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Analysis of the sensible and total ventilation energy recovery potential in different climate conditions. Application to the Spanish case.

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Abstract

Energy recovery elements play a major role in the efficiency and sustainability of building ventilation systems. The use of a sensible or total energy recovery ventilator is a key decision for ventilation systems designers. However, there is a lack of technical tools and developments to support this decision. The authors present a procedure to develop a simple decision tool for designers based on hourly values of the outdoor weather conditions and that can be applied to any kind of building. Results of the procedure are presented in simple-to-use isoline maps and tables. In order to assess credibility of the model used in the procedure, data published in the literature have been used as a reference, showing good accordance. As an example, the procedure has been applied to the Spanish area considering 48 different locations. Results have been presented and discussed. Their analysis shows as the market-accepted recommendation of using energy recovery ventilators in locations with high relative humidity during the summer should be reconsidered.

Keywords:
Ventilation, Energy recovery, Sensible heat, Latent heat, HRV, ERV

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1. Introduction

In most developed countries, energy consumption in residential and commercial buildings represents between 20 and 40% of the total consumed energy above the consumption of other sectors as industry and transport, see Pérez-Lombard [1]. Therefore, there is a strong social concern on this issue. Actually, European legislation has been approved in order to reduce energy consumption in buildings and to promote nearly zero-energy buildings, see EU Directive 2010/31 [2].

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As reported by Pérez-Lombard [1], around 50% of the energy consumption in buildings is due to the HVAC systems, in which a significant part is removed from the buildings through the ventilation system, see ASHRAE Fundamentals [3]. Therefore, the application of energy-savings techniques in these systems is a key aspect.

The indoor air quality has a strong dependence on the air ventilation ratio. As a result, countries around the world have applied regulations that force a minimum ventilation air flow that depends on the building type and the level of occupancy, see ASHRAE Standard [4] and RITE [5].

In a ventilation process, clean outdoors air is supplied into the building and indoor exhaust air contaminated by the internal building activity is extracted. This process results into an important energy consumption if the energy used to thermally condition the extracted internal air is not recovered. Therefore, the air-to-air energy recovery systems between inflow and outflow air plays a major role.

Many different energy recovery equipment are currently available . A recent review has been presented by Zeng et al. [6]. Novel advances on this field are also reported by Deshko et al. [7] and Alonso et al. [8].

This equipment can be classified in two main groups:

- Heat recovery ventilators, known as HRV. They transfer sensible heat between the extracted indoor exhaust air and the supplied clean outdoor air.
- Total energy (or enthalpic) recovery ventilators, known as ERV. They transfer both sensible heat and moisture (latent heat) between the extracted indoor exhaust air and the supplied clean outdoor air.

Energy savings achieved by the ventilation energy recovery systems depend on many different parameters as the kind of recovery system, the indoor and outdoor conditions, the building type and occupancy, and the internal energy and humidity loads.

Many studies have been carried out in order to analyse the energy savings achieved in a HVAC equipment with a specific recovery system, on specific building types (residential or commercial) or on specific outdoor conditions. See for example NG and Payne [9] and Rasouli et al. [10].

Two relevant conclusions of these works can be drawn. From on side, if an analysis of the systems taking into account all involved parameters is to be done, a detailed modelling tools as TRNSYS [11], or EnergyPlus [12] must be used. The use of these tools may be complicated and requires expertise and time, usually far beyond de skills and means of a HVAC designer.

From another side, these papers also show as the performance of both HRV and ERV systems strongly depends on the outdoor climatic conditions. Unfortunately only a few studies have been published comparing the performance of HRV and ERV as a function of the outdoor conditions. Lazzarin and Gasparella [13] performed a technical and economical analysis on these systems. The studies were restricted to three locations where the climate was characterized by cumulative hourly outdoor temperature and enthalpy. Recently, Guillén-Lambea et al. [14] investigated on the sensible and latent energy recovery potential of ventilation systems in 14 different locations in Spain. Mean monthly air temperature and humidity were used to characterize weather conditions. The study focussed on the sensible energy recovery potential of HRV systems and the latent energy recovery potential of the ERV systems. While the works of Lazzarin and Gasparella [13] and Guillén-Lambea et al. [14] give some directives on the suitability of HRV and ERV system in different specific conditions, from them it is not possible to conclude which recovery system may be more appropriate in other situations.

The work here presented provides a procedure to develop a simple decision tool for HVAC system designers for selecting HRV or ERV ventilators in any conditions. The procedure is based on a yearly analysis of the energy saving potentials of both devices making use of hourly values of the climatic data. Two different climatic seasons are considered to account for heating and cooling periods. Results are presented in simple isolines maps and tables. Generic qualitative data of the energy saving potentials of HRV and ERV ventilators are obtained that can be used for any kind of building. As an example, the procedure is applied to the Spanish area, considering 48 different locations. Resulting tables and maps are presented and discussed.

2. Description of the HVAC system

An all air system made up by a primary and indoor subsystem is analysed in this paper. A different air-handling unit (AHU) is used in each subsystem, see ASHRAE HVAC Handbook [15] and RITE [5].

Air is supplied to the building by the primary AHU. This unit consists of a supply ventilator, an exhaust ventilator an energy recovery unit and all additional components required to cover all ventilation loads of the building. Both HRV and ERV are analysed as energy recovery unit.

