Control strategies for Energy Recovery Ventilators in the South of Europe for residential nZEB. Quantitative analysis of the air conditioning demand.

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Abstract.

Mechanical ventilation systems are essential for ensuring the indoor quality of air in nZEB (nearly Zero Energy Buildings) with a high level of airtightness. In cold countries, it has already been demonstrated that Heat Recovery Ventilators (HRV) recovering the sensible energy from air ventilation are needed to achieve the energy demand goals for nZEB set by Passivhaus. In tropical areas with hot temperatures and high relative humidity in the ambient air, the necessity of recovering latent and sensible energy with Energy Recovery Ventilators (ERV) has also been demonstrated. However, in warm climates with medium relative humidity levels, for example in cities located on the Mediterranean coast, the evaluation of the effectiveness of an EVR for residential buildings has to be analyzed and optimized.
This article establishes the effectiveness of several control strategies for ventilation air systems including ERV with the aim of optimizing the air conditioning energy demand of dwellings located in several cities in the South of Europe. Possible control strategies have been analyzed to minimize the undesirable operation of ERVs which could otherwise increase the air conditioning energy demand for winter and summer seasons. The impact of the latent effectiveness and the effect of free-cooling on the air conditioning energy demand is also studied.

Keywords

Energy Recovery Ventilator; Residential dwellings; Mediterranean climate; nZEB;

1. Introduction.

As a consequence of the European Directive 2010/31 [1] regulating energy demand in the building sector, new buildings will have to be nearly zero energy buildings (nZEB) from 2020 (from 2018 in the case of new public buildings). The maximum air conditioning energy demand set by the Passivhaus standard [2], a reference for the definition of nZEB, has been used in this article.

The first obvious action to achieve desired energy demands is to improve the building envelope to reduce thermal losses. The second is to reduce air infiltrations by increasing the airtightness of buildings. However, the reduction of air infiltration means that there is not enough fresh air to guarantee the indoor air quality for occupants. Therefore the inclusion of mechanical ventilation systems becomes mandatory for residential buildings. Hence, ventilation air becomes an important source of energy loss for nZEB. Guillén-Lambea et al.[3] show that ventilation thermal loads account for almost the total thermal loads for residential nZEB located in mild climates and conclude that only buildings located in the hottest cities (of which there are few in the Mediterranean area) are capable of fulfilling the air conditioning demand of nZEB without a Heat Recovery Ventilator (HRV).

Depending on the climate area, the latent load could represent a significant fraction of the total thermal load in air conditioning systems. The energy recovery ventilator (ERV) is an exchanger made of a permeable medium that transfers both moisture and heat from one air stream to another. Suitable permeable materials include cellulose, polymers, and other synthetic membranes [4]. Zhang [5] states that cooling and dehumidifying fresh ventilation air constitutes 20–40% of the total energy load for air conditioning in hot and humid regions. An enthalpy/membrane energy exchanger has been experimentally investigated [6] and the study shows that including an ERV in the mechanical ventilation system instead of a conventional HVAC system reduces the total energy consumption by 8% in tropical climates (Kuala Lumpur) and by 4% in a moderate climate (Sydney). Zhang et al. [7] developed a theoretical thermodynamic model that includes a membrane-based energy exchanger air dehumidification system. Their results show that using a membrane energy exchanger provides energy savings of up to 33% for a commercial building situated in a humid region in China.

Several researchers have looked at control strategies in order to achieve the highest possible performance of ERVs. Rasouli et al. [8,9] investigate the energy savings achieved with the use of an optimized control system for the ERV by performing simulations using TRNSYS of an office building in four North American cities. They find that an ERV not properly controlled may increase the cooling demand, but conclude that an ERV can save energy by up to 10% for an office building in Chicago and 15% in Miami using an optimal control strategy, compared with the use of an HRV only. Liu et al. [10] simulate an apartment in five cities in China demonstrating that the ERV is an effective energy saving method in some of them, but conclude that an ERV is better for non-residential buildings that need more fresh air.

Although membrane ERVs are available on the market, they continue to raise some unanswered questions. For example, what is the performance of these units working under real conditions in real houses, and how does this compare with the performance measured in the laboratory? More importantly, are these products suitable for recovering the humidity in residential buildings located in warm and medium humid climates in the south of Europe?

The present study is focused on the Mediterranean area, where warm climate conditions with medium humidity could justify the use of energy recovery systems as opposed to heat recovery systems alone. For this purpose, a dwelling for a family of four people situated in a block of houses has been modeled in TRNSYS [11]. The model has been validated with monitored values obtained from a real nZEB house. Simulations have been done for different control strategies of the energy recovery system in order to define the maximum recovery energy from ventilation air for each location. The paper's aim is to propose an optimal control for the ERV to minimize the air conditioning energy demand for areas with mild winters and warm and medium-humid summers, characteristic of the Mediterranean area. Additionally, simulations have been performed to check the influence of the latent effectiveness of the ERV and the effect of the free-cooling on the total air conditioning energy demand.

2. Computational model.

2.1 Software.

A computational model has been developed using TRNSYS [12] software to simulate the energy demand for heating and cooling the selected residential housing. A TRNSYS project is typically set up by connecting components graphically in the Simulation Studio. TRNSYS components are referred to as Types. The building model is known as Type56 [13] and is used in this study to simulate the dwelling. The heat exchanger is simulated using the Type667 [14].

TRNSYS also interfaces with various other simulation packages. In our TRNSYS model, the Engineering Equation Solver (EES) is called using Type 66 [15] in order to control the by-pass of the ERV depending on the temperature, humidity and enthalpy of the air streams. EES [16] is a non-linear equation solver that has been used to solve sets of equations to control the operating mode of the ERV, simulating several operating strategies.

The simulations provide the sensible energy demand for heating and cooling and the latent demand for dehumidification and humidification throughout one year on an hourly basis for several cities located in different countries.

2.2. Dwelling description.

The dwelling is taken from a real project built in Spain. This dwelling has been selected as it is a typical dwelling for a family of four persons in the south of Europe. The apartment is located on the top floor of a building of 4 floors. This dwelling has previously been used in a study of the annual envelope energy losses in buildings [17] and in a study comparing the ventilation flow rates in residential buildings imposed by the regulations of some countries [3]. The building area and enclosure technical parameters are indicated in Table 1. The envelope transmittance values are those recommended by Passivhaus [18] for Southern Europe.

2.3. Air Ventilation system.

The air ventilation system layout is represented in Figure 1. The air discharged from the most contaminated rooms (kitchen, bathroom and toilet) never comes into contact with the fresh air entering the dwelling, therefore issues related to air purification and bacterial contamination may not arise. The ERV system also includes a filter for the incoming air flow in order to guarantee the air quality and a second filter for the exhaust air to protect the ERV. The air flow distribution (%) for each room is indicated in Figure 1. The percentages are those recommended by a company which currently develops and commercializes the ERV, based on the occupation and the air volume of the rooms. The energy supplied to the two ventilators for the proposed system will be 0.29 Wh/m^3. (Data supplied by Zehnder Group Iberica IC S.A).

The ventilation air flow is a significant parameter for the energy demand in a nZEB dwelling. The minimum air flow rate recommended or imposed in the regulations of some countries is detailed in a previous article [3]. The Passivhaus standard establishes a value between 30 m^3/h and 32 m^3/h per person (for residential use) [2]. Taking into account that the simulated dwelling is suitable for a family of 4, the total air ventilation rate considered in the model is 120m^3/h. The air ventilation flow will be constant throughout the year, except that an extra ventilation flow is added during five hours of high occupation assumed at the weekend when the air ventilation flow will be 240m^3/h.

