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Performance analysis of a hybrid ventilation system in a near zero energy building

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ABSTRACT

In this research paper, an analysis is developed on the performance of a hybrid ventilation system that combines Earth-to-Air Heat Exchangers (EAHX), free cooling and evaporative cooling Air Handling Unit Heat Exchanger (AHU-HX), all being controlled by a Building Management System (BMS) in a net Zero Energy Building (nZEB), called LUCIA. LUCIA nZEB is the first safe-building against Covid-19 in the world, certified by the international organisation WOSHIE, and located in Valladolid, Spain. The main aim is to optimize the performance of the three systems in such a way that the Indoor Air Quality (IAQ) levels remain within the allowable limits, while maximizing the use of natural resources and minimizing energy consumption and carbon emissions. The approach to satisfy the heating and cooling demand and IAQ levels through zero emissions energy systems is developed, thus anticipating the zero-energy target, set by the European Union for 2050. Results showed that the installed hybrid ventilation system uses heat exchangers for 70% of the operational time, in order to achieve the set parameters successfully. Also, the analysis made by monitoring data, have shown that the control and optimal operation of the hybrid ventilation system allows high energy recovery values with minimum additional electricity consumption. Significant reduction of carbon emissions and operational costs have been achieved.

1. Introduction

In the last years, the European Union has assumed a strong energy and social commitment favouring the environment and climate change mitigation \cite{1}. This has been translated into a number of actions and policies that favour the use of efficient technologies and renewable energy systems, in order to reach the 27% renewable energy target, set for 2030. This aim may increase steadily and reach 100% of the total energy consumption by 2050, according to the estimations of the European Renewable Energy Council \cite{2}.

The building sector takes up to 40% of the energy consumption of the European energy mix, which is significant \cite{3}. For this reason, one of the priority objectives in the EU is to reduce consumption and increase energy efficiency in the building sector. Following the 2010/31/EU Energy Performance of Buildings Directive (EPBD), it was decided to reduce demand in the building sector \cite{4}. To achieve this purpose, the strategies focused on setting up a procedure, whereby Member States have to carry out cost-optimal studies, in order to identify cost-effective energy efficiency packages. These packages will enhance the energy performance of new and renovated buildings. Thus pushing this sector towards the near-zero energy levels, by the end of 2020.

The updated EPBD Directive (EU) 844/2018 of May 30, 2018 has brought about further upgrades to the previous directive. More attention is now given to building renovation, whereby all Member States are required to produce a building renovation action plan by March 2020 \cite{3}. Other new requirements have also been introduced. Including but not limited to mobilising investment in renovation of buildings as: Devising a voluntary common European scheme for rating the smart readiness of buildings, optional for Member States; Promoting smart technologies, mainly for control of temperature and IAQ; Introducing electric mobility mandatory charging points in specific buildings satisfying set criteria; Working towards common national energy performance requirements, in ways that allow cross-national comparisons; Promoting health and well-being of building users, for instance through

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an increased consideration of air quality and ventilation; And proposing the voluntary building renovation passport scheme. In essence, the energy performance rating of a building will no longer be dependent on the primary energy rating, but also on its carbon footprint, smart indicator, indoor comfort and air quality [4]. For this last aim, and in order to achieve high levels of IAQ, it will be necessary to have a good design and management of the system of ventilation in the building [5,6].

The nZEB target, as defined in the EPBD, is achieved first by reducing energy demand through efficient passive design. When this is not sufficient, one can introduce various active and highly efficient air-conditioning strategies, and finally through renewable energy systems. Among the different indicators that define a nZEB building, the Renewable Energy Ratio, RER (kWh/m²-yr) stands out, showing the amount of renewable energy used in the building [7,8]. The building in the case study has an RER of 0.66 (Electricity).

The application of building-focused renewable energy-based HVAC systems are very challenging. It is important to implement HVAC systems with a reduced associated carbon footprint, and which can perfectly match the comfort requirements. Antvorskov [9], discussed the different renewable strategies, integrated in hybrid ventilation systems. All this analysis is carried out under the location, placement and urban environment.

