Universidad de Valladolid

Escuela de Doctorado Universidad de Valladolid

PHD PROGRAMME IN INDUSTRIAL ENGINEERING

DOCTORAL THESIS:

ENERGY SUSTAINABILITY STUDY AND INDOOR AIR QUALITY (IAQ) FOR HEALTH AND THERMAL COMFORT IN TWO CLASSROOM BUILDINGS OF A CAMPUS: STANDARD BUILDING AND NEAR ZERO ENERGY BUILDING (nZEB)

Submitted by *Nada Youssef Ahmed* in fulfilment of the requirements for the PhD degree by the Universidad de Valladolid

Supervised by:
Prof. Francisco Javier Rey Martínez
Prof. Javier M. Rey Hernandez

Universidad de Valladolid

Escuela de Doctorado Universidad de Valladolid

PROGRAMA DE DOCTORADO EN INGENIERÍA INDUSTRIAL

TESIS DOCTORAL:

ESTUDIO DE SOSTENIBILIDAD ENERGÉTICA Y CALIDAD DEL AIRE INTERIOR (IAQ) PARA LA SALUD Y EL CONFORT TÉRMICO ENTRE DOS EDIFICIOS DE AULAS DE UN CAMPUS: EDIFICIO ESTÁNDAR Y EDIFICIO DE CONSUMO DE ENERGÍA CASI NULO (nZEB)

Presentada por *Nada Youssef Ahmed* para optar al grado de
Doctora por la Universidad de Valladolid

Dirigida por:
Prof. Francisco Javier Rey Martínez
Prof. Javier M. Rey Hernandez

ACKNOWLEDGEMENT

I would like to express my heartfelt gratitude to my supervisors, Fransisco Javier Rey Martinez and Javier M. Rey-Hernandez, for their unwavering guidance, mentorship, and scholarly expertise throughout my doctoral studies. Their great opinions and encouragement have shaped my academic growth and study path.

My deepest appreciation goes to my parents for their endless love, sacrifice, and unwavering belief in my abilities. The motivation that they offered was crucial in helping me to achieve academic success and improve my knowledge. I am deeply grateful for their ongoing support and inspiration.

I would like to sincerely thank my sisters for being a source of motivation and for their understanding during the challenging stages of my research. Their encouragement and wisdom have been a constant source of strength, reminding me of the value of family relationships.

Throughout the ups and downs of this academic journey, my husband, Tamim, provided me with endless support, empathy, and encouragement. He deserves a special mention. His faith in my capabilities and the sacrifices he made to guarantee my success were infinite.

To my circle of friends, your friendship and encouragement have made this academic journey more enjoyable. Your presence made the journey more memorable.

I would like to express my deepest gratitude to Prof. Ahmed A. Hanafy for his kind cooperation and encouragement, which helped me along the way.

I gratefully acknowledge the support of the EUSUVA 4.0 Project of UVa, which contributed essential resources and collaboration for this research.

This work also benefited from the scientific exchange and collaboration fostered by the TRAPECIO Network Ibero-American of CYTED.

Finally, I'd like to express my deepest thanks to everyone who has helped and supported me in reaching this significant milestone in my life, no matter how small their role was.

Abstract

The current increase in energy consumption in the construction sector represents in the EU approximately 40% of energy use and more than 30% of annual electricity consumption, which contributes significantly to greenhouse gas emissions with a value of 36%.

Nearly zero-energy buildings (nZEB) offer a sustainable solution in the building sector by reducing energy consumption and CO_2 emissions through high efficiency and the integration of renewable energy sources.

This doctoral research analyses the energetic and environmental aspects of a nZEB lecture building, called INDUVA, on the UVA campus in Spain. The study focuses on the balance between energy efficiency and renewable energies integrated into the INDUVA by evaluating renewable and non-renewable primary energies using a dynamic simulation program called DesignBuilder that is calibrated with experimental data through continuous monitoring in the building with multiple physical and energy consumption parameters, while evaluating key energy efficiency indicators, energy intensity IE of primary, non-renewable and renewable energy as well as HVAC system performances, global warming potential GWP and renewable energy ratio in the building.

A novel aspect of this study is the in-depth analysis of the INDUVA building at the University of Valladolid, an advanced nZEB with high Indoor Air Quality (IAQ) and an integrated Building Management System (BMS) that optimizes energy use and environmental conditions. The building incorporates state-of-the-art ventilation strategies, photovoltaic (PV) solar panels for electricity generation, a geothermal heat recovery system using ventilation air, and a biomass-fired district heating system.

A rigorous methodological approach was employed using DesignBuilder version 7 and its EnergyPlus engine to simulate energy performance in heating, air conditioning, ventilation and lighting by calculating energy balances. The study has also been extended by analyzing the impact of future climate variations from 2022 to 2080 using CCWorldWeatherGen, to highlight the impact of climate change on the energy consumption that the INDUVA building will suffer. In addition, a relocation analysis of the building allowed to evaluate the operation of

the INDUVA building in different climates simulating its energy performance in cities such as Juneau and Warsaw.

Furthermore, this research provides a comprehensive assessment of Indoor Environmental Quality (IEQ) indicators, including indoor air quality, thermal comfort, ventilation efficiency, lighting and acoustics, comparing the results with international standards. The results indicate a reduction in heating demand over time, but an increase in cooling energy use and CO_2 emissions, highlighting the need for adaptable designs.

Finally, a comparative analysis of the INDUVA building (nZEB) is carried out with another standard lecture building on the same UVa Campus, allowing us to obtain valuable information on the nZEB principles on the building's energy demand, as well as on the HVAC systems, especially with mechanical ventilation to achieve a high IAQ. This contributes significantly to the benefits and challenges of implementing standard buildings that we must rehabilitate energetically.

Ultimately, this research contributes to the advancement of sustainable and energy-efficient university campus classroom building design by providing practical recommendations for policymakers, architects and engineers to ensure resilience in an evolving climate context.

Resumen

Objetivos:

El aumento actual del consumo energético en el sector de la construcción representa en la UE aproximadamente el 40 % del uso de energía y más del 30 % del consumo eléctrico anual, lo que contribuye significativamente a las emisiones de gases de efecto invernadero, con un valor del 36 %. Los edificios de energía casi nula (nZEB) ofrecen una solución sostenible en el sector de la construcción al reducir el consumo energético y las emisiones de CO_2 mediante alta eficiencia e integración de fuentes de energía renovables.

Esta investigación doctoral analiza los aspectos energéticos y ambientales de un edificio de aulas nZEB, denominado INDUVA, en el campus de la Universidad de Valladolid (UVA), España. El estudio se centra en el equilibrio entre eficiencia energética y energías renovables integradas en el INDUVA, evaluando la energía primaria renovable y no renovable mediante un programa de simulación dinámica llamado DesignBuilder, calibrado con datos experimentales obtenidos a través del monitoreo continuo de múltiples parámetros físicos y de consumo energético del edificio, y evaluando indicadores clave de eficiencia energética, la intensidad energética (IE) de la energía primaria, renovable y no renovable, así como el desempeño del sistema HVAC, el potencial de calentamiento global (GWP) y la proporción de energía renovable en el edificio.

Metodología:

Un aspecto novedoso de este estudio es el análisis en profundidad del edificio INDUVA, un nZEB avanzado con alta Calidad del Aire Interior (IAQ) y un Sistema de Gestión de Edificios (BMS) integrado que optimiza el uso de energía y las condiciones ambientales. El edificio incorpora estrategias de ventilación de vanguardia, paneles solares fotovoltaicos (PV) para generación eléctrica, un sistema de recuperación de calor geotérmico utilizando el aire de ventilación, y un sistema de calefacción urbana mediante biomasa.

Se empleó un enfoque metodológico riguroso utilizando DesignBuilder versión 7 y su motor EnergyPlus para simular el desempeño energético en calefacción, aire acondicionado, ventilación e iluminación mediante el cálculo de

balances energéticos. Además, el estudio se amplió mediante el análisis del impacto de variaciones climáticas futuras de 2022 a 2080 utilizando CCWorldWeatherGen, para resaltar el efecto del cambio climático en el consumo energético del edificio INDUVA. También se realizó un análisis de reubicación del edificio, evaluando su operación en diferentes climas, simulando su desempeño energético en ciudades como Juneau y Varsovia.

Resultados:

Esta investigación proporciona una evaluación integral de los indicadores de Calidad Ambiental Interior (IEQ), incluyendo calidad del aire interior, confort térmico, eficiencia de ventilación, iluminación y acústica, comparando los resultados con estándares internacionales. Los resultados indican una reducción en la demanda de calefacción con el tiempo, pero un aumento en el consumo de energía para refrigeración y en las emisiones de CO_2, destacando la necesidad de diseños adaptables.

Se llevó a cabo un análisis comparativo del edificio INDUVA (nZEB) con otro edificio de aulas estándar en el mismo campus de la UVA, lo que permitió obtener información valiosa sobre los principios nZEB en la demanda energética del edificio, así como en los sistemas HVAC, especialmente la ventilación mecánica para alcanzar una alta IAQ. Esto contribuye significativamente a comprender los beneficios y desafíos de implementar edificios estándar que requieren rehabilitación energética.

Conclusiones:

En última instancia, esta investigación contribuye al avance del diseño de edificios de aulas universitarias sostenibles y energéticamente eficientes, proporcionando recomendaciones prácticas para responsables políticos, arquitectos e ingenieros, con el fin de garantizar resiliencia frente a un contexto climático cambiante.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

AAHX	Air-to-Air Heat Exchanger
AC	Air-Conditioning
AHU	Air Handling Unit
ANSI	American National Standards Institute
AR6	Sixth Assessment Report
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
AVI	Audio Video Interleave
BPIE	Buildings Performance Institute Europe
BIPV	Building-integrated photovoltaics
BIPV/T	building-integrated photovoltaic-thermal
BMS	Building Management System
BREEAM	Building Research Establishment Environmental Assessment Method
CCworldweathergen	Climate Change World Weather File Generator
CdTe	Cadmium Telluride
CFD	Computational Fluid Dynamics
CIBSE	Chartered Institution of Building Services Engineers
CO_2	Carbon Dioxide
COP	Coefficient of Performance
CTE	Technical Building Code
CV(RMSE)	Coefficient of Variation of the Root Mean Square Error
DALI	Digital Addressable Lighting Interface
DCV	Demand Controlled by Ventilation
DH	District Heating
DSY	Design Summer Year
DXF	Drawing Interchange Format
EAHX	Earth to Air Heat Exchangers
EED	Energy Efficiency Directive
EER	Energy Efficiency Ratio
EES	Energy-Efficient Systems
EMS	Energy Management Systems
EN	European Standards
EPB	Energy Performance of Buildings
EPBD	The Energy Performance of Buildings Directive
EPW	EnergyPlus Weather File
EU	European Union
GAHX	Ground-to-Air Heat Exchanger
GCM	Global Climate Model
GHG	Greenhouse Gases
GSHP	Ground Source Heat Pump
GWP	Global Warming Potential
HadCM3	Hadley Centre Coupled Model, version 3
HCHO	Formaldehyde
HD	High Definition
HQE	High-Quality Environmental
HVAC	Heating, Ventilation, and Air Conditioning

IAQ	Indoor Air Quality
IEQ	Indoor Environmental Quality
INSHT	National Institute for Safety and Health at Work
IPCC	Intergovernmental Panel on Climate Change
kWp	kilowatt peak
LCA	Life Cycle Assessment
LED	Light-Emitting Diode
LEED	Leadership in Energy and Environmental Design
LPB	Low Polluting Building
Met	Meteorological
MVHR	Mechanical Ventilation with Heat Recovery
NDIR	Non-Dispersive Infrared
NIOSH	National Institute for Occupational Safety and Health
NMBE	Normalized Mean Bias Error
NO_2	Nitrogen dioxide
NZEBs	Net zero energy buildings
nZEB	Nearly Zero Energy Building
PCM	Phase Change Material
PE	Primary Energy
PEF	Primary Energy Factor
PID	Proportional – Integral – Derivative
PLCs	Programmable Logic Controllers
$PM_{2.5}$	Particulate Matter 2.5 micrometers in diameter
PM_{10}	Particulate Matter 10 micrometers in diameter
PMV	Predicted Mean Vote
PPD	Percentage of Dissatisfied Persons
ppm	Parts per million
ppb	Parts per billion
PV	Photovoltaics
PVTW	PV-Trombe wall
QEHS	Quality, Environment, Health, and Safety
RCPs	Representative Concentration Pathways
RES	Renewable Energy Systems
RER	Renewable Energy Ratio
RH	Relative Humidity
RITE	Regulation of Thermal Installations in Buildings
RTUs	Remote Terminal Units
SCADA	Supervisory Control and Data Acquisition
TES	Thermal Energy Storage Systems
TMY	Typical Metrological Year
TRY	Test Reference Year
TVOC	Total Volatile Organic Compounds
U	Thermal Transmittance
UK	United Kingdom
UKCIP	United Kingdom Climate Impacts Program
USA	United States of America

Uva	The University of Valladolid
UV	Ultraviolet
VERDE-GBC	Green Building Council Espane
VOC	Volatile organic compound
VRV	Variable Refrigerant Volume
WHO	World Health Organization
2D	Two-Dimensional
3D	Three-Dimensional

1. Chapter 1: INTRODUCTION AND LITERATURE REVIEW

1.1 Introduction

The world is dealing with urgent challenges due to population growth and electricity usage, requiring action to reduce carbon emissions, promote economic growth, and address fossil fuel depletion[1]. 40% of the world's energy consumption and 36% of world greenhouse gas emissions are attributed to the building industry[2]. European (EU) policies promote energy efficiency and renewable production to reach a climate-neutral continent by 2050. According to the European Green Deal[3], vital targets were set for 2030 and 2050, including at least 40% cuts in greenhouse gas emissions to be on track to reach a Greenhouse Gases (GHG) reduction of between 80-95% by 2050 (from 1990 levels), a minimum of 32% share for renewable energy, and not less than 32.5% improvement in energy efficiency[4]. In Addition, energy distribution in buildings must be designed sustainably for the welfare of people and environmental health[1]. Net zero energy buildings (NZEBs) are a viable option to reduce building energy use and carbon emissions because they integrate cutting-edge technologies like high-efficiency mechanical systems, passive design strategies, and renewable energy utilization[5]. The term NZEBs has been defined in various ways. Still, the core concept is that all of the energy needs for the building should be met by on-site energy produced from renewable energy sources. If that is not enough, energy from the local electrical grid can be used. When the energy produced from the on-site renewable energy sources exceeds the needs of the building, the excess energy can be fed into the local grid. It also can be defined as buildings not using fossil fuels and relying entirely on solar and other renewable energy sources to meet their energy needs[6].

1.2 Literature Review

1.2.1 Passive Buildings

Passive buildings, which use passive technologies to reduce or even eliminate active energy supply, have gotten much notice worldwide [7]. Moreover, because of their low carbon emissions and high energy efficiency[7], their development is critical for mitigating climate change and global warming[8].

Hu et al. performed a systematic review and meta-analysis to identify, categorize, and investigate the efficacy of passive cooling strategies for residential buildings. They studied the use of different passive strategies, and the result was a decrease in indoor temperature by 2.2 °C, a 31% reduction in cooling load, a 29% reduction in energy consumption, and a 23% extension of thermal comfort hours[9].

Mohammad et al. investigated the effectiveness of aerogel technologies as a window retrofit method in the United Kingdom (UK) climate. The thermal efficiency of different aerogel systems as alternatives to standard double-glazing systems was evaluated using a two-story residential building. According to the findings, aerogel technology has a high potential for boosting total solar heat energy through windows by occupying high solar heat gain coefficients of up to 0.738 and low Thermal Transmittance (U) values of up to 0.381 W/m^2K. Aerogel window insulation could boost total window heat transfer by up to 33% while decreasing heat demand by 15.5%[10].

Abdou et al. studied the potential of net zero energy building by combining architectural energy efficiency practices and renewable energies. Results showed that 21% of energy saving, 28% in heating load, and 40% in cooling could be achieved by combining building orientation, window type, Window-to-Wall Ratio, wall and roof insulation, and infiltration rate. Furthermore, renewable energy systems can instantly cover 45% of the building energy load [11].

D'agstino et al. investigated passive energy-saving strategies for existing structures, such as improving the thermal insulation of the opaque building envelope and inserting windows with low U value. Eight passive strategies were investigated, each combining various insulation thicknesses and window types. Sensitivity analysis and a comparison of cost-optimal methods and discounted payback were analyzed. The lowest primary energy was obtained with a thickness of 12 cm of insulation and windows with a U of 1.10 W/m^2 K. At the same time, the best scenario was a slight increase in insulation thickness[12].

1.2.2 Photovoltaics

There are many systems to achieve NZEBs; Perez et al. investigated 170 situations for five climatic zones and discovered that photovoltaic energy has significant potential. This makes electrification, mainly using air and ground source heat pumps, the most common construction approach [13].

Reffat et al. examined the effects of design configurations for renewable energy sources, such as positions, dimensions, orientations, PV area sizes, and movement choices to follow the sun. According to the findings, the East façade windows and horizontal axis tracking Photovoltaics (PV) produced 417.68 kWh/m^2 of the most significant renewable energy. The following PV application scenarios with substantial quantities of renewable energy production were identified: 405 kWh/m^2, 399.55 kWh/m^2, and 388.4 kWh/m^2[14].

Shono et al. created a model to determine the hourly PV potential of building surfaces at the area level. The findings indicated that in 2050, the PV power produced could supply 15 to 48% of the building stock's annual energy needs. Large-scale installations with rooftop-mounted PV could increase PV power production, and Building-integrated photovoltaics (BIPV) was an effective tool for achieving a decarbonized society. However, analyses of electricity consumption and generation showed that the larger-scale BIPV installation had detrimental effects on the power system[15].

Abdelrazik et al. proposed that the performance of building-integrated photovoltaic-thermal (BIPV/T) air systems can be maximized if the ideal design parameters, such as tilt angles, configuration arrangements, and fluid flow rate, are appropriately selected. They also found that hybrid BIPV/T with Phase Change Material (PCM) and BIPV/T with concentrators performed better than air- and water-cooled BIPV/T systems in terms of performance[16].

The efficiency balance of two photovoltaic systems (fixed and tracking) and two different kinds of energy balances (yearly and monthly) were compared by D'Agostino et al. The findings demonstrated that a PV surface that meets the NZEB aim annually only sometimes accomplishes the same goal as the monthly balance and that a photovoltaic system with biaxial solar tracking is 50% less minor than a fixed one. Solar tracking devices also exhibit a considerably lower reduction in embodied and operational CO_2 emissions[17].

To determine the ideal BIPV system configuration, Hamzah et al. researched and compared different colored PV modules. The system generated 679.72 MW of energy yearly while reducing CO_2 emissions by 10367.66 tonCO_2/year. It is anticipated to conceal the PV panels' outward look on the structure, maintaining the original architectural style[18].

D'Agostino et al. studied a building's geometric parameters to determine if energy self-sufficiency could be achieved with PV for a specific building. The results showed that square-based residential buildings could be achieved with a maximum of 7 levels, compared to rectangular buildings, L, and courtyard shapes. This supports early design studies on geometry and the planned use of new structures[19].

Geran et al. focused on the importance of an average office building's orientation to find that the optimum PV capacity for an average office building was 600-800 kWp with a south orientation and tilt angle of 30°, with the highest capacity observed for PV systems with a southern-east orientation. As a result, the highest national load in May decreased by 200 MW. The examined PV system can also add up to 36% more years to the life of the overloaded transformer attached to the office structure[20].

Kararti assessed the possible advantages of integrating PV arrays with sliding and rotating overhangs to lower energy consumption and the effects of solar shading. Sliding overhangs were discovered to reach net-zero energy conditions for apartment buildings with large windows and mild climates by reducing energy specific to the building site and integrating with PV modules. The sliding-rotating overhang with no PV can cut the overall energy use of an apartment housing unit by 9.2%, and a sliding overhang placed at the location's latitude can cut the demand for heating and cooling while increasing PV array output[21].

1.2.3 Phase Change Material

Phase Change Material (PCM) can reduce energy demand and increase thermal comfort while keeping indoor temperatures within the comfort range. However, its performance depends on climate conditions, such as the ambient temperature it is used to maintain [22].

Ke et al. proposed three different PV-Trombe wall (PVTW) systems with PCM layers (PCM-PVTW) and analyzed their coupled effects on electrical and thermal performance. A comparison case study was conducted under the ambient conditions of three full days. The results showed that the PVTW system with a PCM layer attached to the absorber's back surface achieved the best electrical performance but the worst passive space heating performance, and the PCM layer thickness and position in cold regions[23].

According to Kalbasi et al., a PCM's sensible storage characteristics and latent storage are influenced by the thermal resistance of the envelopes and setpoint. Sensible storage comprised 54% of the total, while dormant storage comprised 46%. When phase transition is not presented, energy usage in PCM decreases by 9.4 kWh/m^2 compared to 7.1 kWh/m^2 in PCM with phase transition. At the same time, the placement of the PCM close to the uppermost layer increases energy savings by 3.72 kWh/m^2. CO_2 emissions were decreased by 34.9 kg/m^2 and 23.9 kg/m^2 under the latter conditions, respectively, thanks to PCM[24].

Terhan et al. looked into how using two different PCMs integrated into the exterior walls at varying thicknesses and melting temperatures would affect the building's thermal energy performance. Four kinds of exterior walls were designed, with the three-layer BioPCM27 integrated exterior wall offering the most significant heating energy savings (21.32%). The three-layer InfiniteRPCM21C configuration had the best thermal energy efficiency, saving 24.45% in the cooling season and 14.76% in the heating season [25].

Naghneh et al. investigated the use of PCMs to slow down the rate of heat exchange. They found that the position of thermal insulation significantly impacts the location of PCM installation. They recommended that the PCM installation site should be near an indoor rather than an outdoor area and that the internal temperature should be set at 24.19 °C to reduce annual energy usage and CO_2 emissions by 23.6%[26].

Al-Yasiri et al. reviewed the potential of a PCM-incorporated building envelope, focusing on roofs and external walls. They found that limited research has been conducted on cold climates. However, weather conditions are the main factors in specifying the type, quantity, influential position, and encapsulation method. Night cooling/ventilation is adequate in hot climates but limited in scorching locations[27].

Jia et al. investigated the thermal efficiency and energy consumption of prefabricated buildings with PCM in five distinct climate zones. Results showed that PCM placed inside the building wall or roof saves more energy than PCM placed outside, PCM placed on the east or west side of the building wall saves more energy and improves indoor air temperature; cetane has the best energy-saving effect, and the thickness of PCM with optimal energy saving is 10 mm, 10 mm, 20 mm, 30 mm, and 30 mm in the areas of extreme cold, cold, mild, hot summer and cold winter[28].

By utilizing PCM, Wang et al. were able to increase thermal comfort and energy effectiveness in air-conditioned, lightweight structures with a harsh winter and sweltering summer. Results revealed that by minimizing temperature fluctuations, PCM wallboards increase indoor comfort during both the cooling season (summer) and the heating season (winter). Due to distinct solar effects, winter is more efficient than summer. The optimum melting temperature in terms of economic benefit for various rooms is between 22 and 26 °C [29].

1.2.4 Geothermal Energy

Geothermal energy is renewable and ecologically friendly, and it has the potential to be a significant alternative energy source[30].

Wang et al. suggested a new CO_2 hybrid geothermal system that uses CO_2 as the underground working fluid and electricity and waste heat to help the Ground Source Heat Pump (GSHP) with heating, ventilation, and air conditioning. By driving 50 MW of geothermal heat, the suggested system can generate 11.41 MW of electricity, 80 °C of hot water, and 34.76 MW of cold energy. The coupled system's optimal cooling temperature should be eight °C [31].

Li et al. conducted a study on the Earth-Air Heat Exchanger (EAHX) system's energy-saving potential in a multi-story Passivhaus building in various Chinese cities with different climatic conditions. The impressive results showed up to 12.8 kWh/m^2 in yearly building energy load savings in areas with hot and humid summers and cold winters[32].

Stasi et al. investigated an Italian multi-family NZEB that blends central ventilation with fan-coil units fed by ground-source heat pumps. Three hybrid ventilation strategies were compared to assess the potential cooling energy savings: an earth-to-air heat exchanger (EAHX), night hybrid ventilation from 10 p.m. to 6 a.m., and free cooling mode in mechanical ventilation. The results revealed that EAHX saved 20.7% on cooling energy when combined with night and mechanical ventilation, lowering cooling energy demand by 14.4%. Milan demonstrated the most significant energy savings, ranging from 33.7% in Milan to 9.8% in Palermo, with more benefits in the middle of the season when outdoor temperatures are lower[33].

