Energy Efficiency Strategies For Future Educational Buildings: A Case Study in Madrid

Paloma Campo Ruano
  Technical University of Madrid

José María De Lapuerta Montoya (chemalapuerta@gmail.com)
  Technical University of Madrid

Javier García-Germán
  Technical University of Madrid

Jesús M. Menéndez Amigo
  Zero Energy Lab

Irene Cámara Ruiz
  Technical University of Madrid

Research Article

Keywords: Energy efficiency, school, Madrid, Passivhaus Plus, active cooling

Posted Date: January 3rd, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1195995/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License. Read Full License
Abstract

Background

This paper presents a new-built school that works disconnected from the grid and uses energy from renewable sources.

The design is based on a necessary condition from the developer to achieve extremely low energy demands for heating and cooling and total primary energy according to the Passivhaus Plus standard: Furthermore, the total energy consumed can be generated on-site from renewable sources. Through energy efficiency management systems, a very low rate of CO2 emissions are achieved.

Results

In addition to meeting the requirements established by the Passivhaus accreditation, the strategies achieve high levels of internal “well-being” for students and staff members, as recognised in other environmental certifications. This is possible through a holistic and bioclimatic design principle integrated in architectural design.

Conclusions

The installation’s design solves the main challenge in educational use: to respond to the high variations of occupancy in the classrooms and to guarantee a stable temperature and optimum air quality, but, in addition, minimum energy consumption is achieved, and prioritising passive energy sources (GSHX) over active sources (heat pumps) employing integrated monitoring systems.

The educational component in design is fundamental; the building is conceived as an extra learning tool for the pupils involved in the energy process in the building. This promotes awareness and sensitivity to the environmental challenges ahead. This is the first Spanish building (Figure 1) awarded by the Passive House Institute (2021).

Background

Introduction

Colegio Internacional Brains is a new high school building located in Madrid (Figure 1), designed with the premise of proposing a “futuristic vision” for new educational spaces, with large open-plan classrooms, flexible and furnished with all the latest technologies. A lighthouse project to demonstrate minimum levels of energy demand which can be generated by in-situ renewable energy only. This case study is also a proposal for redefining directly high levels of architectural aesthetics with extremely energy efficiency design.
The landscape invades the first floor in this building to extend classrooms and communal areas and invites learning activities outside the classroom. It wants to reflect that there are alternative ways of studying and learning. Large deciduous trees planted to the South anticipate initial passive bioclimatic and solar strategies in early design stages, protect the interior from the intense sunlight in summer and let the natural light and radiation pass through in winter. Artificial lighting under the trunks projects the treetop onto the façade and produces attractive and illusory images.

The compactness ratio of the building is another of the passive design strategies employed at early design stages. The shape optimises the façade surface to the volume of the building ratio and reduces energy losses through the building envelope. However, a small and independent annexe volume marks the entrance to the building and link the existing premises with the new building. This semi-circular shape is key to the morphology of the common interior areas. The glass façade reflections disappear among big trees. This is a welcoming space where teachers and parents can meet.

As we enter and discover the building, the common areas open onto a family of semi-circular spaces, very similar to the entrance volume. The corridor is flooded with benches around the perimeter that informal host meetings between students and teachers, encourage small group working activities, tutorials or individual moments of relaxation.

On the first floor, a small library with a timber grandstand opens up with a raised backyard. Two large sliding doors (with high performance and airtight to reach Passivhaus Plus standards) generate a single connected space from the grandstand and the garden. In this space, people navigate on their tablets while others lie on the lawn or sit on circular benches around the four mature trees.

Inside the gym, circular windows from other school construction sites are set up to peer into the mechanical building room. Every day, the students see how the ground source heat exchanger (GSHX) ducts reach the building and how the heat pumps and the photovoltaic system work. Students can watch the air quality and CO2 levels in every area and the plant where the batteries are plugged in and electricity is stored for cloudy days. White painted signs on the floors promote collective understanding, internal traffic and health and safety regulations. The building itself and its active and passive strategies become an educational living resource. Finally, this educational building is accredited as:

- The first new Passivhaus Plus school in Spain.
- The first off-grid high school in Spain

1. The case study: Building description

This non-residential building is in Madrid, Spain and comprises one volume with a 15 ° deviation from the N-S orientation. The climate of the Madrid region features a warm-temperate climate with hot summers and moderately cold and dry winters (Figure 2).
The school is a two-storey mass concrete and masonry building of nearly 700 m² with an additional non-heated basement of 350 m². The almost rectangular prism volume accommodates nine classrooms, a teachers room, a technical-server room, two WC, one individual office and a computer room on the ground floor (Figure 3).