Khabbaz et al. [10], discussed one of the renewable systems that provides better energy performance to HVAC system, which is the geothermal ground-air system. Geothermal systems can be developed by means of geothermal heat pumps, or as EAHX. Francesco Minichielo et al. [11], discussed the importance of an EAHX recovery to a nZEB building in Mediterranean climate conditions. Their research showed the capacity to save carbon emissions, due to the renewable origin of the system and its high capacity to improve energy parameters, before introducing the air handling unit. They validated a primary energy reduction of 29% and reaching 46% in summer periods. Ji et al. [12], discussed that the hybrid ventilation system is a feasible energy-efficient approach to the design of buildings, regardless of climate. Rackes et al. [13], analysed that the energy savings in HVAC were very vulnerable to the climate and the materials used in the building. The smart strategies implemented achieved 16% primary energy savings in HVAC.

Benhammou et al. [14], discussed that the high energy efficiency in a geothermal heat exchanger must consider the saturation and thermal recovery of the soil. Therefore, the use of this system in an intermittent way, generates better energy efficiency results.

Skye et al. [15], discussed the savings through recovery systems associated with the AHU in different climates. It indicates the energy benefits of using heat exchangers in ventilation, for the winter and summer months, for locations with high climatic variation between both seasons of the year, reaching 20% energy recovery. The savings and benefits of using fan energy exchangers for humid areas were also analysed. Thiers and Peuportier [16], developed a study of a ventilation system, which had a combined heat recovery unit associated with the AHU, and an EAHX recovery system. After the analysis, important savings in energy consumption were reached.

Vaz et al. [11] discussed the analysis of improvements in thermal conditions, in the building sector, by studying the performance of the ground and air of the geothermal heat exchanger. The study shows how the months preceding summer and those preceding winter provide the greatest heat transfer potential. Chiesa [17] showed the balance between EAHX effectiveness and design choices. The potential of this system was optimised over the energy demand of the building was discussed. Woodson et al. [18] discussed a real analysis of an EAHX. The soil temperatures remained constant at around 30 °C, when the outside temperature was 39.5 °C, and the depth of the buried geothermal recovery pipes was 1.5 m. A clear phase shift was observed between the maximum outside temperature, and the maximum ground temperature. In fact, the time of the day when the outside temperature was highest, corresponded to the time when the underground temperature was lowest. As a result, a temperature drop of 7.5 °C was achieved, enabling the achievement of comfort parameters and energy saving. Peng et al. [19], discussed a low-energy ventilation (ILEV) system integrated to primary school buildings. They showed how the operations of the EAHX largely depend on the local weather conditions.

The emphasis on applying hybrid ventilation energy systems is justified for achieving optimal air quality, and energy efficiency. Li et al. [20], discussed a method to achieve IAQ by controlling different parameters, such as temperature, humidity, and CO₂ concentration. This developed strategy focused on reducing excessive carbon concentration in enclosures, and preventing condensation in real-time. Menassa et al. [21], showed significant energy savings by optimizing hybrid ventilation. Thereby, improving thermal comfort, and IAQ. Connick et al. [22], discussed how in hybrid ventilation, natural and mechanically imposed pressure differences are combined. Davies Wykes et al. [23], discussed the results of the relative rates of hybrid ventilation, which are determined by the geometry of the room.

The implementation of a BMS, is essential for controlling and iteratively improving the quality of indoor parameters. However, it needs to be flexible, automated, precise, and smart, in order to provide the expected benefits to achieve the required levels of IAQ. Doukas et al. [24], described the benefits of monitoring systems by BMS, offering assurance of comfort levels in all areas of the building, and providing significant energy savings. Merahtine et al. [25], used a BMS database to study the IAQ along with the CO₂ levels. This study highlights the importance of achieving constant quality indices, at least at the 95% confidence level. He also showed that the energy cost reduction of 12% that was achieved by adjusting comfort parameters, were significantly better than the minimum energy requirements. D. Clark et al. [26], discussed in a case study of smart ventilation, that analysis of the contaminants emitted is key to accurately determining the effectiveness of a specific strategy.