Minichiello et al. used the EnergyPlus computation engine to analyze the energy retrofit of an existing building, taking into account two low enthalpy geothermal systems in the HVAC plants: the Ground-to-Air Heat Exchanger (GAHX) and the Ground Source Heat Pump (GSHP). The findings revealed that a very low value of primary energy requirement of about 60 kWh/m^2 could be obtained (71% compared to the existing building, which was characterized by a gas boiler), with significant savings on annual energy bills and CO_2 emissions [34].

Hebbal et al. compared numerical findings to experimental measurements of soil temperatures at various depths. According to the results, an underground structure with a depth of 2.34 m reduces cooling energy demand significantly during the summer. Furthermore, the investment return time was expected to be 6.5 to 3.25 years with and without state support[35].

D'agstino et al. investigated a Heating, Ventilation, and Air Conditioning (HVAC) system consisting of an AHU for primary air combined with a horizontal-pipes Ground-to-Air Heat Exchanger (GAHX) and fan-coil units. The results revealed that a GAHX for geothermal pre-treatment of the air to be introduced into the AHU is very energy efficient, resulting in total thermal power savings in all cities studied. The best power reduction value (61.5%) for a 100 m pipe-length GAHX is obtained in a city with a continental climate zone, while the worst findings (23.9%) are obtained in a city with a tropical climate zone[36].

Marino et al. designed and simulated an office building in Milan and Palermo, Italy. The HVAC system is fan-coil and the primary air, with or without Earth-to-air heat exchanger (EAHX) and Air-to-Air Heat Exchanger (AAHX). The seasonal analysis indicates that AAHX performs better in the winter, and EAHX performs better in the summer. According to the yearly study, the EAHX is better in hot or mild climates. The combination of the two technologies is better for Milan (energy savings of up to 75%) than Palermo (energy savings of up to 60%) [37].

The authors try to cover several information gaps in the literature; Yang et al. focused on the thermal performance of an earth-air heat exchanger incorporated into a structure and retrofitted with a supplementary water piping system. The cooling capacity of the foundation-integrated water-based earth-air heat exchanger system increased from 3.21 kW to 4.84 kW after mixing with the circulating water from the residential water well, and the moisture removal rate rose from 1.97 kg/h to 4.24 kg/h. Indoor thermal comfort can be met with exit air temperatures ranging from 24 to 26 °C in summer and 20-21 °C in winter[38].

1.2.5 Decarbonization

Buildings account for over one-third of energy use and two-fifths of carbon emissions globally in 2020 [39], posing an existential threat to modern civilization[40]. Buildings are essential in carbon mitigation due to their long lifespans, emitting 8.7 Giga tons of CO_2 in 2020 [41]. The contribution of renewable hydrogen to quicken the EU's shift to a low-carbon economy was examined by Jimenez et al., who also discussed the fundamental issue of where the EU will get affordable and reliable renewable hydrogen[42].

Based on site layout, geometry, structure, envelope, and energy system, Xu et al. suggested an efficient optimization method for energy-saving and life-cycle decarbonization retrofitting of existing school buildings. According to the findings, the retrofitted school can generate 14.36 kWh/m^2 of excess renewable energy annually and save 1,920,853.3 kg of carbon emissions[43].

Nazari et al. conducted a literature survey on heat pump systems integrated with PV modules. They discovered that system efficiency is affected by operating conditions, configuration, and unit characteristics. As a clean power generation technology, PV modules can be combined with heat pumps to improve overall performance in terms of Coefficient of Performance, environment, and economics. CO_2 emissions can be decreased by up to 73% for heating and cooling, making these systems suitable for building decarbonization[44].

Toosi et al. suggested technological solutions to mitigate buildings' impact on climate change, such as improving existing and new buildings' energy and environmental performance with Building-Integrated Photovoltaic and Thermal Energy Storage Systems (BIPV-TES systems). Installing a BIPV-TES system in a residential structure with electric heat pumps can reduce CO_2 equivalent emissions by 21.42% over a 30-year service life[45].

Yung et al. developed a spatiotemporal bottom-up dynamic building stock model to compare the decarbonization potential of various strategies. Natural-gas-free heat transition and renewable electricity supply are the most effective, lowering annual GHG emissions by 21% and 19% in 2050. Rooftop PV, green lifestyle, and wood construction all have comparable potential, with excess electricity generated if installed as much as possible[46].

Borge-Diez et al. investigated the decarbonization potential of heat pumps using a Spanish situation as a case study. The results revealed an 8.43% reduction in total emissions. The integration of electrical climatization systems allows for an increase in renewable energy share in the grid or the integration of electric cars[47].

Padovani et al. evaluated the properties of sustainable heating electrification in isolated rural residential structures in cold climates without natural gas delivery. After a parametric solar photovoltaic (PV) sizing study, the overall life cycle cost, renewable fraction, and greenhouse gas (GHG) emissions were calculated. The findings showed that combining PV with heat pumps can immediately reduce

GHG emissions by up to 50% and by more than 90% over time if renewable energy goals are met [48].

1.2.6 Green Roofs

Current urban growth techniques put more strain on natural landscapes by increasing stormwater runoff and removing waste and pollution[49]. Green roofs are an essential technological and design tool that may assist cities in responding to climate change and improving urban environmental quality[50]. Individual building benefits include enhanced roof life and insulating characteristics, contributing to higher energy efficiency through lower summer cooling and winter heating costs[51].

Dewijendra et al. investigated green roofs, focusing on roof construction to minimize energy consumption and environmental effects. Increased thermal resistance reduced heating demand by up to 71% in the hot and humid areas examined. Green roofs may help lower cooling loads in hot, humid settings and cut a building's energy consumption by 30.7%[52].

Hussien et al. used Design Builder software to conduct roof surveys on 54 buildings in the north of England to evaluate if they were appropriate for Green Roof System adoption. The results indicated that 9% were appropriate, leading to considerable savings in energy usage of 550-1900£ each year[53].

Zahedi et al. simulated and modeled the energy consumption of a theoretical two-story house with a green roof in various climates. Installing a green roof lowered yearly power consumption by 16.3%, 12.5%, and 23% in Tehran, Tabriz, and Bandar Abbas, respectively. According to sensitivity analysis tests, the green roof resulted in annual savings of 562, 660, and 381 dollars, respectively [54].

Algarni et al. used a descriptive-analytical research technique to optimize energy use in office buildings. The results indicated that a green roof with grass vegetation imposed a minor strain on the roof structure and optimized the cooling and heating systems' energy consumption due to its shallow root depth and culture environment. The building's overall energy consumption decreased by 3.6% in six months [55].

Alim et al. investigated green roof performance regarding stormwater retention, runoff quality, building energy consumption, and life cycle cost analysis. A green roof's average water retention capacity is 66.2%, yet it can be a source of pollution when saturated. Green building flooring reduces temperature by 4-6 °C, and there is the potential for energy savings in building heating and cooling. The typical payback time is 16 years [56].

Tariku et al. investigated the energy and rainfall retention performance of broad green roofs in conjunction with a well-insulated roof deck. They discovered that during the rainy season, the rainwater retention capability is just 21%; however, in the summer, it might reach 100%. During the heating season, the heat loss via the green roof is 2% more than a similar roof without a green roof, but it may minimize heat gain by 66% during the cooling season. Green roofs can aid in reducing overheating issues in well-insulated structures[57].

Abuseif et al. provided a parametric analysis of the influence of nine different green roof layouts on outdoor and indoor temperatures and cooling demand at three different metropolitan densities. Green roofs with trees had an enormous impact on lowering inside temperatures than external temperatures, lowering indoor temperatures by up to 7.20 °C and air conditioning electric demands by 60%. Green roofs with trees perform better than standard green roofs in thermal efficiency despite having a more significant green coverage percentage[58].

Andric et al. developed a case study in Qatar to analyze the potential of green roofs and walls as a mitigation technique for the climate-change-driven increase in building energy demand. The results revealed that 5-cm expanded polystyrene and energy-efficient windows were more efficient than green walls and roofs, resulting in a 30% decrease in energy consumption vs. a 3% reduction when a green roof was added. However, other benefits of a green roof should be addressed, such as air quality, the heat island effect, and people's health [59].

1.2.7 Biomass District Heating

Biomass is the most dependable alternative to solar and geothermal, as it is widely accessible and less expensive than other sustainable resources [60]. Volpe et al. proposed a model for the design of prosumer-centered thermal and electrical grids to balance production and consumption. Results showed a reasonable rate of interconnections, 73% of CO_2 emissions avoided, and 55% of emissions reduction from biomass district heating [61]. Based on historical energy usage and demand, Sajid et al. assessed the viability and comparative study of on-site solar photovoltaic (PV) and biomass-fed boilers to decrease reliance on grid-supplied power and coal-fired boilers. They discovered that the most appropriate renewable energy source [62].

Moretti et al. conducted a life cycle environmental assessment of a biomass boiler (100 kW) combined with an absorption chiller unit at a building in central Italy. Experimental data, such as energy usage and emission factors, were used to evaluate the environmental effect. The biomass-fueled system had a less negligible effect on cumulative energy demand and global warming potential[63].

Carpio et al. investigated the impact of biomass stoves on energy consumption and CO_2 emissions in six Iberian Peninsula towns. They discovered that using biomass instead of fossil fuels can reduce CO_2 emissions by up to 95% and economic savings by up to 88% [64].

1.2.8 Indoor Air Quality and Ventilation

Indoor Air Quality (IAQ) is critical to people's health, comfort, and productivity in non-residential facilities such as colleges and schools[65]. It is determined by variables such as ventilation efficiency, pollution sources, and occupant activities. The intricate interplay of HVAC systems, building materials, and occupant behavior creates a dynamic environment that necessitates intentional interventions. Preventive procedures, modern ventilation systems, and thorough monitoring techniques are required to maintain a healthy and comfortable interior atmosphere[66].

Dorizas et al. measured ventilation rates and indoor air pollutants in nine naturally ventilated primary schools in Athens, Greece, throughout the spring. The average ventilation rate exceeded the minimum specified by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE). Carbon dioxide concentrations ranged from 893 to 2082 ppm, with most cases slightly above the prescribed limits. CO_2 concentrations had a positive correlation with student numbers but a negative correlation with ventilation rates. Particles of various sizes were detected and examined, and PM_{10} concentrations exceeded the permissible limits by more than ten times. The indoor/outdoor concentration ratios of PM_{10} and $PM_{2.5}$ were significantly higher than one, indicating that indoor sources were more impacted than outside air. The use of chalk and marker boards has a considerable impact on indoor pollution concentrations[67].

Arindam et al. studied two office buildings and one educational building in Delhi during the pre-monsoon season. They analyzed both buildings' CO_2, $PM_{2.5}$, and VOCs and discovered that the average CO_2 content exceeded the ASHRAE limit. The greater $PM_{2.5}$ concentration in one office building might be attributable to a ductless air-conditioning system, as well as inadequate air circulation and active air filtering. However, the concentrations of various contaminants varied significantly among places. The educational facility showed much lower pollution levels (CO_2: 672 ppm; $PM_{2.5}$: 22.8 μg m^{-3} and VOC: 0.08 ppm) than comparable non-residential buildings[68].

Peter et al. investigated how indoor environmental factors affected employees in office buildings. They measured carbon dioxide, temperature, relative humidity, and pulse in three rooms equipped with air conditioners. The results revealed that two offices (A and B) did not fulfill European Standards EN 15251:2017 criteria for fresh air. For 72% of the stay, the CO_2 content in office A exceeded 1000 ppm, resulting in exhaustion and headaches. People weighing up to 70 kg had higher air temperatures and odors. Those weighing more than 75 kg reported a slight drop in air quality. The CO_2 content in office C was around 800 ppm, resulting in a minor decline in air quality. Pulse monitoring revealed that insufficient fresh air supply might result in the attenuation of employees[69].

Cheng et al. studied the indoor air quality of office buildings in several different climates of China, concentrating on pollutant concentrations such as CO_2, formaldehyde, and TVOC. The study discovered that indoor and outdoor pollution concentrations are strongly associated with poor indoor conditions reported in the morning and afternoon. Health issues might persist even when indoor pollution concentrations are within acceptable levels. The study also found that outside fresh air combined with purifiers/filters should be utilized to minimize indoor pollution levels[70].

1.2.9 Climate Change and CO_2 Emission

Climate change significantly impacts weather variance, affecting building energy demand and heating and cooling requirements[71]. Fossil fuel use, forest destruction, and animal raising contribute to greenhouse gas emissions, amplifying global warming[72] [73].

Chaturvedi et al. extensively evaluated multivariate optimization techniques for designing climate-adaptive nearly zero-energy buildings (nZEBs) in India. The research examined many solutions, including social, environmental, and economic sustainability, emphasizing enhanced energy efficiency and adaptation to India's varied climatic regions. The authors stressed that successful nZEB design requires an equilibrium between passive and active energy strategies underpinned by sophisticated modeling tools and data-driven methodologies. The analysis determined that integrating climate-responsive design solutions might improve energy savings by 30–50%, depending on the geographical area. Furthermore, incorporating renewable energy systems, such as rooftop solar photovoltaics, has shown the capacity to fulfill 70–90% of a building's energy requirements, thus leading to a substantial decrease in carbon emissions. The research determined that using a multi-objective optimization strategy enhances building energy efficiency while guaranteeing long-term economic viability and environmental sustainability[74].

Rodríguez et al. conducted an extensive Life Cycle Assessment (LCA) of many construction technologies for nearly zero-energy buildings (nZEBs) in El Salvador, emphasizing their environmental, economic, and social performance. The research examined these systems' carbon footprint, energy use, and cost-efficiency, considering both operational and embodied energy over the building's existence. Their research indicated that adopting optimal building materials and systems might decrease lifetime greenhouse gas emissions by as much as 40%, mainly via low-impact materials and the integration of renewable energy. Furthermore, energy savings of around 35% were noted compared to traditional building designs, attributable to enhanced thermal performance and efficient energy systems. The research emphasized that these measures might improve overall sustainability, making NZEBs feasible in tropical areas while contributing to climate change mitigation objectives [75].

López-Ochoa et al. examined the effects of climate change on rural residential structures in La Rioja, Spain, and proposed measures for adaptation to enhance their resilience. The research used field measurements and energy models to assess the thermal performance of these structures under anticipated climatic scenarios for 2050 and 2100. The results demonstrated that, in the absence of adaptation, the energy requirement for cooling may escalate by as much as 50%, influenced by anticipated temperature increases of 2-3°C by 2050. The study emphasized the efficacy of passive adaptation techniques, including improved thermal insulation and optimized building orientation, in alleviating the impacts of climate change. The authors showed that these steps might decrease energy usage by around 30%, enhancing thermal comfort and reducing the need for cooling. This research highlights the need to include climate adaptation techniques in designing and repairing rural structures to guarantee their enduring sustainability and resilience amid evolving climatic circumstances[76].

Pajek et al. sought to determine the most efficient passive design strategies to mitigate overheating in a log home situated in a temperate region, using a calibrated thermal model under the SRES A2 climate scenario. The EN 16798-1 adaptive comfort model was used to simulate the building's thermal performance in free-run mode throughout the summer, spanning three time intervals: 2011–2040, 2041–2070, and 2071–2100. The research evaluated six building-related metrics and three organizational metrics. The findings indicated that integrating thermal insulation and thermal mass with natural ventilation (with or without shade) constituted the most effective method, decreasing operating temperatures by as much as 0.5°C for 2011–2040 and 2041–2070. During the period from 2071 to 2100, similar solutions continued to provide significant advantages, achieving reductions of up to 0.6°C. Organizational strategies, including modifications to internal configurations and operating timetables, decreased the operative temperature by 0.35–0.34°C during the first two periods and by 0.36–0.33°C in the third session. These passive design strategies reduced discomfort hours by as much as 40%, markedly enhancing thermal comfort and increasing resilience in anticipation of future climatic scenarios. The results underscore the need to incorporate adaptive thermal comfort solutions into architectural design and legislation to guarantee sustainability and occupant welfare under climate change [77].

The study by Ashrafian investigates the impact of climate change on building performance, emphasizing energy usage, economic consequences, and occupant comfort. The study used a simulation-based approach to assess future weather data in a Turkish school building, with exterior upgrades and photovoltaic applications incorporated to improve energy efficiency. According to the study, primary energy consumption, worldwide expenses, and CO_2 emissions might double in warmer climates, reducing savings from 53-63% to 13-30%. In contrast, these parameters' impact varies slightly in cold regions, with lower primary energy use and CO_2 emissions but greater global prices. Buildings that have been upgraded for high energy efficiency may have increased energy usage and expenditures [78].

Idrissi kaitouni et al. analyzed the thermal energy requirements for indoor comfort and the degree of warming caused by climatic change. According to the findings, Morocco would see varied degrees of temperature increase owing to global warming, resulting in higher cooling needs, particularly in the southern regions, and a general reduction in heating thermal energy needs. According to the report, annual thermal energy demand fluctuations range from 2.7% to 17%, depending on the city. The study also emphasized the importance of assessing the effects of warming climates in local contexts. Furthermore, under Air-Conditioning (AC) failure conditions, indoor overheating hours can increase by up to 27% between current and 2050 climate conditions, while indoor temperature swings approach 1.5 degrees Celsius during the summer's hottest days [79].

Jalali et al. used statistical downscaling to generate future weather data for six New Zealand climate zones. They generated meteorological data using Representative Concentration Pathways (RCPs), notably RCP8.5 and RCP4.5 scenarios. The findings revealed considerable changes in the thermal performance of residential structures, with an increase in cooling load and a decrease in heating load. Warmer climatic zones are projected to transition from heating to cooling dominance. The study emphasizes the need to design for current and future climatic circumstances and lay the groundwork for initiatives to improve building resilience to climate change [80].

Sayadi et al. evaluated changes in primary energy consumption, total energy consumption, and CO_2 emissions for a prototype residential building using various cooling technologies and Typical Metrological Year (TMY) climate files for multiple periods (2001-2020) and the mid-future (2041-2060), including automatic shading. The research found that the available climate files do not accurately reflect the produced climatic changes. When using forecasted TMY and extreme climate files, the necessary cooling energy demand increased from 1.7 to 5.8 times the freely accessible climate file. Within the examined cooling methods and set points, automated shade decreased cooling energy by up to 75%. Primary energy consumption and CO_2 emissions have both dropped [81].

Janssens et al. conducted a study in Belgium's Flanders region to examine the impact of climate change on the Energy Performance of Buildings (EPB). The study calculated random variation of energy performance for six different dwelling typologies using a Revitand Excel-based tool. Four measures were considered to achieve NZEB performance: thermal insulation, energy-efficient ventilation, and renewable energy technologies. The findings revealed an increase in the risk of overheating, an increase in cooling energy use, and a decrease in heating energy use in dwellings. The study concluded that, for the 2050 future climate, total primary energy use will decrease in most cases due to a decrease in heating energy use [82].

D'Agostino et al. studied the effect of climate change on building heating and cooling loads, cost-effective efficiency measures, and renewable energy production. They examined eight European locations and used weather datasets to drive building energy simulations for a standard baseline and an NZEB residential building. According to the analysis, the energy balance in European buildings will change significantly in the future, with heating decreasing by 38%-57% and cooling increasing by +99%-380% depending on location. Roof insulation, window type, solar shading, and envelope finishes will be prioritized in future NZEBs to improve energy efficiency. This will allow renewable energy to cover the building needs better and reduce winter and summer peak demand, especially when combined with short-term electrical storage [83].

Attia et al. investigate the impact of climate change on thermal comfort in a Belgian household, focusing on a nearly zero-energy building with no active cooling. The study quantifies the risks of overheating using three Representative Concentration Pathway (RCP) trajectories and the EnergyPlus program. Using static and adaptive thermal comfort models, overheating hours exceeded acceptable upper thresholds in 2050 and 2100 scenarios. The findings suggest that bioclimatic and thermal adaptation strategies, including adaptive thermal comfort models, will be ineffective in mitigating the effects of global warming, leaving zero-energy buildings vulnerable to overheating by 2050 [84].

Serena et al. conducted a study to compare the annual performance of current and future scenarios of 2050 on a residential nZEB in Rome. They found an average temperature increase of 3.4 and 3.9 degrees Celsius under (Representative Concentration Pathways) RCP4.5 and RCP8.5 scenarios, but increased cooling energy needs and decreased heating energy needs. Annual power consumption increased by 18% due to protracted air conditioning system activation and peak power requirements. Temperature and solar gains reduced adaptive comfort hours by 6.2% and 5.1%, respectively, in the RCP4.5 and RCP8.50s 2050 scenarios. A new combined index for long-term comfort assessments revealed a less severe future penalty due to less pronounced excursions and milder daily temperature swings [85].

Jiale et al. propose a system design based on differential evolution for NZEBs under climate change. They use predicted weather data from Hong Kong to optimize building system sizes and minimize lifecycle costs while meeting user-defined performance constraints. Thermal comfort, energy balance, and grid interaction are all factors considered in the design. Using actual weather data, the proposed design was validated by comparing it to two conventional designs in an office building, achieving a better lifecycle cost and satisfying constraints. With improved performance, the proposed design can be used in practice for NZEB system sizing, particularly considering climate change [86].

Chai et al. conducted a study on the effects of climate change on the lifecycle performance of NZEB in various climate regions. They used the morphing method to generate multi-year future weather data and typical meteorological year (TMY) data to assess NZEB's lifecycle performance. The study discovered that the effects of climate change on energy balance and thermal comfort vary significantly across different climate regions due to changes in building energy use and extremely hot weather conditions. Under climate change, the grid interaction remains relatively stable, with positive consequences because the decrease in exported energy during cooling periods outweighs the increase during heating periods. Mitigation measures had varied characteristics for each performance indicator. Free cooling was more effective in cold and hot-summer climates, although thermal insulation proved less successful (relative to increasing the size of the HVAC system). While adding thermal insulation is ineffective in hot climates since it blocks heat movement from indoors to outdoors. Adopting hybrid energy systems improved grid interaction to some extent, but primarily in the hot summer warm-winter zone due to small increases in exported energy [87].

Javier et al. conducted a study on a zero-energy building (ZEB) in Valladolid, Spain, to better understand the effects of climate change on its zero-energy status. The building is designated a zero-carbon building because it gets all its energy from renewable sources. Using the CCworldweathergen approach, the study simulated and assessed energy consumption for 2020, 2050, and 2080. The results showed that cooling demand would rise dramatically between 2050 and 2080, whereas space heating demand would fall. This would increase the requirement for more biofuels to be burned to meet the increased demand for absorption cooling systems. Furthermore, extra photovoltaic electricity would be utilized within the building, resulting in longer running hours and higher maintenance and replacement expenses [88].

Cui et al. used average-year data to examine the long-term impact of climate change on building energy consumption. They matched this to a 55-year actual weather dataset and ran 559 simulation runs of a prototype office structure in 10 major Chinese cities covering all climate zones. Weather data fluctuated wildly yearly, and average year simulations frequently overestimated or underestimated energy demand and peak load. With personal computers' increasing processing capability, using multiyear simulations for thorough assessments of long-term building performance is critical for improving decision-making and accounting for fluctuations in building energy use [89].

Pengyuan et al. evaluated the performance of Renewable Energy systems for low-energy residential buildings in 10 climate zones across the United States using downscaled future hourly weather data from Global Climate Models (GCM). According to the report, current RE system configurations will lose their ability to reach the zero-energy goal in half of the climate zones. According to the findings, future Near Zero Energy Buildings (NZEBs) should be enlarged and redesigned to address the effects of climate change. Under projected future climate circumstances, RE systems prioritizing PV systems have strong stability and performance [90].

The literature analysis covers various technologies, including phase change materials, green roofs, and photovoltaics (PV), providing a comprehensive overview of the different strategies explored in the pursuit of nearly zero-energy buildings (nZEBs). This thesis focuses empirically on the technologies implemented in the case study building, including passive design strategies, high-efficiency HVAC systems, and the integration of renewable energy sources such as solar and geothermal systems.

The methodological approach is guided by the most relevant and practical techniques observed in real-world applications. The selection of performance indicators—specifically, primary energy consumption, CO_2 concentrations, thermal comfort, and ventilation rates—was based on common metrics found in the literature for evaluating energy efficiency and indoor environmental quality in educational facilities. This ensures that the evaluation system aligns with recognized global standards and produces realistic, quantifiable results pertinent to the context of this research.

1.3 Objectives

The University of Valladolid aims to implement innovative practices in its facilities and become a leading institution in energy efficiency, renewable energy use, decarbonization, and indoor air quality. This presents an excellent opportunity for researching the implementation and utilization of renewable energy systems within buildings. It results from decentralized power generation, which can decrease reliance on fossil fuels and foster a more autonomous and less centralized economy dependent on the same consumer.

Buildings now account for over 40% of global energy consumption and are responsible for 36% of the emissions of harmful gases into the environment. Given their long lifespans, buildings play a crucial role in efforts to reduce carbon emissions. With the projected population growth, the demands of developing nations for new infrastructure, and our growing need for better amenities and comfort in our built environment, the predictions for energy consumption and CO_2 emissions are predicted to climb significantly in the following decades. This is because recent evaluations from international groups that analyze environmental, economic, and social matters have identified the construction industry as capable of combatting climate change.

