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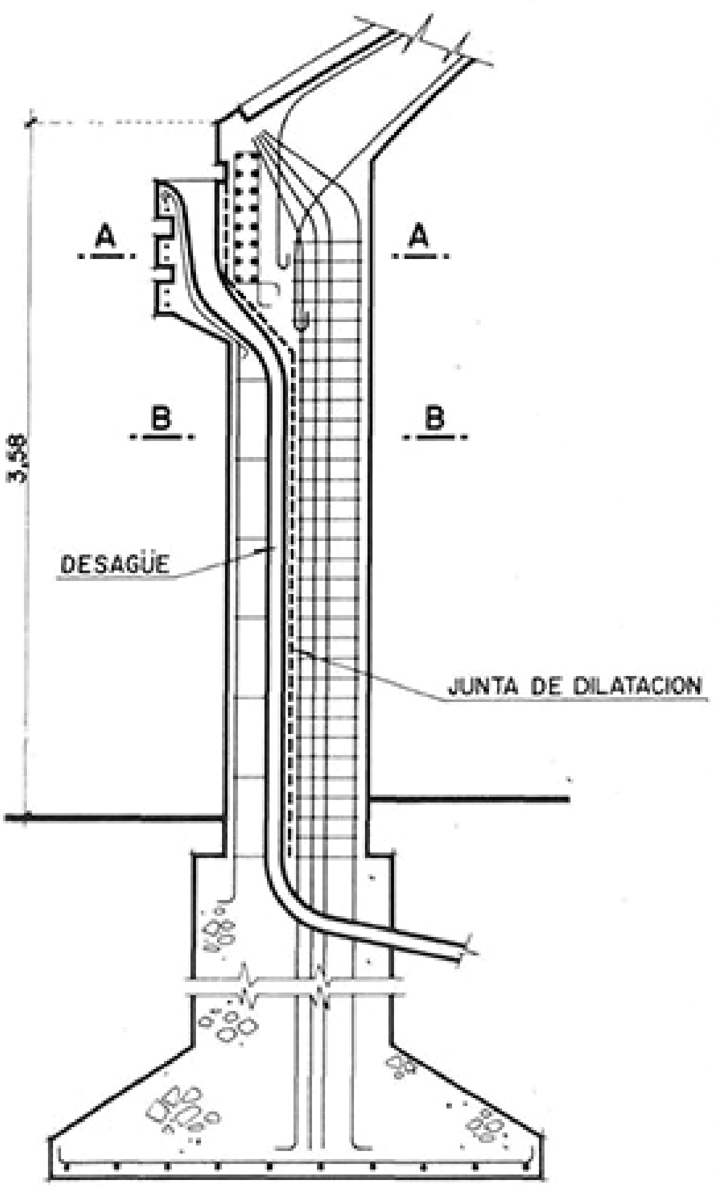