The implementation of BMS control models for the different ventilation systems through feedback control, allows the achievement of optimal air quality conditions. Lee et al. [27], developed this model by proposing a new ventilation control system, based on the variable dynamics of the IAQ, as a function of operating time. Due to this, it was possible to reduce the energy consumption of the ventilation system by 4%, without compromising the IAQ, with PM₁₀ concentration being below 120 μg/m³. Vallianos et al. [28], carried out a study of hybrid ventilation, through modelling and predictive control. They discussed how a strategy of predictive control, increases energy savings, and provides thermal comfort.

This paper provides and analyses experimental data obtained through dynamic energy monitoring of an integrated ventilation system, an EAHX geothermal system, a free cooling system, and an air/air AHU-HX, with indirect evaporative recovery. All these systems are implemented in a multipurpose nZEB located in the city of Valladolid, Spain, with the aim of showing the high benefits resulting from the implementation of this type of strategy, within a zero-carbon building.

2. Case study

2.1. Building

The smart ventilation system studied is installed in the nZEB LUCIA building, a 7500 m² building, designed to be self-sustainable in terms of energy efficiency and renewable energy with near-zero carbon emissions. This ZEB building is located on the Miguel Delibes campus of the University of Valladolid, Spain and it was built as a laboratory for the application of innovative and renewable energy technologies (Fig. 1). The energy model defined for a nZEB building was implemented at the inception and design stages, and therefore, was supported by quality controls throughout the construction of the building, in order to approximate as much as possible the real characteristics that were developed in the model [29,30].

The ratio of renewable energy in the building (RER) is 0.66, achieving a reduction in use of a total of 31% of non-renewable primary energy.
thermal transmittance of 0.157 W/m²K; passive ventilation introduced the implemented eco-design; the increased thermal insulation due to a properties of the building together with natural ventilation capacity, combined with EAHX; and safe-building against covid-19 [33].

In order to achieve this worldwide recognition, it has been based on: the implemented eco-design; the increased thermal insulation due to a thermal transmittance of 0.157 W/m²K; passive ventilation introduced together with natural ventilation capacity, combined with EAHX; and some other sustainable strategies, which have managed to reduce energy demand by more than 50%. The building of study stands out in the PassivHaus modality due to its zigzag facade, where its windows are in a favourable position to the incidence angle of the sun, orienting all the windows towards the south. A design of shades is applied to the windows with the objective of reducing their associated solar gains. Also noteworthy is the argon-filled double glazing that improves the thermal properties of the building’s envelope.

In addition, it is important to mention the building’s commitment to sustainability due to its Life Cycle Analysis (LCA). All the materials used in the construction of this nZEB building, have a recycling process, and they are certified for their reduced energy consumption, and low carbon emissions in the manufacturing, and assembly process. This nZEB building has systems that generate water savings through the reuse of water through separation networks, and a green roof with native vegetation, without the need for irrigation. Therefore, it contributes to lowering the heat island effect, reducing all losses, and providing a greater scope for thermal comfort [34,35] (see Fig. 2).

Artificial lighting primarily employs T5 electronic ballasts with Digital Addressable Lighting Interface (DALI) system [36]. In accordance with European and national lighting directives, the lighting units have been adjusted to cover the demand of 9.7 W/m² for the areas where the laboratories are located, and a demand of 3.8 W/m² for the aisles and corridors connecting the different areas [37]. LED downlights and fluorescent lights have been installed in these areas at the lighting locations, using the DALI System technology [36]. Due to all this technology implemented, together with the passive daylighting approaches (Fig. 3a), a saving of 45% in lighting energy consumption is achieved, when compared to a standard building design.