1.1 Building fabric

The fabric of the building is a ventilated façade with external mineral wool over the masonry brick connected by thermally broken anchors and cladded by tempered glass. The basement ceiling is insulated underneath by a continuous layer of mineral wool board insulation faced with black glass tissue. The upper parts of the building presents a terrace on the first floor and a flat roof with gravel accommodating 140 m² of solar photovoltaic (PV) panels. The insulation of these horizontal surfaces is 200 mm of rigid extruded polystyrene (XPS) boards on top of the concrete slab. The general built-up composition of the thermal envelope for the roof, external wall and floor against the unheated basement is described in Figure 4.

A Passivhaus cold-temperate certified aluminium window and sliding doors have been installed in the building, with triple-pane glazing and warm-edge spacers. The windows were installed in the insulation layer by using a low conductivity composite frame to minimise the thermal bridge of the installation. In addition, low-energy strategies such as thoughtful building geometry, thermal bridge free construction and a clear definition of a single continuous airtight layer were implemented in this building and combined with an internal structural design.

1.2 Building services

The mechanical electrical and plumbing (MEP) designing team proposed to the client a sizeable ground-source heat exchanger with almost 300 m of pipes and average efficiency of the heat recovery of around 30 % (Figure 5). This incoming tempered air feeds two industrial Mechanical Ventilation with Heat Recovery (MVHR) units of 3,600 m³/h, one for each floor and distributed to all the areas through cascade ventilation by rectangular insulated ducts. CO₂ sensors were placed in every classroom, which can automatically regulate the MVHR units’ nominal airflow. The controller is set to reach a maximum upper limit of 1,500 ppm as a recommended value for schools by several studies (De Visser et al, 2008; Canha et al, 2013; Ferreira et al, 2014).

Individual climate units with highly efficient Electronically Commutated (EC) motors provide heating and cooling for each classroom. They are integrated into the suspended ceiling to the ventilation valves. These fan coils are fed by two heat pumps located on the roof of the building. In addition, each of the classrooms has its temperature control system.

Air conditioning is provided throughout the building by fan coils integrated into the ceiling and fed by cold and hot water generated by the air source heat pumps.
Results

2. Design Methodology: Energy efficiency

Since early stages, the design team and the client aimed for a school that could operate off-grid, highly efficient and powered by renewable sources. The target for Passive House certification was also proposed at this early stage (Feist et al, 2007).

The well-known energy demand figure in Passivhaus is 15 kWh/m²a. This figure refers to the maximum annual energy demand for heating and cooling. However, the primary energy demand for the whole building is much higher due to domestic hot water, appliances, lighting and all the technological equipment needed in a modern school (Lizana et al, 2018). The standard also requires very high levels of airtightness and soft certification criteria applied to indoor comfort and hygiene.

The german standard categories the new-built projects into Passivhaus Classic, Plus or Premium. The upper classes can be reached depending on the final Renewable Primary Energy demand (PER) and the building renewable energy generation (Table 1).

Table 1 Passivhaus new-built categories by energy performance

| Category             | PER demand | Energy generation |
|----------------------|------------|-------------------|
| PassivHaus Classic   | 60 kWh/m2a | -                 |
| PassivHaus Plus      | 45 kWh/m2a | 60 kWh/m2a        |
| PassivHaus Premium   | 30 kWh/m2a | 120 kWh/m2        |

The case of Passivhaus Plus is that the building not only reduces energy consumption but generates its own energy, providing, in most cases, with annual net-zero energy balance (Thoua et al. 2015). However, to satisfy the building energy demand in periods where insufficient power is generated, the building can use energy accumulated in batteries, i.e. in winter or foggy days.

The Energy Efficiency Rating consists of a compulsory European label that gives information about its energy consumption and carbon emissions on a scale from A (lowest consumer) to G (highest consumer). Inside the Spanish building regulations, CTE (Código Técnico de la Edificación), a class B or better, is compulsory, but there is no tracking to confirm the building performs in real life as designed. This is a concept known as the Performance Gap (Demanuele, C. et al, 2010). In Passivhaus, there are several quality control tests required to obtain the final certificate. The process is planned and supervised at every stage, being the final result satisfactory for the client (Johnston and Siddal, 2016).