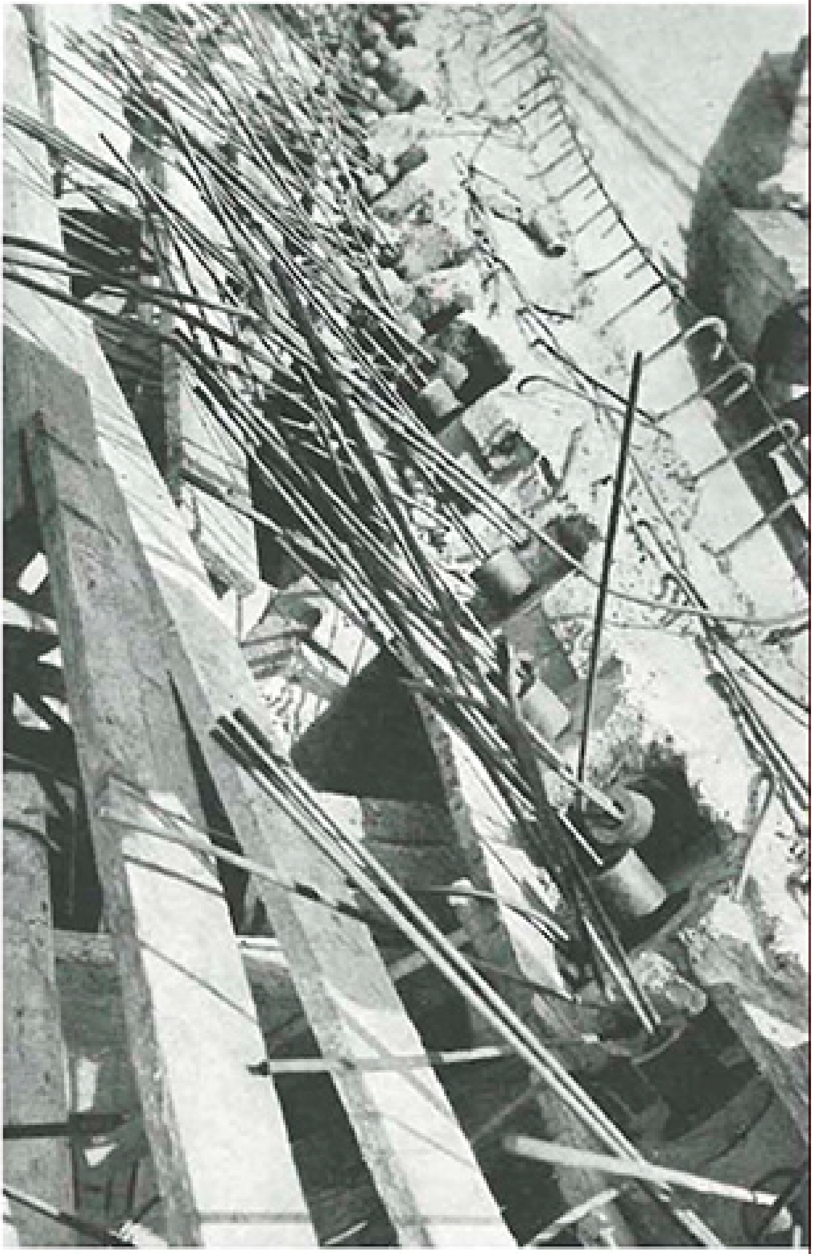

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Technical and constructive energy strategies of the first Passivhaus Plus school in Spain

Estrategias técnica y constructiva del primer colegio Passivhaus Plus en España

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ABSTRACT

A school that works disconnected from the grid, highly efficient, using energy from renewable sources. The design is based on a condition of low energy demand for heating and cooling and a primary energy demand according to the Passivhaus Plus standard: The total energy consumed could come from renewable sources. Through efficient consumption management, a very low rate of CO_2 *emissions is achieved. The strategies considered, in addition to meeting the requirements established by the Passivhaus seal, aim to achieve the concept of "well-being" in other environmental seals or certifications through a bioclimatic lense from the architectural design. First Spanish building awarded by the Passive House Institute (2021).*

Keywords*: architecture; passivhaus; sustainability; school; technical vanguard; energy strategies.*

RESUMEN

Un colegio que funciona desconectado de la red eléctrica, altamente eficiente y que utiliza energía procedente de fuentes renovables. El diseño se basa en una condición de baja demanda de energía para calefacción y refrigeración, y una demanda de energía primaria según el estándar Passivhaus Plus: El total de la energía consumida podría proceder de fuentes renovables. Gracias a una gestión eficiente del consumo, se consigue una tasa muy baja de emisiones de CO_2. Las estrategias tenidas en cuenta, además de cumplir los requisitos establecidos por el sello Passivhaus, pretenden alcanzar el concepto de "bienestar" en otros sellos o certificaciones medioambientales a través de una aproximación bioclimática desde el diseño arquitectónico. Primer edificio español premiado por el *Passive House Insitute* (2021).

Palabras clave*: arquitectura; passivhaus; sostenibilidad; colegio; vanguardia técnica; vanguardia energética.*

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1. INTRODUCTION

Brains is a new high school building located in Madrid, designed with the premise of proposing "new educational spaces", with open-plan classrooms, expandable and equipped with all the latest technologies. Record in consuming only renewable energy. There is a direct connection between architectural and energy design is direct.

Nowadays, buildings must respond, not only to the regulatory needs that are established by European directives such as 2010/31/EU and the subsequent ones that develop it, in the line of reducing CO_2 emissions and energy consumption, but also to the growing implementation of several sustainability certifications (Lead, Breeam, Verde...). All of them are mainly oriented to the design of buildings with a better insulated envelope, with lower energy demand, as well as high efficiency air conditioning systems and using renewable energy sources. In this sense, one of the main requirements of the passivhaus label is to achieve a very low energy demand index (1).