The building has an insitu central heating boiler with a nominal power capacity of 329 kW and an overall cogeneration efficiency of 0.88 (Fig. 3d). The generator is fuelled by renewable energy fuel - biomass, with a consumption rate between 100 and 125 kg/h. This generates electricity to the value of 100–130 kWh/day and a thermal energy production of 200–220 kWh/day, of which 100–110 kWh/day is supplied at 90 °C and the remaining 100–110 kWh/day at 450 °C. The generation of electrical energy is developed by means of four engines rectified to work with waste gas from biomass (Fig. 3b), with an individual nominal power of 112 kW, which generates 130 kWh/day. This cogeneration system supplies 88% of the building’s electricity demand. The remaining 12% of the electrical demand is covered by photovoltaic panels (PV) implemented on the roof and the vertical south façade of the building [7].

This building is fully monitored and has a BMS. Its HVAC and all energy systems, together with the defined consumption points within the building, are recorded by the energy meters and managed through the ModBus connection protocol [38]. There are one hundred electrical grid analysers, which are distributed in all the areas, with which active energy, reactive energy, phase voltage, and frequency of each area are logged. This enables a more efficient control of the energy consumption of the building, plus the analysis of the usage behaviour and the comfort range per area.

The management and control of all energy and electrical parameters are developed by the BMS through the supervisory control and data acquisition software (SCADA). In this case study, Desigo™ (Siemens) is used [39]. This system generates a very specific integrated management protocol for all the systems and installations, as well as a predictive control of the building’s response. This is being assisted by the data that is collected from all the sensors and PLCs by the SCADA, with a supervision of the building performance, warning of any discordance with the parameters previously set.

The nZEB LUCIA building works as a magnificent experimental unit, to serve as a model for the various tests and analyses of specific energy.
efficiency measures, or state-of-the-art energy systems. All this is implemented, in order to encourage a new package of measures. It is associated with a radical change in the design and construction of future buildings, whether renovated or new, towards zero carbon emissions.

2.2. HVAC system

The HVAC system, combines heating, cooling, ventilation system, geothermal recovery, evaporative recovery, absorption system and free cooling system, all with high efficiency to supply the demand.

The building’s HVAC is an air-water mixed system, with an AHU operating at a constant flow rate of up to 15,000 m$^3$/h (Fig. 4). This flow is used for heating, cooling and ventilation of each area of the building. The all-water system controls the heat load and the sensible cooling demand, by means of a 4-pipe fan coil system. These fan coils provide the possibility of simultaneous heating and cooling, with the aim of covering the individual demand for each area of the building. This HVAC system works as a support to the necessary thermal demand, when the passive systems of the building do not achieve the air quality parameters.

The smart control of the AHU is managed by enthalpy control, providing high accuracy in both demand inputs and output. This control of the AHU is associated with a constant air flow or a set temperature. With this management model, the temperature and humidity parameters set by the Spanish regulations are perfectly reached (40%-60% humidity and 21 °C to 26 °C according to the winter or summer months,
This smart management control allows to operate the AHU with the geothermal heat recovery unit, using free-cooling, and air/air recovery with an evaporative system. These systems are all monitored by temperature and relative humidity sensors, enthalpy sensors and IAQ sensors. All of them are connected to the BMS system, being able to work at the same time. According to the choice of the smart SCADA management, improving the energy demand parameters and obtaining a high and constant IAQ.

The absorption unit, and a conventional chiller, are used as cooling generation systems to cover the remaining cooling demand. The absorption system, with its cooling tower dissipates the residual heat to the atmosphere and provides a power of 176 kW at an EER of 0.7. On the other hand, the conventional chiller system provides a power of 232.7 kW at an Energy Efficiency Ratio (EER) of 3.3.

Fig. 5 shows the ventilation system scheme, controlled by the BMS. The absorption unit, and a conventional chiller, are used as cooling generation systems to cover the remaining cooling demand. The absorption system, with its cooling tower dissipates the residual heat to the atmosphere and provides a power of 176 kW at an EER of 0.7. On the other hand, the conventional chiller system provides a power of 232.7 kW at an Energy Efficiency Ratio (EER) of 3.3.