2.4. Internal loads.

The internal loads consist of sensible and latent heat transfers due to occupants, appliances and lighting. The lighting load is only sensible. The model includes sensible and latent loads due to occupation, and the nominal load is calculated by considering four people in the house: 1 person in the kitchen, 1 person in the main bedroom and 2 people in the living room. The heat generation according to different degrees of activity follows the values detailed in the ISO 7730: 2005 [19]. The nominal values applied to the model are shown in Table 2.

For lighting and equipment a load of 2.5 W/m^2 and a computer with a monitor in the living room with a load of 230W, have been considered.

The nominal latent and sensible loads are multiplied by a coefficient depending on the time of day, related to the occupancy indicated in Table 3.

2.5. Comfort parameters

The room temperature set is 20°C for heating and 26°C for cooling, following the Passivhaus recommendations and the European Standard EN 15251:2007 [20] regarding the indoor environmental input parameters for the design and assessment of the energy performance of buildings.

As regards relative humidity, the simulations were also performed using the values recommended by the Passivhaus standard with a relative humidity set at 30% for winter and 60% for summer.

2.6. Selection of climate data and cities.

The climate data files are taken from the Meteonorm meteorological database [21].The Typical Meteorological Year (TMY 2) weather data format is compatible with TRNSYS using a Type15-6 and contains hourly weather data for yearly building energy analysis.

The climate considered in the study is common in Italy, Southern France, Spain and Greece, and representative cities from the Mediterranean area have been selected taking into account the different humidity levels found close to the Mediterranean area. These values are not so important as for cities located in tropical climates, cases which have already been studied by other authors whose results show the advantages of ERV systems in such locations. Zhang [22] found good results for ERV systems in the south of China, were the summer is long, hot and humid. The novelty of the present study is the evaluation of the effectiveness of an ERV in a climate where humidity levels are not as high as in tropical climates.

The locations of the selected cities are shown on the map in Figure 2. The mean season air temperatures and relative humidity (winter and summer) are given in Table 4. Table 4 also includes the percentage of the latent energy in the ambient air calculated on an hourly basis throughout the year [23].

2.7. Model validation.

A real house has been used to validate the TRNSYS model. In absence of measured data accessible from a nZEB dwelling, due to the scarcity of housing blocks following the nZEB requirements in Spain (as those required for Passivhaus), the measured data coming from a monitored single family house have been used in order to eliminate possible model errors that could come from improper model parameters selection.

The house was monitored and measured (room temperatures, outdoors temperature and energy consumption) throughout one year. It is located in Collsuspina, a town 70 km north of Barcelona (Spain), not on the coast. The house was built following the Passivhaus standard. Accordingly, the energy performance, technical characteristics and the comfort conditions are the same as those for the dwelling under study.

The technical properties of the building enclosure are shown in Table 5. The ground floor has two bedrooms, one bathroom and one toilet and the first floor a living room and a kitchen.

Four persons live in the house, two adults and two children. Their habits have been studied to define the sensible and latent heat transfers due to occupants. The internal source loads have been obtained from the electrical energy consumption of the house.

The house has a mechanical ventilation system including a HRV. The HRV has a measured effectiveness of 0.84 at 120 m^3/h. The supply air ventilation flow is 40% for the living room and 30% for each of the two bedrooms. Of the exhaust air flow, 45 % leaves the kitchen, 35% the bathroom and 20 % the toilet.

The house has electrical radiators as a heating source and does not have cooling devices. The temperature set values for the house are 20ºC in winter and 26ºC in summer.

The monitored values are: internal temperatures (ground and first floor), ambient temperature, total electrical energy consumption of the house, electrical energy consumption due to the mechanical ventilation system and electrical energy consumption due to the electric radiators.

The simulations were performed for February, a cold month. The real ambient air temperature was measured on an hourly basis and included in the model. However, further climatological data were needed to perform the simulations (solar radiation loads), therefore the data for Barcelona city (as the closest city) from the Meteonorm meteorological database have been used.

The energy demand in winter was obtained through the electrical consumption of the radiators. For February 2016 this was 74.02 kWh. The heating demand for the same month obtained from the model was 70.68 kWh. For electrical radiators a COP= 1 should be used, then the error obtained is 4.5%.

The uncertainties which could explain the difference are:

• Only the ambient temperature introduced in the TRNSYS model is the real value of the temperature in Collsuspina.

• The real opening and closing of the door and windows is not included.

The measured and simulated air temperatures have been compared (for both the ground floor and the first floor), obtaining comparable values. Figure 3 shows the temperatures during one day in February.

The TRNSYS model used in the simulations is exactly the same as that used for the validation. Only the building model (Type56) for Collsuspina has been replaced for the proposed dwelling model.

In conclusion, it is considered that the error (4.5%) is small enough to ensure that the data obtained from the simulated dwelling are sufficiently consistent to be able to reach solid conclusions.

3. Control strategies for Energy Recovery Ventilators in the South of Europe.

The control strategies have been analysed separately for the winter season (from October to May) and the summer season (from June to September). Heating demand and cooling demand calculations have significant differences.

3.1. Control strategies during winter season.

Three winter strategies (WINTER 1, WINTER 2, WINTER 3) have been simulated in TRNSYS for each of the Mediterranean cities, modifying the EES type to control the by-pass in the recovery system. The strategies depend on the outdoor air temperature and humidity, as shown in Table 6.

WINTER 1 simulates a ventilation system with an ERV which has a control based only on the sensible energy. If the outdoor air temperature is lower than the indoor air temperature, the supply air will pass through the heat exchanger to recover energy (a situation occurring almost all of the time for all the studied cities), otherwise the by-pass will be open. This situation will reduce the maximum sensible heating demand. However, this is not the optimum condition for recovering the latent energy.

WINTER 2 simulates a ventilation system with an ERV which has a control based only on the latent energy. If the outdoor air absolute humidity is lower than the indoor air absolute humidity, the by-pass will be open and the supply air will not pass through the heat exchanger. Otherwise, the by-pass will be closed. This situation will reduce the maximum dehumidification demand but as sensible energy is not recovered the heating demand will increase.

A third simulation has been added, WINTER 3, which simulates a ventilation system with an HRV for the purposes of comparison. The control system will open the by-pass only if the outside temperature is higher than the indoor temperature (almost never).

3.2. Control strategies during summer season.

Four summer strategies (SUMMER 1, SUMMER 2, SUMMER 3, SUMMER 4) have been simulated in TRNSYS, modifying the EES type to control the by-pass. These are shown in Table 7.

SUMMER 1 simulates a ventilation system with an ERV which has a control based on the sensible energy. If the outdoor air temperature is lower than the indoor air temperature, the by-pass will be open and the supply air will not pass through the heat exchanger to cool the dwelling (a situation occurring during nights). Otherwise, the by-pass will be closed. This situation will reduce the maximum sensible cooling demand but will be not the optimum for recovering the latent energy.

SUMMER 2 simulates a ventilation system with an ERV which has a control based on the latent energy. If the outdoor air absolute humidity is lower than the indoor absolute humidity, the by-pass will be open and the supply air will not pass through the heat exchanger. Otherwise, the by-pass will be closed. This situation will reduce the maximum dehumidification demand but the sensible cooling demand is expected to be higher than for the SUMMER 1 strategy.

SUMMER 3 simulates a ventilation system with an ERV. The control system will check firstly the outdoor and indoor air temperature to apply the appropriate control as follows:

1) If the outdoor air temperature is higher than the indoor temperature the supply air will pass through the ERV.