In order to keep indoor comfort conditions (temperature and humidity), indoor air is recirculated through an indoor air handling unit. This equipment covers the external and internal building energy loads.

The use of this specific system type facilitates a decoupled analyses of the ventilation process. However, as the ventilation load of a building does not depend on the HVAC system , results and conclusions arisen in this work can be extended to any other kind of air HVAC system.

2.1. Energy recovery devices

Two energy recovery devices are here analysed: heat recovery ventilators (HRV) and enthalpy recovery ventilators (ERV). An schematics of these kinds of devices is shown in Fig. 1.

The HRV device transfers sensible heat between the indoor air and the supply air. Heat transfer process on a psychometric diagram taking place in a HRV is shown in Fig. 2. Accordingly, and assuming that the indoor and outdoor mass flows rates are the same, the HRV effectiveness is calculated according to the following equation

$$\epsilon_s = \frac{q_s}{q_{s,max}} = \frac{T_o - T_{os}}{T_o - T_i} = \frac{\Delta T_o}{\Delta T_{max}} \tag{1}$$

where ϵ_s is the HRV effectiveness, and the subindex s stands for sensible.

Heat transfer process in the enthalpic recovery ventilator ERV is also shown in Fig. 2.

The enthalpic recovery ventilator ERV transfers both sensible heat and humidity between the indoor air and the supply air. This moisture recovery process results into latent heat transfer between the indoor air and the supply air. The performance of the ERV ventilators is then represented by the latent effectiveness ϵ_l and the total effectiveness ϵ_t which are calculated according to the following equations:

$$\epsilon_l = \frac{q_l}{q_{l,max}} = \frac{w_o - w_{os}}{w_o - w_i} = \frac{\Delta w_o}{\Delta w_{max}} \tag{2}$$

$$\epsilon_t = \frac{q_t}{q_{t,max}} = \frac{h_o - h_{os}}{h_o - h_i} = \frac{\Delta h_o}{\Delta h_{max}} \tag{3}$$

In the ERV and HRV used in ventilation systems these effectivenesses range from 50 to 80%, see ASHRAE HVAC Handbook [15] and Besant and Simonson [16] .

In summer season, the HRV systems operate when the outdoor temperature is above the indoor temperature, and in winter season when the outdoor temperature is below the indoor temperature. On the other hand, the ERV systems operate depending on the values of the indoor and outdoor enthalpy. During the summer season the outdoor enthalpy must be above the indoor enthalpy, and during the winter season the outdoor enthalpy must be below the indoor enthalpy. See ASHRAE Journal [17].

According to these operation conditions, different zones in the psychometric diagram can be drawn defining those areas in which the HRV and ERV systems are able or not able to operate. They are defined as energy recovery zones and are shown in Fig. 3.

As the sensible and enthalpic energy recovery zones differ, the ERV and HRV device actuated according to these zones may not be working at the same time for some periods. While one device may be recovering energy the other may not be able to operate. This aspect plays a major role in the yearly heat recovering potential of each of them.

3. Formulation

The instantaneous total ventilation load, $q_{v,t}$, is the required power to condition the ventilation air from outdoor conditions, $h_{o,t}$, to indoor conditions, $h_{i,t}$. It is calculated as a sum of two components, the sensible part which is driven by a temperature increment ΔT between the indoor and outdoor conditions, and a latent part driven by the humidity ratio increment Δw between the indoor and outdoor conditions. Accordingly, the instantaneous ventilation load is calculated as described by the following equations, where the properties of the humid air are taken from ASHRAE Fundamentals Handbook [18]:

$$q_{v,t} = m_v \Delta h_t = m_v(\Delta h_s + \Delta h_l) \tag{4}$$

$$q_{v,t} = m_v\{1.006(T_o - T_i) + [w_o(2501 + 1.86T_o) - w_i(2501 + 1.86T_i)]\} \tag{5}$$

The ventilation air condition process corresponding to an instant during the summer season is illustrated on the psychometric diagram in Fig. 4.

This process may ideally be carried out by a sensible heat recovery device and a latent heat recovery device. However, no latent heat recovery devices for building ventilation are available on the market, instead the enthalpic heat recovery devices ERV can be used that recover both sensible and latent heat. Therefore the HVAC designer must take the decision of using a sensible heat recovery device HRV or a ERV device. This is not a straightforward decision, and usually due to time and cost design restrictions no detail analysis can be performed.

The ERV device recuperation limit is Δh_t, while the HRV recuperation limit is Δh_s. A simple design analysis based on the hypothesis of $\Delta h_t \geq \Delta h_s$ is usually used. See for example as in Fig. 4 Δh_t is significantly larger than Δh_s. With this analysis the conclusion is that with an ERV device more energy will be recovered than with a HRV device. If this hypothesis is accepted, the decision on which device may be used can only be based on a cost analysis of the extra cost of the ERV devices and the cost of the incremental energy that can be recovered with this devices with respect to the HRV devices.

However, the hypothesis of $\Delta h_t \geq \Delta h_s$ is not always true, and in some conditions the use of a ERV device may result into lower recovered energy than with a HRV device. This effect is illustrated in Fig. 5. This example corresponds to a dry ambient situation in the summer period in which the outdoor humidity ratio is lower than the indoor humidity ratio, $w_o < w_i$. In these conditions a ERV device recovers sensible energy and losses latent energy, resulting into a total recovered energy Δh_t lower than the sensible recovered energy Δh_s. Therefore, in some situations the use of a ERV device results into lower energy savings than a HRV device.