The Brains International high school energy demand is 14 kWh/(m2a) for heating and 1 kWh/(m2a) for cooling. Thus, the final primary energy demand is 55 kWh/(m2a), as shown in Figure 6.
According to the Passivhaus Plus standard, the total energy demand can be generated from renewable sources. A significantly reduced rate of Carbon Dioxide (CO2) emissions is achieved through efficient energy management. In addition to meeting the requirements established by the Passivhaus standard, the strategies are considered to achieve the concept of well-being, considering the principles of other environmental seals or certifications (Hopfe and McLeod, 2015).

*The heating energy demand is significantly reduced in a Passive House building. That is why hot water and electricity consumption is so important in new construction, where this is taken into account in a meaningful and future-oriented way*”

Dr. Wolfgang Feist, Passive House Institute

While in cold climates, the aim is to ensure that buildings do not lose heat and get solar gains from the outside, in other warm and temperate climates like Madrid, high temperature fluctuations are complex throughout the year, with cold winters and very hot summers (Berry et al., 2014). Therefore, the solution is to insulate against the cold and keep the interior environment with low temperatures in summer as far as possible. Passive cooling measures are essential: solar shading with architectural elements like eaves or softening fresh air outside. The challenge is increased in educational buildings, where occupancy variations in each space are higher (Clevenger and Haymaker, 2006). For example, a classroom can change its occupancy from 0 to 30 people, so overheating must be planned and avoided. The Passivhaus standard for warm climates currently sets the acceptable overheating percentage value limit for summer thermal comfort at 10% of the annual hours.

The feeling of warmth varies with the climate, habits, peculiarity of the users, and the perception of the environment. Nevertheless, increasing plus or minus one degree or up to 5% in humidity conditions significantly affects consumption and energy efficiency (Comunidad de Madrid, 2011).

### 2.1 Implemented passive strategies.

The solar passive strategies implemented to achieve a high level of internal thermal comfort and well-being are:

- Large thicknesses of continuous thermal insulation throughout the envelope (16 cm outside, 7 cm inside), thermal bridges free (ψ≤0,01W/(mK)). The building works as a “thermo”. Also, its internal thermal mass stores the interior heat or coolness for a very long period. Construction systems transmittances are very low: opaque locks with U≤ 0,15W/(m2K) and installed windows with Uw≤0,8W/(m2K). North-facing carpentry with Tripalit glass and solar control to the South. All glazing panes have a low-emissivity coating.
- Airtightness of the envelope (n50<0.6), through the fitting of an internal airtightness membrane with a low diffusion permeability value (Sd) on the warm side of the building’s skin to avoid any condensation risk.
According to the energy balance simulations carried out for the Efficiency Criteria of the Passive House, the results show that:

- An envelope optimisation and ventilation system efficiency in the building's project design are a key component. Brains is located in Madrid, a region of Spain known for its high temperature fluctuation between seasons. With that demand of cooling in summer and heating in winter, it would require an increase in power generation and larger energy storage systems. This contributes to lower energy prices in use and maintain the complexity of the systems to a minimum.

- Within the envelope, the insulation of the façade and the windows play the major role. The energy performance of the windows affects the building's global performance in winter and summer as well as reducing thermal bridges with triple glazing and an adequate installation.

- Heat pump systems have one of the highest efficiency rates in the market. The energy demand remains in the Passive House criteria range.

- Cooling in summertime can be covered with photovoltaic panels installed on the rooftops which feeds the inverter air source heat pump which generates cold water.

- The high levels of airtightness were the most significant issue to achieve the value required by the standard.

The results clearly illustrate that a high level of heating efficiency is more critical than for cooling when looking at using resources responsibly and sustainably – the reason being the simultaneity of renewable Energy availability and energy demand over the course of the whole year (Lakshmi and Ganguly, 2018).

The energy demand is relatively constant throughout the year, so the share of direct electricity is high, and the Primary Energy Renewable (PER) factor is low. In contrast, heating is necessary only in winter. In order to provide enough energy in winter, electricity must in part be produced in summer and stored with very high losses for the winter, which results in a high PER factor.

In addition to these requirements, which are indispensable in Passivhaus, the building is designed with compactness, orientation, wind control and vegetation integration. Deciduous trees are planted in front of the South and West-facing classrooms to protect them from the sun in summer and allow sunlight in winter.