2) If the outdoor air temperature is lower than the indoor air temperature then:

a) If the outdoor air absolute humidity is higher than the indoor absolute humidity and the latent energy to be recovered is higher than the sensible energy to be added to the dwelling, the supply air will pass through the ERV.

b) Otherwise, the supply air will pass through the by-pass.

SUMMER 4 simulates a ventilation system with an HRV to recover only sensible energy, for the purposes of comparison. The air will pass through the heat exchanger if the outdoor air temperature is higher than the indoor air temperature to reduce the cooling sensible energy demand.

4. Sensitivity of the latent effectiveness of the ERV.

The ERV recovers the sensible and the latent energy following eq.1.

$$\dot{Q}_{TOT,rec} = \dot{Q}_{s,rec} + \dot{Q}_{l,rec} = \dot{m}_{exh} \cdot (h_{exh,in} - h_{exh,out}) = \dot{m}_{sup} \cdot (h_{sup,out} - h_{sup,in}) \quad (1)$$

Where

$\dot{m}_{exh} = \dot{m}_{sup} = \dot{m}_{vent}$ for a balanced system is the ventilation air mass flow (Kg/s).

$h_{exh,\,in}$ is the enthalpy of the exhaust air at the inlet of the energy exchanger (kJ/kg $_{dry\text{-}air}$)

$h_{exh,\,out}$ is the enthalpy of the exhaust air leaving the energy exchanger (kJ/kg $_{dry\text{-}air}$)

$h_{sup,\,in}$ is the enthalpy of the fresh air at the inlet of the energy exchanger (kJ/kg $_{dry\text{-}air}$)

$h_{sup,\,out}$ is the enthalpy of the fresh air leaving the energy exchanger (kJ/kg $_{dry\text{-}air}$)

The heat recovery $\dot{Q}_{s,rec}$ (kW) depends on the sensible effectiveness of the heat exchanger and can be calculated using eq.2,

$$\dot{Q}_{s,rec} = \varepsilon_{sens} \cdot \dot{Q}_s \quad (2)$$

Where

$\dot{Q}_s$ is the sensible energy demand due to the air ventilation (kW)

ε_{sens}, the sensible effectiveness of the heat exchanger (-) for balanced systems, is defined by eq.3.

$$\varepsilon_{sens} = \frac{(T_{exh,in} - T_{exh,out})}{(T_{exh,in} - T_{sup,in})} \quad (3)$$

$T_{sup,in}$ is the temperature of the supply air at the inlet of the heat exchanger (ºC)

$T_{sup,out}$ is the temperature of the supply air exiting the heat exchanger or of the supply air entering the dwelling (ºC)

$T_{exh,in}$ is the temperature of the exhaust air entering the heat exchanger (ºC) or the exhaust air temperature leaving the dwelling (ºC)

$T_{exh,out}$ is the temperature of the exhaust air exiting the heat exchanger (ºC)

While the moisture recovery $\dot{Q}_{l,rec}$ (kW) depends on the latent effectiveness which can be calculated using eq.4.

$$\dot{Q}_{l,rec} = \varepsilon_{lat} \cdot \dot{Q}_l \quad (4)$$

Where

$\dot{Q}_l$ is the latent energy demand due to the air ventilation (kW)

ε_{lat} is the latent effectiveness of the heat exchanger (-) defined by eq.5,

$$\varepsilon_{lat} = \frac{(w_{exh,in} - w_{exh,out})}{(w_{sup,in} - w_{exh,in})} \quad (5)$$

$W_{sup,in}$ is the supply air specific humidity at the inlet of the heat exchanger ($kg/kg_{dry-air}$)

$w_{sup,out}$ is the supply air specific humidity exiting the heat exchanger ($kg/kg_{dry-air}$)

$w_{exh,in}$ is the exhaust air specific humidity at the inlet of the heat exchanger ($kg/kg_{dry-air}$)

$w_{exh,out}$ is the exhaust air specific humidity at the outlet of the heat exchanger ($kg/kg_{dry-air}$)

Following the equations, the sensible and latent effectiveness of the energy recovery system determines the energy loads of the air conditioning system due to ventilation air. The energy savings from the ventilation air of an ERV should be directly proportional to the sensible and latent effectiveness.

Woods [24] published a large review of ERV technologies for air conditioning systems. The data provided in his research confirms that the latent effectiveness is generally less than the sensible effectiveness. Zhang et al.[25] showed that while the sensible effectiveness remains practically constant, the latent effectiveness depends on the material permeability and the operating conditions (the air temperature and humidity). Several research studies have examined this phenomena [26,27]. Mardiana-Idayu and Riffat [28] state that heat recovery systems typically recover about 60–95% of the heat. Mardiana et al. [29] discuss the physical and performance parameters of a heat recovery unit and the significance of these parameters for the operation and efficiency of the system.

For the first set of simulations, the sensible effectiveness and latent effectiveness of the ERV remain invariable; their values are 0.9 and 0.6, respectively (results in Section 6.2 below). The effectiveness values have been selected taking into consideration the higher performances of ERVs currently available on the market as a first approach.

For the second set of simulations, the sensible effectiveness remains at 0.9 while the latent effectiveness varies in steps of 0.1 in order to find the optimum value for the selected cities (results in Section 6.3 below).

5. Natural ventilation and free-cooling.

Other strategies such as opening windows are necessary and highly recommended for Mediterranean cities, which have some difficulties in meeting the Passivhaus requirements for cooling demands. Additional specific actions and design modifications could be implemented to reach the required level of cooling demand, such as high performance shading devices or an optimal orientation as well as extending the time during which windows are open.

In summer, when the outdoor temperature is lower than the indoor temperature, the outside air could be used to reduce the cooling energy. In order to reduce the cooling demand, natural ventilation or free cooling are essential.

Natural ventilation is a technique whereby the entry of outside air into a building by natural means (not mechanical) is allowed. The outside air should enter the dwelling by opening the windows. The action thus depends on human factors, which is a drawback for calculating the energy efficiency of a dwelling. The infiltration due to opening windows is as required by Spanish law [14].

In a third step, simulations have been performed opening the windows during summer months between 01h am and 08h am, inclusive. During this time interval, it is assumed that the external living spaces have air infiltration caused by opening windows of 4 air changes per hour.

Free-cooling is a technique whereby the entry of outside air is allowed inside a building controlled by mechanical means. In fact it is controlled mechanical ventilation and takes advantage of many benefits of natural ventilation and eliminates much of its drawbacks, such as the human factor. Additional simulations have been carried out for a doubled ventilation air flow (240 m^3/h) during summer nights.

Section 6.4 shows the results for simulations performed applying natural ventilation and free cooling.

6. Results and discussion.

Firstly, as a base case, the results obtained without energy recovery in the ventilation system are presented to evaluate the benefits reported by the use of recovery systems for the cities under study (Section 6.1).

In the first step (Section 6.2), the control strategies are evaluated. The sensible effectiveness remained at 0.9 and the latent at 0.6.

In the second step (Section 6.3), the sensible effectiveness remained at 0.9 while the latent varied in steps of 0.1 (from 0.4 to 0.9).

In the third step (Section 6.4), simulations have been performed with the best control strategy and applying natural ventilation and free cooling strategies.

6.1. Base case: without energy recovery system.

Figure 4 shows the sensible and latent air conditioning demands for the simulated dwelling (in summer and in winter) without any energy recovery system for the ventilation air for each city under study. Simulations without an energy recovery system have been done in order to ascertain by comparison the benefits of the different recovery strategies proposed.