This situation occurs when the indoor/outdoor temperature ΔT and the humidity ratio difference Δw have contrary sign, resulting into the following conclusion:

$$(T_o - T_i)(w_o - w_i) = \Delta T \Delta w < 0 \Rightarrow \Delta h_t < \Delta h_s \tag{6}$$

Therefore, an ideal ERV should be able to operate as a HRV device in this conditions, however commercial ERV devices are not able to handle it.

The example presented in Fig. 5 where the condition of Equation 6 applies, corresponds to an instant during the summer season. This is not the only situation in where this condition applies. If the isolines corresponding to the indoor values of temperature, enthalpy and humidity ratio are plotted on the psychometric diagram, it is divided in 6 zones, see Fig. 6. In 4 of the six resulting zones, the condition represented in Equation 6 applies, i.e. zones 1b, 2, 3b and 4. Therefore, the condition $\Delta h_t \leq \Delta h_s$ may occur frequently.

The question is if in these cases an enthalpic recovery device can save less energy than a sensible heat recovery device. Therefore, the analysis must focus on the energy savings of the ERV and HRV devices. In zones 2 and 3b during the summer season, and zones 1b and 4 during the winter season, despite recovered sensible and latent heat in a ERV device have opposite signs, they both have to be considered as recovered energy and can result into energy savings of the HVAC systems.

When a recovered energy results into a reduction of energy consumption it has to be computed as an energy saving. Therefore, the energy recovery potential of an enthalpic device, Δh_t, must be calculated by adding the absolute values of the recovered sensible, Δh_s, and latent, Δh_l, heat as assessed in ASHRAE Journal [17].

Therefore,

$$\Delta h_t = |\Delta h_s| + |\Delta h_l| \tag{7}$$

where

$$|\Delta h_s| = 1.006|T_o - T_i| \tag{8}$$

and

$$|\Delta h_l| = |w_o(2501 + 1.86T_o) - w_i(2501 + 1.86T_i)| \tag{9}$$

The absolute values of Δh_t and Δh_s represent the total and sensible heat recovery potential, i.e. the maximum energy per kg of ventilation air that could be recovered by using heat recovery devices with an effectiveness of 1.

The total and sensible recovered energy per unit of time, can then be obtained by multiplying these enthalpic increments by the ventilation mass flow rate m_v and the ERV or HRV effectiveness.

The sensible recovered energy when using a HRV device is then obtained from

$$q_{rec,s} = m_v 1.006|T_o - T_i|\epsilon_s \tag{10}$$

And the total recovered energy when using a ERV device is obtained from

$$q_{rec,t} = m_v(1.006|T_o - T_i|\epsilon_s + |w_o(2501 + 1.86T_o) - w_i(2501 + 1.86T_i)|\epsilon_l) \tag{11}$$

where ϵ_s and ϵ_l are the sensible and latent effectiveness of the energy recovery devices as described in Section 2.1.

The energy recovered R for a certain period can be obtained from a time integration of Equation 10 and Equation 11 over the whole period. Accordingly, and assuming hourly constant values of all involved variables, the resulting equations for the energy recovered are

$$R_s = 3600 \sum_{n=1}^{N} m_{v_n} 1.006|T_{o_n} - T_{i_n}|\epsilon_{s_n} \tag{12}$$

$$R_t = 3600 \sum_{n=1}^{N} m_{v_n}(1.006|T_{o_n} - T_{i_n}|\epsilon_{s_n} + |w_{o_n}(2501 + 1.86T_{o_n}) - w_{i_n}(2501 + 1.86T_{i_n})|\epsilon_{l_n}) \tag{13}$$

where N stands for the number of hours of the analysed period.

In order to evaluate the energy recovery potential of a HVAC system using a ERV and HRV, a new variable referred as H (in GJ/kg_{da}) is defined. It is calculated from Equations 12 and 13, assuming ideal effectiveness (i.e. $\epsilon_s = \epsilon_l = 1$) and unitary constant value of the ventilation mass flow rate when the ventilation operates and 0 otherwise. The resulting equations read:

$$H_s = 3600 \sum_{n=1}^{N} \delta_n 1.006|T_{o_n} - T_{i_n}| \tag{14}$$

$$H_t = 3600 \sum_{n=1}^{N} \delta_n(1.006|T_{o_n} - T_{i_n}| + |w_{o_n}(2501 + 1.86T_{o_n}) - w_{i_n}(2501 + 1.86T_{i_n})|) \tag{15}$$

where δ takes the value of 1 in those hours when the system is operating, and the value of 0 when it is not operating.

See as previous equations are ideal approximations of the energy recovery where secondary energy losses are neglected. Principal secondary energy losses are the electrical energy used to run the ventilation devices and the energy losses related to ice formation, see ASHRAE Journal [17]. These secondary energy losses may be relevant if an estimation of the absolute value of the energy recovery is carried out. However, their value is similar for a ERV or HRV working at the same conditions, and therefore the difference between the potential energy recovery defined as $\Delta H_{ts} = H_t - H_s$ is not significantly affected by this assumption.

Additionally, beyond these secondary energy losses, there are other relevant phenomena that may introduce additional variations in the recovered energy as the building type, the internal loads, specific ventilation needs and system control criteria. Again, as their value would be similar for a ERV or HRV working at the same conditions, the difference between the potential energy recovery ΔH_{ts} is not expected to be significantly conditioned due to these phenomena.