In this building (Fig. 1), the garden invades the first floor, as an extension of classrooms and common areas, and invites learning outside the classroom. It wants to reflect that there are alternative ways of studying and learning. The large deciduous trees to the south (the slab breaks to leave 1.25 metres of topsoil), anticipate passive bioclimatic strategies in the design, protect the interior from the strong sunlight in summer and let it pass through in winter. Their artificial lighting under the trunks projects the treetop onto the façade and produces attractive and unreal images.

The compactness of the building is another of the passive design strategies employed. Its shape optimises the façade surface in relation to the volume of the building, and reduces energy losses through the building envelope. However, there is a small annex volume, which marks the entrance to the building, and whose "key" shape anticipates the morphology of the interior common areas. Its specular façade disappears among big trees. It is a welcoming space where teachers and parents can meet.

As we move through the building, the common areas open onto a family of semicircular spaces, formally similar to the entrance volume, with benches around the perimeter that host meetings between students and teachers, and encourage small group work, tutorials or individual moments of relaxation.

On the first floor, a library with a wooden grandstand opens up with the raised garden. Two large sliding doors (with high performance and sophistication to reach Passivhaus Premium standards) generate a single connected space out of the grandstand and the garden, where some people browse on their tablets while other people lie on the lawn or sit on circular benches around the four mature trees.

Inside the gym, portholes recycled from other construction sites are set up for the students to peer into their machine room. Every day, the students see how the Canadian wells reach the building, how the aerothermics and photovoltaics work. They can see all the air quality and CO_2 controls in each space, and the place where the batteries are plugged

Figure 1. Construction of the Brains school completed. De Lapuerta Campo architects. Photography: Manuel Ocaña.

in and electricity is stored for grey days. With white painted signs the collective understanding and knowledge is achieved. The building itself and its strategies become an educational window.

The first new Passivhaus Plus school in Spain.

The first off-grid school.

2. ENERGY EXCHANGE

From the beginning, we worked in a school, with high occupancy, (2, 3) that could operate off-grid, highly efficient, powered by energy from renewable sources. The design starts from a condition of low energy demand for heating and cooling: <15 kWh/(m^2a) (10 kWh/(m^2a) for heating and 10 kWh/(m^2a) for cooling) and a primary energy demand of 67 kWh/(m^2a) (renewable primary energy demand is 40 kWh/(m^2a)). According to the PassivHaus Plus standard: The total energy consumed could be from renewable sources (4). A very reduced rate of CO_2 emissions is achieved through efficient consumption management, taking into account this building is in a warm climate country (5) The strategies considered, in addition to meeting the requirements established by the Passivhaus seal, seek to achieve the concept of well-being, considering the principles of other environmental seals or certifications.

2.1. Executed strategies

The strategies implemented to achieve the user's wellbeing are**:**

- Large thicknesses of continuous thermal insulation throughout the envelope (16 cm outside, 7 cm in-side), free from thermal bridges ($\psi \leq 0{,}01$W/(mK). The building works as a "thermos". It stores the interior heat or coolness for a very long period. Construction systems transmittances are very low: opaque locks with U≤ 0,15W/(m^2K) and installed windows with Uw≤0,8W/(m^2K). North-facing carpentry with Tripalit glass and solar control to the south. All glazing has a low-emissivity coating (Fig. 2).
- Airtightness of the envelope (n50<0.6), through the installation of airtightness sheets with low diffusion value (Sd) on the warm side of the skin of the building, to avoid condensation.

In addition to these requirements, which are indispensable in PassivHaus, the building is designed with compactness, orientation, wind control, and the vegetation integration. Deciduous trees are placed 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 optimum quality and renewal of indoor air. The air supply to the heat recovery system is preheated or precooled by Canadian wells. In this way, the heat recovery system will consume less energy when heating or cooling the ventilation air. The primary energy demand of the building is 67 kWh/(m2a), (heating, DHW and electricity).