High airtightness and insulation levels are accompanied by a heat recovery ventilation system that ensures lower infiltration losses and the intake of fresh indoor airflow. The building is designed with these principles confirming that the envelope works along with the services to an efficient electrical power regime (Figure 7). This results in a lower energy bill and ultimately in less energy global consumption.

The air supply to the heat recovery system is pre-heated or pre-cooled by the ground source heat exchanger.

**2.2 Renewables and energy generation.**
In renewable energy production, photovoltaic panels have been installed on the roof, which generates electricity for self-consumption. The surplus energy produced is stored in batteries, resulting in an energy self-sufficient and net-zero energy building. The Passivhaus Plus standard defines a minimum requirement for the renewable primary energy demand (PER) of less than 45 kWh/m²a, and a renewable energy generation of more than 60 kWh/m². The renewable energies used are:

- A 141 m² photovoltaic solar array on the roof, generating 22 kW of electricity for self-consumption (Figure 8). The surplus is stored currently in batteries, which in the future will be sized according to the present electricity demand profile of the school to achieve a net-zero building. As a result, the maximum consumption during the academic year 2020-21 has been 39,117.40 kWh/year, which has gained a percentage reduction of 67% from the existing building.
- Ground source heat exchanger to pre-heat and pre-cool the building’s intake of fresh air. With a monitored power of 20,719 kWh/year for heating and 23,624 kWh/year for cooling, and an overall reduction percentage of 15.7%. The saving in CO2 emissions is 4,466.17 kg in heating and 3,560.56 kg in cooling.
- Use of stored energy in the form of heat from the outside air using air sour heat pumps to cover the demand for heating, cooling and domestic hot water. For domestic hot water (DHW) production, the school uses CO2 technology, with a 30kW output and 35 kW for heating/cooling production.

2.3 Ventilation and air conditioning system.

The school monitors individual comfort conditions per classroom (temperature, humidity, CO2 concentration). In addition, a high definition in instrumentation and controlling the transfer of renewal air and air-conditioning is monitored continuously. In terms of the equipment used in the introduction of Passivhaus strategies, these are the principal units:

1. Air to water heat pump is placed as an active element within the energy equipment. It includes an outdoor compressor unit placed on the roof for the production of domestic hot water. This works employing a CO2 refrigerant gas R744 and a three-phase 400v/50Hz power supply. It provides a nominal heat output of 30 kW. It heats the mains water from 17 °C to 65 °C with a wet-bulb temperature of 12 °C outside air and can reach up to 90 °C.
2. This pump is connected to a cylinder tank by means of insulated pipes running around the outside of the building into the mechanical plant room.
3. High efficiency heat recovery units with an 85% certified recovery output. Their flow range is from 250 – 3600 m³/h and is certified by de Passive House Institute. This airflow is pressure-constant due to a control unit that makes it possible. The ducts that connect these heat recovery units are designed to ensure air tightness. They are coated on the outside with an aluminium sheet reinforced with Kraft paper and a glass mesh. This coat acts as a vapour barrier while presenting a 25 mm reinforced glass insulation on the inside. It has great mechanic resistance. Its thermal conductivity is 0.035 to 0.038 W/ (mK), its fire resistance is B-s1, d0 and its water tightness is class D.
4. The GSHX or Canadian wells consist of ducts buried in the ground at a certain depth and are covered by a thick layer of soil. In this case, it has been used grade 2 silt for optimum heat transfer, and the layer above has to be 30 cm thick minimum. The external air is conducted through the conduits and exchanges heat with the soil that surrounds the ducts. By doing so, the air gains or loses heat before entering the building, making the heat recovery units work more efficiently.

5. Modern energy management systems can automate the prioritisation of passive energy sources (GSHX) to active production sources (air-to-water heat pumps). This is used in the school to optimise and reduce the electricity consumption of the mechanical systems using variable airflow in their distribution. In addition, a monitoring system implemented allows the comfort conditions to be parameterised and monitored remotely and in real-time.

The following table reflects the energy demand of the building:

Table 2. Comparative energy demand for the building.

| ENERGY DEMAND - BRAINS SCHOOL |       |
|-------------------------------|-------|
| kWh/m² year of heating         | 14    |
| kWh/m² year of cooling         | 11    |
| kWh/m² year total              | 16.7  |
| % demand reduction for the building to regulations | 42,9  |

The following table (Table 2) describes the final energy demand of the building with the energy rating of the national energy certification scheme (CTE) and the Passivhaus Plus certification achieved:

Table 3. Comparative table. The energy rating of the building and certification system used.
In this section, the case study lists the different boundary conditions related to the use of the building that also allows a reduction in energy consumption and efficiency. This includes water consumption and indoor air quality limits. In addition, a monitoring exercise of variables for the academic year 2020/21 is also presented.

