.4	51.1	32.7
PExSn = 0	16.8	62.7	45.9
Fan at Speed 2	T0v2 [°C]	T2v2 [°C]	ΔTv2 [°C]
ExSn = 0	18.5	50.3	31.8
PExSn = 0	17.0	61.6	44.6

Table 6
Threshold T_0 temperatures for economic savings.

Fan at Speed 1	T2v1 [°C]	T0v1 [°C]	ΔTv1 [°C]
EcoSn = 0	20.0	16.8	3.8
Fan at Speed 2	T2v2 [°C]	T0v2 [°C]	ΔTv2 [°C]
EcoSn = 0	20.0	17.0	3.6

(3.1) If indoor temperature T_2 remains at 20 °C and outdoor temperature is below 18.5 °C (ES = 0) or below 16.9 °C (PES = 0), the recovery system is advantageous, from an energy perspective.

(3.2) At those temperature conditions, the recovered energy $\rho_0\dot{V}(h_1 - h_0)$ is equal to the electricity consumed in the fans, either in final energy or primary energy, since (ES = 0, PES = 0). However, the exergy of the recovered energy $(\rho_0\dot{V}b_1)$ is not equal to the electrical energy consumed but it has a much lower value, since the preheated temperature T_1 is very close to the ambient conditions, whereas electricity is all exergy. Then, as the quality factor of the recovered energy is very low, the exergy savings are negative (ExS<0). In other words, a very high quality energy (electricity) is used in the fans to recover a very low quality energy. Table 8 contains the numerical results of this analysis.

(3.3) As shown in Table 7, a temperature difference (T_2-T_0) higher than 32 °C (ExS = 0) or higher than 45 °C (PExS = 0) is required in order to obtain exergy or primary exergy savings.

(3.4) Nevertheless, if the electricity used to feed the recovery system is fueled by renewable sources, from an ecological point of view, heat recovery is beneficial straight away, that is, at any time when $T_0 < T_2$.

Table 7
Summary of the work.

RESEARCH	DESCRIPTION	EQUATION	VALUE
SAVING ANALYSIS	Fuel ES	Eq. (17)	561 kWh
	Elec. ES	Eq. (17)	2 kWh
	Fuel PES	Eq. (20)	670 kWh_{PE}
	Elec. PES	Eq. (20)	4 kWh_{PE}
	EcoS	Eq. (25)	6.4 €
ENERGY & EXERGY EFFICIENCY	εv1 | εv2	Eq. (2)	87.3% | 86.1%
	η1	Eq. (4)	89%
	η2	Eq. (5)	31%
	η3	Eq. (6)	3.17
	ϕ2	Eq. (9)	4.0%
	ϕ3	Eq. (10)	4.4%
MINIMUM (T_2-T_0) FOR SAVINGS	ES = 0	Eq. (19)	1.6ºC | 1.5ºC
	PES = 0	Eq. (20)	3.2ºC | 3.0ºC
	ExS = 0	Eq. (22)	32.7ºC | 31.8ºC
	PExS = 0	Eq. (24)	45.9ºC | 44.6ºC
	EcoS = 0	Eq. (25)	3.8ºC | 3.6ºC

*ES: Energy Saving *ε: Average Effectiveness.
*PES: Primary Energy Saving *η: Average Efficiency.
*ExS: Exergy Saving *ϕ: Average Exergy Efficiency.
*EcoS: Economic Saving * value Speed 1 | value Speed 2.

Table 8
Recovered energy ρ0Vh1-h0 and recovered exergy ρ0Vb1, quality factor of the recovered energy (QF) and exergy savings (ExS) at each fan velocity.

Fan at Speed 1	ΔTv1	ρ0Vh1-h0	ρ0Vb1	QF	ExS
ESn = 0	1.6 °C	15.6 kWh	0.04 kWh	0.24%	−15.6 kWh
PESn = 0	3.1 °C	37.6 kWh_{PE}	0.19 kWh_{PE}	0.5%	−37.4 kWh_{PE}
Fan at Speed 2	ΔTv2	ρ0Vh1-h0	ρ0Vb1	QF	ExS
ESn = 0	1.5 °C	14.3 kWh	0.03 kWh	0.23%	−29.7
PESn = 0	3.0 °C	34.3 kWh_{PE}	0.17 kWh_{PE}	0.5%	−34.2 kWh_{PE}

(3.5) Therefore, the results obtained show the convenience of using ventilation systems with heat recovery from an energy point of view, but not so if an exergy analysis is performed.

6. Conclusions

During a winter season, the behavior of a double flow ventilation system with heat recovery in a dwelling in Vitoria-Gasteiz (Basque Country) was monitored. Every 10 min air velocities and temperatures of the extract and exhaust airflows as well as power consumption of the fans were measured and registered. Likewise, appropriate sensors were arranged to make an analysis of the indoor air quality and with that purpose, CO_2 sensors were placed in each room of the dwelling.

The effectiveness of the recovery system was calculated every 10 min, resulting in an average value of ε = 86.6% for the heating season. Likewise, the energy and exergy efficiencies were calculated every 10 min, as well as the average values, resulting in η = 31% and ϕ = 4% respectively, being the ratio ϕ/η equal to 0.13. One can appreciate the difference between these numerical values due to the different meanings of those efficiencies. Besides, during the study period, a reduction of 63% of energy consumption was achieved with an energy saving of 116.8 kWh.