Climate change is a global issue of great importance since increasing temperatures may substantially influence building energy efficiency and the comfort of indoor thermal conditions. The anticipated changes in weather patterns can affect building cooling and heating systems. Our planet's mean surface temperature has increased by 1.2 degrees Kelvin since the late eighteenth century due to the escalating release of carbon dioxide into the atmosphere and other anthropogenic activities.

In 2020, the sector emitted 8.7 gigatons of CO_2, making it a significant driver of climate change. Therefore, it is crucial to understand the extent to which buildings can withstand the effects of climatic changes, whether they are well equipped to handle climate change, and how much these phenomena might affect interior comfort conditions. Specific objectives were established for 2030 and 2050, including a minimum reduction of 40% in greenhouse gas emissions. These goals aim to reduce greenhouse gas emissions by 80-95% by 2050, compared to the recorded levels in 1990.

In response to this situation, the idea of constructing buildings with zero energy, net zero, or nearly zero energy consumption, nZEB has been developed in Europe and various states in North America. These buildings are specifically designed to suit the climate of their location, considering factors such as orientation, insulation, natural lighting, and more. As a result, they significantly reduce the energy needed and energy use for heating, cooling, ventilation, domestic hot water, and lighting. Additionally, they minimize energy consumption through efficient active systems and incorporate renewable energy generation. This concept is entirely defined and has various issues: How and where can net zero be achieved? What is the minimum amount of energy considered nearly zero for different climates and building types? What percentage of this energy can be generated through renewable sources such as photovoltaic, wind, geothermal, and biomass within the building or its surrounding area?

The objective of the thesis is to examine energy performance, Indoor Air Quality, IAQ, and ventilation to obtain a healthy building besides thermal comfort and environmental impact regarding the operational Global Warming Potential, GWP of Climate change of two classroom buildings, one standard and the other nZEB, which have obtained high sustainability ratings through LEED and VerdeGBCe certifications. Specifically, the study focuses on classroom buildings on the UVa Campus. The aim is to assess how the "Sustainable" indicators, KPI´s of HVAC, lighting, and renewable energy systems, contribute to achieving nearly zero energy consumption and low carbon emissions. Additionally, the thesis aims to investigate the impact of these systems on indoor conditions, particularly the quality of the IEQ indoor environment (ventilation, IAQ, thermal, acoustic, and visual comfort). This is important as we spend approximately 90% of our time in built environments, and these factors significantly influence our well-being and health. This thesis also aims to provide a comprehensive approach to estimating the effects of future climate change on nZEB in Valladolid and other locations. It will specifically focus on several climatic scenarios and their influence on building energy consumption till the end of the century. Furthermore, it assesses the ability of nZEB to maintain optimal indoor environmental quality IEQ.

This research focuses on a critical question: Can a nearly zero-energy building (nZEB), designed and used on a university campus, significantly reduce operational energy consumption and improve indoor environmental quality (IEQ) compared to a conventional classroom building?

This study argues that the nZEB, through the integration of passive design, high-performance HVAC systems, and renewable energy sources, will demonstrate a marked improvement in energy efficiency and indoor comfort. It is expected to substantially lower primary energy consumption while maintaining indoor air quality, thermal comfort, and ventilation rates within the levels required by international standards.

Moreover, we hypothesize that this performance advantage will persist when evaluated against climate change scenarios through long-term dynamic modeling.

The hypothesis will be tested by conducting a comparative analysis of two classroom buildings on the UVa campus, utilizing calibrated energy modeling, observed indoor environmental quality data, and assessments under projected future weather scenarios.

1.4 Research Gap and Methodological Contributions

The dynamic performance of nZEBs in various climate regions remains inadequately examined, especially concerning the impact of relocation on energy efficiency and occupant comfort. Most current research optimizes nZEBs for certain climates or expected future circumstances; however, few investigate their performance across diverse climatic conditions. The gap is significant because architectural designs must be resilient and adaptive to the dual challenges of climate change and urbanization.

This research presents a comprehensive methodological framework for quantifying the impact of various climate scenarios on energy consumption and indoor comfort through 2080. The methodological contribution involves the development of a calibration-based methodology using the DesignBuilder–EnergyPlus platform, with simulation results validated against actual monitored data from the INDUVA building's BMS and SCADA systems. This ensured increased model accuracy using performance metrics such as CV(RMSE) and NMBE. The use of CCWorldWeatherGen to generate future and relocated climate data provided an innovative approach for assessing nZEB adaptation and resilience under changing climatic conditions.

Furthermore, this work presents a performance-based benchmarking framework that identifies key performance indicators —such as total and non-renewable primary energy, renewable energy ratio, CO_2 emissions, and comfort metrics—to assess energy and environmental performance uniformly across building typologies through a comparative analysis between the INDUVA nZEB and a standard campus building. This integrated methodological and experimental contribution advances scientific understanding of nZEB performance and adaptation, offering a verified framework that may guide future energy regulations and campus retrofitting strategies.

Finally, although a growing quantity of research examines IEQ in educational institutions, the majority depend on static, single-condition assessments and neglect the impact of occupancy on environmental variables. Experimentally, this thesis addresses the gap by performing a dual-condition, occupancy-sensitive evaluation of IEQ in three university classrooms from various architectural eras. Measurements were conducted in both unoccupied (after over 8 hours of inactivity) and occupied (after 50 minutes of classroom use) conditions across nine locations within each classroom. Standardized, calibrated instruments and UNE/ISO-compliant methodologies were utilized to measure fluctuations in air quality, thermal comfort, illumination, and acoustics, providing a unique experimental perspective on the impact of design period and ventilation systems on indoor environmental performance.

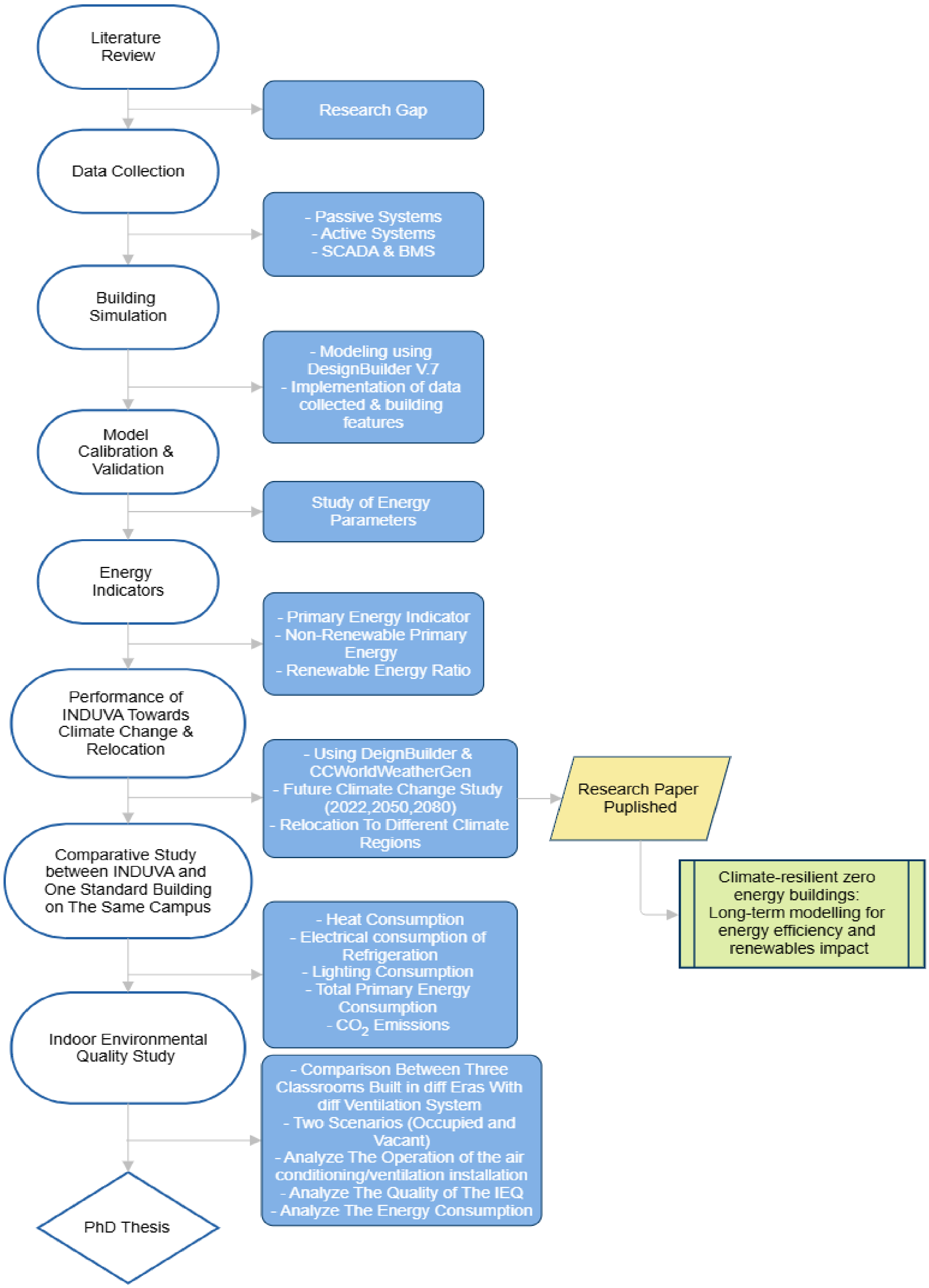


Figure 1.1 PhD Methodology

2.Chapter 2: ENERGY SUSTAINABILITY IN nZEB BUILDINGS IN Europe, SPAIN

2.1 Introduction

Buildings are responsible for approximately one-third of greenhouse gas emissions, accounting for about 40% of the world's primary energy use (Figure 2.1). This has led the European Union to set an ambitious target of achieving 'nearly zero' energy buildings by the end of 2020. The Energy Performance of Buildings Directive (EPBD-2018) defines a nearly zero-energy building as one with an extremely high energy efficiency, where most of the energy required is generated from renewable sources located on-site or nearby[91].

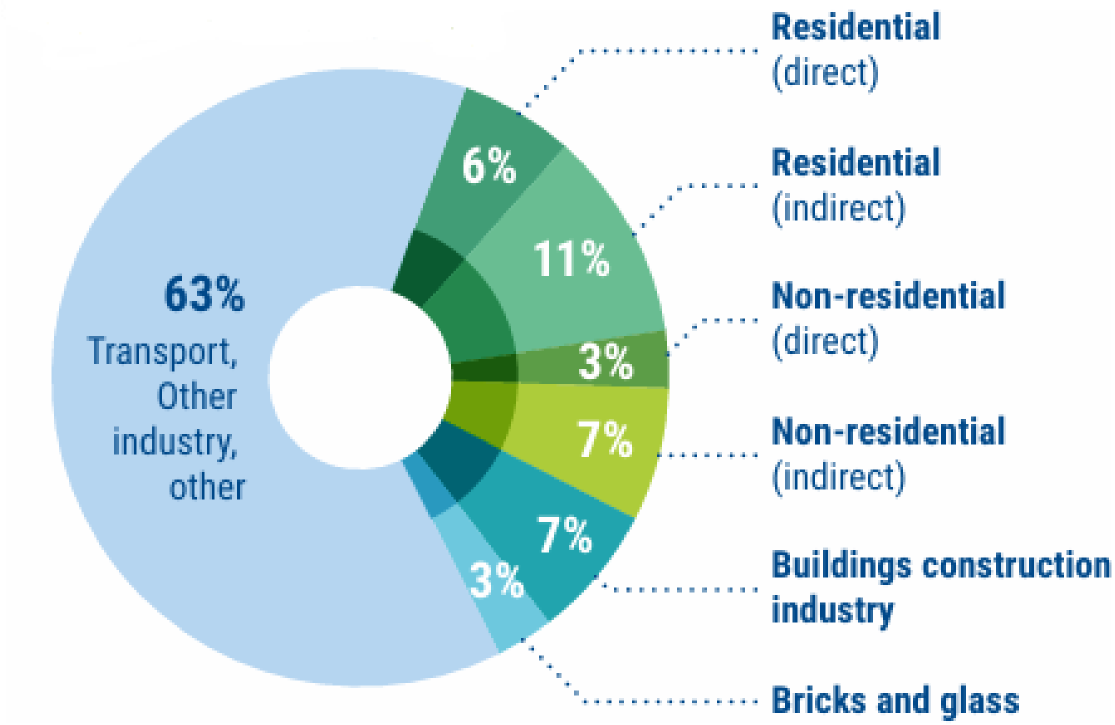


Figure 2.1 Share of buildings in global energy and process emissions

The Spanish Government has taken significant steps to improve building energy efficiency by incorporating the Energy Performance of Buildings Directive (EPBD-2018) into national legislation. This has been achieved through two primary documents - one for energy conservation in existing buildings and another for energy conservation in new structures. These publications provide comprehensive guidelines for building energy efficiency, including nearly zero-energy buildings. This approach aims to reduce energy consumption and carbon emissions by increasing the use of renewable energy sources and improving building insulation. The Spanish Government has set the target of achieving nearly zero-energy buildings for new constructions by 2020 and for existing buildings by 2050. The EU has published a new EPBD 2024 about Zero-emission buildings, ZEmB [92].

To achieve this goal, it is crucial to understand the current state of energy sustainability and construction rules concerning nearly zero-energy buildings in Europe, particularly in Spain. This includes identifying energy-efficient building materials and technologies and developing energy performance assessment and certification methods.

Staying up-to-date with the latest research findings can provide industry professionals and policymakers with valuable insights, enabling them to make better-informed decisions when choosing the most appropriate technology or approach to achieving practically zero-energy buildings. The European Union, China, and several other countries collaborate to promote energy efficiency development, including adopting nearly zero-energy building standards. This highlights the importance of international cooperation in achieving sustainable and energy-efficient buildings [93].

The concept of a nearly zero energy building (nZEB) is a building that has an extremely high energy performance. Currently, nZEB has become integral to Europe's strategy for reducing carbon emissions and improving energy efficiency in the building sector. With continued innovation and investment, nZEBs are expected to play a crucial role in achieving the EU's long-term climate and energy goals. These buildings will have a very low energy consumption, almost reaching zero, and renewable sources will readily meet the little energy demand (Figure 2.2).

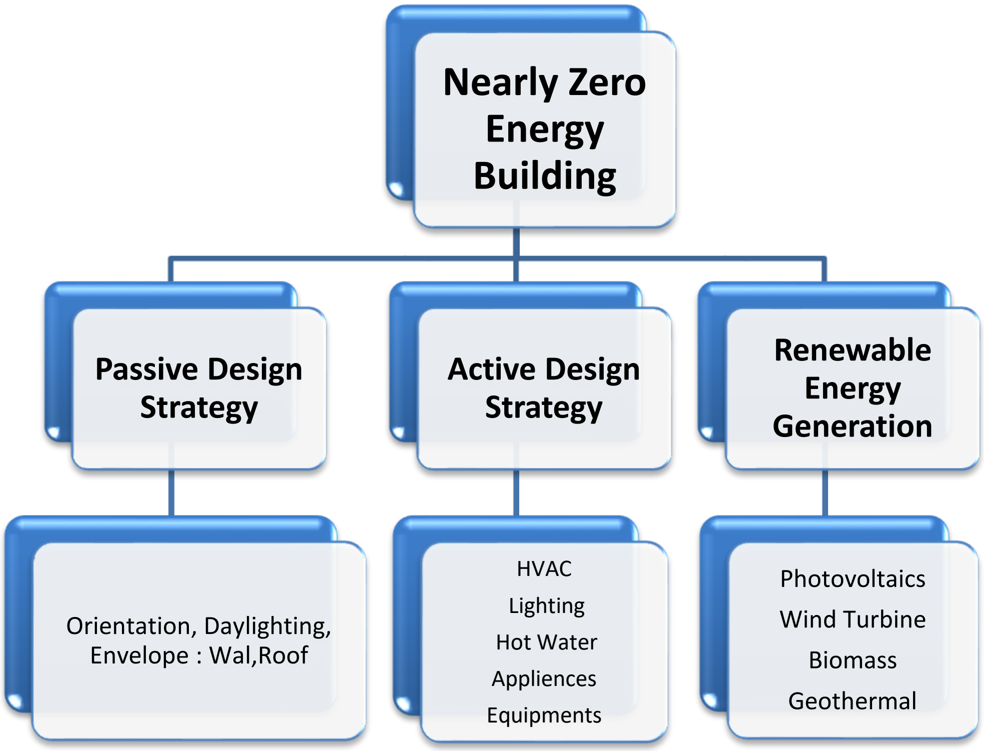


Figure 2.2 Nearly Zero Energy Building Design

This will be applied to new structures by the end of 2020 and to all existing buildings by 2020. The European Union is very concerned about the energy consumption and greenhouse gas emissions associated with buildings. The nZEB objective was included in the Energy Performance of Buildings Directive (EPBD) in 2010 and further strengthened in 2018 [94]. Therefore, all the new buildings shall be planned and erected as nZEBs by 2021. Nevertheless, only a few member states have undertaken this effort and begun to enhance the energy efficiency level of buildings per the regulation. Based on the research conducted by the Buildings Performance Institute Europe (BPIE) about the new nearly Zero-Energy Buildings (nZEBs) building rate in several European countries, only a few countries have shown a significant and favorable rate of constructing these new nZEBs [95]. The pace is either sluggish or minimal for other nations, including Spain. This suggests that Spain's environmentally friendly consciousness is still in the learning stage. Hence, this study aims to identify the potential avenues and forthcoming policies that might be adopted to promote and facilitate the development of nearly Zero Energy Buildings (nZEBs) in Spain.

2.2 The Aims of Nearly Zero Energy Buildings (nZEBs) in the EU

1) Reduce Energy Consumption:

a) **High Energy Efficiency**: Minimize the energy required for heating, cooling, ventilation, lighting, and other building operations.

b) **Low Energy Demand**: Design buildings with deficient overall energy demand through effective insulation, airtightness, and passive design techniques.

2) Increase Renewable Energy Use:

a) **On-Site Renewable Energy**: Integrate renewable energy sources such as solar panels, wind turbines, and geothermal systems to meet the building's energy needs.

b) **Near-Site Renewable Energy**: Utilize renewable energy produced nearby, such as community wind farms or district heating systems.

3) Reduce Greenhouse Gas Emissions:

a) **Climate Goals**: Contribute to the EU's overall climate objectives by reducing CO_2 emissions from the building sector.

b) **Sustainability**: Promote sustainable building practices that lower the environmental impact of buildings over their entire lifecycle.

4) Enhance Indoor Comfort and Health:

a) **Thermal Comfort**: Use efficient building design and technologies to ensure consistent and comfortable indoor temperatures.

b) **Air Quality**: Improve indoor air quality using advanced ventilation systems and non-toxic building materials.

5) Economic and Social Benefits:

a) **Lower Operating Costs**: Reduce energy bills for occupants through high energy efficiency and renewable energy use.

b) **Job Creation**: Stimulate the green economy and create jobs in construction, engineering, and renewable energy sectors.

c) **Energy Security**: Reduce dependence on fossil fuels and enhance energy security by diversifying energy sources.

As per the European Union (EU) objectives, renewable sources, including on-site or nearby renewable energy production, should meet a substantial portion of the energy demand. The widespread development of Nearly Zero Energy Buildings is crucial for meeting the necessary standards. Moreover, the presence of renewable energy generation and energy-utilization systems in towns is vital. Integrating several renewable energy sources in a building may significantly improve its energy self-sufficiency and boost the overall energy resilience of such structures [96].

Photovoltaic (PV) technologies are crucial in the architectural advancement of nearly zero-energy buildings (nZEBs). These advanced systems use semiconducting materials that use the photovoltaic effect to transform sunshine into electricity. As a result, buildings may significantly reduce their reliance on traditional energy infrastructures. In Near Zero Energy Buildings (nZEBs), photovoltaic (PV) systems are not just additional components but are intimately integrated into the design and structure of the building. This integration encompasses a range of elements, including roofs, facades, and even transparent photovoltaic windows, which have the dual function of producing power and providing thermal insulation. This dual functioning makes a considerable contribution to the overall energy efficiency of the structure.

Nearly Zero Energy Buildings (nZEBs) strive to balance their yearly energy consumption and on-site renewable energy generation by adopting Photovoltaic (PV) technology. This allows them to aim for a net-zero or near-zero energy balance. Reducing both the carbon footprint and the operational expenses of buildings is of utmost importance. Moreover, photovoltaic technologies contribute to the stability of the power grid by decreasing the maximum power demand and improving the reliability of the energy supply. Recent progress in photovoltaic (PV) technology, including the development of dual solar panels that can absorb sunlight from both sides and Building-Integrated Photovoltaics (BIPV) that can be directly embedded into building materials, has significantly increased the possibilities for energy capture and architectural creativity. These technological breakthroughs enhance the versatility and efficiency of photovoltaic (PV) systems in different climatic conditions and urban environments.

Furthermore, using photovoltaic (PV) technology in nearly zero energy buildings (nZEBs) aligns with broader environmental goals, significantly reducing greenhouse gas emissions. Focusing on locally produced renewable energy facilitates the shift towards a decentralized energy system, fostering resilience and sustainability. Integrating PV systems into buildings not only provides environmental advantages but also improves the visual and practical features of the structures, increasing their value and attractiveness.

The continuous advancement and integration of smart grid technologies enhance the effectiveness of photovoltaic (PV) systems in near-zero energy buildings (nZEBs). Smart grids enable the efficient control and distribution of energy, allowing buildings to use and provide surplus energy to the grid. The bidirectional movement of energy facilitates the efficient use of energy resources and improves the overall stability and dependability of the energy grid. The importance of PV technologies is anticipated to expand as legislation and standards for NZEBs (Net Zero Energy Buildings) progress, leading to advancements in building design and energy management.

To increase the use of renewable energy for on-site renewable energy integration, geothermal technologies are crucial for advancing practically near zero-energy buildings (nZEBs) since they effectively use the Earth's subsurface thermal energy to supply heating, cooling, and hot water. Geothermal systems differ from traditional heating and cooling systems by using consistent temperatures under the Earth's surface to achieve energy efficiency and sustainability instead of relying on fossil fuels. Typically, these systems include ground-source heat pumps (GSHPs) that use a network of underground pipes, called ground loops, to transmit heat between the building and the ground.

During winter, the Ground Source Heat Pump (GSHP) retrieves heat from the ground and transmits it to the building. Conversely, the GSHP reverses this process in the summer by transferring heat from the building back into the ground. This approach effectively minimizes the need for electrical power compared to conventional HVAC systems by using the Earth's stable temperature. Consequently, it reduces operating expenses and has a minor environmental impact on carbon emissions.

Integrating geothermal systems into nZEBs aligns with minimizing energy consumption via renewable energy sources. These systems are often combined with sophisticated building envelope technologies, such as high-performance insulation and energy-efficient windows, to optimize their efficacy. Geothermal technologies substantially contribute to the overall energy balance of nZEBs by maintaining a steady interior temperature with low energy input.

Moreover, the flexibility of geothermal systems in accommodating different building types and sizes makes them an adaptable alternative for residential and commercial Near Zero Energy Buildings (nZEBs). The technique also facilitates using other renewable energy systems, such as solar thermal collectors, by offering an additional heating and cooling source. Moreover, the durability and minimal upkeep needs of geothermal systems boost their attractiveness, providing a sustainable and economical option for the whole lifespan of the structure.

Integrating geothermal technology in NZEBs also promotes broader environmental and economic goals, including reducing greenhouse gas emissions and promoting energy self-sufficiency. Geothermal systems bolster the robustness of energy infrastructure by reducing dependence on foreign fuels and improving energy security. Additionally, geothermal energy fosters local employment opportunities in installing, upkeep, and supervising these systems, generating economic advantages in conjunction with environmental sustainability.

Heat pumps are advantageous for nZEBs since they can efficiently supply heating and cooling functions with a single unit, minimizing the need for separate systems. Dual functionality is essential for preserving the strict energy balance necessary for nZEBs. In addition, heat pumps may be combined with other renewable energy systems, such as solar panels, to increase energy efficiency and sustainability even further. For instance, the electricity produced by solar panels may be used to operate the heat pump, resulting in a synergistic system that optimizes the utilization of renewable energy.

An essential benefit of heat pumps is their Coefficient of Performance (COP), which quantifies the heat output per unit of electrical input. Contemporary heat pumps can achieve COP values ranging from 3 to 4 or higher. This indicates that they can provide three to four times more energy output than they consume. The excellent efficiency of nZEBs considerably reduces primary energy use, therefore fitting to minimize environmental impact.

In addition, heat pumps enhance indoor air quality and provide optimal comfort. Ensuring stable interior temperatures and humidity levels provides a more healthful living environment. Advanced versions include elements such as air filtration and dehumidification, further augment interior comfort and promote better health.