2.2. Renewable energy production

In terms of renewable energy production, photovoltaic panels have been installed on the roof, which generate electricity for self-consumption. The surplus energy produced will be stored in batteries, resulting in an energy self-sufficient and zero consumption building. The PassivHaus Plus standard defines a renewable primary energy demand (PER) of less than 45 kWh/m^2a, and a renewable energy generation of more than 60 kWh/m^2. The renewable energies used are:

- A 141 m^2 photovoltaic solar field on the roof, generating 22 kW of electricity for self-consumption (6). The surplus will be stored in batteries, which in the future will be sized according to the actual electricity demand profile of the activity, so as to achieve an energy self-sufficient building, with zero consumption. A production power of 22 kW has been achieved. The maximum consumption has been 39,117.40 kWh/year, which has achieved a percentage reduction of 67% (Fig. 3).
- Horizontal geothermal energy through a system of Canadian wells to heat and cool the building's ventilation air. With a power of 20,719 kWh/year for heating and 23,624 kWh/year for cooling, and a reduction percentage of 15.7%. The saving in CO_2 emissions is 4,466.17 kgCO_2/m^2year in heating and 3,560.56 kgCO_2/m^2year in cooling.
- Use of stored energy in the form of heat from outside air by means of air heaters to cover the demand for heating,

Figures 2. Large thicknesses of continuous thermal insulation throughout the building skin. Carpentry with tripalit glass.

cooling and DHW demand. For DHW pro-duction, we use CO_2 technology, with a 30kW output and 35 kW for heating/cooling production.

Figure 3. Photovoltaic solar panels on the rooftop.

2.3. Ventilation and air conditioning system

By measuring the individual comfort conditions per classroom (temperature, humidity, CO_2 concentration), a high definition in instrumentation and control of the transport of renewal air and air-conditioning water is achieved. With all the above, it is possible to automate the prioritization of passive energy sources (Canadian wells) with respect to active production sources (aerothermal), as well as to reduce the electricity consumption of both applications, by means of variable flow in their distribution. All of this is reflected in a monitoring system that allows the comfort conditions to be parameterized and monitored remotely and in real time.

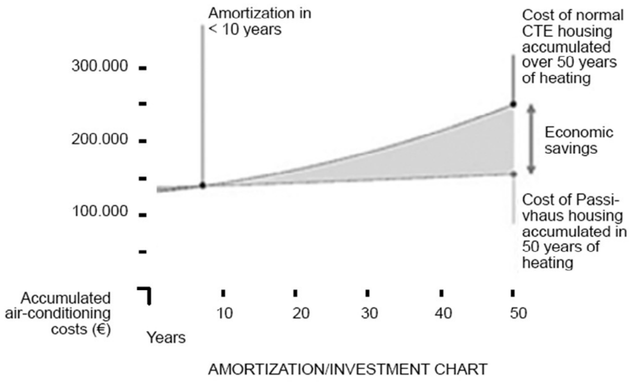


Figure 4. Investment- amortisation graph.

The cost of construction was around 2300 €/m2, which compared to an equivalent building that strictly complied with the regulations represented an increase of around 30 %.

This additional cost is installing airtightness measures, mechanical ventilation with heat recovery units and good quality windows and doors. However, the studied return of investment of the building, as per 2021 energy prices, has a payback of 9 years thanks to a minimal energy cost. Furthermore, it increases the value of the property (Fig. 4).

The table 1 reflects the energy demand of the building:

Table 1. Energy demand.

ENERGY DEMAND - BRAINS SCHOOL	
kWh/m² year of heating	10
kWh/m² year of cooling	10
kWh/m² year total	16.7 joint demand
% demand reduction for the building with respect to regulations	42,9

The table 2 details the energy demand of the building and the energy rating of the building and the certification system used:

Table 2. Energy and emissions rating description.

EMISSIONS (CTE)		ENERGY DEMAND (PASSIVE HOUSE)	
CO_2 emissions [$kgCO_2/m^2$año]		Primary energy of CO_2 [kWh/m²año]	
Global CO_2 emissions rating	4,08 - A	Global primary energy consumption	36,1 kWh/(m2a)
Partial indicator: heating emission	0,8 kg CO_2/(m²a)-A(0.1)	Partial indicator: primary energy heating	4,5 kWh/(m²a)-A(0.1)
Partial indicator: cooling emission	1,5 kg CO_2/(m²a)-A(0.2)	Partial indicator: primary energy cooling	8,6 kWh/(m2a)-A(0.2)
Partial indicator: DHW emission	1 kg CO_2/(m²a)	Partial indicator: primary energy DHW	6,2 kWh/(m²a)
Partial indicator: light emission	3,6 kg CO_2/(m²a)	Partial indicator: primary energy lighting	21,5 kg CO_2/(m2a)