All the cities have higher latent energy demand for summer than for winter. Almeria, Palermo and Murcia have greater cooling demand than heating demand. Palermo has the highest dehumidification energy demand with 35% of the total air conditioning energy.

The Table 8 shows the percentage of the latent energy demand for the selected cities, those values can be compared with the percentage of the latent energy in the ambient air showed in Table 4.

6.2. Control strategies for the ERV.

The sensible effectiveness and latent effectiveness of the ERV remain invariable, their values being 0.9 and 0.6, respectively.

Murcia (41%), Palermo (51%) and Almeria (43%) are the cities with the highest percentage of latent energy in the ambient air (see percentages in Table 4). The results for Murcia, as an example of a city with high potential for latent energy recovery, are shown in Table 9. The calculated sensible and latent energy demand without any recovery system (base case) are also reflected in Table 9 for comparison.

For the winter season, the sensible demand is much more important than the latent demand and therefore a control strategy based on temperature is the most suitable. The results confirm that the control strategy based on temperature (WINTER 1) is the most appropriate since it can reduce sensible heating demand by 73% and only slightly increase the dehumidification demand by 3%. The total energy demand during winter is reduced by 58% compared with an air ventilation system without energy recovery. The control strategy based on latent demand (WINTER 2) reduces the sensible demand insignificantly, by a mere 6%, and the latent demand is reduced by just16%. This slight reduction is due to the fact that most of the time the humidity in the indoor air is higher than outdoors because of internal gains, hence the supply air does not pass through the ERV.

Finally, the values obtained for a HRV (WINTER 3) are the best for the winter season. This is due to the fact that using an ERV the moisture transfer occurs from the dwelling to the incoming air and the humidity is returned to the house. Hence, at this time operating an ERV increases the latent energy as it is added to the supply air.

For the summer season, the results indicate than the use of an ERV slightly reduces the cooling demand as a non-significant energy load is added by the air ventilation. The cooling demand is more influenced by other parameters such as internal loads and solar radiation. Besides, the use of a HRV (SUMMER 4) does not significantly reduce the energy demand of the dwelling, and its inclusion in the air ventilation system does not seem to be profitable.

The reduction obtained by the temperature control strategy (SUMMER 1) is not so significant as to justify the use of an ERV: 3% for sensible demand and 14% for latent demand resulting in 7% of the total energy demand. Accordingly, temperature control during summer is not appropriate.

Otherwise, a control strategy based on the humidity control (SUMMER 2) significantly reduces the latent demand by 18% but increases the sensible cooling demand by 11% because the outdoor fresh air is heated by the indoor air before entering the dwelling, worsening the sensible demand. In consequence, the reduction is less than 1% of the total energy demand during summer.

The enthalpy control system checks every hour the potential sensible and latent energy demands to be recovered (SUMMER 3) in order to control the by-pass. The sensible cooling demand is not affected, but the latent demand is reduced by 27% and the total energy demand by 11% during summer.

The results obtained for all the cities indicate that the ERV optimal control is WINTER 1 + SUMMER 3. Figure 5 shows the results in all the selected cities applying this optimal control.

Comparing Fig.5 with Fig. 4, the sensible heating demand due to air ventilation has been almost eliminated. The sensible cooling demand remains almost invariable, the reductions being between 4 %

and 0%. The greatest reduction is for Palma de Mallorca and Cagliari with 4%, followed by Naples, Rome, Marseille, Valencia and Almeria with 3%. The lowest is for Murcia and Alicante with 0%. This is due to the fact that the cooling demand is principally affected by internal gains and radiation heat much more than by the ventilation air. The cooling load due to the ventilation air is almost unappreciable. The results show that in summer the difference in sensible cooling demand without and with energy recovery applying SUMMER 1 or HRV (controlled by temperatures) for Murcia is just 0.5 kWh/m^{2}y (see Table 8).

The latent demand is slightly increased in the winter season for all the cities except for Palermo. However, in summer the dehumidification energy demand is reduced in all the cities by more than 17%, except for Marseille where the latent energy demand increases by 4%. The largest reduction is obtained in Palermo with 32%.

Cooling demand is higher than the heating demand using the ERV in all the cities except Marseille. Looking at the total demands, the reductions in sensible and latent demand throughout the year with an optimized control for the ERV compared with a ventilation system without an energy recovery ventilator are shown in Figure 6. The reduction in the total air conditioning energy demand when including an HRV in the air ventilation system has also been included in order to show the extra reduction provided by the ERV.

Marseille and Cagliari show an increase in the total energy demand when including an ERV instead of an HRV. The extra reduction in the air conditioning energy demand when installing an ERV instead of a HRV is the greatest for Palermo (5.1%). For Almeria and Murcia the extra reduction is 2.4 % and 2.2 %, respectively. For the rest of the cities the reduction is almost negligible.

6.3. Latent effectiveness of the ERV.

A more complete analysis has been carried out on the latent effectiveness. In a second step, additional simulations have been performed to check the impact of the latent recovery effectiveness on the air-conditioning energy demand. The sensible effectiveness remained invariable while the latent effectiveness varied in steps of 0.1. The control strategy was WINTER 1 and SUMMER 3 (W1_S3) as these provide the best results.

The simulations were performed for Valencia and Palma de Mallorca as cities with moderate latent energy demand, for Murcia and Almeria as cities with medium latent energy demand, and for Palermo as the city with highest latent energy demand. The results are shown in Figure 7.

For all the cities, the winter dehumidification demand increases when the latent ERV efficiency is increased. This is because the control strategy is based on winter temperatures, and the exchange of sensible energy prevails over latent energy as it is much more important. However, to avoid an increase in the latent demand, outdoor air should not pass through the ERV if its absolute humidity is less than that of the housing. In such a case, by passing through the ERV, the outdoor air absorbs moisture from the housing which is reintroduced. Thus, increasing the latent efficiency leads to greater demand for dehumidification in winter. In contrast, in the summer season increasing the efficiency decreases the latent demand because the outdoor humidity is almost always higher than that of the dwelling and therefore the air is dried before entering. In order to obtain the optimal latent effectiveness, the addition of winter and summer latent demands should be analyzed.

For Valencia and Palma de Mallorca, the total latent energy demand rises when the latent effectiveness increases. This is because the latent energy demand increases more in winter than it decreases in summer and therefore the total balance, contrary to expectations, is worse. There is an optimum value for latent effectiveness on these cities: 0.5. If the effectiveness is further reduced to 0.4, then the total latent demand increases again.

For Murcia the optimum value is between 0.6 and 0.7 at which the total latent energy demand remains constant at the minimum value. For Almeria the optimum value is 0.6. For Palermo, the city with the greatest latent energy, the optimum value for latent energy demand is 0.8.

An increase in the sensible effectiveness (ε_s) leads directly to a reduction in the sensible demand. This obvious fact cannot be applied to the latent effectiveness for Mediterranean cities were an increase in the latent effectiveness (ε_l) does not lead directly to a reduction in the latent demand as, in some conditions, the humidity will be transferred in the wrong direction for energy savings.

6.4. Natural Ventilation and Free cooling.

Simulations applying free cooling and natural ventilation have been performed in order to check their impact on a dwelling with a mechanical ventilation system. The simulations were carried out using the control strategy SUMMER 3, as this was revealed to be the best in terms of energy demand during summer.

The results for Murcia are shown in Table 10 for natural ventilation SUMMER 3 OW (Open Windows) and for Free Cooling SUMMER 3 FC.

The natural ventilation reduces the sensible cooling demand by 35%, which is very effective. However, it is not appropriate for latent energy which is increased by 131%. The total energy demand during summer is increased by 21% compared with the result with closed windows (SUMMER 3).