Fig. 5 shows the ventilation system scheme, controlled by the BMS. The operating mode of all systems combined, is based on the outdoor climatic data, setting the best option for the air supply to the AHU. There is the possibility of obtaining the supply air flow straight from outside. Alternatively, air can be passed through the AHU of the EAHX system, to pre-condition it. The SCADA management system always considers the energy parameters associated with the flow and determines the airflow to the AHU. The choice of fresh air supply source is controlled by the BMS, through an external damper that balances the flows to obtain the most advantageous air mix, and to optimize energy efficiency. The purpose is to achieve the required minimum IAQ levels, according to European and Spanish standards, and the pre-existing indoor, outdoor and ground conditions [34]. Table 1 shows the smart management topology that is enthalpy (h) controlled and set to ensure stable and acceptable IAQ levels.

### Table 1

| Strategy          | Operation Mode Period                                      |
|-------------------|-----------------------------------------------------------|
| EAHX (input)      | hbuilding < hset & hset > houtside & hEAHX < hOutside    |
|                   | (Winter months)                                           |
|                   | hbuilding > hset & hset < houtside & hEAHX < hOutside     |
|                   | (Summer months)                                           |
| Outside (input)   | hbuilding < hset & hset > houtside & hEAHX < hOutside     |
|                   | (Winter months)                                           |
|                   | hbuilding > hset & hset < houtside & hEAHX < hOutside     |
|                   | (Summer months)                                           |
| EAHX + AHU-HX     | hbuilding < hset & hset > houtside & hEAHX < houtside &   |
|                   | hEAHX < hset (Winter months)                              |
|                   | hbuilding > hset & hset < houtside & hEAHX < houtside &   |
|                   | hEAHX < hset (Summer months)                              |
| Outside + AHU-HX  | hbuilding < hset & hset > houtside & hEAHX < houtside &   |
|                   | houtside < hset (Winter months)                           |
|                   | hbuilding > hset & hset < houtside & hEAHX < houtside &   |
|                   | hEAHX < hset (Summer months)                              |
| EAHX + Free Cooling | hbuilding > hset & hset < houtside & hEAHX < houtside & |
|                   | hEAHX < houtside & NO AHU-HX (Summer months)               |
| Outside + Free Cooling | hbuilding > hset & hset < houtside & hEAHX < houtside & |
|                   | hEAHX < houtside & NO AHU-HX (Summer months)               |

Fig. 5. Ventilation System Scheme controlled by Building Management System. (Free Cooling Damper – 1; AHU HX Damper – 2, EAHX Damper – 3; and Outside Air Supply Damper – 4).
The EAHX system has a total of 52 buried pipes with a diameter of 0.2 m each. Each pipe has a surface of 0.031 m². The soil where the buried EAHX pipes are located is clay soil with a density of 2700 kg/m³, a calorific value of 0.8 kJ/(kg·°C), and a thermal conductivity of 2.9 W/(m·K). The volume of the soil where the EAHX pipes are buried, prevents thermal saturation of the soil. Each buried pipe is 16 m long, which provides a total length of 832 m to exchange heat. This geothermal exchanger has been designed to save 112,740 kWh/year, with a reduction of 21 tonnes of related carbon dioxide emissions. Fig. 6 shows an overview of this system.

When there is a demand for cooling in the areas, the BMS control turns on the free-cooling mode, as long as, the outside temperature is lower than the enthalpy of the area to be climatized. Thereby, increasing thermal efficiency. This choice is very useful for providing night-time ventilation, off-hours of building operation, in spring, autumn, and summer.

Fig. 7 shows the control scheme of the air ventilation system, which includes the location of the temperature, humidity, CO₂ concentration, network analysers and enthalpy sensors. It also represents the different operation modes of the HVAC System, managed by its smart SCADA control. By means of the SCADA, the data acquisition is collected and analysed. Due to all this smart control, a feedback loop is generated, in order to use the most optimal systems, and to learn predictive operation based on iterative processes. The smart control of the ventilation system selects the most energy efficient strategy, according to the enthalpy comparison. Due to this, an optimal strategy is offered, with economic and energy savings.