We have obtained that under the perspective of the First Law, energy savings starts to be obtained after recovering heat during 5.5 weeks. Calculating the annual energy demand of the dwelling by the degree-days methodology, we conclude that the energy savings achieved with this recovery-system in the heating season is 561 kWh. If the analysis is performed considering the primary energy, due to the high primary energy conversion factor of electricity, 15 weeks are needed for the recovered heat to compensate the additional electricity consumption of the recovery system. Therefore, the additional electricity consumption is fully compensated during wintertime and, for this climate, there is no need to use the HRS in summer conditions. After all, according to Spanish policies, no cooling system is required in such climate.

Likewise, the difference between indoor and outdoor temperatures (T_2-T_0) from which the operation of the recovery system is beneficial has been calculated for the heating period. We can conclude that there are energy savings when that difference is higher than 1.5 °C ($T_0 \leq 18.5$ °C) and in order to achieve primary energy savings, that difference should be bigger than 3.1 °C ($T_0 \leq 16.9$ °C). In this respect, and in view of these results, this HRS can be located in any part of the Basque Country, since the outdoor air temperature is below 18 °C during most of the heating season, specifically during 99.8% of the time in Vitoria-Gasteiz, 97% in Bilbao and 93% in San Sebastian.

If the calculations were to consider exergy, we can conclude that to achieve exergy savings, such difference in temperature should be higher than 31 °C ($T_0 \leq -11$ °C) and to achieve primary exergy savings, the difference should be higher than 45 °C ($T_0 \leq -25$ °C). These results show us that using a ventilation system with heat recovery does not allow exergy savings to be obtained. This great discrepancy between the values obtained using energy or exergy is because electricity is a high quality energy, and this energy is used to recover thermal energy at relatively low temperatures and, therefore, of low quality.

When an economic point of view is considered, we have seen that the difference in temperatures between the interior and the exterior of the dwelling should be higher than 3.6 °C during the heating season ($T_0 \leq 16.4$°C). Then, for a thermal comfort temperature of 20 °C, there are economic savings with heat recovery when the outdoor temperature is lower than 16.4 °C. Nevertheless, in order to make a full economic analysis, it is necessary to know the extra cost of this HRS compared to a mechanical system without heat recovery, so as to assess the return time. For the climatic conditions of Vitoria-Gasteiz, we have obtained a payback time of 164 years. The conclusion is that heat recovery systems are more advantageous as the climate gets more extreme, that is, when winters are colder and summers hotter.

The CO_2 concentration measured during the period shows that indoor air quality is very good in all the rooms of the dwelling, having an IDA1 quality index most of the time. Therefore, from the point of view of air quality, the ventilation system with heat recovery performs in a very satisfactory way.

In summary, we can conclude that, under the First Law perspective, these ventilation systems with heat recovery are suitable in cold climates, such as that of Vitoria-Gasteiz, as well as in the other cities of the Basque Country, working only during the heating period. On the other side, the conclusions are different if an exergy analysis is performed. As previously mentioned, this is due to the fact that the energy driving the ventilation system with heat recovery is electricity, a high-quality energy, whereas the energy saved is thermal energy at a temperature near the environment and, therefore, of very low quality. With the current prices of electricity and fossil fuels and the investment costs needed, the annual savings are small and the payback time required is long.

Note

Taking into account the current state in relation to the COVID 19 pandemic, for safety reasons and putting this criterion before that of energy efficiency, the general recommendation on ventilation systems with heat recovery is to disable the heat recovery exchanger.

Author statement

The specific contributions made by each author (A Picallo-Perez, J M Sala, M Odriozola-Maritorena, J M Hidalgo, I Gomez-Arriaran) are hereupon listed.

Conceptualization: Ideas; formulation or evolution of overarching research goals and aims.

A Picallo-Perez, J M Sala, M Odriozola-Maritorena, J M Hidalgo, I Gomez-Arriaran

Methodology: Development or design of methodology; creation of models

A Picallo-Perez, J M Sala

Software: Programming, software development; designing computer programs; implementation of the computer code and supporting algorithms; testing of existing code components

A Picallo-Perez, M Odriozola-Maritorena

Validation: Verification, whether as a part of the activity or separate, of the overall replication/ reproducibility of results/experiments and other research outputs

J M Sala, M Odriozola-Maritorena, J M Hidalgo

Formal analysis: Application of statistical, mathematical, computational, or other formal techniques to analyze or synthesize study data

A Picallo-Perez, J M Sala, M Odriozola-Maritorena

Investigation: Conducting a research and investigation process, specifically performing the experiments, or data/evidence collection

A Picallo-Perez, J M Sala

Resources: Provision of study materials, reagents, materials, patients, laboratory samples, animals, instrumentation, computing resources, or other analysis tools

J M Sala, M Odriozola-Maritorena, J M Hidalgo

Data Curation: Management activities to annotate (produce metadata), scrub data and maintain research data (including software code, where it is necessary for interpreting the data itself) for initial use and later reuse

M Odriozola-Maritorena, J M Hidalgo, I Gomez-Arriaran

Writing - Original Draft: Preparation, creation and/or presentation of the published work, specifically writing the initial draft (including substantive translation)

A Picallo-Perez, J M Sala

Writing - Review & Editing: Preparation, creation and/or presentation of the published work by those from the original research group, specifically critical review, commentary or revision – including pre-or postpublication stages

J M Sala, M Odriozola-Maritorena, J M Hidalgo

Visualization: Preparation, creation and/or presentation of the published work, specifically visualization/ data presentation

Ana Picallo-Perez, José Mª Sala

Supervision: Oversight and leadership responsibility for the research activity planning and execution, including mentorship external to the core team

J M Sala

Project administration: Management and coordination responsibility for the research activity planning and execution

José Mª Sala

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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