As a conclusion, it is important to point out as Equations 12 and 13 define the potential energy savings, because they are the maximum energy savings that can be achieved by an ideal system in which all hypothesis previously described apply.

3.1. Validation

In order to verificate the model used by the authors to compute the results presented hereafter, the data presented by Guillén-Lambea et al. [14] has been used as reference. They consist of the maximum possible recovered energy for an apartment of $80m^2$. Calculations are performed for 16 different locations in Spain. Values of the sensible and total energy recovered R_s and R_t during the summer and winter periods are presented for all the locations. All these results have here been reproduced using equations 12 and 13 and the boundary conditions and numerical parameters described by Guillén-Lambea et al. [14]. Results of the verification process are presented in Table 1. As can be observed absolute differences between results reported by Guillén-Lambea et al. [14] and those obtained by the authors are always below 0.2 GJ, and relative differences are always kept below 3%.

4. The procedure

An hourly simulation is carried out during a complete year by means of equations 12 and 13 in intervals of one hour. Therefore, calculations are performed both with HRV and ERV devices.

The energy recovery potential difference ΔH_{ts} is then calculated for the heating season, the cooling season and the whole year.

These calculation are repeated for different locations over the analysed geographic area, e.g. over a country.

All obtained values of ΔH_{ts} are then presented on an isoline map over the analysed area. The ERV devices will be recommended in those zones with larger values of ΔH_{ts}, and the HRV in those zones with lower values.

4.1. Outdoor and indoor conditions

Hourly outdoor temperature and humidity data along a year are used.

Constant indoor conditions (temperature and humidity) have been used during the whole heating and cooling periods. Temperature has been set to 21 ^oC and humidity to 40% during the heating season (winter), and to 24 ^oC and 50% respectively during the cooling season (summer).

4.2. Heating and cooling mode

Two different climate periods are considered, the heating period (winter) and the cooling period (summer).

The days of the year to switch the HVAC system from heating to cooling mode and vice-versa is a key aspect for an accurate analysis of their performance. A simple model assuming a predefined number of months during winter and summer may result into non realistic calculations, because the switch mode day is highly dependent on the climate conditions and the building loads.

In any case, a minimum difference between the indoor and outdoor temperature is usually considered in order to take into account the internal loads, see EN14825 [19]. On the other hand, it is also reasonable to switch the mode when several days of low temperatures (winter) or high temperatures (summer) occur, without taking into account previous punctual decrease or increase of temperatures.

In this work, switch mode from summer to winter is set when for at least three consecutive days the mean outdoor daily temperature decreases below 16^oC. On the other hand, switch mode from winter to summer is set when for at least three consecutive days the mean outdoor daily temperature increases above 20^{o}C. See as the temperature switch points of 16^{o}C and 20^{o}C, are 4^{o}C below the comfort temperatures of 20^{o}C and 24^{o}C.

5. Results

The seasonally and yearly energy savings potential of a HVAC system using the HRV and ERV energy recovery devices have been calculated for 48 different locations in Spain. Climatic data of the main 48 cities as provided by IDAE HVAC Guide [20] have been used. They consist of hourly values of outdoor temperature and humidity along a year.

A summary of the results with a sample of 14 locations is presented in Table 2.

For each location the results are presented for the winter, the summer and the whole year. The sub-indexes $wint$ and $summ$ are used for winter and summer, while no sub-index is used for the yearly values. For each season and for the whole year, three values are presented: the savings potential when using a ERV device, H_t, the savings potential when using a HRV devices H_s, and the difference of savings represented by ΔH_{ts} where $\Delta H_{ts} = H_t - H_s$.

Results of the energy recovery potential difference between the systems with the ERV and HRV devices, ΔH_{ts} are also presented on a isoline map over the whole Spanish geography. The values of ΔH_{ts} range from -25 to 145 GJ/kg_{da} in steps of 10 GJ/kg_{da} resulting in a total of 17 coloured zones.

In those zones in which ΔH_{ts} is small or negative, installation of HRV devices is recommended because the extra cost of the ERV devices may not be amortised. Only in those zone with larger values of ΔH_{ts} the use of ERV devices is recommended.

As presented in Fig. 7, during the summer season the energy recovery potential with both ERV and HRV devices is limited. Only in small southern and eastern areas close to the coast ERV devices offers a substantial increment of the energy recovery potential. Therefore, in HVAC systems designed only for the summer season in Spain, the use of ERV devices is only recommended in this small area. This is an important result, because HVAC designers in Spain usually recommend the use of ERV devices in zones with high values of relative humidity.

The map corresponding to the winter season is shown in Fig. 8. The energy recovery potential is much more relevant than during the summer season. Therefore, the design of the energy recovery devices for HVAC systems working all year round often depend on the winter season. The ΔH_{ts} map shows some areas located at the colder central and northern geographies with values of ΔH_{ts} up to 145 GJ/kg_{da}. In these areas the use of ERV devices for HVAC systems designed only for the winter season is highly recommended.

Results for the whole year are presented in Fig. 9. As it can be observed, inland areas in the northern part of the Spanish geography present major values of ΔH_{ts}, showing yearly values up to 145 GJ/kg_{da}.