For Free Cooling, the sensible cooling demand is reduced by 8% but the latent demand is increased by 11% and the total energy is reduced only by 1.5% during summer compared with SUMMER 3.

7. Conclusions.

Eleven cities located on the Mediterranean coast in Southern Europe have been selected for this study. The Mediterranean climate is warm with medium relative humidity levels.

Simulations were performed to check the suitability of including ERVs instead of HRVs in air ventilation systems. Possible ERV control strategies have been analyzed separately for the winter and summer seasons.

The optimum strategy during winter is a control based only on the sensible energy. When the outdoor air temperature is lower than the indoor temperature, the supply air passes through the ERV. Otherwise, it passes through the by-pass. This situation reduces the maximum sensible heating demand. However, does not represent the optimum for the recovery of the latent energy.

For all the cities except Palermo (the most humid city studied), the use of an HRV instead of an ERV results in lower values for the air conditioning demand in the winter season.

The optimal strategy found for the summer season is based on the enthalpy control. If the outdoor air temperature is higher than the indoor temperature, the supply air will pass through the ERV. If not, the air humidity and the potential latent and sensible energy demands should be calculated. If the outdoor air absolute humidity is higher than the indoor humidity and the potential latent energy demand to be recovered is higher than the sensible energy demand added to the dwelling, the supply air will pass through the ERV. If not, the supply air will pass through the by-pass.

The reduction in energy demand resulting from installing an ERV and applying the control strategy proposed in this article (for sensible effectiveness of 0.9 and latent effectiveness of 0.6) is very significant compared to the absence of a recovery system. Nevertheless, it is not very notable when compared to the use of an HRV.

Palermo achieves a reduction in the air conditioning energy demand of 27.3% with an ERV, 5.1% more than installing an HRV. For Palermo, Murcia and Almeria, the cities with percentages of latent energy in the ventilation air higher than 40%, the use of an ERV instead of an HRV could be recommended as effective for the reduction of air conditioning energy demand (5.1%, 2.4% and 2.2% respectively).

For three cities, Rome, Marseille and Cagliari, with percentages of latent energy in the ventilation air lower than 21%, the installation of an ERV instead of an HRV is not recommendable. For Marseille and Cagliari the air conditioning energy demand is increased. For Rome (17% of latent energy in the ventilation air) the energy demand remains unchanged.

For the rest of the cities, where the percentage of the latent energy in the ventilation air is between 23% and 27%, the use of an ERV instead of an HRV is not justified by the results obtained. A more in-depth and specific analysis is recommended for the cities with a percentage between 30% and 40% (Alicante 32%).

The results demonstrate that the cooling demand is slightly affected whereas heating is heavily impacted by the air ventilation flow. Analyzing the values obtained for the cooling demand in the Southern Europe cities when ERVs are installed, it is worth noting that the cooling demand is higher than the heating demand in all cities except Marseille.

Simulations for different levels of latent effectiveness while maintaining the sensible effectiveness invariable have been performed. An increase in latent effectiveness could increase the latent energy demand, as the optimum value should be calculated taking into account the dehumidification energy demand in both the summer and winter seasons.

In summer, the latent energy demand decreases when the latent effectiveness of the ERV increases. However, unexpectedly the opposite occurs in winter. The result is that in some cities, such as Valencia and Palma de Mallorca, increasing the latent effectiveness, contrary to expectations, increases the total latent energy demand.

The greater the latent potential energy that may be recovered, the higher is the optimum value of the latent efficiency. This is the case of Palermo, where the optimum value for latent effectiveness is 0.8 (for 0.9 sensible efficiency), but the reductions obtained in the total energy demand are not significant.

For Murcia and Almeria, the optimum value for latent effectiveness is 0.6.

Simulations applying natural ventilation and free cooling have been performed. Opening windows during summer nights is a very effective way of reducing the sensible demand under nZEB requirements, but it is not appropriate for latent energy which substantially increases.

Furthermore, simulations have been performed for a double ventilation air flow during summer nights (Free Cooling). The sensible cooling demand is reduced, but latent demand is increased and the total energy is reduced by only 1.5% during summer for Murcia, compared with the absence of free-cooling.

8. Further research.

Future work should include a detailed economic analysis. Dehumidifiers have a non-negligible cost. In some cases, the extra cost of an ERV instead of an HRV could be justifiable if the dehumidifier can be removed.

An analysis of energy consumption versus investment should also be carried out.

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Figure 1. Air ventilation system layout.

Figure 2. Mediterranean cities selected.

Figure 3. Air temperatures.

Figure 4. Air conditioning energy demand in the selected cities without energy recovery in the ventilation air system.

Figure 5. Energy demand in the selected cities with the optimal control strategy of the ERV (WINTER 1+ SUMMER 3).

Figure 6. Reduction in air conditioning energy demand (%).

Figure 7. Latent energy demand for εs=0.9.

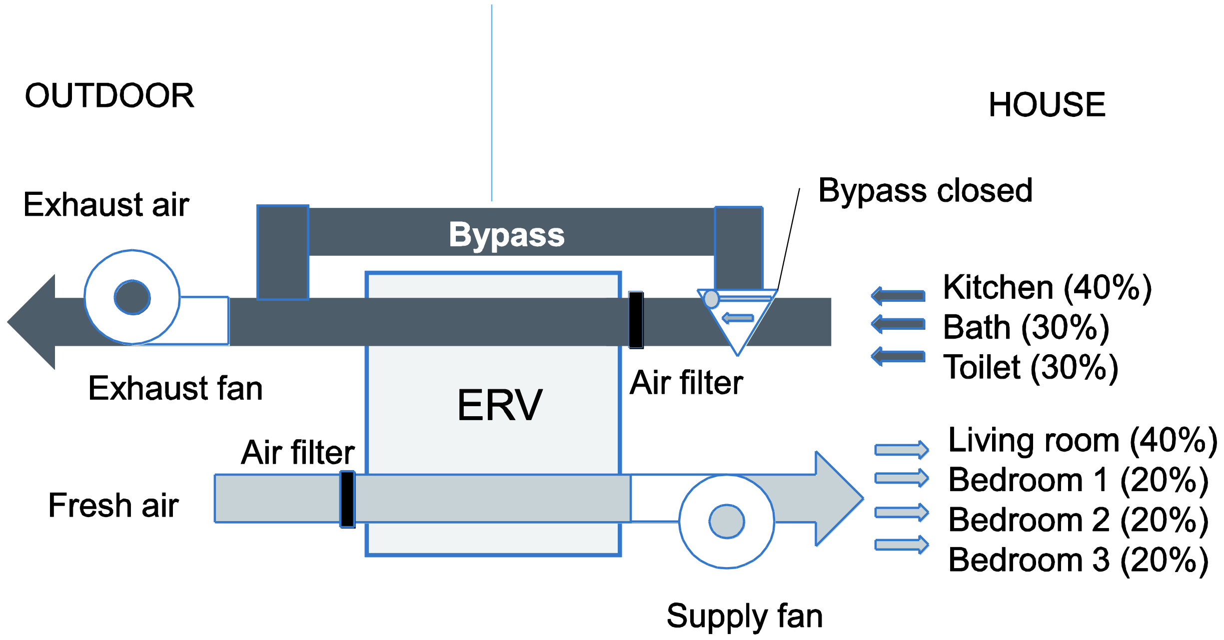

Figure 1. Air ventilation system layout.