The energy systems of heat recovery, for the geothermal system and the evaporative recovery or free cooling system, operate in accordance with the parameters determined by the set point in the different areas of the building. If the energy demand is required by the building and the smart enthalpy control validates it, the heat recovery systems are activated, in order to offer a better energy use, with significant savings. There are IAQ sensors measuring the CO₂ concentration, set between 300 and 700 ppm. (Indoor Air Quality of Spanish Standards (IDA) have different air quality levels. IDA 1 (350 ppm) – optimum air quality for hospital, clinics and laboratories, up to IDA 3 (800 ppm) – medium air quality for offices, residences, reading rooms, museums, classrooms) [40]. Above it, the smart control system provides an increase in airflow from the ventilation system, until the CO₂ level within the building zone is reduced. Thus maintaining the IAQ below the maximum set limit.

The control mode of the smart ventilation system always prioritizes the use of energy recovery systems, instead of using the biomass heating or cooling, by the absorption machine and/or chiller system, respectively. If the demand in the building is not covered, the generation of heating and cooling from energy resources is required. The free-cooling mode increases the energy efficiency of the system and provides cooling for several areas of the building, as well as providing the required mechanical ventilation to achieve the desired IAQ.

Due to the combined energy recovery system, all the operating modes described above are highly efficient. However, the choice to operate a specific mode, based on the external climatic conditions and the set indoor parameters, will maximize cost-effectiveness as well. Therefore, investment in a smart strategy for ventilation with high levels of IAQ is justified.

The energy consumption of the fans used in the ventilation system, is an interesting parameter to analyse, in order to carry out the combined operation mode, and to achieve energy savings, and carbon emissions reductions. The AHU has two fans integrated into the system, a supply fan and a return fan rated at 11 kW and 15 kW, each. The use of a heat recovery system, or other systems, alters the number of hours of operation of the built-in fans to achieve the parameters of indoor energy demand. The smart management of the system allows energy consumption savings, or economic savings, and lower environmental impact.

3. Results and discussion

The energy analysis of the ventilation system in the LUCIA HVAC system, begins with the acquisition of operational data and its analysis by the SCADA system. The limitations of the study are defined by all-air or mixed systems, always combined with AHU. Fig. 8 shows the number of operating hours of the ventilation system of the building per month versus the total monthly hours. The ventilation system remains stable throughout the year, with a reduction in operational hours during months that have higher number of holidays such as in April, August, and December.

3.1. Working hours per strategy

Within the range of months with the highest number of operating hours, due to the climatic conditions of Valladolid, the months of February, March, May, and October become more pronounced. Although these months belong to different seasons, geothermal recovery, according to the thermal inertia stability of the soil, obtains the highest operating values.

Fig. 9 shows the contribution of the different smart energy strategies applied to the ventilation system, in terms of operating hours in 2019. From Fig. 6 (SCADA) above, one can note two inlet dampers on the top left, namely, the inlet from the exterior area, “Outside” and the air inlet from the EAHX. The total operating hours is the sum of the hours of use for both inlets. The priority is given to the geothermal heat recovery system.
system without conditioning. However, if air conditioning is required, the system directs the air from the AHU either through the evaporative heat recovery unit or through the free-cooling ventilation.

Fig. 9 also shows the months during which free-cooling ventilation occurs. The period that the demand for cooling is highest is from March to October. Most of those months, the free cooling introduced in the different areas of the building, is supplied through the inlet damper by the geothermal heat exchanger, due to its smart management model that covers the required demand. While in August, September, and October, the external weather conditions provide better enthalpy parameters, thus allowing the supply of fresh air directly from the outside, avoiding the use of the EAHX system.

The evaporative heat recovery system is the most widely used in Summer and is activated by the Smart Control System of the SCADA, as shown in Fig. 9. This heat recovery, of the Air Exchanger Unit, covers the highest energy demand in the winter period, from November to March.