6. Conclusions

The authors have developed a methodology in order to evaluate the potential of using ERV or HRV devices in HVAC systems. Results are presented in isoline maps of energy recovery potential differences between the two devices. From these maps, the HVAC system designer can take straightforward conclusions on which energy recovery device may best fit in a specific project. This results into a significant saving of time and costs during the design process.

Specific results for the Spanish climate have been calculated and presented by means of a seasonal and yearly analysis of HVAC systems with ERV and HRV devices in 48 different locations. From the analysis of the obtained data, it has been shown that the standard market-accepted recommendation of using ERV devices in locations with high relative humidity during the summer as Barcelona should be reconsidered. Results show as HRV devices in locations as Barcelona may be more cost-effective than ERV devices.

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Nomenclature

cur	current
ERV	enthalpic recovery ventilator (sensible + latent)
H	energy recovery potential (GJ/kg_{da})
h	enthalpy (kJ/kg_{da})
HRV	heat recovery ventilator (sensible)
m	mass flow (kg/s_{da})
q	heat or energy load (kW)
N	number of hours in a calculated period
R	energy recovered (GJ)
ref	reference
T	temperature (^oC)
w	humidity ratio (g_w/kg_{da})
δ	operation status, 1 when operating 0 otherwise
Δ	difference, variation or increment
ΔH_{ts}	energy recovery potential difference, H_t-H_s (GJ/kg_{da})
ΔR_{ts}	energy recovered difference, R_t-R_s (GJ)
ϵ	effectiveness

Subscripts

da	dry air
i	indoor air
ie	indoor exhaust air (after heat exchanger)
l	latent
n	index corresponding to the current hour
o	outdoor air
os	outdoor supply air (after heat exchanger)
rec	recovered
s	sensible
$summ$	summer
t	total
ts	total - sensible
v	ventilation
w	water
$wint$	winter

References

[1] Pérez-Lombard, L. and Ortiz, J. and Pont, C., 2008. A review of building energy consumption information. Energy and Buildings, 40, 394-398.

[2] European Commission, 2010. Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings. Official Journal of the EU, L153, 13-35.

[3] ASHRAE Fundamentals Handbook, 2017. Chapter 16: Ventilation and infiltration.

[4] ASHRAE Standard 62.1, 2016. Ventilation for acceptable Indoor Air Quality. American Society of Heating, Refrigerating and Air-Conditioning Engineers.

[5] RITE, 2013. Reglamento de instalaciones trmicas en los edificios, Ministerio de Industria, Energa y Turismo, Spain.

[6] Zeng, C. and Liu, S. and Shukla, A., 2017. A review on the air-to-air heat and mass exchanger technologies for building applications. Renewable and Sustainable Energy Reviews, 75, 753-774.

[7] Deshko, V.I. and Karvatskii, A.Y. and Shkhodub, I.O., 2016. Heat and mass transfer in cross-flow air-to-air membrane heat exchanger in heating mode. Applied Thermal Engineering, 100, 133-145.

[8] Alonso, M.J. and Mathisen, H.M. and Aarnes, S. and Liu, P., 2017. Performance of a lab-scale membrane-based energy exchanger. Applied Thermal Engineering, 111, 1244-1254.

[9] NG, L.C. and Payne, W.V. 2016. Energy use consequences of ventilating a net-zero energy house. Applied Thermal Engineering, 96, 151-160.

[10] Rasouli, M. and Ge, G. and Simonson, C.J. and Besant, R.W. 2013. Uncertainties in energy and economic performance of HVAC systems and energy recovery ventilators due to uncertainties in building and HVAC parameters. Applied Thermal Engineering, 50, 732-742.

[11] Klein, S.A, 2000. TRNSYS: A Transient System Simulation Program. Egineering Experiment Station Report 38-13. Solar Energy Laboratory, University of Wisconsin, Madison.

[12] EnergyPlus, 2018. http://www.energyplus.net/.

[13] Lazzarin, R.M. and Gasparella, A., 1998. Technical and economical analysis of heat recovery in building ventilation systems. Applied Thermal Engineering, 18 (1-2), 47-67.

[14] Guillén-Lambea, S. and Rodríguez-Soria, B. and Marín, J.M., 2016. Evaluation of the potential energy recovery for ventilation air in dwellings in the South of Europe. Energy and Buildings, 128, 384-393.

[15] ASHRAE Handbook of HVAC Systems and Equipment, 2016. Chapter 26: Air-to-Air Energy Recovery Equipment.

[16] Besant, R.W. and Simonson, C.J., 2003. Air-to-air heat exchangers. ASHRAE Journal, 45 (4), 45-52.

[17] ASHRAE Journal, 2012. Total Energy Wheel Control In a Dedicated OA System.

[18] ASHRAE Fundamentals Handbook, 2013. Chapter 16: ventilation and infiltration. and infiltration

[19] EN14825, 2014. Acondicionadores de aire, enfriadoras de líquido y bombas de calor con compresor accionado eléctricamente para la calefacción y refrigeracin de locales: ensayos y clasificación en condiciones de carga parcial y cálculo del rendimiento estacional.

[20] IDAE HVAC Guide, 2010. Instituto para la Diversificación y Ahorro de la Energía, Guía técnica de ahorro y recuperación de energía en instalaciones de climatización. Madrid.