The 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 %

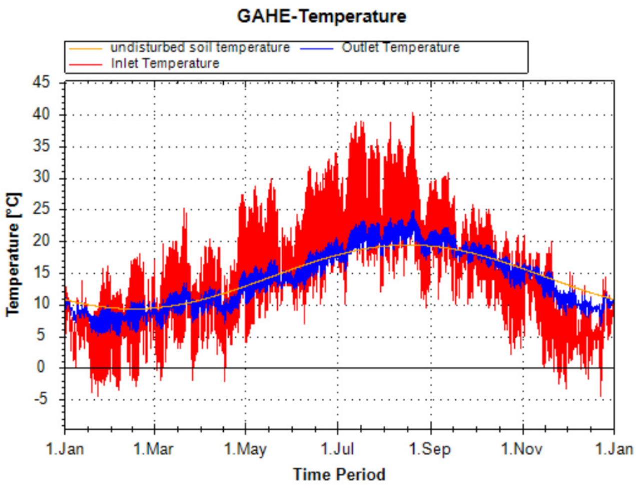


Figure 5. Dynamic simulation for fresh air intake temperatures through the GSHX.

(Figure 5 and 6). This incoming temperated air feeds two industrial MVHR units of 3,600 m3/h, one for each floor and distributed to all the areas through cascade ventilation by rectangu-lar insulated ducts. CO_2 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 (7-9).

Individual climate units with highly efficient EC motors provide heating and cool-ing 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.

3. NATURAL RESOURCES. WATER AND MATERIALS (MATERIAL EXCHANGES)

As to produce domestic hot water (DHW), there is an aerothermal system with CO_2 refrigerant gas, which is completely ecological and has a very high production efficiency, what allows a very low electricity consumption for the changing rooms' showers and zero impact, as no fluorinated gases are used for the thermodynamic cycle (10).

The entire plumbing system installed in the building is designed to reduce the water consumption in sanitary equipment with water economizers: timed push buttons in showers and taps, water-saving tap rosettes, so that the flow rate is reduced by 40% to 60% compared to an ordinary tap, Urimat waterless urinal bowls and efficient flush toilets.

In the open spaces of the plot a permeable landscaped environment is configured. There is a forest of birch and maple trees that generates a comfortable environment around it. This is favoured by the absorption of solar radiation through shadows and cooling surfaces and minimises the amount of paving. The irrigation system implemented, through the use of in-line pressure emitter pipes, minimises evaporation losses, avoiding run-off. Next chart shows the percentage reduction in drinking water consumption (Table 3):

Table 3. Water saving applied strategies.

APPLIED STRATEGIES	REDUCTION OF DRINKING WATER CONSUMPTION
Timed taps	Between 30% and 40% with respect to untimed taps
Aerators or flow reducer on taps	40% reduction compared to taps without aerator
Irrigation with buried self-compensating drip	Between 40% and 50% compared to a sprinkler system
Urinals	100%

The origin of the wood materials is an issue that has been carefully handled as well as the choice of construction materials in terms of processing and transport distance from the point of extraction and/or manufacture. This model has a category II eco-label with verified data based on the board used under the S-P-00272 standard. It is a reusable and recoverable material for the building. The responsible choice of materials has been taken into account, prioritizing aspects such as local origin and choosing renewable natural or recycled industrial materials.

4. INDOOR AIR QUALITY

The airtight skin of the building and the efficient ventilation system, allow humidity and indoor draughts to be controlled and ensures an air renewal at 50 Pa of 0.6 h-1 (11). The ventilation system with heat recovery includes high efficiency F8 filters in the fresh air intake and G7 filters in the exhaust, which do not allow the passage of harmful particles in sus-

Figure 6. Construction of the BRAINS school. Installation of the Canadian wells.

pension 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, CO_2 levels in the classrooms are controlled by atmospheric probes and probes placed in the return ducts of the ventilation system, favouring the concentration and cognitive capacity of the students (Fig. 7).