Heat pumps provide not only technological advantages but also economic benefits. Although the initial installation cost may exceed typical systems, the long-term savings from reduced energy usage and the possibility of receiving subsidies or incentives for renewable energy installations may compensate for these expenses. Furthermore, the durability and minimal maintenance needs of heat pumps make them a financially efficient option for the whole lifespan of the structure.

District heating and cooling systems play a crucial role in advancing near Zero-Energy Buildings (nZEBs) by substituting a portion of the energy demand to be met by renewable sources, providing a collaborative method for controlling thermal energy for several buildings. These systems facilitate thermal energy generation and are distributed to individual buildings via a network of insulated pipes.

Using large-scale production and distribution, district heating and cooling systems may achieve greater efficiency and improved resource management than standalone systems in individual buildings.

Thermal energy in district heating systems is often produced from various sources, including renewable energy options like biomass, geothermal, and solar thermal, as well as waste heat from industrial operations or power production. This centralized generation enables the use of cleaner and more sustainable energy sources, resulting in a substantial reduction in the carbon footprint of the heating supply. The heat is then transported via an intricate system of underground pipes to the adjacent structures, supplying them with space heating and domestic hot water.

District cooling works on a similar concept, with its primary emphasis being providing chilled water for air conditioning. Centralized cooling facilities use energy-efficient technology to create chilled water, such as absorption chillers driven by waste heat or renewable electricity. Subsequently, the cooled water is conveyed to structures via an insulated network of pipes, which is used in air handling units and fan coil systems to lower the temperature of interior areas. This approach is especially advantageous in densely populated locations since it may effectively mitigate the urban heat island phenomenon and decrease the total power consumption during peak cooling hours.

District heating and cooling systems provide several benefits for nZEBs. They offer a dependable and uniform supply of thermal energy, which is essential for upholding the rigorous energy performance standards of nZEBs. Utilizing renewable energy sources and waste heat in these systems aligns with the sustainability objectives of nZEBs, contributing to reducing greenhouse gas emissions and dependence on fossil fuels. In addition, the economies of scale attained by centralized manufacturing may reduce operational expenses and enhance energy efficiency.

In addition, incorporating district heating and cooling systems facilitates the adoption of smart energy management techniques. These systems may be integrated with thermal energy storage technologies, such as hot water tanks or phase change materials, to store surplus thermal energy during periods of low demand and release it at peak times. This improves the overall adaptability and durability of the energy system, guaranteeing a steady and effective provision of heating and cooling.

Implementing district heating and cooling systems in nZEBs facilitates community-wide energy planning and coordination. Establishing connections across various structures promotes the exchange of resources and cooperative endeavors to enhance energy efficiency and sustainability. Implementing this comprehensive strategy may substantially reduce total energy use and environmental footprint, contributing to broader climate and energy objectives.

Biomass technologies have become essential to the effort toward nearly zero-energy buildings. They provide a renewable and sustainable option for heating and generating power, serving as an alternative to traditional fossil fuels. Biomass encompasses organic substances, including wood pellets, agricultural leftovers, and specific energy crops, which may be transformed into energy using many methods. These technologies are particularly applicable to nZEBs since they aid in decreasing dependence on non-renewable energy sources and reduce buildings' carbon footprint.

Heating is one of the primary uses of biomass in buildings. Biomass boilers and stoves use the combustion of organic materials to generate heat, which may be harnessed for space heating and domestic hot water production. These systems are specifically engineered to function with exceptional efficiency, sometimes surpassing 80-90%, which makes them a practical choice for reducing energy use. Contemporary biomass heating systems have sophisticated controls and automation to maximize combustion efficiency and guarantee environmentally friendly burning, facilitating the release of particulate matter and other harmful substances.

Within the framework of nZEBs, biomass heating systems may be combined with other renewable energy technologies to form a hybrid solution that optimizes energy efficiency and sustainability. A dependable and uniform heat supply may be achieved year-round by integrating a biomass boiler with solar thermal panels. The solar panels provide heat during bright times, while the biomass boiler takes over during cloudy or cold months. This method not only improves the overall ability of the structure to withstand and recover from energy-related challenges but also guarantees a consistent supply of renewable energy.

Another notable use, especially in urban settings, is biomass utilization in district heating and cooling networks. District heating systems use centralized biomass boilers to generate heat, transmitted via an interconnected network of insulated pipes to several buildings. This method enables the generation of energy on a large scale, which minimizes the need for separate heating systems in each building and maximizes the benefits of economies of scale. Furthermore, biomass may be used in district cooling systems, where the thermal energy generated from biomass combustion powers absorption chillers to create chilled water. This chilled water is then circulated to provide cooling. This integration not only improves energy efficiency but also helps achieve urban sustainability objectives by decreasing dependence on fossil fuels and lowering the release of greenhouse gases.

nZEBs use biomass to promote sustainable waste management by using agricultural wastes, forestry by-products, and organic waste that would otherwise be dumped. This offers a sustainable energy source and contributes to the circular economy by converting garbage into useful energy. Furthermore, biomass systems may be specifically engineered using materials obtained from nearby sources, minimizing transportation emissions and promoting local business growth.

According to extensive scientific research in the field of nZEB, it has been established that passive design approaches, such as building orientation, natural ventilation, and insulation, play a crucial role in reducing energy consumption. Additionally, the integration of Energy-Efficient Systems (EES), including lighting, HVAC, and appliances, further enhances the overall energy performance of nZEB. Furthermore, using Renewable Energy Systems (RES), such as solar panels and geothermal heat pumps, contributes significantly to achieving the near-zero energy goal in buildings. This comprehensive approach, encompassing passive design, energy-efficient systems, and renewable energy technologies, is pivotal in realizing successful integrated nZEB solutions (Figure 2.3).

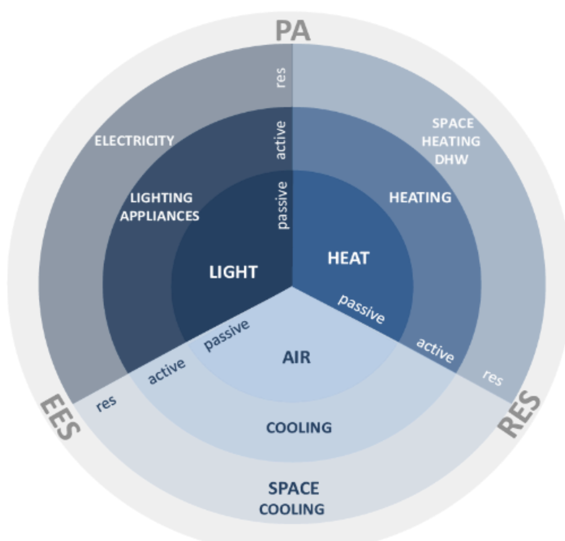


Figure 2.3 nZEB design -PA, EES, RES

2.3 The Technical Aspects of Studying a nZEB in the EU

1) Building Envelope, Passive Strategic:

a) **High Insulation Levels**: Use materials with high thermal resistance to minimize heat loss or gain through walls, roofs, and floors.

b) **Air Tightness**: Ensure minimal air leakage to prevent energy loss and maintain indoor air quality.

c) **High-Performance Windows**: Install triple or double-glazed windows with low-emissivity coatings and gas fills for better insulation.

2) Ventilation and Air Quality:

a) **Mechanical Ventilation with Heat Recovery (MVHR)**: Use systems that recover heat from exhaust air to preheat incoming fresh air, reducing heating demand.

b) **Natural Ventilation**: Incorporate design features that allow for natural airflow, reducing the need for mechanical ventilation.

3) Heating and Cooling Systems HVAC. Active Strategic:

a) **Heat Pumps**: Employ air-source or ground-source heat pumps for efficient heating and cooling.

b) **Passive Solar Design**: Orient buildings to maximize solar gain in winter and minimize it in summer, reducing the need for active heating and cooling.

4) Renewable Energy Integration:

a) **Photovoltaic (PV) Panels**: Install solar PV panels to generate electricity on-site.

b) **Solar Thermal Systems**: Solar collectors provide hot water and support space heating.

c) **Wind Turbines**: Incorporate small-scale wind turbines where feasible to generate electricity.

5) Energy Management Systems, EMS:

a) **Smart Meters**: Implement smart meters to monitor and optimize energy use.

b) **Building Management Systems (BMS)**: Use BMS to monitor and control with SCADA and DALI software applied to HVAC systems, such as heating, cooling, lighting, and ventilation, based on occupancy and external conditions.

6) Water Management:

a) **Efficient Fixtures**: Install low-flow fixtures and appliances to reduce water consumption.
b) **Rainwater Harvesting**: Collect and use rainwater for non-potable purposes, such as irrigation and toilet flushing.

7) Lighting and Appliances:

a) **LED Lighting**: Use energy-efficient LED lighting throughout the building.
b) **Energy Star Appliances**: Select high-efficiency appliances and equipment to reduce energy consumption.

8) Material Selection and Sustainability:

a) **Sustainable Materials**: Choose materials with low embodied energy, preferably recycled, recyclable, or sourced locally.
b) **Lifecycle Assessment, LCA**: Consider the environmental impact of materials and systems over their entire lifecycle, from production to disposal.

When the energy requirement of a nearly zero-energy building reaches a critical level, renewable energy sources can provide almost all of the necessary energy. The concept of near-zero energy buildings applies to both new and extant structures. Construction and design of newly constructed buildings must prioritize energy efficiency and adequate insulation. This encompasses strategies for building construction that reduce thermal bridging and use passive solar gain. The building envelope and the heating, cooling, and ventilation system specifications can be optimized by utilizing the opportunities presented by building information modeling. The primary objective is to renovate and modernize pre-existing structures to achieve the almost zero energy target. Particular attention should be paid to balancing energy conservation measures (such as renovations) and the potential implementation of renewable energy technologies. The practically non-existent energy performance is quantified as the primary energy factor. This metric computes the proportion between the building's primary energy consumption and its ultimate energy demand. Applications that prioritize energy efficiency over using renewable energy sources, such as electric vehicles and plug-in hybrids, may benefit from a substantial portion of their energy consumption being derived from electricity. The nearly zero-energy building consumes the energy required for ventilation, illumination, space heating, refrigeration, and domestic hot water. When calculating total energy consumption, the power needed by technical building systems such as illumination, ventilation, heating, and domestic hot water must be accounted for. Certifications and honors such as a passive house, High-Quality Environmental (HQE), Bâtiment Basse Consommation (BBC-Effinergie), which is translated to "Low Energy Building," Minergie, Casa Clima, Green Star, and wellness are given upon structures that exhibit exceptional qualities in terms of energy efficiency, performance, and comfort across various countries and regions. The EPS is provided to demonstrate the structure's energy efficiency and is essential for compliance with building codes and regulations. The United Kingdom implemented a nearly zero energy target for newly constructed public buildings in 2019; it is the responsibility of public authorities to serve as a model for implementing energy efficiency policies. The European Quality, Environment, Health, and Safety (QEHS) Foundation, which prioritizes health, safety, and quality, could serve as a model for creating non-residential nZEBs that consume almost no energy [97].

Energy sustainability is crucial for achieving nearly zero energy buildings (nZEB), as it ensures current energy requirements are met while ensuring future generations have access to the same level of energy quality. This requires an integrated design process that aligns with the 'nearly zero energy ' goal to provide equitable and reliable energy and resources while minimizing environmental damage. The European Union supports renewable energy sources and energy efficiency to establish a more sustainable energy system with lower carbon emissions. The goal is to achieve an energy-efficient and decarbonized economy, as specified in directives like the Energy Efficiency Directive (EED) and the Energy Performance of Buildings Directive (EPBD)[92], [98].

The Energy Performance of Buildings Directive (EPBD) 2024 establishes a comprehensive structure to eliminate carbon emissions in the construction industry, along with the European Union's goal to achieve climate neutrality by 2050. This edition of the EPBD emphasizes a revolutionary strategy for enhancing the energy efficiency of buildings and reducing carbon emissions. It includes a wide range of regulatory measures and incentives to substantially reduce the environmental impact of both new and existing buildings [92].

One of the fundamental components of the EPBD 2024 is the requirement for all newly constructed buildings to have zero emissions by 2030. This encompasses rigorous energy efficiency requirements and the use of renewable energy technology. Buildings must achieve energy neutrality by generating an equivalent amount of energy to what they use each year via renewable energy sources located on-site or nearby to maintain a balanced energy budget. The directive also mandates using sophisticated building materials and construction methods that improve thermal efficiency and reduce energy wastage.

The EPBD 2024 sets forward ambitious rehabilitation objectives for already constructed structures. By 2030, at least 35% of the European Union's building stock must be renovated to comply with zero-emission regulations. This entails enhancing insulation, windows, and heating systems to the utmost efficiency criteria, incorporating renewable energy sources, and implementing intelligent energy management systems. The guideline advocates for extensive rehabilitation rather than cosmetic repairs, guaranteeing sustainable energy savings and long-term sustainability.

In addition, the EPBD 2024 highlights the need to reduce carbon emissions from heating and cooling systems since they play a significant role in building emissions. It promotes substituting fossil fuel-dependent systems with renewable energy technologies such as heat pumps, solar thermal, and district heating and cooling networks. These solutions decrease emissions and improve energy resilience and security by reducing reliance on foreign fuels.

The order also includes implementing building renovation passports, which provide comprehensive and customized long-term rehabilitation plans for specific structures. The passports include suggestions for gradual improvements to achieve zero-emission status, guaranteeing that building owners own a concise and feasible strategy. This method enables incremental enhancements, making the shift towards buildings with zero emissions more manageable and economically viable.

The EPBD 2024 embodies the European Union's comprehensive strategy for sustainability, integrating regulatory norms with incentives and support systems to facilitate the shift towards a building industry that emits no carbon. The directive intends to engage all stakeholders, including governments, corporations, and individuals, towards attaining a climate-neutral built environment by establishing clear objectives and a robust implementation structure.

A comprehensive approach is required to fulfill the goals of the Energy Performance of Buildings Directive (EPBD) for 2024, which aims to achieve zero emissions in nearly zero-energy buildings. This approach will entail the integration of sophisticated technology, creative design concepts, and sustainable behaviors. One key measure is optimizing the building's energy efficiency to decrease the total energy need. The first focus is on high-performance building envelopes, which consist of excellent insulation, airtight construction, and energy-efficient windows. These features reduce heat losses and improve the structure's passive performance. These techniques guarantee the building maintains pleasant internal conditions with little energy use.

Integrating renewable energy systems is another vital component. Photovoltaic (PV) panels, wind turbines, and solar thermal collectors may be strategically positioned to produce electricity and heat from renewable sources, efficiently compensating for the building's energy use. For example, photovoltaic panels may be incorporated into the roof or walls of a structure to capture solar energy, while solar thermal systems can provide hot water and heating. These technologies facilitate the ability of buildings to generate an equivalent amount of energy to what they use, aligning with the objective of zero emissions.

HVAC systems with advanced technology also have a crucial function. Ground-source and air-source heat pumps, such as heat pumps, are very efficient and use renewable energy to transport heat instead of producing it, substantially reducing greenhouse gas emissions. When combined with intelligent controllers and energy management systems, these HVAC solutions enhance energy efficiency by automatically altering temperatures according to occupancy and external circumstances, guaranteeing that energy is used only when and where it is necessary.

Water conservation methods and sustainable landscaping also assist in the achievement of zero-emission goals. Implementing low-flow fixtures, rainwater collecting, and greywater recycling methods effectively reduces the need for drinkable water and minimizes the energy consumption associated with water heating and treatment. Incorporating green roofs and walls may have many benefits, including improved insulation, reduced urban heat island effects, enhanced biodiversity, and chances for integrating renewable energy.

Energy storage technologies, such as batteries, play a vital part in balancing the amount of energy produced and the amount used, particularly in buildings that primarily depend on intermittent renewable energy sources. These systems provide a continuous and stable energy supply by storing excess energy produced at peak times and releasing it when demand is high. This also helps to decrease reliance on non-renewable energy sources.

The choice of materials also influences the carbon footprint of nZEBs. Utilizing low-carbon, locally procured, and recycled materials throughout the building process decreases the energy and emissions linked to the manufacturing and delivering materials. Cutting-edge materials, such as cross-laminated wood and high-performance concrete, improve longevity and energy efficiency, enhancing the structure's overall sustainability.

Both behavioral modifications and occupant engagement have similar significance. Educating building occupants on energy-saving techniques, such as using appliances efficiently, being mindful of lighting use, and implementing adequate ventilation, may result in substantial decreases in energy consumption. Real-time building automation systems effectively monitor and control energy use, offering valuable insights and promoting the adoption of sustainable habits among inhabitants.

Construction and related activities contribute to global resource depletion and environmental degradation, negatively affecting present and future quality of life. Efficient construction methods, particularly in nZEB, require a thorough understanding of energy administration, as current structures often use non-renewable resources, leading to significant carbon dioxide emissions and waste generation. Comprehensive strategies promoting social, economic, and environmental sustainability are necessary to implement energy sustainability in all stages of building development, including historic buildings. These strategies should involve controlling pollution, reducing waste, responsibly using resources, and integrating the building into the local ecosystem throughout its life cycle.

To achieve the target of the EU, which consists of three primary objectives: reducing greenhouse gas emissions, increasing the proportion of renewable energy, and enhancing energy efficiency. Initially, it is imperative to achieve a minimum of a 40% decrease in domestic greenhouse gas emissions by 2030 (with a 30% reduction by 2020 and an 80% reduction by 2050). Furthermore, the European Union has set a target that at least 32% of the energy used within its member states would be derived from renewable sources by 2030, with a previous target of 20% by 2020. Furthermore, achieving a minimum enhancement of 32.5% in energy efficiency is essential. The European Union has established collective aims that are expected to be accomplished by all member states. However, each member state also has specific goals they must meet. Spain is dedicated to reaching its national goal of 60% renewable energy by 2050. This would enhance the security of the energy supply and support the environmental goals of the Union, namely by diversifying the energy mix with sustainable and low-carbon sources. The organization and operation of the European Union. Three fundamental energy principles are in place to facilitate the energy market and enhance energy competitiveness to guarantee efficient energy flow across EU Member States. These principles include prioritizing energy efficiency and promoting energy[99] [99], [100].

Several technologies make it possible to improve efficiency in a variety of different areas. Energy efficiency is the primary concept guiding the design of an nZEB. It is recommended that the first stage of the project consist of identifying and eliminating the locations that are causing energy waste. In a near-zero energy building (nZEB), energy-efficient solutions include high-efficiency windows, additional insulation in the walls and roofs, and heating and cooling systems, HVAC, that are energy efficient. Through various approaches and technologies, the energy efficiency of nZEB has the potential to increase. All materials and technology that are environmentally benign and energy efficient, such as a double-faced façade. Moreover, the use of passive design principles and the utilization of renewable energy resources are also important. In the first place, passive design techniques include constructing a structure to let in natural light and air, using solar heat gain during the winter months, and preventing such heat gain from occurring during the summer months. This may be accomplished by the form and orientation of the structure, the use of shade, the window and door fabric specification, and the planning and placing of the heating and cooling systems. It is possible to use thermal mass to take in solar radiation during the day and then release such energy at night.

Another important aspect of efficiency at the building level is using renewable energy sources. The use of renewable energy resources has the potential to reduce the consumption of fossil fuels, as well as the production of pollutants and greenhouse gases, and it also has the potential to reduce the cost of power. On the other hand, the recast of the directive on the energy performance of buildings brought to the introduction of nearly zero-energy buildings. This was done to accelerate the transformation of the building industry into a high-performing and energy-efficient sector. Additionally, the proportion of energy that comes from renewable sources is attainable via long-term and renewable energy sources. It used to be that national regulation would cover the energy needed for heating, domestic hot water, cooling, ventilation, HVAC, and lighting. The energy performance of a building is dependent on how much energy is utilized for it. The energy from non-depletable sources, namely the sun, water, and wind, is referred to as resources. These materials are regarded to be environmentally friendly.

Passive design solutions can effectively remove the need for mechanical heating and cooling in buildings. The passive design utilizes the low winter light in the southern sky to warm a structure while preventing the higher summer sun in the eastern and western skies from entering. It also uses the prevailing winds from the southeast to cool the building. As a result, various areas inside a structure will have distinct climatic and aesthetic characteristics. The design must be tailored to the specific local climate and site circumstances.

Passive systems should be prioritized as the first consideration for energy saving in construction, wherever possible. All passive design solutions take into account the climate of the building location. Varying climates need different passive tactics. In sustainable building design, several factors are considered, including landscaping, energy conservation, effective use of mechanical systems, and adherence to local community rules.

There are several passive design solutions available to accomplish the objective of enhancing energy efficiency. Flexible techniques allow adjustments to be made in response to varying climatic conditions. In a homogeneous environment, many solutions may be required to achieve the overarching goal of creating an energy-efficient structure. Survey the surrounding environment of the building to reveal the possibilities of crucial viewing areas and the use of passive heating. The term used to describe this procedure is "SUN PATH PROJECT." A cartographic representation will illustrate the structure's location and the sun's orientation at various daily intervals. Furthermore, the primary areas for observation are delineated inside the structure. Through analysis of the "SUN PATH" diagram, the designer may determine the optimal locations for windows on various sides and elevations of the building. This allows for the selection of energy-saving glazing systems that reduce heat loss.

Additionally, the analysis helps identify the sorts of passive strategies that can be used. Many passive heating techniques optimize the effective use and equitable distribution of heat accumulation throughout the day: Direct, indirect, and isolated gain. The first stages of planning a sustainable building include determining the precise position and alignment of the structure. Significant energy savings can be achieved by comprehending the climate and local environment, implementing a well-thought-out development and landscape plan, and selecting an appropriate passive design strategy. Furthermore, a more effective balance between providing natural light and preventing overheating during the summer can be attained.

To achieve high energy efficiency, appropriate insulation is required to prevent heat absorption or loss while maintaining thermal comfort. The building envelope must have proper insulation material and thickness in the walls, roof, and floor to avoid thermal bridges. The use of high-performance insulation gives a higher insulation factor than ordinary insulation. Spray foam, fiberglass, cellulose, and foam board are examples of high-performance insulation materials that may be utilized in a building envelope. All these materials have outstanding thermal performance and are thin. For example, foam board insulation is a rigid insulating material ideal for the building envelope and has a greater R-value than conventional materials like fiberglass. It comes in various thicknesses to fulfill thermal resistance requirements and is often used in steel and metal structures that need a more excellent insulation factor. It is usually made of densely packed polystyrene or polyurethane, both noted for their resilience. Spray foam insulation is air and water-resistant, non-toxic, non-flammable, and inert. It expands to form a continuous, impermeable barrier with a high R-value while reducing air leakage.

High-performance insulating materials are compact and efficient for their thickness. Finally, high-performance insulation can significantly improve a building's energy efficiency due to its improved thermal performance and lower thickness than regular insulation. It is an excellent strategy to guarantee that a building achieves the highest degree of whole-life performance as new laws, climate change, and technological efforts all work toward the same ultimate low energy or zero carbon objective. Finally, whether low, medium, or high density, each high-performance insulating material has been created and extensively tested to increase thermal and energy efficiency constantly.

Efficient HVAC systems are another significant factor in improving nZEB's energy efficiency. Limiting energy loss within the heating, ventilation, and air conditioning systems is crucial to attaining nearly zero-energy buildings' low heating and cooling needs. Several methods exist to decrease the energy use of HVAC systems. Enhancing the efficiency of the energy converter itself is an effective approach.

In the case of chiller and heat pump systems often found in residential and commercial buildings, adopting highly efficient components such as variable speed drives and energy-efficient motors may help minimize power use. In addition, the use of free cooling may significantly enhance the energy efficiency of refrigeration systems. This operates by harnessing the cooling effect of low exterior air temperatures, eliminating the requirement for mechanical cooling via a compressor. Free cooling may be accomplished by immediately circulating outside air through the heat exchanger or via an intermediary heat exchanger to take advantage of the lower temperatures outdoors. This approach is particularly efficient in countries with temperate temperatures like Spain. In such regions, the amount of heat generated within buildings is relatively consistent throughout the year, making removing excess heat the primary concern in the cooling process.

Furthermore, implementing energy management systems that possess the ability to acquire knowledge and adjust accordingly to the specific demands of a building may effectively diminish energy use by guaranteeing that HVAC systems alone provide the necessary heating and cooling precisely when required. By using machine learning to track the use patterns of a facility and analyze the impact of weather on building occupancy, the system may autonomously regulate the heating or cooling output and modify the time schedules accordingly without requiring input from the user.

An ideal renewable energy system would effectively manage the compromises between the excessive capacity of renewable energy production and the battery system. Excessive production of renewable energy would provide an excess that can be stored, guaranteeing a consistent and reliable energy supply. Simultaneously, battery storage, using energy storage and power electronic interfaces, has the potential to aid in grid stability. The battery may store power produced by sustainable energy sources, such as solar panels. The battery can provide a consistent power supply by converting and delivering the stored energy, even at night or on overcast days.