### 3.1 High-quality aesthetics and mobility

There is a green plot from the street with a raised garden with large trees, which is multiplied by the reflections generated by the green glass façade. The design and location of the building, a quiet residential area, invites students in the final years to use sustainable transport, such as bicycles, for which a parking area has been provided.

### Discussion

#### 3 Building boundary conditions and monitoring

In this section, the case study lists the different boundary conditions related to the use of the building that also allows a reduction in energy consumption and efficiency. This includes water consumption and indoor air quality limits. In addition, a monitoring exercise of variables for the academic year 2020/21 is also presented.
Universal accessibility criteria have been considered while designing the project. From the public road access, there is an accessible itinerary that extends to all building floors, including the basement. An accessible double boarding has resolved it, and three stops lift.

The common semi-circular spaces favour the meeting between users (Figure 11). The first space is at the entrance for parents’ reception and meeting with teachers; then, on the ground floor, the corridor opens onto a second space with benches and tables. This layout encourages work in small groups or tutorials; at last, on the first floor, the corridor becomes a space with a plough that opens onto the garden, inviting the pupil to understand the outside area as a potential place for learning.

### 3.2 Indoor air quality parameters

Ensuring optimal indoor air quality has been a priority at the school. However, poor indoor air quality (presence of biological agents) implies adverse health effects. For example, it contributes to the Sick Building Syndrome (OMS), directly affecting the respiratory tract, digestive tract or skin.

The relationship between outdoor and indoor concentrations of chemical pollutants has been estimated through various studies, showing significant differences in favour of higher concentrations in indoor environments. Examples of this can be seen in the Environmental Protection Agency (EPA) publication on research showing differences according to the estimated hours spent indoors (Vargas and Gallego, 2005).

Special care must be taken in an educational building, as air quality influences psychological and social conditions directly affect learning (reference). Therefore, the school must be a safe, clean, healthy and well-ventilated space.

The airtight skin of the building and the efficient ventilation system allows humidity and indoor draughts to be controlled and ensure an air renewal greater than 0.3 h⁻¹. The ventilation system with heat recovery includes high-efficiency and low-pressure loss F8 filters in the fresh air intake and G7 filters in the exhaust. The filters (Figure 12) do not allow the passage of harmful particles in suspension into the building, nor the entry of chemical and biological contaminants of various origins, which is especially advisable in the current times of pandemics. On the other hand, CO₂ levels in the classrooms are controlled by atmospheric sensors and probes placed in the return ducts of the ventilation system, favouring the concentration and cognitive activities of the students. The CO₂ simulation forecast yearly levels smaller than 1,000 ppm (Figure 13).

Although Passivhaus requires mechanical ventilation, it is also compulsory to obtain good natural light and natural ventilation. The aim is to get the most of natural lighting, with the idea of needing the minimum necessary support from artificial and energy efficiency lighting. The architectural design defines smaller windows openings to the North and larger openings to the South, where solar gains take
advantage of the winter sun. The summer solar radiation at West and South orientations are protected by direct and indirect shading.

Despite the inclusion of a double-flow ventilation system to ensure high indoor air quality, the noise level caused by the air valves does not exceed 25 dB (A) in the classrooms. In addition, the high level of insulation and the high quality of the building windows and doors reduce external noise levels prevalent in Madrid city centre.

The building is designed to remain closed during adverse weather intervals, guaranteeing fresh and hygienic air renewal. However, there is the possibility of opening windows and doors to the outdoors, at least for every classroom. This can be recommended when the outside temperature is pleasant and the openings do not cause energy losses, noise or nuisance. The communal work areas and classrooms are thus transformed into shaded garden spaces.