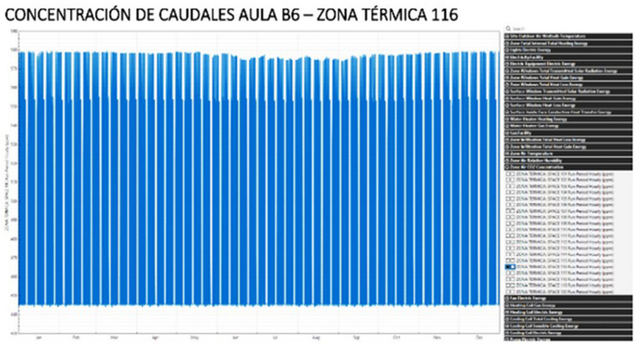


Figure 7. Estimated Co_2 concentration in classroom B6.

The starting point is to make the most of natural lighting, with the idea of needing the minimum necessary support from artificial lighting, with low consumption. The design of controlled openings to the north, and the opening of large openings to the south, where the winter sun is taken advantage of and the summer sun is protected by the recessing of the driveway.

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's joinery reduce external noise levels, eliminating noise pollution (Fig. 8).

Although the building is designed to remain closed, guaranteeing air renewal, there is the possibility of opening up to the outdoors, for example through two large sliding doors to the garden on the first floor, especially when the outside temperature is pleasant and the opening does not cause energy losses. The communal work areas and classrooms are thus transformed into shaded garden spaces.

4.1. Charts of indoor air quality levels

The following charts reflect the materials and their toxicity, daylighting efficiency and sound absorption levels with respect to the specifications of the Technical Building Code (CTE) (12).

Justification of materials and their toxicity level, considering it is not a residential building (Table 4):

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

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

Justification of natural lighting efficiency, the DF (Daily Factor) has been calculated (Table 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 with respect to the specifications of the Technical Building Code (CTE) (12).

Figures 8. Visualization of the installation through a porthole, visualization of the Canadian wells and insulation on the façade.

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 dB	$D_{2m.nt.Atr}$ = 50 dB
Of the protected enclosures against watering in the enclosures of installations	D_{nTA} = 50 dB (A)	D_{nTA} = 55 dB (A)
	L_{ntw} = 60 dB	L_{ntw} = 60 dB
Of the enclosures protected against watering generated in enclosures not belonging to the same unit use enclosures I.	$R_{ATabiques}$ =33 dB (A)	$R_{ATabiques}$ =46 dB (A)
	D_{nTA} = 50 dB (A)	D_{nTA} = 55 dB (A)
	L_{ntw} = 65 dB	L_{ntw} = 65 dB

5. SOCIAL ASPECTS AND INNOVATION

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 CO_2 controls are made visible and accessible through informative screens when entering the building.

From the street there is a green plot 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.

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 basement. It has been resolved by accessible double boarding elevator.

The semi-circular common spaces favour the meeting between users. There is a first space 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, which encourages work in small groups or tutorials; at last, on the first floor, the corridor becomes a space with a harrow that opens onto the garden, inviting the pupil to understand the outside space as a potential place for learning.

The building focuses on the PassivHaus strategy as a challenge. Design principles are established based on achieving an intelligent and sustainable building, which prioritizes the heat flows control for a future in which significant temperatures are predicted (Fig. 9):

- Building orientation and position on the plot: the starting point is a building design in which distribution responds to lighting needs, where solar protection elements (eaves and set-back of the carpentry) are combined with natural elements (vegetation). Adult trees located in front of the classrooms are leafy but deciduous, so they protect from the sun's strong incidence in summer but allow its passage in winter.
- Vegetation in exterior spaces as a strategy to reduce effects from the heat island generated by the hard pavements, what generates a fresh environment and reduces pollution, improving exterior air quality.
- Exploitation of the ground thermal inertia at -3 meters depth, to pre-heat or pre-cool the intake air.
- Use of the Sun as a renewable energy source.

6. USER FEEDBACK AND MONITORING

The temperature and relative humidity readings for every classroom and the fitting rooms / WC are constantly recorded. The readings show a homogeneous behaviour even with changeable exterior conditions (Fig. 10) The school is now also recording CO_2, power generation and power consumption for the building (Fig. 10).

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 (Figs. 11, 12 and 13).