Table 1: Verification. Comparison of reference values (ref) and current values (cur) of the recovered energy for the testing cases (GJ)

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city	winter			summer			yearly		
	$R_{t,wint}$	$R_{s,wint}$	$\Delta R_{ts,wint}$	$R_{t,summ}$	$R_{s,summ}$	$\Delta R_{ts,summ}$	R_t	R_s	ΔR_{ts}
	ref/cur	ref/cur	ref/cur	ref/cur	ref/cur	ref/cur	ref/cur	ref/cur	
Alicante	6.3/6.2	5.9/5.7	0.4/0.4	2.5/2.5	0.1/0.1	2.4/2.4	8.8/8.6	6.0/5.9	2.8/2.8
Almera	4.6/4.5	4.0/3.9	0.6/0.6	3.1/3.0	0.4/0.4	2.7/2.7	7.6/7.5	4.4/4.3	3.3/3.2
Ávila	10.8/10.9	10.4/10.4	0.4/0.4	0.3/0.3	0.2/0.2	0.1/0.1	11.0/11.1	10.6/10.7	0.5/0.5
Barcelona	6.5/6.5	5.8/5.9	0.6/0.6	1.7/1.7	0.1/0.1	1.5/1.6	8.1/8.2	6.0/6.0	2.2/2.2
Bilbao	7.6/7.6	7.3/7.3	0.3/0.3	0.9/0.9	0.1/0.1	0.8/0.8	8.5/8.5	7.3/7.4	1.2/1.2
Girona	8.2/8.2	7.9/7.9	0.3/0.3	0.8/0.8	0.2/0.2	0.6/0.6	9.0/9.0	8.1/8.1	0.9/0.9
Madrid	6.9/6.8	6.3/6.2	0.6/0.6	1.5/1.5	0.3/0.3	1.2/1.2	8.4/8.3	6.6/6.4	1.8/1.8
Mlaga	4.6/4.5	4.5/4.4	0.1/0.1	0.6/0.6	0.3/0.3	0.2/0.2	5.2/5.0	4.8/4.7	0.3/0.3
Murcia	6.6/6.5	5.4/5.3	1.2/1.2	2.8/2.8	0.2/0.2	2.6/2.7	9.4/9.3	5.5/5.4	3.9/3.9
P. Mallorca	7.0/6.9	6.3/6.2	0.7/0.7	1.9/1.9	0.3/0.3	1.6/1.6	8.9/8.8	6.6/6.5	2.3/2.3
Sevilla	5.1/5.1	5.0/4.9	0.2/0.2	1.5/1.5	0.9/1.0	0.6/0.6	6.6/6.6	5.9/5.9	0.7/0.7
Valencia	6.0/5.9	5.6/5.4	0.5/0.5	1.7/1.7	0.3/0.3	1.4/1.4	7.7/7.6	5.8/5.7	1.9/1.9

Table 2: Summary of the savings potential for some of the studied cities (GJ/kg_{da}).

city	winter			summer			yearly		
	$H_{t,wint}$	$H_{s,wint}$	$\Delta H_{ts,wint}$	$H_{t,summ}$	$H_{s,summ}$	$\Delta H_{ts,summ}$	H_t	H_s	ΔH_{ts}
Ávila	**468**	322	**146**	**0**	2	-2	**468**	324	**145**
Almería	109	95	**14**	108	20	88	218	115	103
Barcelona	212	177	35	64	7	58	276	184	93
Bilbao	240	199	41	19	2	17	259	201	58
Burgos	437	**332**	105	1	1	0	438	**333**	105
Cádiz	**108**	**90**	18	112	10	102	220	**100**	120
Huelva	122	101	21	59	21	38	**181**	123	58
La Coruña	220	187	33	0	**0**	0	220	187	33
Madrid	302	219	83	3	14	**-12**	305	233	72
P. Mallorca	141	122	19	**122**	14	**108**	263	136	127
Pontevedra	194	1678	26	7	3	4	200	170	30
Sevilla	137	118	19	61	**36**	25	198	154	44
Valencia	182	143	39	84	12	72	266	155	111
Zaragoza	275	211	64	22	15	7	30	226	71
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
maximum	**468**	**332**	**146**	**122**	**36**	**108**	**468**	**333**	**145**
minimum	**108**	**90**	**14**	**0**	**0**	**-12**	**181**	**100**	**30**

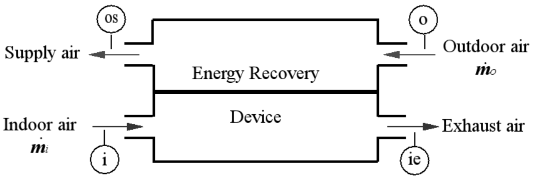

Figure 1: Schematic of an energy recovery device.

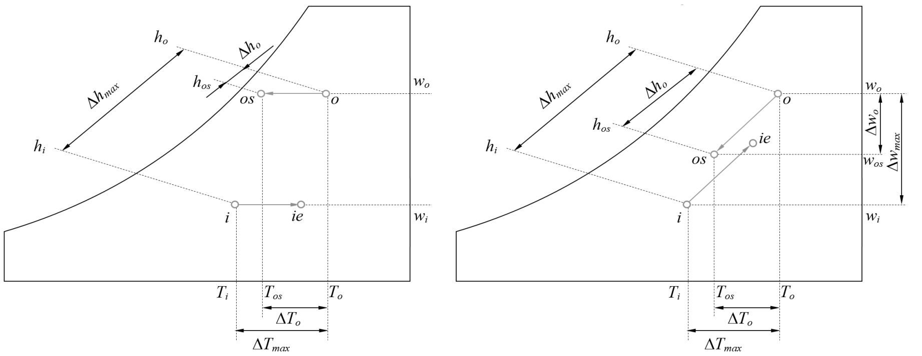

Figure 2: Cooling mode heat transfer process in the psychometric diagram for a HRV (left) and a ERV (right).