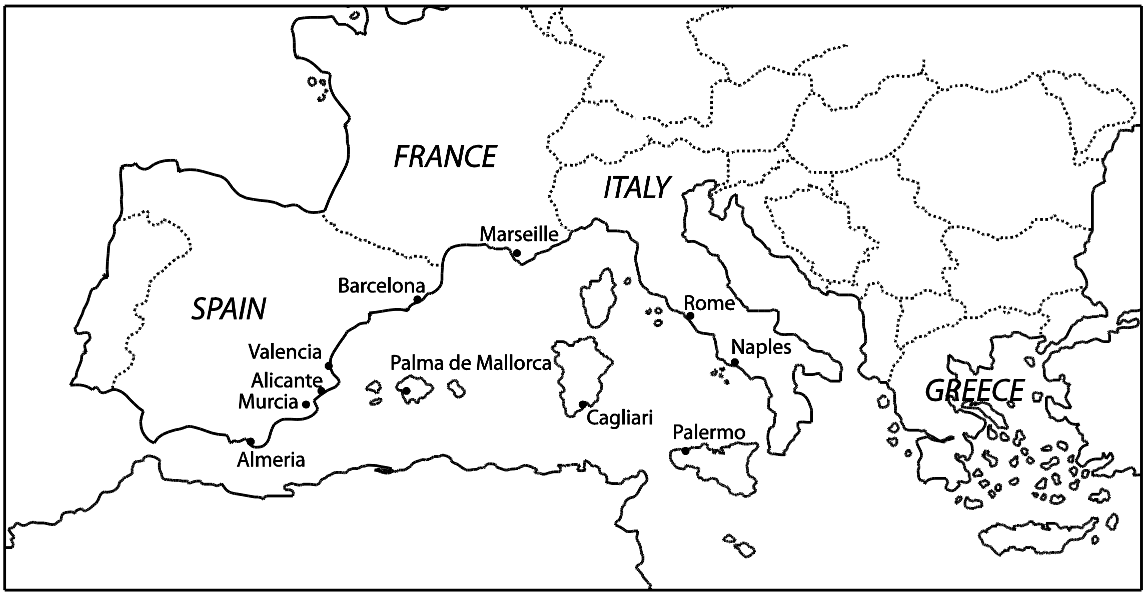

Figure 2. Mediterranean cities selected.

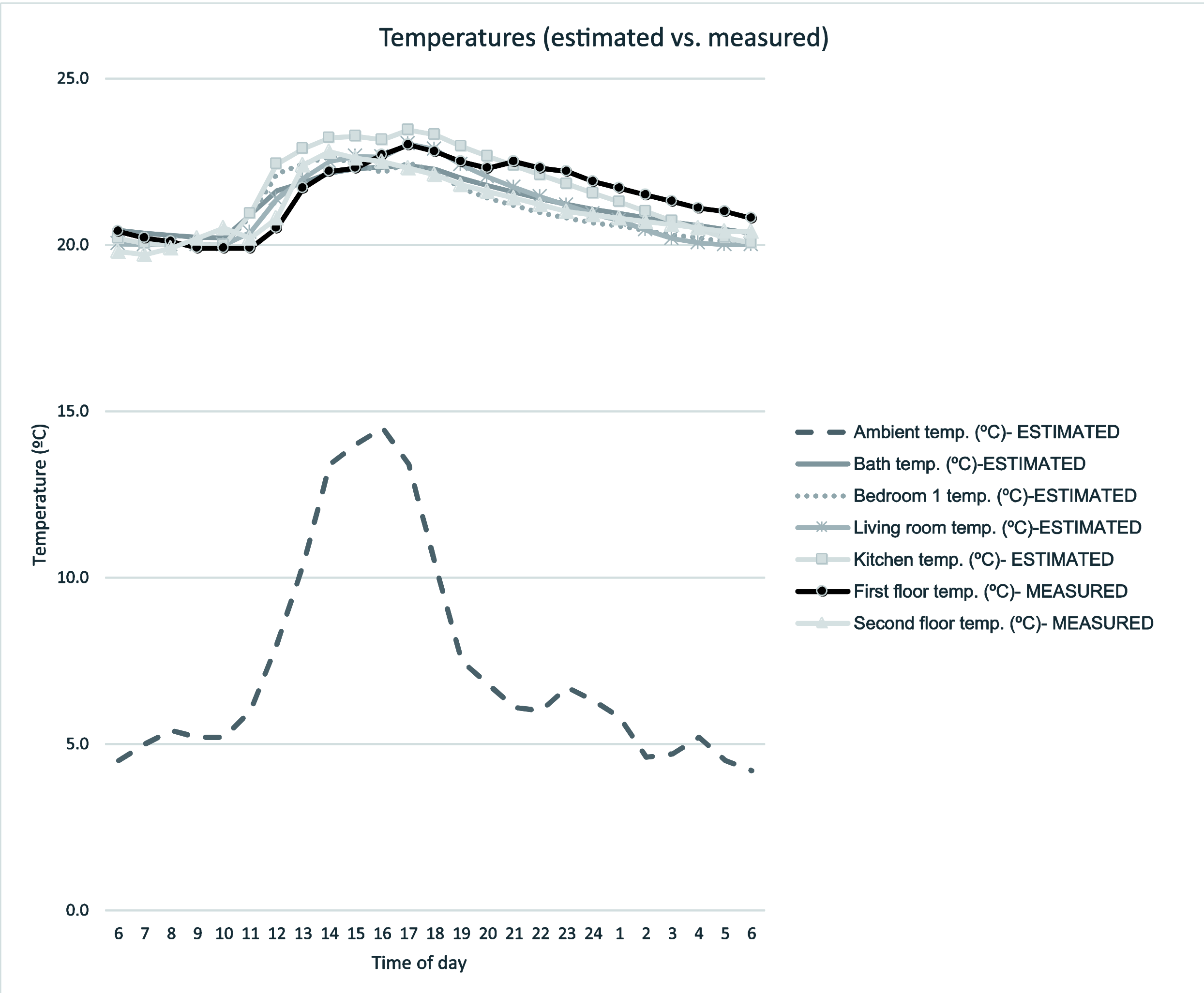

Figure 3

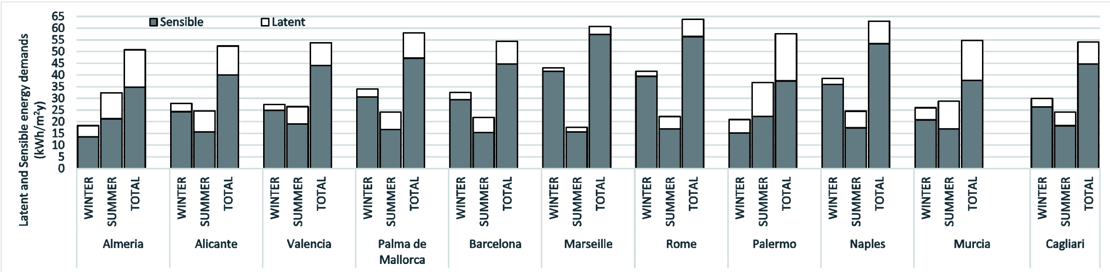

Figure 4. Air conditioning energy demand on the selected cities without energy recovery in the ventilation air system.