Therefore, as shown in Fig. 10, the free cooling system has its greatest requirement to cover the energy demand of the building during the summer period, from March to October. The remaining period uses the evaporative recovery system of the AHU.
3.2. Energy consumption per strategy

When analysing the energy consumption of the AHU, Table 2 shows the energy consumption of the air handling unit spread over each renewable energy system combined with the HVAC. February represents the month with the highest electricity consumption in the ventilation system, reaching almost 2 MWh/month. In February, the AHU-HX and EAHX recovery systems, have their highest use. On the other hand, the free cooling energy system reaches its peak use in May and September with a total energy consumption of about 1 MWh/month.

Fig. 11 shows a graphical representation of the energy consumption of both systems used for ventilation (i.e. the geothermal heat recovery and the free cooling). The average electrical consumption of almost 500 kWh/month, is attributed to the free cooling system. It is important to point out that during the first months of the summer, the smart control of the ventilation system makes more use of the AHU that is linked to the geothermal recovery system. Thus, providing better enthalpy conditions to the inlet air. In contrast, during the months close to the end of the summer period, this approach is less used, and the air is directly taken from outside.

Fig. 12 shows the operation mode of the indirect evaporative heat exchanger AHU-HX at the AHU according to its two air inlet dampers, either via the geothermal exchanger air inlet, or via the outdoor air inlet. It is shown how the smart system, chooses first the heat recovery of EAHX before using the evaporative heat exchanger AHU-HX. The analysis shows how in the winter season, heat exchangers are used more often, in order to adapt the parameters to the indoor set requirements, and to regulate the IAQ.

The use of geothermal heat recovery is the most commonly used option, of the different ventilation systems. This is the cheapest strategy and is given priority through the control of the BMS, depending on the set parameters, and the prevailing conditions. However, its use is not exclusive to satisfy all the thermal comfort parameters, as shown in Fig. 13. In fact, at times two systems could be working together, such as in the case of the months between March and October, where the AHU-HX is also required to operate. May and September are the months with the highest level of geothermal heat recovery, as a support for the building’s free cooling system. For the remaining months, the best option according to the energy requirements, is the use of the geothermal recovery system, with the evaporative recovery system.

Fig. 14 shows the operation of the outdoor air inlet damper, and how the combined system between outdoor air inlet and free cooling is limited to the summer period. In contrast, in the winter period, the outdoor air inlet goes directly to the AHU-HX.

3.3. Economic costs per strategy

Table 3 shows the costs incurred, based on the average electricity tariffs in Spain for 2019, due to the use of the fans that regulate the ventilation system (Table 3). For this building, all these costs are not actually incurred, as energy is generated from the installed solar photovoltaic systems to power the ventilation equipment. This table shows a validation of the economic costs adjusted by the implementation of different energy systems that contribute to achieve the parameters of thermal comfort and IAQ.

Fig. 15 shows the annual economic costs required to operate each system according to the actual operation regime. It is shown that this hybrid ventilation system uses heat recovery 70% of the working time, in order to achieve the set parameters successfully. For the remaining time, the system used is that of free cooling. The economic costs involved in the use of recovery units, amount to a total of 2666.4 Euro per year, being 1239 Euro related to the combination of the use of both recovery units, geothermal and AHU recovery system. The BMS always chooses the most cost-effective system to achieve the IAQ parameters (Fig. 15.).

This work shows that the correct use of a hybrid ventilation system, allows high energy recovery values with minimum electricity consumption. In this study, being a ZEB building, the use of the hybrid ventilation system reduces the electrical demand for HVAC operation. The payback period for this hybrid ventilation system in a near-zero-

![Fig. 10. Working hours in stand-by, free cooling and AHU-HX for each month.](image)
energy building is 8 years. Compared to other renewable strategies, it required only 12.5% of its lifetime to recover the invested costs. In addition, it provides economic benefits for approximately 35 years. Due to the operation and correct maintenance of the system, significantly CO₂ emissions are saved, and the operating costs of a 7500 m² nZEB, and a ventilation flow of 15000 m³/h, are cut below 5000 Euros per year.

The benefits of using a smart control system in the hybrid ventilation strategy, provides substantial economic savings per year. Fig. 16 shows how this savings amounts to 55%, compared to the standard ventilation strategy.