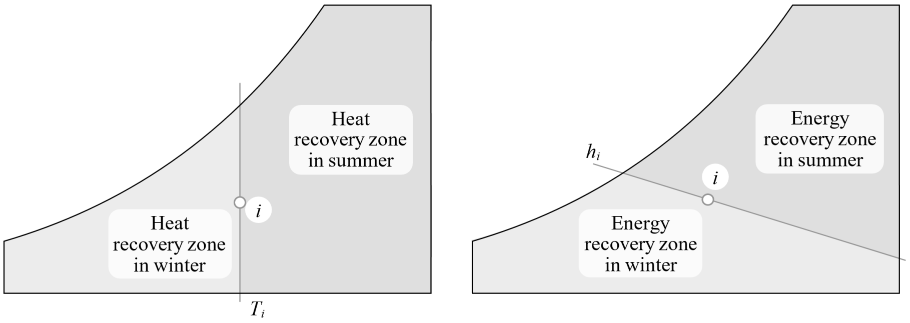

Figure 3: Energy recovery zones: sensible heat zones of the HRV systems (left) and enthalpic heat zones of the ERV systems (right).

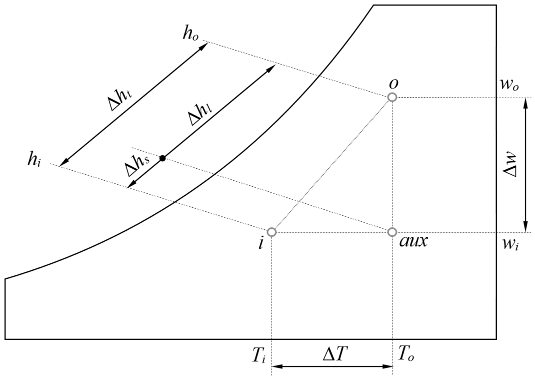

Figure 4: Ventilation enthalpy differences in summer.

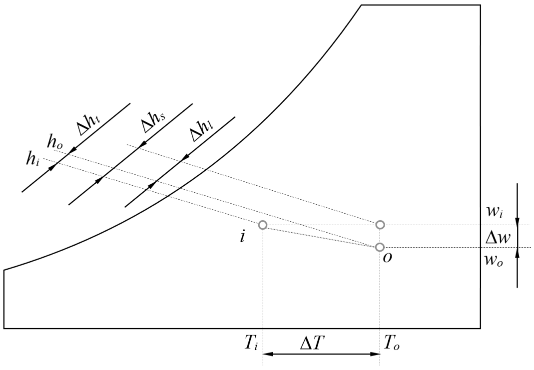

Figure 5: Ventilation enthalpy differences in summer and dry ambient.

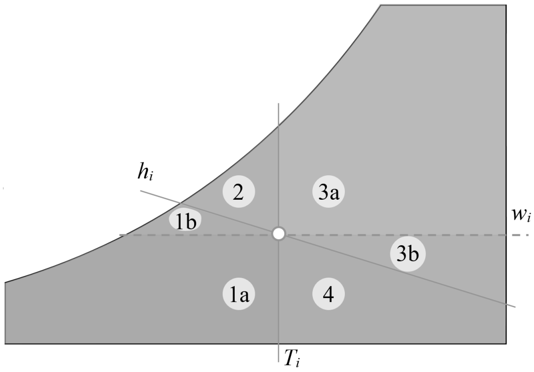

Figure 6: Enthalpic, sensible and latent heat recovery zones in winter and summer.