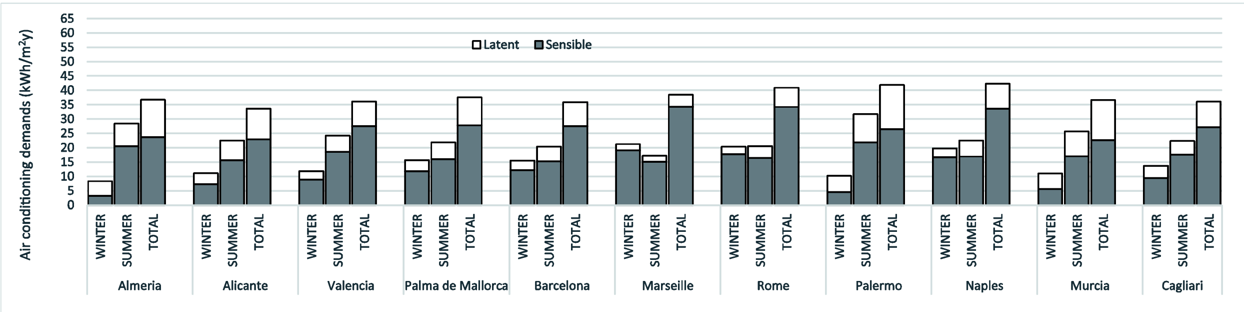

Figure 5. Air conditioning energy demand for the optimal control strategy of the ERV (WINTER 1 + SUMMER 3).

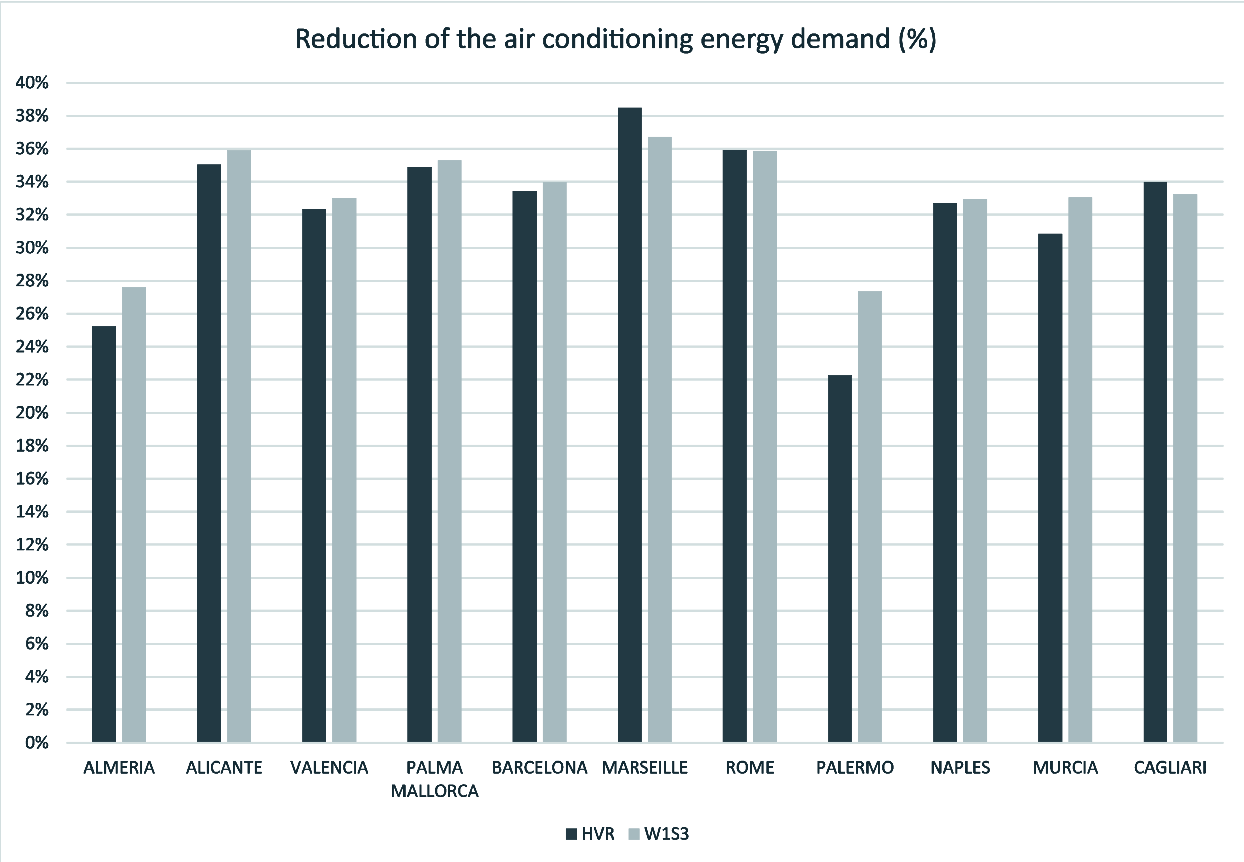

Figure 6. Reduction in air conditioning energy demand (%).

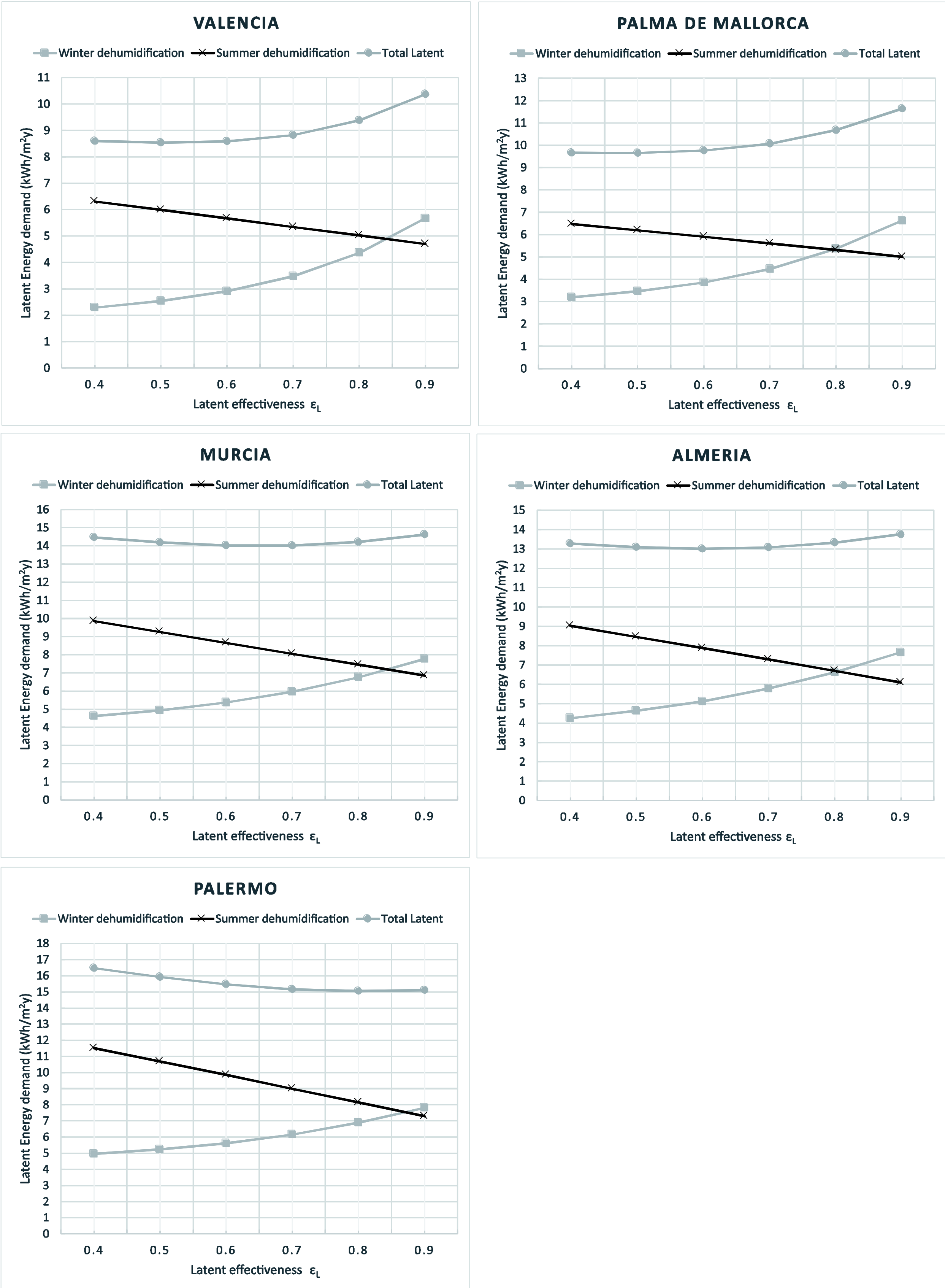

Figure 7. Latent energy demand for εs=0.9.