A future scope of study would be to integrate other renewable systems, such as the heat pump in recovery mode, and to study indirect evaporation systems with ceramic material.
4. Conclusions

This study focused on the relevance of high efficiency and quality of ventilation in IAQ indicators, in order to fulfill European and Spanish regulations. It is important to achieve high thermal comfort and high IAQ in a nZEB building. A mechanical ventilation system is used for this purpose, but with smart combination of different ventilation topologies, one can achieve the three goals of sustainability, namely cost-effectiveness, energy efficiency and lower carbon emissions and better indoor climate.

The smart management of the HVAC system is achieved by combining 3 highly innovative technological systems, for better ventilation and higher IAQ, by controlling and regulating the different energy parameters setting the indoor air quality in the building. This control is

Table 3
Energy Costs per strategy in Euros (€).

| Mode                   | Jan  | Feb  | Mar  | Apr  | May  | Jun  | Jul  | Aug  | Sep  | Oct  | Nov  | Dec  | Tot  |
|------------------------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| Standby/Off            | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    |
| Free-Cooling           | 0    | 0    | 19,44| 41,52| 92,04| 54   | 61,44| 43,56| 58,2 | 14,52| 0    | 0    | 384,72|
| Outside-Free Cooling   | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 185,28|
| TOTAL-Free Cooling     | 0    | 0    | 20,16| 42,84| 101,04|66,72 |76,08 |87,72 |125,4 |50,04 |0    |0    |570   |
| AHU HX                 | 80,64|108,48|103,56|49,2  |48,96 |48,12 |72,36 |23,76 |19,8 |54    |135,6 |109,8|854,28|
| Outside-AHU HX         | 55,2 |118,08|87,84 |30,96 |47,52 |36,24 |12   |1,44  |0    |65,04 |10,8  |13,8 |478,92|
| TOTAL-AHU HX           | 135,84|226,56|191,4 |80,16 |96,48 |84,36 |84,36 |25,2  |19,8 |119,04|146,4 |123,6|1333,2|
| TOTAL                  | 135,84|226,56|211,56|123  |197,52|151,08|160,44|112,92|145,2|169,08|146,4 |123,6|1903,2|

Fig. 14. Fans energy consumption due to the Outside air inlet. Free Cooling and AHU- HX per month.

Fig. 15. Energy Costs at LUCIA nZEB by Ventilation system type (Free Cooling Damper – 1, AHU HX Damper – 2, EAHX Damper – 3 and Outside Damper – 4) – see Fig. 3.
made up by the dynamic monitoring of the various energy parameters. Through the SCADA implemented in the building, the analysis of the optimal energy consumption is carried out to the entire HVAC system. HVAC system is the most demanded item of energy consumption, in any building. This smart hybrid ventilation system, integrated into the LUCIA nZEB, makes it a Covid-19 safe building.

The study has been conducted under a continental climate, but is exportable to another type of climate. The smart HVAC management system always provides the optimal parameters for any demand for comfort. All of this, combined with the high efficiency energy systems implemented, is achievable.

For the purpose of saving energy consumption, a ventilation system is used combining a geothermal air heat recovery system, an indirect evaporative heat recovery system and a free cooling system. The ventilation system of the nZEB building is controlled in a smart way, with probes and sensors to measure the different energy parameters, analysed by the SCADA within the BMS control.

The analyses showed how the use of these energy efficiency systems controlled by the BMS, at constant air flow, allows energy recovery for 70% of the working time. Moreover, it provides a low cost of 2666.4 Euros per year, thus achieving the comfort parameters and the IAQ levels. The operational cost for using these smart systems, is balanced by the building’s on-site electricity generation systems, mainly from solar photovoltaics. The smart management of all these systems combined, reaches a total energy cost of almost 5000 Euros per year, for an air ventilation system of 15,000 m$^3$/h and a useful area of 7500 m$^2$. This study represents a possible model to implement in other buildings, because of the economic and electrical savings generated and the possibility of achieving net zero-energy status through the maximisation of the use of natural sources of heat sources and heat sinks.

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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