Additionally, the smart building energy management system and the energy storage management system may operate simultaneously to enhance the energy efficiency of the building and provide supplementary services to the power grid. If the amount of renewable energy produced is insufficient to meet the energy needs of the building and the electricity from the grid is utilized instead, any surplus energy created by the renewable sources may be stored in the battery. Alternatively, when the system identifies that the battery is depleting its stored power, the building will switch to grid-connected mode to reduce the total electricity expenses. In the future, this project will focus on exploring a comprehensive energy management system that efficiently monitors and controls both the electrical and temperature aspects of the building.

Integrating nZEBs into smart cities entails using smart building management systems that continuously analyze and optimize energy use in real time. These systems use sensors and data analytics to regulate heating, cooling, lighting, and ventilation according to occupancy patterns and external weather conditions, providing the highest energy efficiency. Smart thermostats and controlled lighting systems may minimize energy waste by dynamically modifying settings using real-time data and optimizing energy use to match the occupants' requirements.

In addition, nZEBs in smart cities often integrate renewable energy sources, including solar panels, wind turbines, and geothermal systems. These structures produce their energy, reducing dependence on the power grid and decreasing carbon emissions. The excess energy generated may be redirected into the city's energy grid, assisting other buildings and infrastructure. This concept of decentralized energy production improves the capacity of the city to withstand and recover from energy disruptions and supports the city's broader objectives for sustainability.

Energy storage options, such as sophisticated battery systems, are essential for achieving Near Zero Energy Buildings in smart cities. These storage systems enable buildings to store surplus energy produced during peak production periods, which may be used during periods of high demand or when renewable energy supply is insufficient. This guarantees a consistent and trustworthy energy supply, reducing reliance on non-renewable energy sources and improving the building's ability to sustain itself.

Nearly Zero Energy Buildings play a crucial role in smart cities by focusing on individual buildings and including community-wide energy management. District energy systems, which efficiently provide heating and cooling from a centralized facility to several buildings, have the potential to be fueled by renewable energy sources and seamlessly integrated with Net Zero Energy Buildings (NZEBs). This cooperative method optimizes energy efficiency and facilitates the sharing of resources, resulting in substantial reductions in energy use and emissions within the community.

In addition, NZEBs play a role in achieving the objectives of smart cities by enhancing air quality and mitigating the urban heat island effect. Green roofs and walls, such as those made of vegetation, provide natural insulation and minimize heat absorption, decreasing the need for artificial cooling systems. These characteristics not only improve the energy efficiency of the building but also help in generating a more pleasant and healthier urban environment.

Regulations from the European Union mandate that all 28 nations attain a nearly zero-energy level. The Energy Performance of Building Directive (EPBD) first established the benchmark for nearly zero-energy buildings, with progressive objectives for achieving this target in 2020-25. By the end of 2020, all new buildings in the European Union were mandated to comply with the rule of achieving nearly zero energy levels.

Nearly zero-energy buildings, as defined by the EPBD 2018, demonstrate an exceptional level of energy efficiency[91]. The minimal amount of energy needed is mainly supplied by renewable sources, which may be located either on-site or nearby. The Energy Efficiency Directive, EED, mandates that all Member States outline their plans for achieving the necessary enhancement in energy efficiency of buildings owned by national and local authorities. Additionally, they must develop long-term national strategies to attract investment for renovating residential and commercial buildings nationwide. According to the Renewable Energy Directive (EU) 2018/2001, all Member States must guarantee that a certain amount of energy is derived from renewable sources [101]. This includes energy used for heating and cooling, transportation, and a higher goal for electricity.

According to the European Buildings Database and the Buildings Performance Institute Europe, the evaluations for nZEB are determined by three factors: the danger of overheating without mechanical cooling, the supply of natural ventilation and daylighting, and the use of energy from renewable sources. Furthermore, the EPBD mandates that member states must have a system of periodic inspections for heating and air conditioning systems. This is referred to as domestic legislation.

Consequently, several member nations have created training programs and ongoing professional development courses in building automation. For instance, the Building Controls Industry Association in the UK offers the Smart Controls and Health Checks Course. The EPBD incorporates a pioneering standardization process, empowering the European Committee for Standardization (CEN) to create European standards for nine crucial domains, such as building automation and controls. These standards have mostly been embraced.

The Energy Performance of Buildings Directive (EPBD) has significantly contributed to attaining European energy objectives and advancing the sector.

The European Union actively promotes the advancement of nZEB by consistently issuing rules and requiring member states to implement energy-efficient measures. The benefits of nZEB are evident, as they help alleviate the pressure on national energy resources and contribute positively to the environment. Europeans may have a substantial and favorable impact by adopting such techniques. While implementing nearly zero-energy requirements, it is essential to consider the many effects on climate, architectural design, and regional factors.

The Technical Building Code (CTE) is the primary regulatory standard for buildings in Spain. It includes a series of laws outlining the specific criteria that buildings must meet regarding safety and livability. The CTE also contains the energy efficiency criteria for buildings[102], [103].

The Spanish regulations and standards are periodically updated to align with emerging technology and to facilitate the gradual decrease in the energy consumption of buildings, as mandated by the European Union. The energy efficiency criteria and the document that must be adhered to differ depending on the classification of the building. Nevertheless, all the standards are strict and closely aligned with the goals set by the European Union.

The country's territory is segmented into several climatic zones to address the variations in primary energy values throughout Spain. Each zone is allocated a unique energy demand value that corresponds to the structures situated inside that zone. Consequently, the energy needs and primary consumption depend on the building's geographical placement. Furthermore, renewable energy sources, such as solar and wind power, must be included in the construction of buildings.

Solar thermal energy must cover between 30%-70% of the Spanish weather in each home's domestic hot water demand to generate domestic hot water or meet energy needs. This proportion is relatively high and contributes to the rapid spread of solar thermal energy. It is crucial to emphasize that the standards explicitly state that the energy produced by renewable sources must comply with existing regulations, guarantee long-term viability, and actively encourage the use of renewable energy.

2.4 National Regulatory Framework: CTE DB-HE 2019 and RITE

This study references pivotal European legislation, notably the EPBD and the EED, which necessitate the integration of this research within Spain's specific national regulatory context. The Spanish Technical Building Code (Código Técnico de la Edificación - CTE), particularly through its Energy Efficiency Document (DB-HE 2019), establishes mandatory thresholds for non-renewable primary energy consumption and CO_2 emissions for various building types. These thresholds are meticulously defined based on specific building typologies—such as residential, commercial, and industrial structures—and regional climatic zones, thereby serving as benchmarks for assessing compliance with Spain's energy performance objectives [104].

Additionally, the Regulation on Thermal Installations in Buildings (Reglamento de Instalaciones Térmicas en los Edificios - RITE) provides detailed technical specifications related to HVAC systems. It specifies mandatory ventilation rates, thermal comfort levels, and other interior environmental conditions crucial for the welfare of occupants in residential and commercial buildings[105].

Together, these two regulations provide vital national criteria that support the broader energy efficiency goals set by the EU, making them directly relevant to the detailed simulations and IEQ assessments conducted in this thesis. By evaluating the performance of the INDUVA building against the standards established in DB-HE 2019 and the requirements outlined in RITE, this research offers a thorough and substantiated analysis of its classification as a nZEB in accordance with actual Spanish regulatory standards. Thus, the findings will not only demonstrate compliance but also contribute to the discourse on sustainable building practices within the evolving European context of norms.

3.Chapter 3: Case Study of INDUVA Near Zero Energy Building

3.1 Description of Building and Layout

INDUVA is a university building on the University of Valladolid campus, mainly used for teaching (bachelor's and master's degrees in industrial engineering). Classrooms are connected to the rest of the buildings at the Mergelina headquarters via a glass corridor that houses the communications core (staircase and two elevators) on each of the six floors, resolving the height difference through ramps with a slope of less than 6%, ensuring total accessibility between buildings and access points. To an old building that is undergoing rehabilitation, Figure 3.1.

Figure 3.1 INDUVA building, UVA

The INDUVA classroom project, which began in 2015, aimed to provide a one-of-a-kind facility for these degrees, addressing the challenges faced by students and teachers in three locations. The University of Valladolid (UVa) decided to build a new classroom and renovate the existing Faculty of Sciences building. The project was ambitious, integrating the new building into an existing building undergoing rehabilitation and deeply rooted in the university's culture. The University of Valladolid aimed to incorporate energy efficiency and low environmental impact into the project. Furthermore, the University of Valladolid, which has long been devoted to developing a more sustainable and efficient campus, desired that the project incorporates energy efficiency and low environmental impact.

INDUVA building is certified by LEED certificate (Leadership in Energy and Environmental Design) with a score (platinum, 85 points) [106], which is a worldwide recognized certification program managed by the United States Green Building Council. Also, it is certified by VERDE-GBCe (Green Building Council Espane), a sustainability accreditation that recognizes a building's environmental values; the building received the VERDE 5 LEAVES certification [107]. It evaluates the building's efficiency, environmental effect, and sustainable practices. The accreditation represents a commitment to environmentally friendly and resource-efficient building and operation. The building was also awarded the Sustainable Construction Award of Castilla y León in the equipment category.

The University's previous experience with sustainable buildings, together with the integrated design, allows for the attainment of a building with nearly zero energy consumption, which can serve as a reference in the requirement of Directive 2010/31/EU relating to the energy efficiency of buildings. Buildings in that EU Member State must take the required steps to guarantee that minimum energy efficiency standards exist, such that all public buildings developed in Europe must have nearly zero energy use, and the Public Administration must set an example [108].

The building within Mergelina's headquarters has 34 classrooms with varying capacities, totaling 5,845.93 m^2. Each floor has three classrooms for 96 students, one for 60 and two for 40 students, except for the ground floor, which has two small classrooms replaced by technical spaces. The basement features a reception room for air from geothermal, earth-to-air heat exchangers (EAHX). The ground floor has three entrances, two main halls, a concierge, a vending area, a recycling area, and toilets. From the first to the fifth floors, there are three large classrooms, one medium classroom, two small classrooms, bathrooms, and circulation areas; the layout of the building is shown in Figure 3.2. The roof will be used for technical maintenance and house technical installation teams. The height of each floor is 2.9 m, and false ceilings are 1.2 m. Stairs and elevators connect all floors.

The project's energy aspect focuses on maximizing efficiency for high occupancy with discontinuous and variable use patterns. It uses a hybrid of passive and active technologies, renewable energy resources, demand management, and advanced passive solutions (Figure 3.3).

Figure 3.2 Layout of INDUVA building

3.2 Passive Systems

Regarding the passive design, the building has a compact design. The design strategy starts with reducing energy consumption through the building envelope. Because of the very compact structure, the surface in contact with the outside is reduced, minimizing losses and optimizing solar gains. Similarly, wind exposure is reduced, allowing for more excellent infiltration management.

Figure 3.3 Actual photo of the INDUVA building

The building's orientation is essential for passive architecture. The classrooms are placed such that they open through wide windows towards the northeast and southwest facades, allowing for more internal illumination. Still, they are also sheltered from direct radiation by a system of vertical and horizontal sunshades and screening components that give enough shading. On the other hand, the northwest and southeast facades are nearly entirely closed, shielding the teaching rooms from thermal losses in winter (to the north) and solar thermal gains in spring and summer (to the south). They only open in specific places of the central hallway, providing the user with lighting and views of the outer gardens (Figure 3.4).

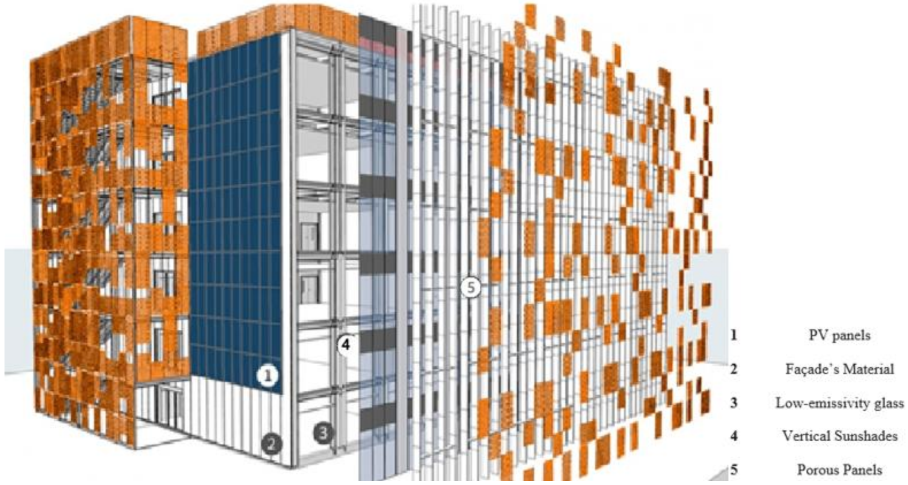


Figure 3.4 The vertical sunshades and porous panels

Another primary concern is the building's insulation. Thermal transmission coefficients employed in the building envelope are stricter than those required by Spanish CTE regulations and ASHRAE standards [109], [110]. The insulation coefficients used (U=0.16 $W/m^2.K$ in facades and U= 0.15 $W/m^2.K$ in green roof), as well as the high-insulation carpentry and low-emissivity glass and transmittance close to U=1.1 W/m^2 ˚C, limit transmission losses and thus reduce heating demand by more than 90% and cooling demand by 85%. Furthermore, the influence of thermal inertia obtained in the building's façade and structure (reinforced concrete), particularly with the roof, which has abundant vegetation covering more than 70% of its area, must be considered.

The university classroom building is designed to optimize natural light. The large windows allow natural light to enter the room, further enhanced by horizontal parasols that reflect the outside light onto the classroom's ceiling, increasing the entrance depth. The stairs and communication cores of the classroom with the main building of the university complex are fully glazed to reduce the use of electric lighting, taking advantage of the fact that this space will be shaded most of the time due to its location and geometry. In interior corridors and classrooms with little natural light, this is supplemented by the Parans system, which introduces natural light via optical fiber. This system captures natural light on the roof with gyrovagos collectors and transmits it to the interior points with fiber optic wiring. Because of its flexibility and low diameter, the optical fiber may be placed into thin pipes and carry natural light to endpoints without interfering with the building's construction or overall distribution. Natural light integration is recommended for economic reasons, as it reduces electricity demand and implies greater comfort and health. When integrated with each luminaire's Digital Addressable Lighting Interface (DALI) control system, these methods enable a 75% reduction in lighting energy consumption compared to a baseline situation using traditional controls. These values were corroborated by comparison with SCADA-monitored usage data.

Another innovative passive system uses phase change material (PCM) as mixed composition panels of dry wall and micronal in laminated gypsum board PCM. Two classrooms in the building (3.4 and 3.6) were selected to increase thermal inertia, which is critical for reducing heat loads. Those two classrooms are similar in layout, orientation, and capacity to the other two, allowing future comparisons to detect capacity and temperature fluctuations and draw conclusions about the system's use. The classes chosen may be most susceptible to heat. The intervention of this system in the tempering of the heat is assumed, as the effect of the variation in night-day temperature in the Valladolid climate in June, July, and September, whose high temperatures will be hard to manage without active systems, will only cause the delay in the expected thermal wave to decrease the interior temperature by a few degrees. Since it is believed that there will not be any classes in August, August is not included in this relationship. Logically, however, this system, which could be viewed as passive, will still carry out its intended purpose.

The green roof, which is part of the overall project, boosts biodiversity so that the whole surface of the project is "green" somehow. This strategy's impacts extend beyond energy savings since it not only minimizes the heat island effect but also promotes biodiversity by insulating, creating habitats for wildlife, absorbing air pollution, extending the cover's life by shielding the surface from Ultraviolet (UV) light and reducing the heat island impact on the environment using sedum-type plant covers, which are also drought resistant. The extensive research that will be done to maintain, restore, and recover the nearby green space, the trees, and the gardens will round out the focus on increasing the overall biodiversity, which will significantly impact the environment close by and help the city. Rainwater collection and reuse are other sustainable solutions employed by INDUVA.

Construction materials with environmental declarations, low energy production or certificates of low emissions in their manufacturing, ecological materials with a high content of recycled material, easily recyclable and reusable, as well as locally sourced and manufactured products, are all used in the design to minimize the building's ecological footprint. This is necessary as the construction industry moves toward a low-carbon circular economy. Low-toxicity or 'healthy' materials are also utilized (without additional formaldehyde or volatile organic compounds -VOC-...) to reduce indoor pollution and avoid negative health effects. Waste creation, control, and recycling analysis have been incorporated into the project phase, construction, and the building's anticipated usage period.

3.3 Active Systems

Active systems are also integrated with passive systems. Active systems in buildings are technologies and components that use mechanical or electrical means to actively regulate and optimize many elements of building performance. These systems are critical in improving efficiency, comfort, and sustainability.

Renewable energy uses clean and sustainable energy sources to satisfy a building's energy demands while reducing consumption and greenhouse gas emissions. Installing solar panels to generate power from sunlight or geothermal systems to tap into the Earth's inherent heat can be examples of renewable energy.

Photovoltaic system architectural integration has been implemented. The southeast façade, which is blind to minimize heat gains, replaces the ventilated façade's sealing material with a photovoltaic glass covering. The system includes 272 panels set in a vertical position, producing a 90˚ angle regarding the horizontal floor, reducing non-renewable primary energy usage by more than 10% (Figure 3.5). Cadmium Telluride (CdTe) is the material used to make solar cells. This new technique comprises a thin layer of semiconductor that absorbs and turns sunlight into electricity. One of the primary advantages is the cheaper cost compared to standard crystalline silicon plates. Furthermore, this technology has a lower carbon footprint and the quickest amortization period among all solar technologies. Another critical benefit of Cadmium Telluride is its excellent performance and dependability since this type of module may survive for more than 25 years. Furthermore, these facilities are ecologically favorable because they emit insignificant air pollutants and greenhouse gases compared to the current electricity grid. Each solar panel measures 1200mm x 600mm and has a thickness of 6.9 mm, taking up a total area of 205,269 m^2 on the building's southeast façade. The Cadmium Telluride panel weighs 12 kg, and the junction boxes have a degree of protection IP65, according to the international standard IEC 60529 Degrees of Protection.

Figure 3.5 Installation of Photovoltaics

The geothermal energy system (EAHX) is used as a supporting element of the building's ventilation and air conditioning system by taking advantage of the subsoil's surface layer's stable temperatures, which are higher than ambient in winter and lower in summer (Figure 3.6). This technique involves burying certain ducts a few meters from the subsoil and circulating air through them, exchanging air from the outside with the structure's interior. This method employs the thermal behavior of the subsoil, which maintains excellent thermal stability due to its vast mass, so avoiding cold and heat peaks.

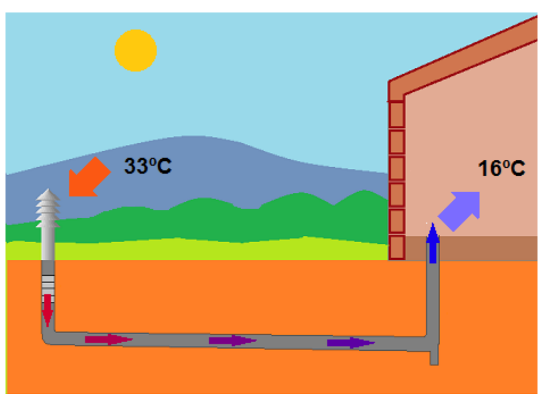


Figure 3.6 Air entering the EAHX in the summer

The EAHX system consists of 28 buried tubes with a 315 mm diameter and a 2 m depth. This system's energy equivalent contribution is 29,654 kWh per year

(17,136 kWh for heating and 12,518 kWh for cooling), reducing the biomass in the DH and the electricity needed to condition the thermal comfort of the air inside the building (Figure 3.7).

Figure 3.7 Geothermal system (EAHX). View from outside, inside, and installation process

Advanced technologies and sensors were installed to maximize many areas of building operation and energy efficiency. A CO_2 probe and a temperature sensor are placed in each classroom to control the mechanical ventilation demand, ensuring adequate indoor air quality, which activates two variable air volume boxes to control the supply of outdoor air linked to impulsion and return so that it is only ventilated according to actual needs and a variable number of students.

The following subsystems are installed in air conditioning, depending on the individual needs of each type of space: - Induction with four tubes in the classrooms, which allows for the provision of cold and heat within the rooms regardless of the time of year, considering the necessity for refrigeration essentially throughout the year. The minimal ventilation airflow required for the rooms is sufficient to provide the appropriate heating input. Fancoil to 4 tubes in the aisles and distributors. In the case of corridors and distributors, heating and cooling loads are not primarily determined by ventilation but rather by direct occupancy fluctuation, necessitating the recirculation of air from the room via fancoils with four high-efficiency fans. This enables individualized treatment of each classroom in the building, considerably increasing occupant comfort. Furthermore, it removes the need for fans to cool down in classrooms since the ventilation flows allow the space to be heated or cooled without requiring air recirculation within the room. The building receives heat from renewable District Heating (DH), which is produced by biomass and runs from the Miguel Delibes Campus (where the thermal power plant is situated) to the INDUVA building.

The primary air conditioner manages the ventilation flow via constant differential pressure, through constant differential pressure and a rotary enthalpy heat recovery, employing variable flow synchronous rotor fans with built-in frequency converters to guarantee that the proper outside air is given to each of the building's boxes. Energy consumption can be reduced, comfort levels can be optimized, and maintenance activities can be expedited by automating and fine-tuning building functions. The control system automates outside air collection techniques such as entire or partial from the EAHX system, direct outside air intake, heat recovery utilizing sorption recuperators, adiabatic return humidification, and free cooling systems.

An air conditioner on the building's roof has been placed and equipped with heat and cold batteries to be able to temper the air before introducing it into the interior of the building, as well as a heat recuperator, Daikin Model Air Handling Unit (D-AHU Professional) with a flow rate of 82,125 m^3/h, to provide adequate ventilation in the various sections. The air conditioner controls the outside airflow, either purely from outside or combined with air from Canadian wells, EAHX, according to the ventilation requirements to bring it into the building at a required temperature. Thus, it included a rotating sorption recuperator to improve system efficiency, which is a technology that recovers humidity from expelled air when the expelled air is more favorable than the outside air, allowing humidification lances to be eliminated, which in dry environments like Valladolid requires very high energy consumption with adiabatic humidification in the return when cold supply is needed (Figure 3.8). This reduces energy consumption in refrigeration, which is also limited by the use of natural free cooling to supply primary air whenever the use of chillers is required, and by partially or entirely eliminating the use of the refrigeration installation to cool the rooms that need it, depending on the time of year. The chosen recovery system incorporates an F-7 filter in the exhaust air of the rotary sorption recovery unit, which captures both sensitive and latent heat with an efficiency exceeding 64%. Additionally, it incorporates an elevated F9 filter in the output section, Figure 3.9, positioned before the silencer. The supply air has three filtering stages: an initial stage consisting of a G-4 filter, followed by an F7 filter (both located before the air enters the air conditioner); finally, an F-9 filter is fitted before the air enters the impulsion silencer. The installed filtering system surpasses the regulatory requirements.

A network of ducts is used to transfer the air that has been pre-treated in the battery unit throughout the building. This controls the hygrothermal conditions in each classroom and enclosed space. The thermal treatment system consists of low-profile air treatment units with double coils (4 tubes), which do not have a fan and are responsible for keeping the areas at the desired temperature.

Each room in the system has a monitored damper that regulates and balances the airflow. These dampers are included in both the air supply and extraction processes. The classroom air circulation is controlled by a carbon dioxide (CO_2) sensor, which operates based on occupancy. These sensors are positioned at the rear of each classroom, at a height of 1.5 meters. The ventilation system will operate automatically based on the level of CO_2 in the classroom, ensuring that at least 30% of the maximum occupancy is always maintained.

A damper system regulates the exhaust airflow from the classrooms by monitoring the difference in pressure between the classrooms and the corridors. Air treatment devices connected with a fan have been put in the corridors, where the demand for air is lower. The toilets have a ventilation system that removes and releases stale air outdoors. Fresh air is brought into the toilets by transferring air from the connecting hallways.