Table 1. Building enclosure technical parameters

Building enclosure	Total Area (m^2)	Transmittance U ($W/(m^2K)$)
External Walls	North: 15.7	0.34
	South: 18.2	
	East: 20.0	
	West: 6.8	
Floor	81.15	0.26
Roof	81.15	0.26
Windows	North: 8.4	1.40
	South: 10.8	
	East: 0.0	
	West: 0.0	
Airtightness n_{50}=0.60 ACH (maximum infiltration level stated by Passivhaus Ceiling height 2.5m.		

Table 2. Rates of heat gain from occupant spaces according to ISO7730.

	Nº of persons	SENSIBLE LOAD FOR 1 PERSON (W)	LATENT LOAD FOR 1 PERSON (W)
Kitchen	1	75	95
Bedroom	1	60	40
Living room	2	65	55

Table 3. Coefficients of internal loads applied in the model depending on the time of day.

	TIME OF DAY- WORKING DAY					TIME OF DAY- WEEKEND				
	0-7	**7-13**	**13-15**	**15-20**	**20-24**	**0-9**	**9-12**	**12-17**	**17-22**	**22-24**
Sensible & Latent Loads due to occupancy	0.50	0.25	1.00	0.50	0.75	0.50	0.25	2.00	0.50	1.00
Lighting, equipment and devices	0.00	0.50	0.00	1.00	0.50	0.00	0.50	1.50	1.00	0.50

Table 4. Mean season (winter and summer) air temperature and relative humidity. Meteonorm meteorological database. Percentage of the latent energy in the ambient air [23].

Cities	Winter	Summer	Year	% of latent energy on ventilation air[23]

ALMERIA	T (ºC)	15.6	24.5	18.5	
	HR (%)	74.6	71.5	74.0	43%
ALICANTE	T (ºC)	14.8	24.0	17.9	
	HR (%)	68.5	70.0	69.0	32%
VALENCIA	T (ºC)	14.4	23.4	17.4	
	HR (%)	65.0	70.0	67.0	24%
PALMA DE MALLORCA	T (ºC)	12.7	22.7	16.0	
	HR (%)	78.4	74.3	77.0	26%
BARCELONA	T (ºC)	12.2	21.7	15.3	
	HR (%)	77.9	77.8	78.0	27%
MARSEILLE	T (ºC)	11.2	22.1	14.8	
	HR (%)	70.9	64.5	69.0	7%
ROME	T (ºC)	11.5	22.6	15.2	
	HR (%)	74.8	67.5	72.0	17%
PALERMO	T (ºC)	15.7	24.6	18.7	
	HR (%)	73.3	76.0	74.0	51%
NAPLES	T (ºC)	12.4	23.1	16.0	
	HR (%)	73.0	71.0	72.0	23%
MURCIA	T (ºC)	13.9	23.1	16.9	
	HR (%)	77.4	76.3	77.0	41%
CAGLIARI	T (ºC)	13.3	23.3	16.7	
	HR (%)	76.4	67.3	73.0	21%

Table 5. Technical properties of real building enclosure.

Building enclosure	**Total Area (m^2)**	**Transmittance U ($W/(m^2K)$)**
External Walls	North: 35.2	0.127
	South: 27.8	
	East: 28.2	
	West: 25.1	
Floor	50.0	0.165
Roof	50.0	0.122
Windows	North: 4.1	1.060
	South: 13.9	
	East: 1.8	
	West: 4.9	
External door	North: 2.3	1.000
Airtightness n_{50}=0.32 ACH		

Ceiling height 2.5m

Table 6. Strategies for energy recovery in the winter season.

WINTER	Control Strategy		
Outdoor air temperature vs Indoor air temperature (T_{out}, T_{in})	**Strategy for sensible energy demand**	**Strategy for latent energy demand**	**HRV for comparison**
$T_{out} < T_{in}$	ERV	If $w_{out} > w_{in}$ then ERV else By-pass open	HRV
$T_{out} > T_{in}$	By-pass open		By-pass open
	WINTER 1	**WINTER 2**	**WINTER 3**

T_{out}: outdoor air temperature; T_{in}: indoor air temperature;

w_{out}: outdoor air absolute humidity; w_{in}: indoor air absolute humidity

Table 7. Strategies for energy recovery in the summer season.

SUMMER	**Control Strategy**			
Outdoor air temperature vs Indoor air temperature (T_{out}, T_{in})	**Strategy for sensible energy demand**	**Strategy for latent energy demand**	**Optimal strategy**	**HRV for comparison**
$T_{out} < T_{in}$	By-pass open	If $w_{out} > w_{in}$ then ERV else By-pass open	If ($w_{out} > w_{in}$ and $Q_l > Q_s$) then ERV else By-pass open	By-pass open
$T_{out} > T_{in}$	ERV		ERV	HRV
	SUMMER 1	**SUMMER 2**	**SUMMER 3**	**SUMMER 4**

T_{out}: outdoor air temperature; T_{in}: indoor air temperature;

w_{out}: outdoor air absolute humidity; w_{in}: indoor air absolute humidity

Q_l: Latent energy to be recovered; Q_s: Sensible energy to be recovered;

Table 8. Percentage of the latent energy demand.

CITIES	**% Latent energy**
Almería	31%
Alicante	24%
Valencia	18%
Palma de Mallorca	19%
Barcelona	18%
Marseille	6%
Rome	12%

Palermo	35%
Naples	15%
Murcia	31%
Cagliari	17%

Table 9. Energy demands for Murcia depending on the control strategy of the ERV.

	Energy demand (kWh/m²y)		
Winter strategies	Sensible Heating demand (kWh/m²y)	Dehumidification demand (kWh/m²y)	Total Winter demand (kWh/m²y)
WITHOUT RECOVERY	20.7	5.2	26.0
WINTER 1	5.6	5.4	11.0
WINTER 2	19.4	4.4	23.8
WINTER 3 (HRV)	5.6	3.9	9.6
Summer strategies	Sensible Cooling demand (kWh/m²y)	Dehumidification demand (kWh/m²y)	Total Summer demand (kWh/m²y)
WITHOUT RECOVERY	17.0	11.8	28.7
SUMMER 1	16.5	10.1	26.6
SUMMER 2	18.8	9.7	28.5
SUMMER 3	17.0	8.7	25.6
SUMMER 4 (HRV)	16.5	11.7	28.3

Table 10. Energy demands for Murcia depending on the control strategy of the ERV

Summer strategies	Sensible Cooling demand (kWh/m²y)	Dehumidification demand (kWh/m²y)	Total Summer demand (kWh/m²y)
SUMMER 3	17.0	8.7	25.6
SUMMER 3 OW	11.0	20.0	31.0
SUMMER 3 FC	15.7	9.6	25.3

OW: Open Window; FC: Free Cooling