Table 4 reflects the materials and their toxicity, daylighting efficiency and sound absorption levels concerning the Spanish national building regulations (CTE, 2019). In addition, the values of the materials and their toxicity level are validated for non-residential building:

Table 4 Justication of materials and their toxicity level. (Data obtained from the technical data sheets and material certificates provided by the suppliers).

| MATERIAL           | SITUATION                      | TOXICITY LEVELS | PROJECT                                      |
|--------------------|--------------------------------|-----------------|----------------------------------------------|
| Isaval Duin        | Painting, wall and ceiling     | 30/30 g/l       | Free of toxic substances (VOCs) and odors.   |
| ecological matt    | finishes                       |                 |                                              |
| Finsa Boards       | Continuous furniture in        | 130/300 g/l     | E1 classification. Low VOC varnish,          |
|                    | corridor                       |                 |                                              |

Also, the validation of natural lighting efficiency, the DF (Daily Factor) is shown in 5:

Table 5. Justification for the effectiveness of natural lighting

| ROOM                | DF  | ROOM                | DF  |
|---------------------|-----|---------------------|-----|
| Classrooms B1 and B2| 2,03| Classroom B7        | 2,27|
| Classrooms B3, B4, B5| 4,30| Classroom E1        | 3,31|
| Laboratory          | 2,35| Classroom E2        | 2,97|
| Male Toilets        | 2,33| Ground Floor Aisle  | 3,66|
| Women's toilets     | 2,04| Corridor Floor 1    | 0,35|
| Classroom B6        | 3,94| Teachers' room      | 4,32|
Table 6. below compares the sound level with the highest sound protection level for the specifications of the Spanish national Technical Building Code (CTE).

Table 6. Comparative acoustic level of BRAINS school with normative values. (Data obtained from the technical data sheets and material certificates provided by the suppliers).

| PROTECTION                                                                 | NORMATIVE VALUES | PROJECT VALUES |
|---------------------------------------------------------------------------|------------------|----------------|
| Of the protected enclosures against watering from the outside              | Exterior $L_d = 55$ | $D_{2m,nt,Atr} = 30 \text{ dB}$ / $D_{2m,nt,Atr} = 50 \text{ dB}$ |
| Of the protected enclosures against watering in the compartments of installations | $D_{nTA} = 50 \text{ dB (A)}$ / $D_{nTA} = 55 \text{ dB (A)}$ | $L_{ntw} = 60 \text{ dB}$ / $L_{ntw} = 60 \text{ dB}$ |
| Of the enclosures protected against watering generated in enclosures not belonging to the same unit, use enclosures I. | $R_{ATabiques} = 33 \text{ dB (A)}$ / $R_{ATabiques} = 46 \text{ dB (A)}$ | $D_{nTA} = 50 \text{ dB (A)}$ / $D_{nTA} = 55 \text{ dB (A)}$ / $L_{ntw} = 65 \text{ dB}$ / $L_{ntw} = 65 \text{ dB}$ |

3.3. User feedback and monitoring

The building is designed to become a reference model for students learning about efficiency and sustainability, involving them in the building’s energy cycles and processes. To this end, the arrival of the Canadian wells to the heat recovery unit, the photovoltaic panels or the CO2 controls is made visible and accessible through informative screens when entering the building.

The modern aesthetics of the building and the mirror effect cladding is making an impact already in the area. The client and final user are impressed with the performance of this Passivhaus school in terms of energy savings. The building is also providing a comfortable and healthy work environment (Figure 14).

Furthermore, the temperature and relative humidity readings for every classroom and the fitting rooms / bathrooms are constantly recorded. The readings show a homogeneous behaviour even with changeable exterior conditions (Figure 15) The school is now also recording CO2, power generation and power consumption for the building.

The building focuses on the Passivhaus strategy as a design principle. It can be stated that the operational performance on the first months of activity is as expected on the energy model. (Figure 16, 17, 18, 19, 20, 21, 22)
Conclusions

The Brains International High School in Madrid represents a paradigm shift in the energy design of educational buildings. It starts from approximating the passive solar strategies through fundamental architectural and landscape parameters such as orientation, compactness, and its relationship with its surroundings. Aesthetically, the building uses reflective and coloured envelopes, which cause their dissolution in the garden. In addition, the deciduous trees favour the extension of the outdoor space and play a vital role as an energy design strategy.

The installation’s design solves the main challenge in educational use: to respond to the high variations of occupancy in the classrooms and to guarantee a stable temperature and optimum air quality, but, in addition, minimum energy consumption is achieved, and prioritising passive energy sources (GSHX) over active sources (heat pumps) employing integrated monitoring systems.

The use of state-of-the-art technology in heat recovery, aerothermal and photovoltaic systems, and the storage of surplus energy produced in batteries, is reflected in the initial calculations and the experience of the users.