Figure 3.8 Air Handling Unit System (AHU)

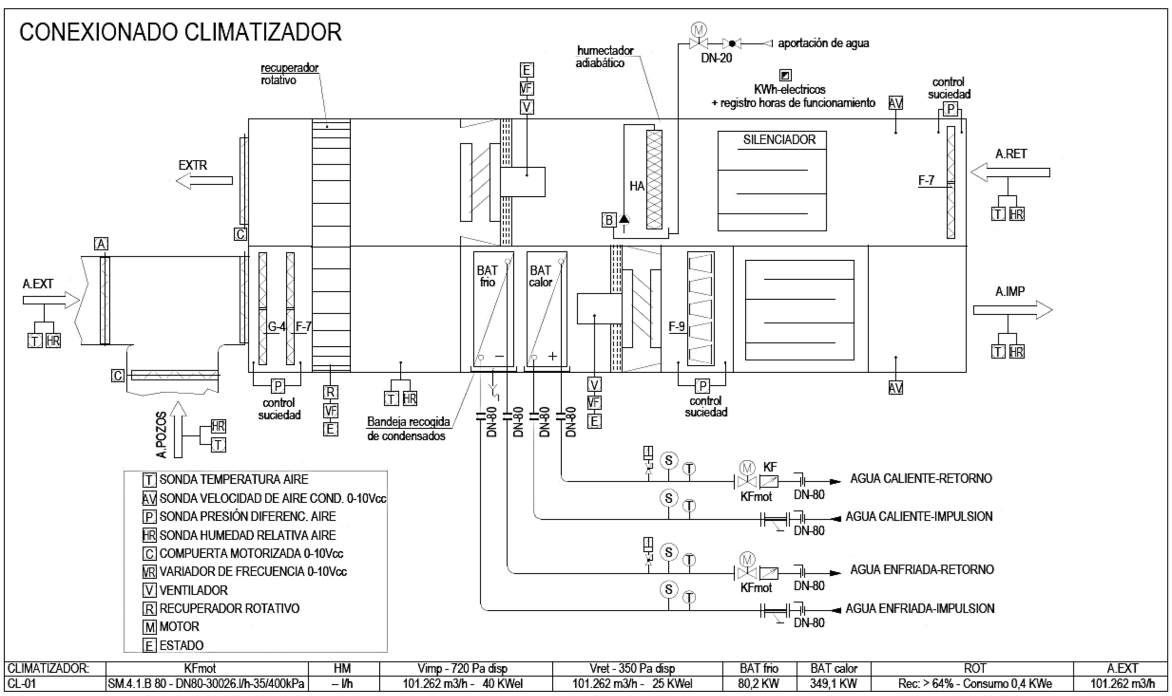


Figure 3.9 Diagram of AHU

For the production of cold, an air-water chiller, Daikin Model EWAD 360TZXR, was installed on the roof, which also has a heat recovery circuit and has the following features: Refrigeration power of 360 kW with a minimum capacity of 23.5%, power input of 113 kW, Energy Efficiency Ratio (EER) of 3.18 (Figure 3.10).

Free cooling is an environmentally friendly method used in nearly Zero-Energy Buildings (nZEB) to lower interior temperatures without using mechanical refrigeration. It makes use of natural climatic conditions. This method often utilizes natural ventilation, evaporative cooling, or the use of cold night air to disperse heat from the structure, resulting in a significant reduction in energy usage. Within the framework of nZEB, the concept of free cooling is in line to reduce energy consumption while ensuring optimal indoor comfort. Nearly Zero Energy Buildings may balance lower energy use and excellent thermal comfort by combining free cooling with high-performance building envelopes and efficient energy systems. This integration contributes to the overall sustainability and resilience of the built environment.

Free cooling is implemented in the heating and cooling system of the INDUVA building. Utilizing HVAC systems in all building areas makes it feasible to remove the heat produced in the climate control batteries and deliver chilled air, ranging from 12º C to 16º C, to the rooms without relying on the building's cooling systems. This system offers inherent passive cooling by using main air when coolers are required, and depending on the season, it might partly or entirely remove the need for the room's cooling system. The recuperator will spin and stop operation for free cooling when the outside air's enthalpy is lower than the extracted air's. This results in a significant decrease in the amount of energy needed for cooling.

Figure 3.10 Daikin Air-Water Chiller

One of the project's goals is to offer enough illumination in educational areas for various functions such as projection, work, and exams. A high-efficiency Light-Emitting Diode (LED) lighting system with DALI control enables the creation of appropriate lighting settings. Presence detectors are given to decrease glare, provide uniformity, and save energy. Two lighting controls exist: customizable DALI and zone with ON/OFF luminaires controlled by power loss. The university administration establishes time regulations that are coordinated with school schedules. The SCADA data confirmed a significant reduction in lighting energy usage in the INDUVA building, consistent with the simulation results. The performance evaluation supports the claim that there has been a 75% decrease in energy use compared to traditional lighting systems that do not incorporate daylighting or automated management.

To synchronize all the energy systems, security, monitoring, and remote management, the University is incorporating a Building Management System (BMS) for DALI, ventilation, cooling, lighting, district heating, HVAC systems, geothermal tubes, and photovoltaics adjustment, as well as University-developed features such as access control and video surveillance. The integrated system strives to give occupants maximum thermo-hygrometric and visual comfort, allowing the building's energy production and lighting systems to be tailored to individual demands while minimizing energy waste.

3.4 BMS-SCADA Energy and Management Systems

Monitoring the performance of nZEB is crucial to determine whether the design objectives have been met and if the projected energy demand and supply have been fulfilled. Given the aim of obtaining exceptional energy performance, it is crucial to have precise knowledge of the energy consumption rate and its seasonal fluctuations. It is essential to determine if nZEB is meeting expectations and to get the necessary data for research and development to enhance nZEB's energy efficiency. Monitoring tools for nZEB performance should be thorough and customized for each unique nZEB, considering the intricate nature of integrated renewable energy systems. These tools are crucial for delivering up-to-date information on energy use and renewable energy supply. It is important to include energy monitoring at every step of nZEB projects to achieve the desired goals and gather data to validate the energy performance during its lifespan.

To research nZEB, it is crucial to have a monitoring system that gathers real-time data on energy usage and renewable energy supply. The data produced may be used for essential design refinement and validation of energy modeling. When feasible, it is possible to compare simulation predictions with real-time data acquired to validate the precision of energy simulation techniques. This approach is also helpful for determining the cause of any disparity between the simulated and actual energy performance. It does so by pinpointing the specific moment when the divergence happened and the corresponding actions. Data gathering is crucial for obtaining information about energy demand and supply trends to identify the most effective strategies for aligning energy supply with demand. This may optimize energy efficiency by mitigating the unfavorable impact of inefficient methods on data preservation.

Building Management Systems (BMS) are computerized systems that assist in automating a building's services. Building automation systems oversee and regulate the electrical and mechanical equipment, including ventilation, lighting, power, fire, and security systems. c Additionally, it is employed to detect and rectify any issues present in the existing systems. Supervisory Control and Data Acquisition (SCADA) systems are used in many industries to oversee, gather, and analyze real-time data and manage and mechanize equipment at a distant site.

The primary objective of BMS-SCADA integration is to oversee the complete building automation system, with BMS control units managing the infrastructure. Information about infrastructure control must be sent to the SCADA system via a specified communication protocol, such as MODBUS. The SCADA system can present the current infrastructure condition and enable control using a graphical representation that can be interacted with by clicking.

Integrating an integrated BMS-SCADA system relies heavily on meeting the necessary hardware and software criteria. The hardware requirements for BMS (Building Management System) are simple since BMS control systems are integrated into the building's infrastructure. The hardware requirements for SCADA are elevated due to the significant emphasis on data collection. The servers, Remote Terminal Units (RTUs), and Programmable Logic Controllers (PLCs) of the Supervisory Control and Data collection (SCADA) system must possess sufficient processing capabilities to manage data collection and control operations effectively for the entire building system.

The sensors and actuators used for data collection and equipment control exhibit significant similarities between BMS and SCADA systems. Actuators used in Building Management Systems (BMS) often serve as output devices responsible for regulating and manipulating other devices. A relay is the most often used actuator controlled by an output signal from the BMS that turns it on or off. Relays regulate the operation of fans, pumps, and other non-digital equipment. Utilizing digital actuators, such as I/O modules, allows for more precise control over equipment that uses digital control techniques. SCADA systems use diverse actuators to accommodate the enormous diversity of equipment under their control. Within a standard SCADA system, various actuators may vary from basic relays and motor starters to more advanced ones like variable speed drives and smart instruments. Step controls and Proportional – Integral – Derivative (PID) controllers may function as actuators by modifying setpoints for controlled devices. Software-based SCADA actuators use logic integrated inside the SCADA system to control devices and alter the state of equipment depending on specific time or event triggers.

Measuring information from the environment and representing it in a way that an automated system or user can understand is the basic idea behind having sensors. Sensors are essential in building automation since they consistently provide information to the controller. This input enables the controller to make accurate decisions and efficiently manage the different outputs of the system. Building automation systems use diverse sensors, such as temperature, humidity, light level, CO_2, motion, pressure, and airflow sensors. Each of these sensors has a distinct function and plays a role in controlling and optimizing the building's environment.

The monitoring of temperature is essential for obtaining maximum energy efficiency. A little deviation of only 1 degree Celsius in the temperature of a specific area would lead to a significant 6% modification in the energy use for both heating and cooling functions, following a general guideline. For optimal management and to prevent needless heating or cooling of empty zones, it is strongly advised to put temperature sensors in all zones and preferably in every individual space within those zones. This methodical technique enables precise regulation, avoiding excessive heating or cooling. Furthermore, the degree of comfort experienced by persons is a crucial factor to consider when considering temperature monitoring.

For instance, when a temperature sensor is set up to observe the ambient temperature in a room. The controller will start the heating system when the temperature drops below a pre-established set point. On the other hand, when the temperature exceeds a distinct threshold, the heating system will be turned off. This simple but effective approach to constructing automation may significantly reduce energy use and cost savings. Conversely, a more sophisticated illustration uses a PID-controlled variable air volume air conditioning system. This advanced system includes a sensor that measures the room's temperature, which is used as an input for the PID controller. The PID controller regulates the heating or cooling input to the system by assessing the differences between the actual temperature and a pre-defined set point. This controller's implementation guarantees optimal comfort and stability for the residents of the building while simultaneously decreasing energy usage. Ultimately, sensors are an essential element of building automation.

Along with temperature, air quality significantly impacts occupant productivity and general well-being. There is a growing recognition that the air quality inside a building substantially influences the productivity of the people within. Air quality sensors, namely carbon dioxide (CO_2) sensors, play a crucial role in this context. CO_2 sensors may provide vital information on the ventilation levels in a building (Figure 3.11). The carbon dioxide concentration in the atmosphere is a reliable gauge for assessing the general quality of indoor air inside a structure. Elevated CO_2 levels above the acceptable criteria (ranging from 1000 ppm to 900 ppm) for extended durations indicate poor indoor air quality, which may adversely impact occupant comfort and result in health problems such as headaches or sleepiness. Elevated amounts of CO_2 may impair cognitive function in individuals. However, activating the HVAC system can mitigate these problems by preventing the accumulation of CO_2 and eliminating any other harmful pollutants the inhabitants produce.

By using the data gathered from these sensors, it becomes feasible to control the ventilation rate, often accomplished by variable speed drives on fan motors, according to the occupancy of the building. This sensible strategy guarantees that energy is not wasted on unnecessary ventilation when not required; this methodology is called Demand Controlled by Ventilation, DCV. In addition, the presence of high levels of carbon dioxide (CO_2) in outdoor air suggests that it is mainly produced inside, making it a valuable predictor of the number of people inside a structure. This critical data is especially advantageous for comparing various occupancy periods and assessing the effects of any building configuration modifications. Figure 3.12 shows the monitored Temperature and CO_2 levels in the classroom.

Figure 3.11 CO_2 sensor

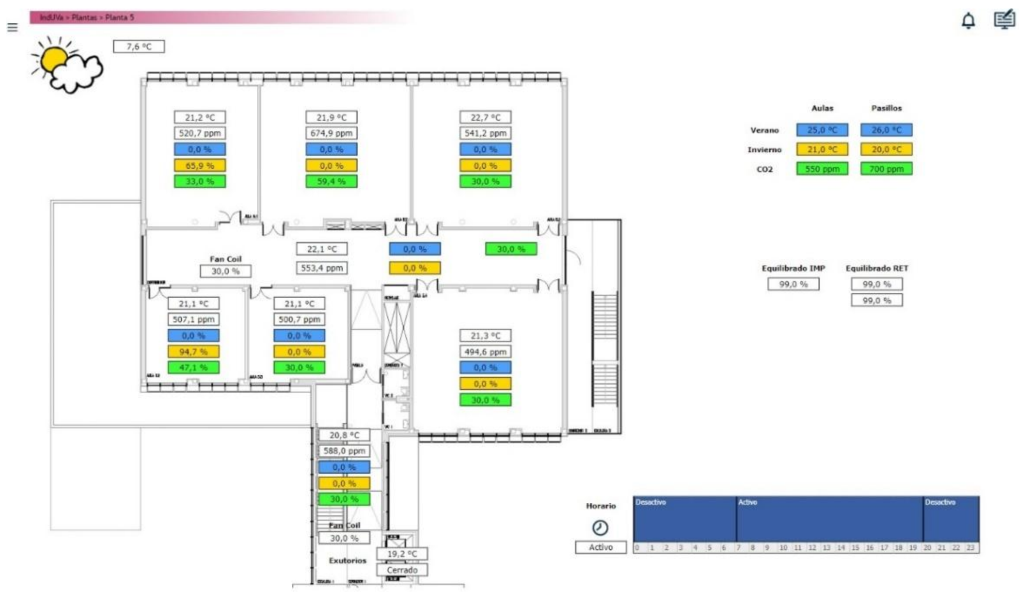


Figure 3.12. Monitoring of Classrooms

To enhance air quality, one might augment the airflow entering the area to diminish the concentration of contaminants inside the space. An airflow meter monitors the airflow in both the supply and exhaust systems (Figure 3.13). The real-time data from the airflow meter is sent to the BMS-SCADA system to monitor and manage the ventilation, ensuring a healthy room environment. An air flow meter is used to quantify air movement, and it establishes communication with the BMS-SCADA system using the MODBUS protocol. The disparity in these currents is immediately acquired. By adjusting the area of the flow plate while keeping the fan speed constant, it is possible to get a precise and accurate airflow rate without any errors. The fan speed will be adjusted by changing the location of the flow plate until the calculated measurements match the actual measurements and there is no variation in flow. Equilibrium has been achieved; conditions may be assessed using the MODBUS communication protocol and additional sensors like temperature sensors in the room.

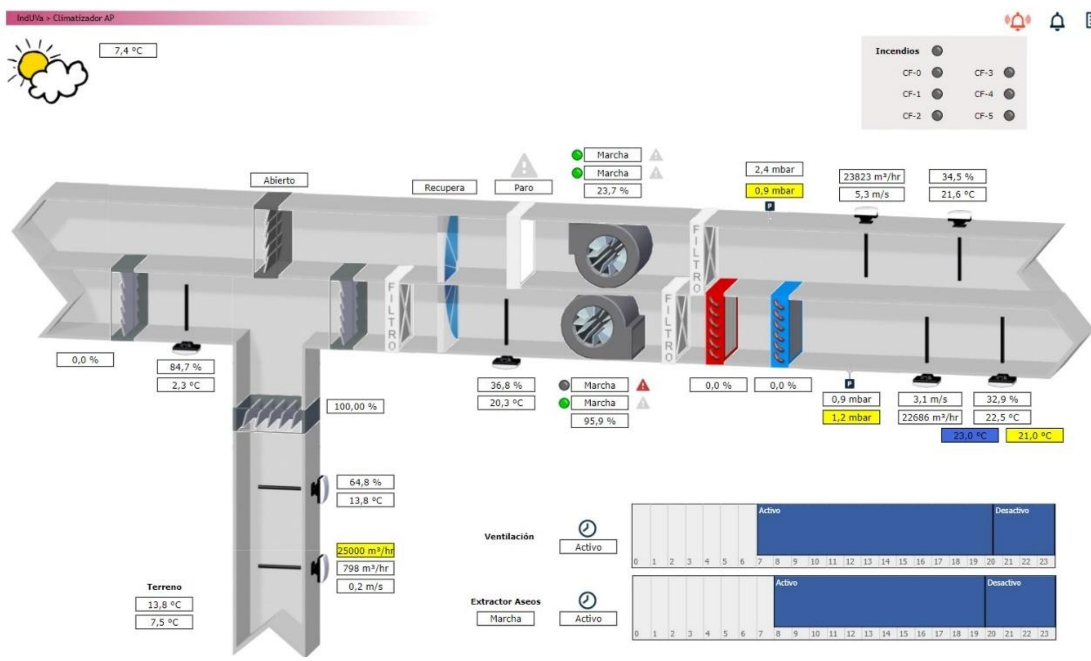


Figure 3.13 SCADA Screenshot of AHU

Humidity significantly affects comfort, with individuals generally feeling comfortable between a 40-60% humidity range. Elevated humidity levels may impact health by increasing susceptibility to dust mites, mold, viruses, and bacteria. Elevated humidity levels could have detrimental impacts on a structure and its contents. During the summer, as external temperatures rise, the relative humidity within may cause discomfort for those inside buildings. Air conditioning often extracts moisture from the air, cools indoor air, and eliminates latent heat. Under some circumstances, if the temperature reaches a suitable level, air conditioning may be turned off because the increased humidity puts a more significant strain on the system. This may lead to indoor air temperatures comparable to those found outdoors, resulting in an uncomfortable studying or working environment. Consequently, the air conditioning is often reactivated at a lower temperature setting, escalating cooling energy use and expenses. Prolonged continuation of this behavior might result in an energy bill that exceeds initial expectations. By monitoring the moisture level in the air and applying a plan to regulate it, it is feasible to maintain conditions that are comfortable for people while using less energy.

A humidity sensor is a device that monitors and provides information about the relative humidity present in the air. This element significantly influences indoor air quality. To deal with the humidity problems, a humidity sensor has been positioned in the return air outside the Air Handling Unit (AHU) to measure the moisture content of the incoming air. When the humidity level is very high, and there is a chance of rain, the Air Handling Unit (AHU) will momentarily cease operation to prevent the entry of wet air into the building. This aids in preserving optimal interior humidity levels and reduces the likelihood of window condensation. If condensation occurs, it may indicate the need to decrease the interior relative humidity even further. Elevated indoor relative humidity may also induce a sensation of increased coldness or heat in the inhabitants, regardless of the actual temperature. As a result, the controller will modify the heating or cooling settings to maintain constant comfort. The AHU does this task by monitoring the humidity and temperature levels inside and outside. It then utilizes a complex algorithm to identify the most energy-efficient mode of operation.

This section focuses on the Digital Addressable Lighting Interface (DALI) communication protocol, which has been widely used in lighting systems due to its impressive energy-saving features. To include DALI devices in the building's scheduling, zoning, diagnostics, and energy efficiency schemes, it is essential to integrate the BMS-SCADA with the Digital Addressable Lighting Interface (DALI). A DALI Gateway/Master is a device that links a DALI installation to a bus-based system and offers many functionalities that enhance system flexibility and communication. The DALI Gateway enables the formation of DALI luminaire groups, facilitates light status monitoring, and offers standard networking features. The data acquired from the luminaires may be used in applications, particularly in Building Management systems.

Non-residential buildings use a substantial amount of energy due to electrical illumination. Substituting conventional light bulbs with energy-efficient LED lights greatly aids in reducing power use, hence enhancing energy efficiency. To achieve this objective, supplementary equipment and systems are included as integral components of contemporary intelligent building systems. These systems are managed by a building management system (BMS) that includes a supervisory control and data acquisition (SCADA) system. Given the abundance of devices inside the system and the intricacy of their operations, it is essential to strategize their management and ensure seamless collaboration. The primary obstacles encountered when integrating a DALI system into a building management system originate from the inherent differences in the development of these systems, including variations in functionality, communication protocols between devices, and communication rates. A method for the real-time management, coordination, and regulation of DALI lighting, together with its interoperability with the primary BMS SCADA, may be shown. The primary concept is that the motion sensor directs attention to a "behavior" originating from the DALI network, enabling sensors to interact with each other rather than just with the lighting actuator via PLCs.

Implementing lighting control systems in buildings offers a substantial opportunity for energy conservation, with possible savings ranging from 20% to 60%. The extent of the savings depends on factors such as the absence of control, lighting prototypes, and the eventual installation of the BMS and SCADA systems. The implementation of personal control devices is crucial. Furthermore, it is essential to integrate Day/Night control systems with zone control, timetable set-up, and real-time monitoring for optimal effectiveness. Energy efficiency in buildings may be achieved by implementing integrated control systems that rely on sensors and light-level readers. The typical practice for integrating the lighting control system into the Building Management System (BMS-SCADA) is to utilize the Modbus technical protocol. This protocol is widely used in buildings and offers excellent flexibility for various applications.

The key to attaining nZEB's aim is optimizing energy efficiency. The abundant monitoring data provided by BMS and SCADA systems provides a comprehensive understanding of building systems' operational status and energy consumption. Using this data to detect inefficiencies in building systems, we can devise a strategy to address these problems, save energy, decarbonize, and reduce economic costs.

The INDUVA model is a pioneering framework that seamlessly integrates adaptable passive design elements with sophisticated intelligent active systems, creating a highly efficient energy solution. The passive design features include a cutting-edge ventilated façade that enhances thermal comfort and reduces energy consumption, double glazing with integrated shading devices to minimize solar heat gain, and a mechanical ventilation system. This system employs advanced CO_2 and temperature sensors to dynamically control airflow, ensuring optimal indoor air quality and energy efficiency. The simulation of these passive systems utilized real-time BMS control logic, allowing for an accurate assessment of their performance under various environmental conditions.

On the active systems front, the model incorporates a high-efficiency geothermal Earth-to-Air Heat Exchanger (EAHX) that utilizes the consistent temperature of the ground to pre-condition incoming air, thereby significantly lowering heating and cooling demands. Additionally, the demand-controlled ventilation system is complemented by heat recovery technology, which captures and reuses waste heat, further enhancing overall energy efficiency. The integration of renewable energy sources is also critical; photovoltaic (PV) panels generate clean electricity, while a biomass-based district heating system provides a sustainable source of heat, effectively reducing reliance on fossil fuels.

All these components are meticulously managed through a comprehensive BMS-SCADA platform, which enables real-time monitoring and control of building systems, enhancing operational efficiency and reliability. The incorporation of actual monitored data, coupled with the adaptive operation of the building's envelope, creates a robust framework for energy management.

As a result, the INDUVA model stands as a cutting-edge nearly Zero Energy Building. Its innovative design not only emphasizes energy resilience but also serves as a realistic digital twin, providing valuable insights into building performance and sustainability practices. The combination of advanced technologies and intelligent design principles makes the INDUVA model a benchmark for future energy-efficient building designs.

4. Chapter 4: Dynamic Energy Simulation of the INDUVA Building. Calibration and analysis of results

4.1 Building Simulation

Building energy simulation is a computational procedure that models the design of a building and performs calculations based on the laws of physics. It involves calculating results such as peak loads, system size, and energy usage over a specific period. This data can be used to approximate utility expenditures and evaluate the cost-effectiveness of design methods.

Energy modeling tools make initial design decisions, select components or materials, and decide on retrofits. During the first design phase, simulation is used to evaluate design concepts. However, the availability of restricted information can hinder the ability to perform full simulations. Simulation is also useful in selecting components or materials, as it allows for cost-benefit analysis. Energy simulation is a valuable tool for making retrofit decisions. It helps to choose cost-effective solutions by considering aspects such as building orientation, climatic conditions, and the performance of the current building envelope. In addition, it helps forecast future energy conservation and calculate the return on investment for various retrofit alternatives. The model must be calibrated using the actual performance data obtained from the building.

4.1.1 DesignBuilder Software

The selection of DesignBuilder version 7, which uses EnergyPlus as a computational engine, was based on its ability to model a building's current environmental and energy efficiency accurately. DesignBuilder is a highly advanced software tool widely used in architectural and engineering design to simulate and analyze the performance of buildings. The software is known for its adaptability and intuitive interface, which allows users to model, evaluate, and improve the energy efficiency of buildings. The software's comprehensive simulation capabilities enable analysis of thermal comfort, daylight availability, and energy consumption, offering valuable insights into the overall environmental impact of the structure. DesignBuilder uses sophisticated building physics algorithms, allowing users to analyze various design scenarios and evaluate the impact of different architectural and HVAC solutions on energy efficiency. Their compliance with various building energy standards and certification systems improves their suitability in multiple situations. In addition, using the ASHRAE heat balance methodology, this application calculates the dimensions of heating and cooling systems and provides tailor-made comfort models. EnergyPlus has undergone rigorous testing and certification by the American National Standards Institute (ANSI) and ASHRAE standards, making it highly regarded and widely used in the scientific community [111].

Building energy simulation requires a systematic approach and involves a large amount of data. Basic information required includes location and climate files, building geometry, envelope components, building services, and building usage. Weather files provide hourly environmental conditions, such as temperature, humidity, wind speed, and solar radiation. However, some locations may not have a weather file, so a weather file from another location with similar conditions may be used. The building's geometry includes elevation and floor plans, while envelope components include building details, window glass, frame, and shading devices. Building services include information on equipment capacities, energy efficiency, location, and controls. The use of the building requires hourly values for occupancy, lighting, equipment, thermostat set point, and HVAC operation.