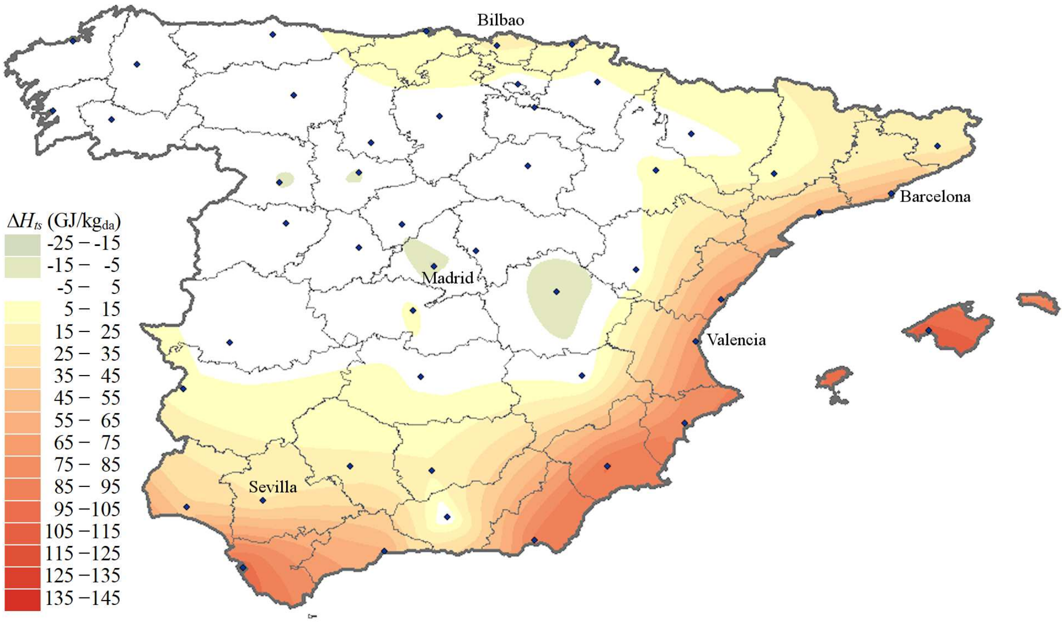

Figure 7: Energy recovery potential difference in summer.

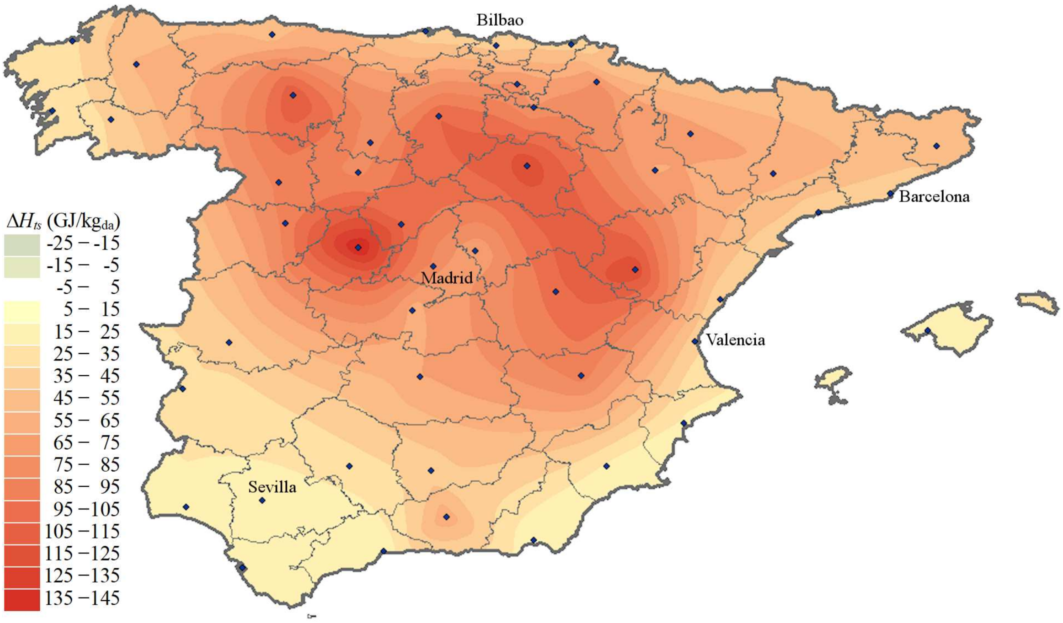

Figure 8: Energy recovery potential difference in winter.

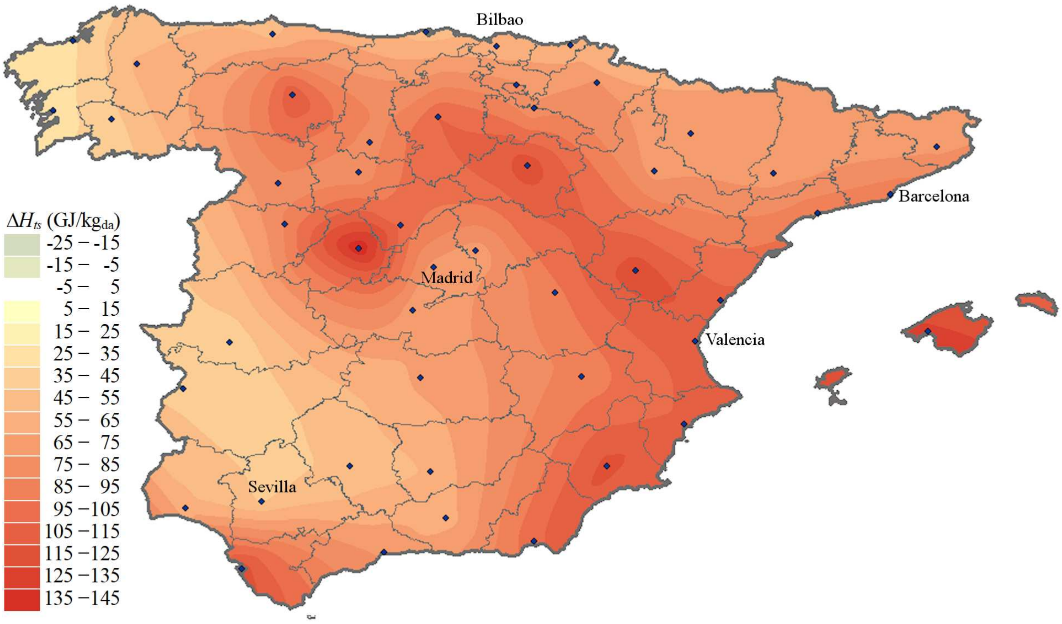

Figure 9: Yearly energy recovery potential difference.