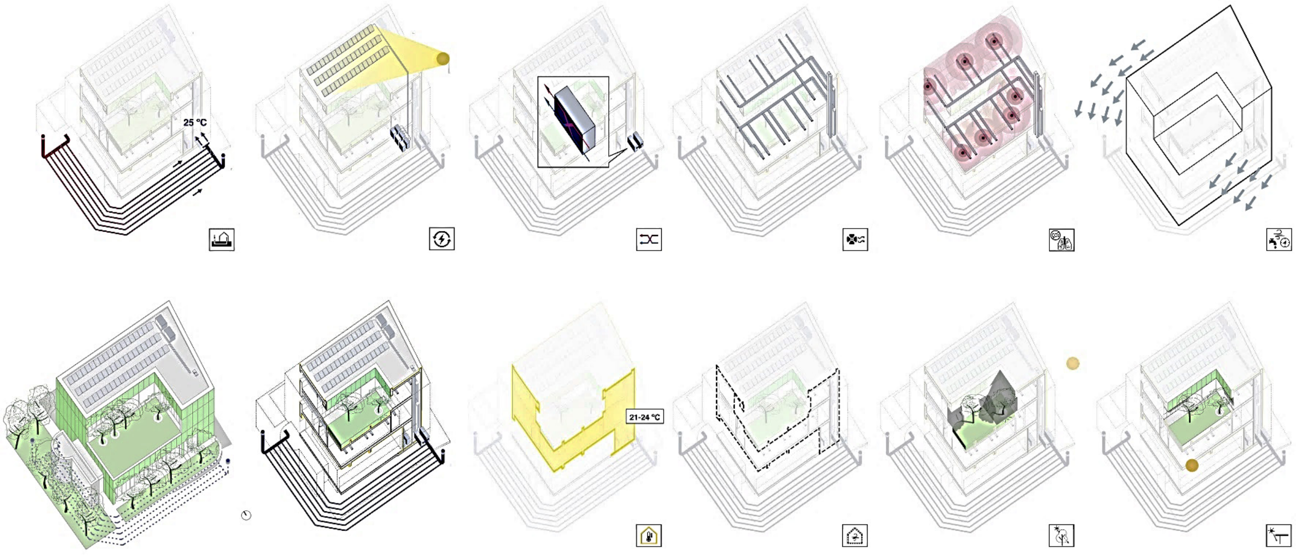


Figure 9. Different environmental strategies in the builidng.

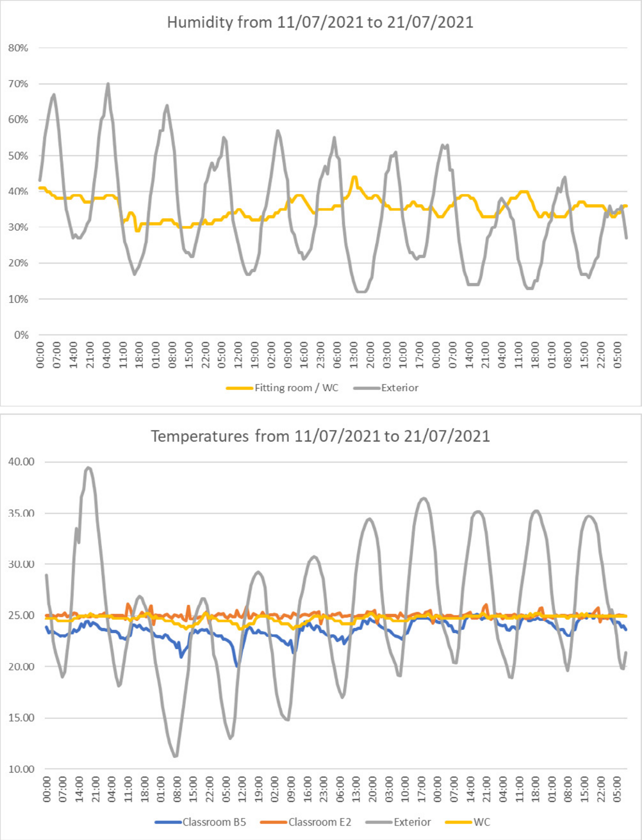


Figure 10. Humidity (above) and temperature (below) readings for several school areas during July 2021.