4.1.1.1 Location of The Building

DesignBuilder models are structured in a simple hierarchy (Site- Building - Block- Zone- Surface- Opening). In the hierarchy, the default data is transmitted from the top level. Therefore, block data is inherited from the building level, zone data from block data, and surface data from zone data. This allows users to configure settings at the building level, which will apply to the entire building, or at the block level, which will modify the data for all zones and surfaces within the block.

After creating a new site file, the location template must be chosen as the building location and weather data source (Figure 4.1). The Location specifies the geographic coordinates and weather information of all structures within this area. Users can import data from other location templates or modify the default data from the Location Model Data tab at the site level.

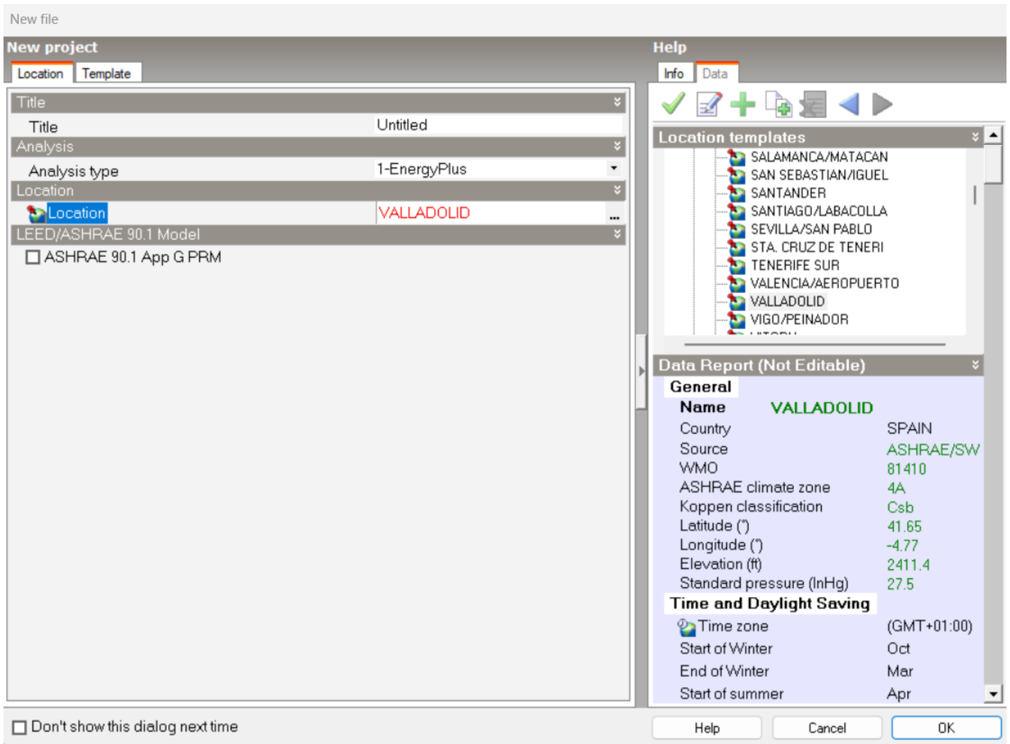


Figure 4.1 Selecting the location of the building

4.1.1.2 Building Geometry

DesignBuilder simplifies the process of developing architectural geometry, allowing users to correctly represent structures' physical attributes. The software provides easy-to-use tools for specifying architectural components such as walls, floors, ceilings, windows, doors, and partitions. Users can enter precise measurements, angles, and positions to replicate the structure's layout within a simulated three-dimensional environment. In addition, DesignBuilder allows the import of building geometry from various AutoCAD software formats, facilitating the seamless integration of pre-existing designs. After determining the structure of the building, users can assign specific material characteristics to each component. These characteristics include thermal conductivity, emissivity, and reflectivity, which contribute to an accurate representation of the building's outer layer.

In our scenario, we had the 2D DXF file for each level. These files were similar to each other in terms of design but differed in terms of internal structure. The "add new block" function created a line and traced the 2D design. The line was then extruded to achieve the desired height for each floor, thus completing the entire structure, as shown in Figure 4.2. As stated above, the building consists of a basement, a ground floor, and five more floors.

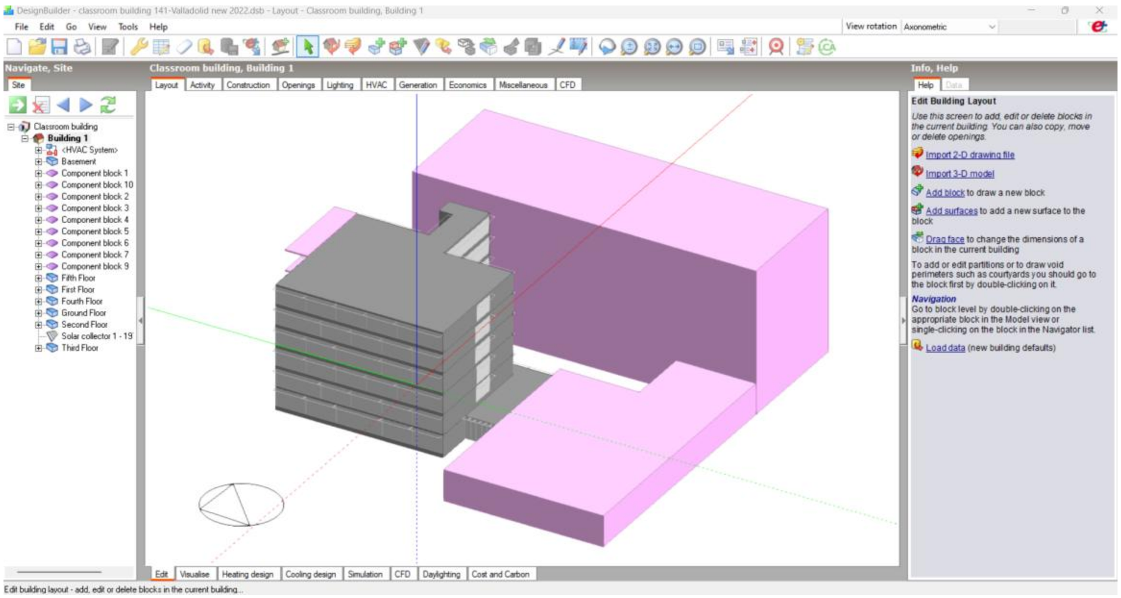


Figure 4.2 Geometry construction with DesignBuilder software

The main interface of DesignBuilder, known as the main screen or edit screen, is displayed when opening or creating a file. This is where the three-dimensional representation of the building is generated, and its information is assigned to specific categories such as Activity, Construction, Openings, Lighting, and HVAC. Users can also access analytical modules such as Visualization, Heating Design, Cooling Design, Simulation, Computational Fluid Dynamics (CFD), Daylighting, Cost, and Carbon tabs. Below is an illustration of the DesignBuilder editing interface.

4.1.1.3 Activity Tab

The user can choose which activity template to use as the default activity-related data source for the building on the activity page. In this scenario, the building condition type is non-residential (Figure 4.3).

This tab also contains additional information:

- Occupancy levels include times that incorporate time and holidays; Metabolic rates in the building can be selected based on the type of activity, such as low activity for classroom activities, and clothing requirements for people in the building during the summer and winter should also be considered.

- Holiday scheduling, including annual national holidays and summer vacations, should be considered.
- Usage levels of equipment, such as computers or other devices, should be determined if they are present in the building.
- The environmental control system encompasses several factors, such as the desired temperature range for heating and cooling, the specific level of illuminance required, and the amount of fresh air needed depending on the activity.

All this data can be configured for the entire building at the building level and individually adjusted for each classroom. For example, the number of people is set to zero at the building level to account for empty areas, such as toilets and cleaning rooms, and then the number of students is changed for each classroom based on the number of students.

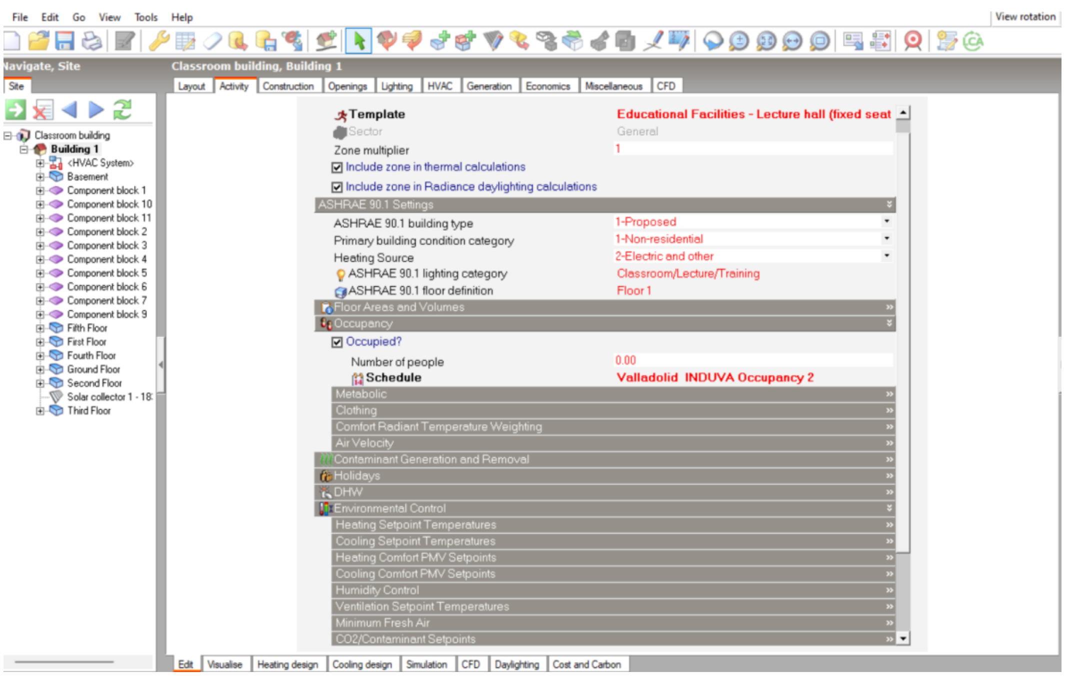


Figure 4.3 Screenshot of the Activity tab in DesignBuilder

4.1.1.4 Construction Tab

By accessing the Construction tab, the user can open the group header boxes and modify the intricate composition of walls, ceilings, floors, ceilings, partitions, and other elements used in constructing the structure. DesignBuilder's inheritance/default system makes it easy to define building structures quickly and effortlessly. This is achieved by importing template data and configuring global settings at the building, block, and zone level. The diagram in Figure 4.4 illustrates the positions of the different surface types and the corresponding structures that will be implemented on them. In addition, it displays definitions for the block and zone dimensions.

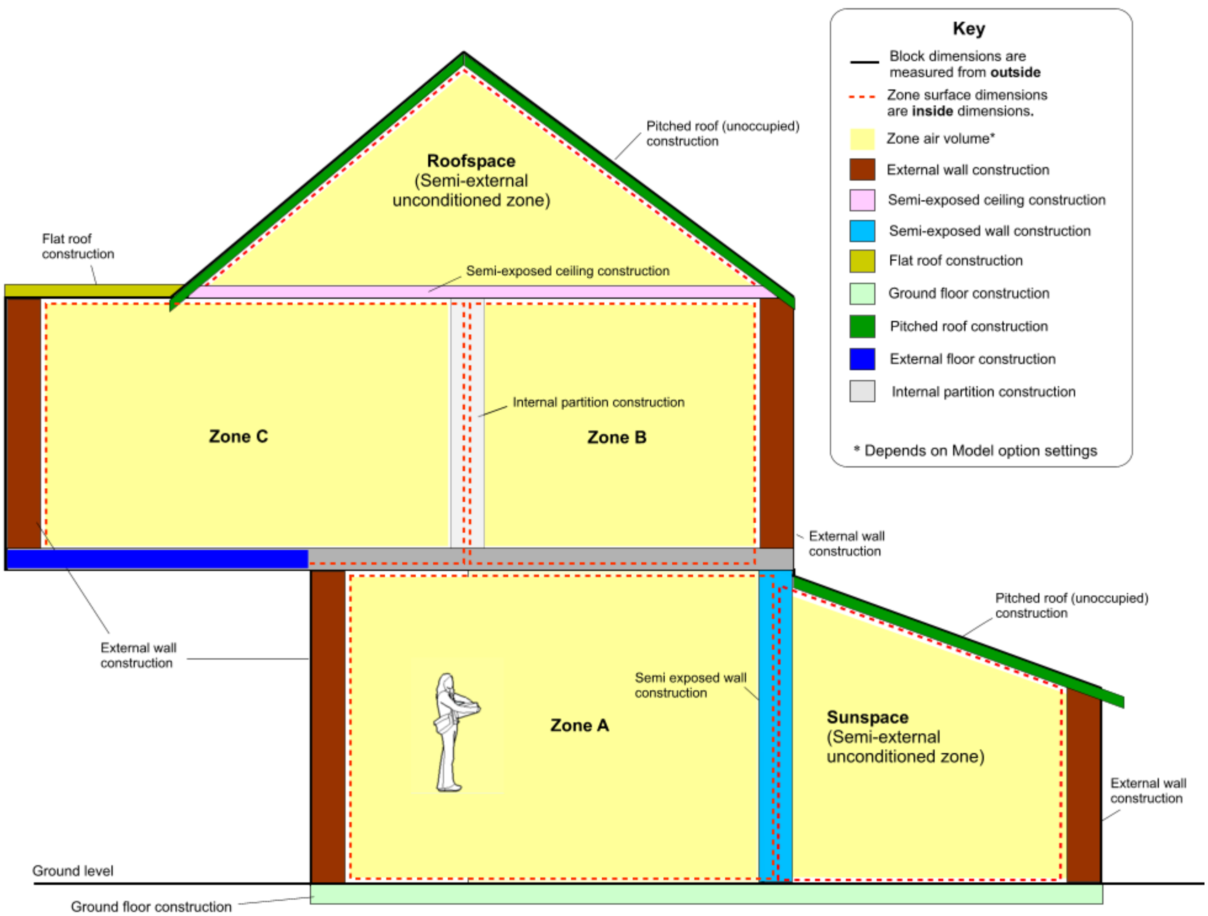


Figure 4.4 Types of Construction in DesignBuilder

DesignBuilder classifies constructions into the following types:

- Exterior walls: The term "exterior wall" refers to all vertical surfaces of a structure that are immediately exposed to the outside environment. In regions with low temperatures, it is typical for these structures to include a layer of insulation.

- An under-grade wall refers to a wall located next to the ground. These data are not considered if the model does not include underground barriers.
- A flat roof is a structure used for horizontal exterior surfaces. The structure representing a level roof requires distinct layers, including the slab, insulation, and roof finish.
- A pitched (occupied) roof refers to the construction of sloping surfaces in areas where people reside. In regions with low temperatures, this structure usually incorporates an insulating layer.
- A pitched (unoccupied) roof refers to the sloping surfaces on the outside of a building that are uninhabited and are located in semi-outdoor areas that are not climate-controlled.
- Internal partitions: Internal partition construction refers to creating internal partitions, which are walls that divide blocks into different zones. It also includes the construction of partitions between blocks, which are internal walls shared with other blocks.
- Semi-exposed walls are used to divide inhabited spaces from semi-exterior or non-conditioned regions. They usually include a certain amount of insulation.
- Semi-exposed roofs refer to using a roof enclosure that separates inhabited spaces from unconditioned semi-outdoor regions, mainly when the latter is located above. The structure must have different layers: the slab, the insulation, and the false ceiling.
- Semi-exposed floors refer to floors used in spaces that are partially exposed to the weather or not air-conditioned.

DesignBuilder uses an automated process to identify areas considered "external" and organize the layers of the building envelope accurately.

- Ground floor: The ground floor structure connects all the interior areas and the ground floor. Site soil temperatures are used to calculate the temperatures of all surfaces that are in direct contact with the soil.
- Basement Ground Floor: The basement ground floor structure is explicitly used for ASHRAE 90.1 models. It applies to areas where the floors are directly close to the ground and the area block lacks an outer edge, often indicating that they are basements.

- External flooring refers to an outdoor floor, such as the floor of a cantilevered section of a building or any other area where there is no ground or other space underneath. External floor construction should include the installation of slabs, insulation, and raised floor layers.
- Internal floor construction refers to floors within inhabited areas, including slabs, air gaps, raised floors, and suspended ceilings.

Within the options mentioned above, the user can choose a particular material from the library or specify it by indicating the number of layers and defining each layer along with its thickness. Alternatively, the user can also choose the material's U-value in W/m^2. k as in our scenario (Figure 4.5).

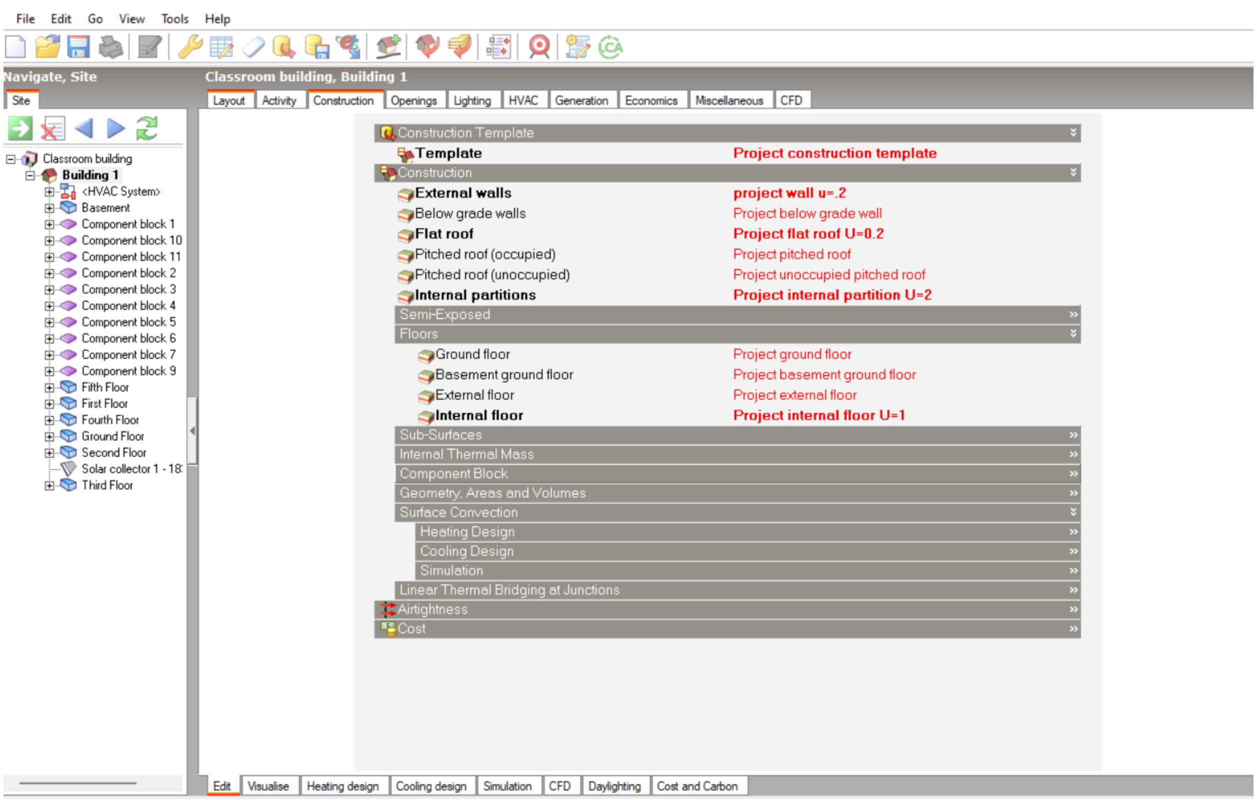


Figure 4.5 Screenshot of the Construction tab in DesignBuilder

4.1.1.5 Openings Tab

In DesignBuilder, the word "opening" refers to any opening in the building envelope that differs from its design composition. Once the user selects the glazing template, they will be presented with five types of openings to configure if they exist in the building. Figure 4.6 shows the screenshot of the INDUVA building simulation.

- Exterior windows: The data in the "Exterior glazing" section refers to all exterior wall glazing materials. The user can modify the data for the following aspects: dimensions, window-to-wall ratio, frame, shading, and operation.
- Internal windows: The data categorized in the "Internal glazing" section pertains to all glazing materials installed on the internal partition walls. In addition, the user can modify the dimension, frame, and operation data.
- Pitched roof: The parameters for the roof window size closely resemble those of external walls, with some notable differences. The façade configuration is only applicable to sloping roofs. This data does not include information about flat roofs. To include windows on flat roofs, it is advisable to design them at ground level or replicate them from other building facades. Flat roofs do not use the façade mechanism because they lack the necessary features to set thresholds, height, and width, such as top and bottom surfaces. The façade options available are limited to 0-None, Fixed Width and Height and Infill Surface (100%).
- Doors: Doors made with DesignBuilder are opaque and can be added to the model by selecting the Door Hardware option and going to the corresponding surface. This installation consists of replacing one of the windows with a solitary door. Alternatively, users can gain more control over the location of doors by navigating to the surface level and using the Draw Door command, as shown in our example. If custom openings have been specified in the surfaces, changes in the door layout model data in the Opening tab are not considered.
- Vents: Vents in DesignBuilder simulate airflow through openings. Selecting the appropriate surface and selecting the option of installing vents simplifies the addition of vents to the model. This facility has a solitary vent placed under each window. Alternatively, users can have more control over the placement position of the vents by navigating to the surface level and using the Draw Vent command as doors are drawn.

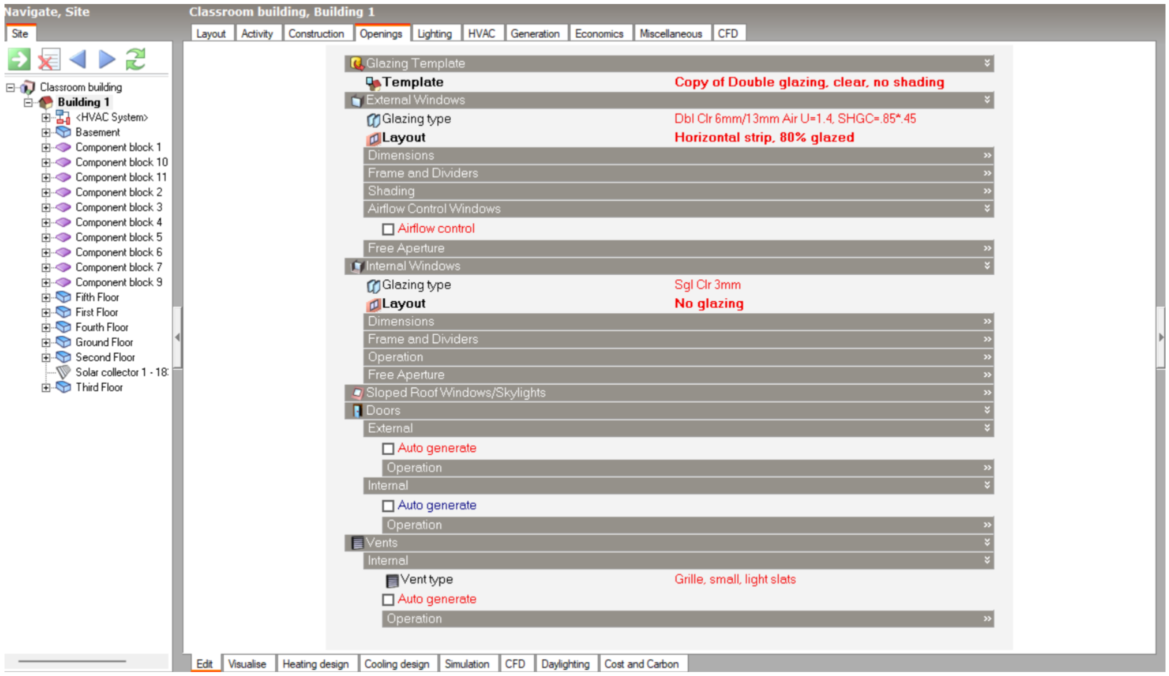


Figure 4.6 Screenshot of the opening tab

4.1.1.6 Lighting Tab

To upload generic lighting data, the user needs to click on the Template option under Lighting Template. When you choose a lighting template from the list, the data associated with the selected template will be imported into the model. Lighting in the area is categorized into task and general lighting. These categories can be expanded to provide specific lighting characteristics that may vary from the default settings imported from the template.

DesignBuilder allows users to choose one of the five types of luminaires shown in Figure 4.7. The data for the return air fraction, radiant fraction, visible fraction, and convective fraction vary depending on the type chosen. Users can also program the operation of the lights based on occupancy.