The educational component in design is fundamental; the building is conceived as an extra learning tool for the pupils involved in the energy process in the building. This promotes awareness and sensitivity to the environmental challenges ahead.

The pupils can easily understand the energetic functioning of the building through visualisation strategies of the rooms where the Canadian wells are taken to and providing access to the roof with photovoltaic panels and visualisation of indoor and outdoor air quality data via information screens.

The design and construction of a Passivhaus Plus, as simulated by Passive House Planning Package (PHPP), delivers outstanding thermal performance and comfort for a building with a very different occupancy and use. The final construction cost of the project, including the external garden and interiors, was approximately 2,500 € / m².

Methods

- The objective of the study has been the thermal behaviour of a building through its design with passive and active elements of energy production, always prioritising the passive ones. The building is designed to behave like a “thermos flask” to ensure low consumption compared to a normal building. The case study is located in Madrid. This building intended for a school so that the high student occupancy is an advantage and the building adapts depending on the human heat generated.

- Multidisciplinary team of architects and engineers analysing the energy performance of an award-winning Passivhaus building. The materials used in the construction of the building have always had the characteristics endorsed and recommended by the passivhaus institute. Specialised materials
with high performance in thermal insulation and watertightness to guarantee that the accumulated heat remains inside the building.

- The passive processes that have been used to ensure a near-zero energy building have been of two types: passive and active. In the category of passive resources, it is used the airtightness of doors, walls, and windows, high-performance thermal insulation, Canadian wells and for solar protection, deciduous trees and south-facing eaves. In the category of active resources, air-to-water heat pumps and heat recovery units are combined to ensure a good thermal performance. These elements are studied throughout the year to observe their behaviour at different seasons.

- After thermal performance studies, it is known that, in terms of consumption and pupil ratio, the results show that this school consumes between six and eight times less energy than a school with a standard construction. The Canadian wells surrounding the building generate free cooling 80% of the year and the photovoltaic panels located on the roof, produces 80% of the time. Preheated or pre-cooled air is supplied to the technical room. As the temperature of the ground is constant throughout the year, between 14 and 18 C, the indoor temperature is reduced in summer and increased in winter.

**Abbreviations**

GSHX - Ground source heat exchanger

PV – Photovoltaic

XPS - Extruded polystyrene

MEP - Mechanical electrical and pumbling

MVHR - Mechanical Ventilation with Heat Recovery

EC - Electronically Commutated

CTE - Código Técnico de la Edificación

CO2 - Carbon Dioxide

PER - Primary Energy Renewable

DHW - Domestic hot water

ROI - Return on Investment

EPA - Environmental Protection Agency

PHPP - Passive House Planning Package

**Declarations**
Ethics approval and consent to participate
Not applicable

Consent for publication
Not applicable

Availability of data and materials
The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Competing interests
"The authors declare that they have no competing interests" in this section.

Funding
The source of funding is private (De Lapuerta + Campo Architects, co-authors of the article and architects of Brains School).

Authors' contributions
PC and JL carried out the architectural and energy design project based on the client's needs in coordination with Zero Energy engineering (led by JM), and performed the Project Management work. They provided architectural and energy design data and approved the final manuscript.

JM designed the installation and contributed energy data and interpretation of in-use building monitoring data to the manuscript. He approved the final manuscript.

JG contributed to the drafting of the manuscript and approved the final manuscript. He approved the final manuscript.

IC worked as Project leader and contributed the drafting of the manuscript. She approved the final manuscript.

All authors have agreed both to be personally accountable for the author's own contributions and to ensure that questions related to the accuracy or integrity of any part of the work, even ones in which the author was not personally involved, are appropriately investigated, resolved, and the resolution documented in the literature.

Acknowledgements
Not applicable
References

1. Berry, S., Whaley, D., Saman, W., & Davidson, K. (2014). Reaching to net zero energy: the recipe to create zero energy homes in warm temperate climates. Energy Procedia, 62, 112-122.

2. del Estado, B. O. (2019). Real Decreto 314/2006, de 17 de marzo, por el que se aprueba el Código Técnico de la Edificación.

3. Canha, N., Almeida, S. M., Freitas, M. C., Täubel, M., & Hänninen, O. (2013). Winter ventilation rates at primary schools: comparison between Portugal and Finland. Journal of Toxicology and Environmental Health, Part A, 76(6), 400-408.