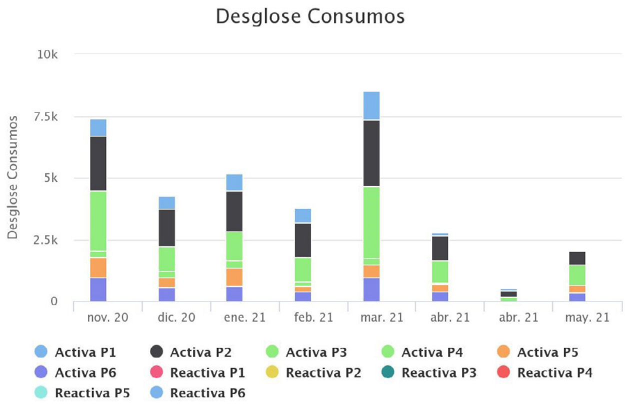
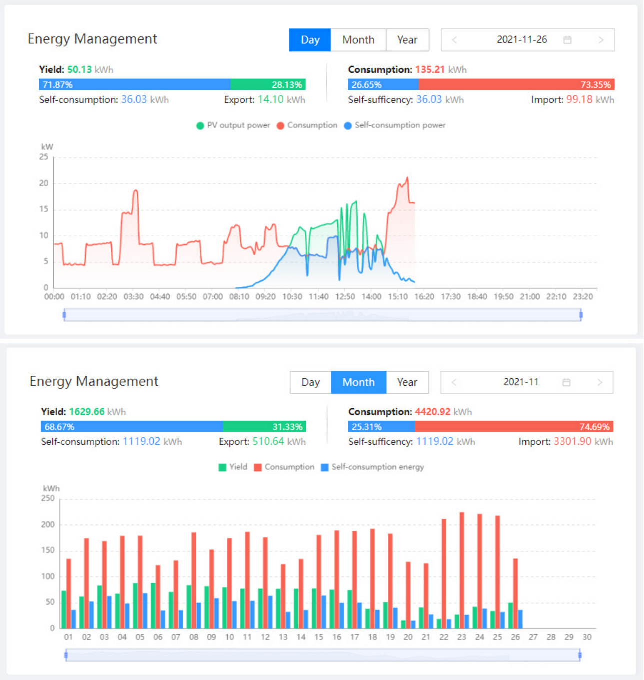


Figure 11. Breakdown of monthly electricity consumption from November 2021 to May 2021.

Figure 12. Consumption comparison between 2020 and 2021.



Yield: 50.13 kWh
71.87% 28.13%
Self-consumption: 36.03 kWh Export: 14.10 kWh

Consumption: 135.21 kWh
26.65% 73.35%
Self-sufficency: 36.03 kWh Import: 99.18 kWh

Yield: 1629.66 kWh
68.67% 31.33%
Self-consumption: 1119.02 kWh Export: 510.64 kWh

Consumption: 4420.92 kWh
25.31% 74.69%
Self-sufficency: 1119.02 kWh Import: 3301.90 kWh

Figure 13. Photovoltaic daily and monthly consumption.

7. CONCLUSIONS

Brains school represents a paradigm shift in the energy design of educational establishments. It starts from an approximation of the passive 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 own dissolution in the garden (Fig. 14). The deciduous trees favour the extension of the outdoor space and play a key role as an energy design strategy.

The fact that for the first time in 25 years a building in Spain and southern Europe has been recognised by the Passive House Institute as the best Passive House building has to do not only with the recognition of architectural values but also with the realisation that the Passivhaus standard is not only suitable for cold climates in northern Europe, but also allows for highly energy-efficient buildings in continental climates such as Madrid, with very cold months in winter and very hot months in summer. It is also possible to reconcile high occupancy use requiring high air renewal with the apparently sealed envelope required by the passive house, thanks to systems such as the Canadian wells that allow the large volume of renewal air to reach the air conditioning systems pre-heated and pre-cooled.

The installations 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, a minimum energy consumption is achieved and prioritising passive energy sources (Canadian wells) over active sources (aerothermal) by means of monitoring systems.

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

Figures 14. Construction of the BRAINS school. Placement of curved mirrors and glass in the envelope.

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

The students can easily understand the energetic functioning of the building through visualization strategies of the rooms where the Canadian wells are taken to as well as providing access to the roof with photovoltaic panels and a visualization of indoor and outdoor air quality data via information screens (Fig. 8).

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