4. Clevenger, C. M., & Haymaker, J. (2006, June). The impact of the building occupant on energy modeling simulations. In Joint International Conference on Computing and Decision Making in Civil and Building Engineering, Montreal, Canada (pp. 1-10).

5. Comunidad de Madrid (2011). Guía el estándar Passivhaus. Edificios de consumo energético casi nulo.

6. Demanuele, C., Tweddell, T., & Davies, M. (2010, September). Bridging the gap between predicted and actual energy performance in schools. In World renewable energy congress XI (pp. 25-30). UAE Abu Dhabi.

7. Feist, W., Pfuger, R., Kaufmann, B., Schnieders, J., & Kah, O. (2007). Passive house planning package 2007. Specifications for Quality Approved Passive Houses, Technical Information PHI-2007/1 (E), Darmstadt, Passivhaus Institut (December 2007).

8. Ferreira, A. M. D. C., & Cardoso, M. (2014). Indoor air quality and health in schools. Jornal Brasileiro de Pneumologia, 40, 259-268.

9. Hopfe, C., & McLeod, R. (2015). The Passivhaus Designer’s Manual: A technical guide to low and zero energy buildings. Routledge.

10. Johnston, D., & Siddall, M. (2016). The building fabric thermal performance of Passivhaus dwellings —does it do what it says on the tin?. Sustainability, 8(1), 97.

11. Lakshmi, S., & Ganguly, S. (2018). Simultaneous optimisation of photovoltaic hosting capacity and energy loss of radial distribution networks with open unified power quality conditioner allocation. IET Renewable Power Generation, 12(12), 1382-1389.

12. Lizana, J., Serrano-Jimenez, A., Ortiz, C., Becerra, J. A., & Chacartegui, R. (2018). Energy assessment method towards low-carbon energy schools. Energy, 159, 310-326.

13. De Visser, E., Hendriks, C., Barrio, M., Mølnvik, M. J., de Koeijer, G., Liljemark, S., & Le Gallo, Y. (2008). Dynamis CO2 quality recommendations. International journal of greenhouse gas control, 2(4), 478-484.

14. Thoua, C., Lumley, M., Hines, J., Montazami, A., Mavrogianni, A., Gaterell, M., & Grant, N. (2015). Case study: Review of control strategy for a primary school built to PassivHaus standard. In CIBSE Technical Symposium.
15. Vargas and Gallego (2005) Calidad ambiental interior: bienestar, confort y salud. Revista Española de Salud Pública 2005; 79: 243-251, Francisco Vargas Marcos e Isabel Gallego Pulgarín

**Figures**

**Figure 1**

Construction completed of the Brains school. De Lapuerta Campo architects.
Figure 2

Climate properties for the building site (Madrid city centre)

Figure 3

School floor layout

Figure 4

General composition of the thermal envelope
Figure 5

Dynamic simulation for fresh air intake temperatures through the GSHX
**Figure 6**

School final energy demands.

---

**Figure 7**

Large thicknesses of continuous thermal insulation throughout the building skin. Windows with tripalit glass.

---

**Figure 8**

Photovoltaic panels on the roof.

---

**Figure 9**
Axonometric diagram of the projective strategies carried out at the BRAINS school. (Source: De Lapuerta Campo Arquitectos)

Figure 10

Return on Investment (ROI) chart for buildings in comparison to Spanish CTE (REFERENCIA).

Figure 11

Construction of the BRAINS school. Placement of curved mirrors and glass in the envelope.

Figure 12

Construction of the BRAINS school. Visualisation of the GSHX
Figure 13

Modelled CO2 levels (ppm) in classroom B6.

Figure 14

Visualisation of the installation through a porthole, visualisation of the GSHX and insulation on the façade Porthole to see the entrance of the wells into the building; Installation of Canadian wells; Termic insulation in façade. (Source: De Lapuerta Campo Arquitectos)

Figure 15

Humidity (above) and temperature (below) readings for several school areas during July 2021.
Figure 16
Breakdown of monthly electricity consumption from November 2021 to May 2021

Figure 17
Consumption comparison between 2020 and 2021

Figure 18
Photovoltaic consumption: energy yields and environmental benefits

Figure 19
Photovoltaic consumption: energy yields and environmental benefits
Figure 20
Photovoltaic consumption: energy yields and environmental benefits

Figure 21
Photovoltaic daily and monthly consumption

Figure 22
Photovoltaic daily and monthly consumption