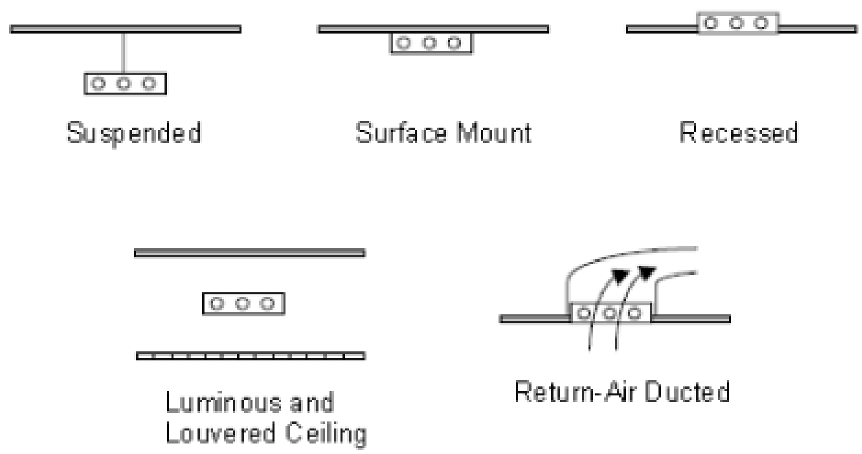


Figure 4.7 Typical luminaire

4.1.1.7 HVAC Tab

To import generic HVAC data, the user must click on the "Template" option in the HVAC Template section. From there, they can choose a template from the list of available HVAC templates. Once the selection is made, the data for the selected template will be loaded into the model. The remaining portion of this HVAC portion is divided into two main sections that discuss the two HVAC model options: simple HVAC and detailed HVAC, the latter used in our specific scenario.

DesignBuilder has a sophisticated HVAC module that allows users to create accurate models of HVAC systems and simulate how they will behave in the context of the building. Users can precisely specify HVAC components, including air handling units, chillers, boilers, cooling towers, fans, dampers, and control systems. The program allows users to define equipment capacity, operating hours, set points, and control techniques. Users can examine the effectiveness of HVAC systems in various operating situations, evaluate the consequences of design choices or control methods, and improve system performance to achieve energy efficiency goals and comfort standards.

The heating and cooling parameters in the detailed HVAC simulations do not affect the simulations themselves; instead, they serve to show or hide programming data. However, they are consistently used in calculations for heating and cooling design. Humidity and temperature setpoints and ventilation requirement data for heating and cooling design calculations are obtained from the Activity tab, independently of the HVAC Activity Detail Data option.

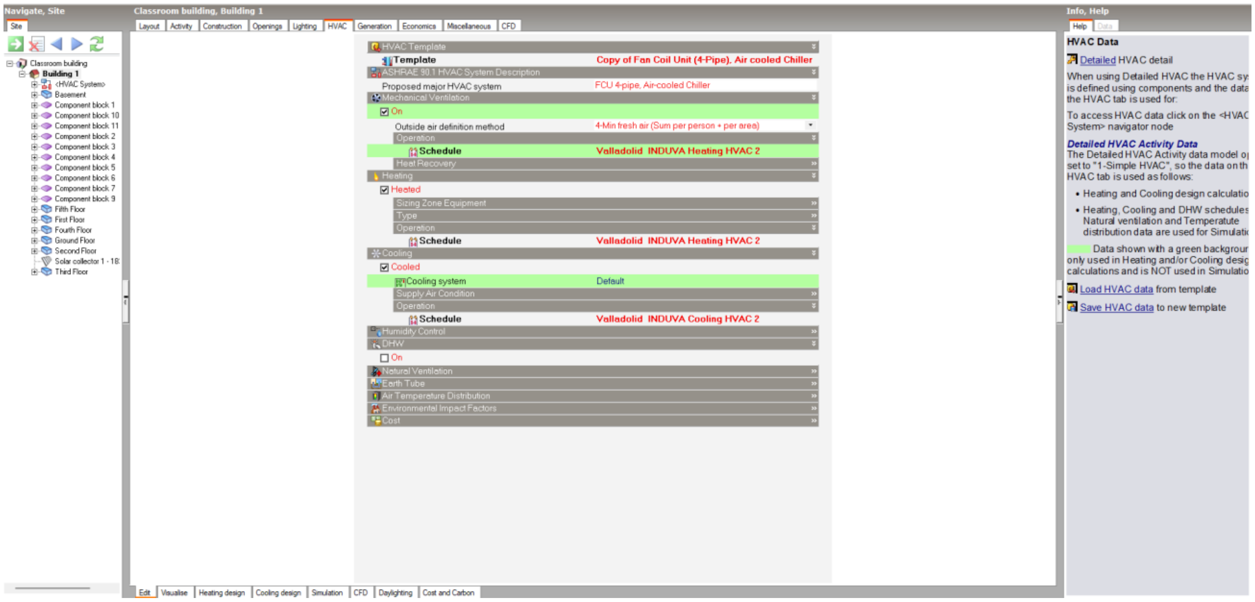


Figure 4.8 Screenshot of the HVAC Detailing tab

The user must choose the HVAC option detailed under the HVAC heading in the Model Options dialog box to get complete information about the HVAC system. When you close the Model Options window, a new node is displayed in the browser tree list, as shown in Figure 4.9.

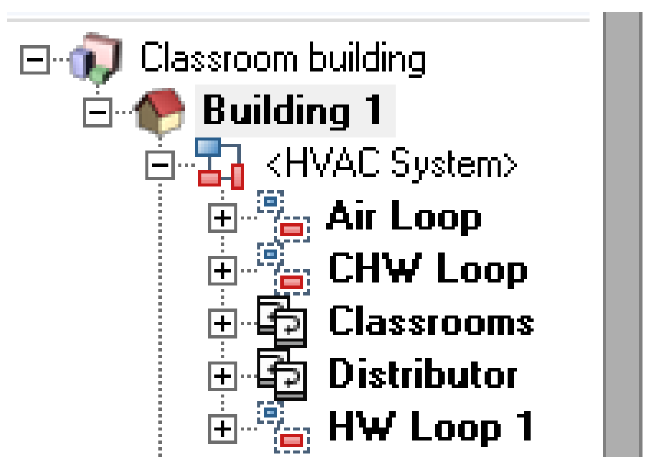


Figure 4.9 List of Navigator trees detailed HVAC

DesignBuilder's HVAC system models are built by combining predefined air and water distribution circuits with zone groups, resulting in fully integrated systems. Air and water circuits consist of various HVAC components interconnected by pipes or ducts to create distribution systems. These loops can be modified to include any additional components needed and then linked to related components in other loops or to zoned heating, cooling, and ventilation equipment to create integral systems (Figure 4.10).

Zone groups are used to organize multiple zones that share the same HVAC equipment. Each zone within the group can have different team classifications. The zone group mechanism streamlines the construction of the HVAC scheme by requiring that only one set of equipment and connections be described for the entire group. This allows the flexibility to modify the attributes of zones within the group without affecting the overall configuration. Once the loops, zone groups, and set-point managers have been set up and the necessary connections have been made with the corresponding equipment, an EnergyPlus simulation can be performed on the integrated model of the building and HVAC system.

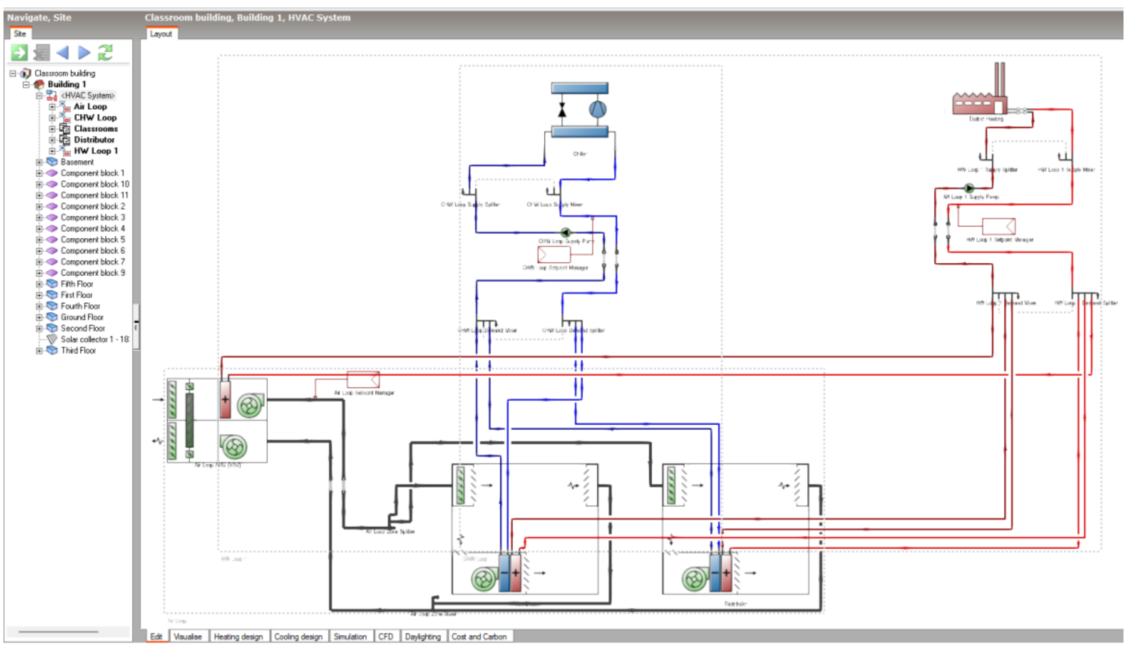


Figure 4.10 Detailed HVAC loop

4.1.1.8 View Table

The Model Data tab on the Display screen provides tools for visualizing model data in a graphical format, as shown in Figure 4.11. One option available is to access the building and glazing components used for each surface and window of the model. In addition, the section can cut through the building and get a transparent view (Figure 4.12).

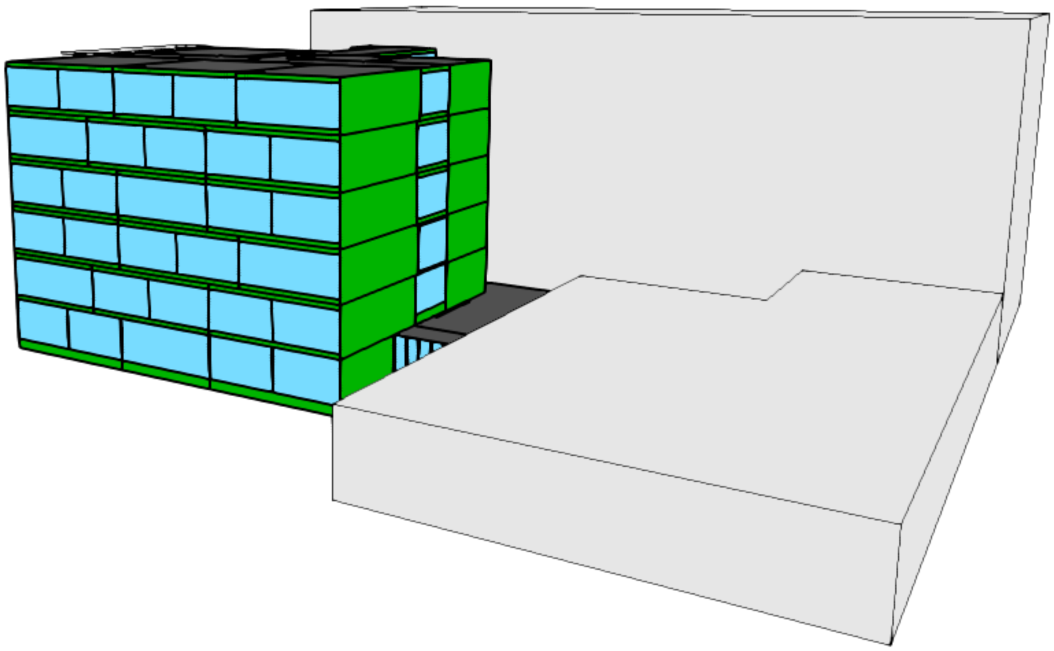


Figure 4.11 View of the INDUVA building

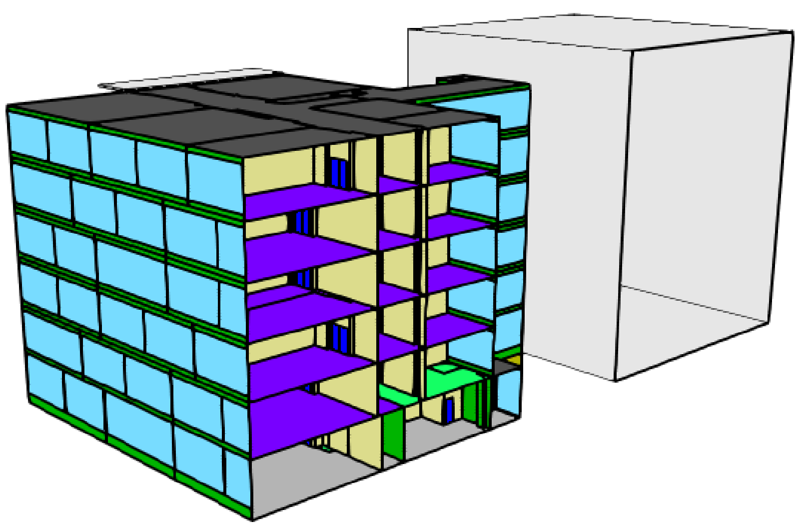


Figure 4.12 Section cut of the INDUVA building

The user can obtain a realistic rendered version of the model, which shows textured surfaces, through the Rendered Version tab on the Display screen (Figure

4.13). Observe the impact of the sun's shadow on any given day throughout the year. Export the photos produced in many formats and create AVI movies on the stage.

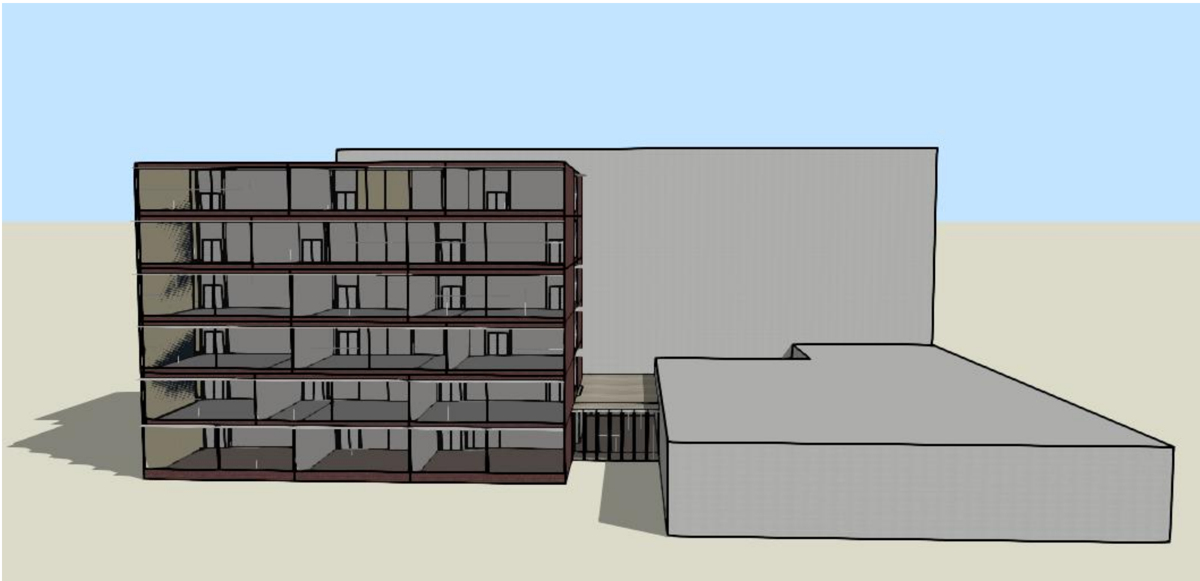


Figure 4.13 Rendered view of the building

4.1.1.9 Heating Design Tab

Heating design calculations are conducted to determine the required size of heating equipment needed to handle the most extreme winter weather conditions expected at the site location. The heat loss in each zone is added to a safety factor (default value of 1.5) to achieve the optimal heating design capacity. Traditionally, ASHRAE provides steady-state techniques for performing design calculations. To access the heating design data, select the Heating Design Display tab. If the required data has not yet been produced, an automated calculation of the heating design is initiated to create the data (Figure 4.14).

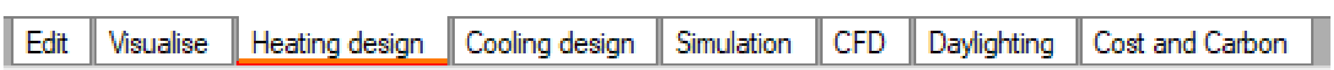


Figure 4.14 Heating Design tab

4.1.1.10 Cooling Design Tab

Cooling design calculations are performed to determine the necessary capacity of mechanical cooling equipment needed to handle the most extreme weather conditions observed during the warmer summer at the site location. Temperatures in areas without mechanical cooling are determined by considering the impact of natural or mechanical ventilation if these choices are made on the HVAC tab of the zone. ASHRAE provides standard design estimates for HVAC systems that use periodic steady-state approaches, such as the admittance and response factor methods. The design refrigeration capacity is obtained by multiplying the maximum refrigeration load in each zone by a safety factor, normally set at 1.3.

4.1.1.11 Simulation Tab

The Simulation tab of DesignBuilder software functions as a centralized platform for performing energy simulations and evaluating building performance. Users have access to EnergyPlus' extensive simulation capabilities. This allows for an in-depth examination of thermal loads, energy consumption, and occupant comfort. Users can access various items in this tab, including weather data, building schedules, HVAC systems, and internal earnings. The interface allows users to choose simulation periods, define custom simulation parameters, and perform many simulations for analysis. The results are displayed in many ways, such as graphical outputs and comprehensive reports, which make it easy to evaluate and improve construction plans comprehensively.

During the simulation period, users can determine the start and end dates of the simulation by specifying the day and month in the Model Options dialog box (Figure 4.15). The Calculation Options dialog box allows the user to choose specific periods for the simulation in the right pane (Annual Simulation, Summer Design Week, Typical Summer Week, All Summer, Winter Design Week, Typical Winter Week, All Winter).

The user can choose the reporting interval for the output, which can be set to monthly, daily, hourly, or sub-hourly. However, it is essential to note that selecting smaller intervals can generate significant data, leading to a slower simulation process and larger DesignBuilder files.

Selecting the number of simulation stages per hour is essential for the EnergyPlus Zone Heat Balance model. Determines how often iterative heat transfer and load calculations are performed for each virtual hour of simulation. Possible options include the following numeric values: 2, 4, 6, 10, 12, 30, and 60.

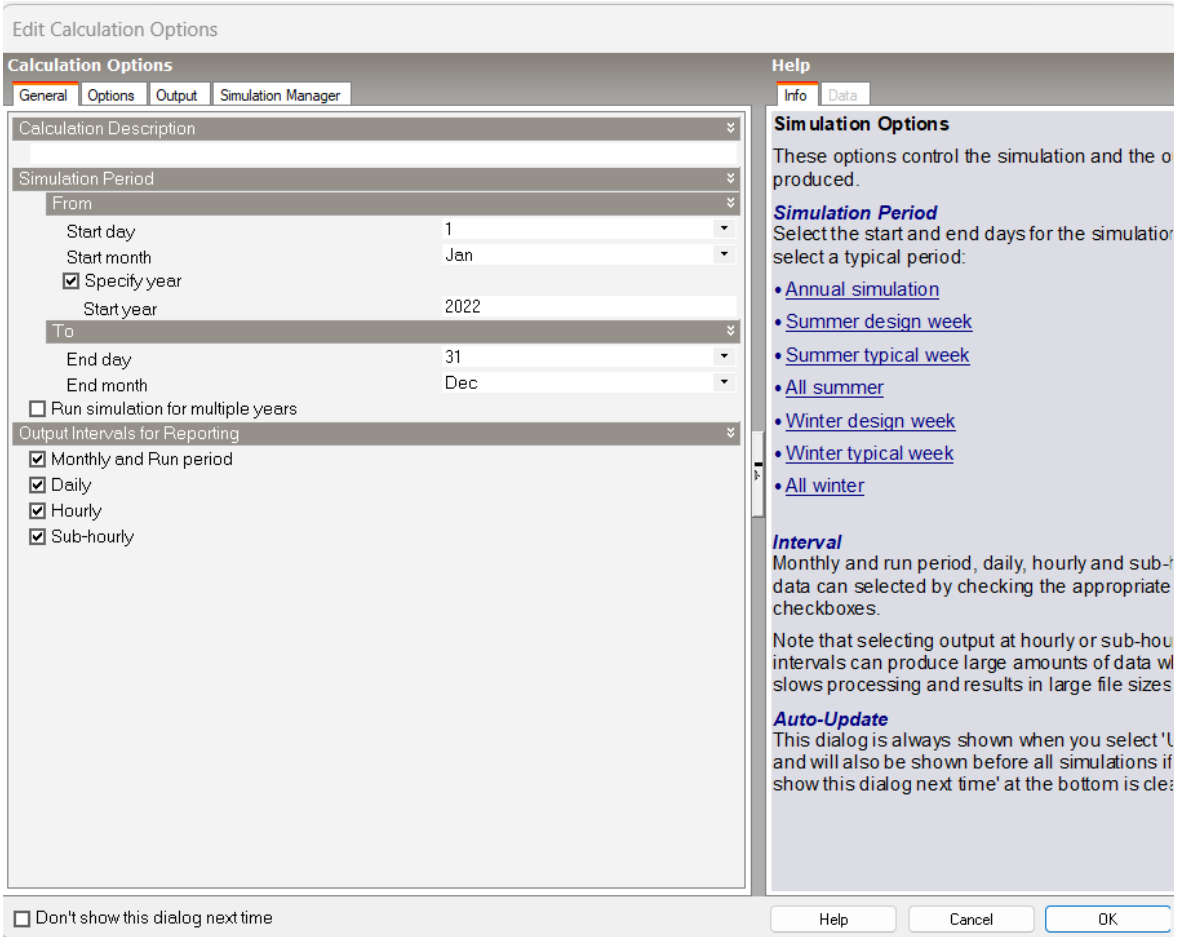


Figure 4.15 Screenshot of the Simulation tab

To present the results, the user has the option to choose from the following options:

- All: All factors related to fabric and ventilation heat gains/losses, internal gains (excluding heating design), temperatures, and dry bulb outdoor air temperature.
- Site Data: Provide all site data.
- Comfort: This includes indoor air, radiant and comfort temperatures, and relative humidity.
- Internal Gains: This category includes internal sources of heat and power, such as equipment, lighting, occupancy, solar radiation, and HVAC heating/cooling systems.

- Fabric and ventilation: This refers to the heat that the area obtains from different surfaces, such as walls, floors, and ceilings, as well as from the ventilation system. Negative numbers imply a decrease in thermal energy within the space, resulting in heat loss.
- Fuel Breakdown: indicates fuel consumption categorized by system type.
- Fuel Totals: Fuel consumption is categorized by fuel type.
- CO_2 Emissions - Weight-based measurement of carbon dioxide emissions.

This data can be displayed in four ways: Chart, Grid, Chart and Table, and Table.

The DesignBuilder model of the INDUVA building was created with an integration of monitored data and specified library parameters. The following data was collected directly from the building's monitoring system (SCADA–BMS) and by field measurements:

- Location of the building.
- Internal air temperature range for heating and cooling, together with relative humidity levels.
- Actual occupancy patterns and schedules derived from classroom records and sensor-based monitoring.
- Metabolic rate determined by activity level, clothing, and holiday schedule.
- Ventilation rates and equipment operational schedules.
- Thermal transmittance (U-values) of the envelope for each type derived from construction data.
- Type and arrangement of glazing.
- Lighting template, intensity, and scheduling.
- Profiles of electrical and thermal energy usage for lighting and plug loads.
- Detailed HVAC, components, and schedules.

The remaining parameters were sourced from DesignBuilder or standard databases, adhering to ANSI and ASHRAE 90.1 guidelines. This differentiation guarantees that all observed variables accurately reflect the building's actual functioning, whereas default parameters are utilized just in instances when measurement data is lacking.

4.1.2 CCWeatherGen

CCWeatherGen, an acronym for Climate Change Weather Generator, is an advanced software application created specifically to generate future weather files that include the anticipated effects of climate change. Its origins can be attributed to the UK Climate Impacts Program (UKCIP), created through a thorough study and cooperation between academic institutions and industry specialists specializing in environmental and building sciences.

CCWeatherGen was developed in response to the growing need for accurate climate data to support building design and performance assessments. The researchers recognized that conventional weather archives relying on historical data were inadequate to simulate the future climate conditions the structures would support. Therefore, the purpose of developing CCWeatherGen was to bridge this gap by creating a program capable of producing weather files that accurately represent future possibilities.

This program uses Microsoft Excel and is compatible with most building performance modeling systems. It aims to convert CIBSE/Met Office and TRY/DSY meteorological datasets into climate change, TMY2, or EPW files. The process begins with obtaining climate prediction data from global climate models (GCMs). The dataset includes many environmental parameters, such as temperature, humidity, solar radiation, wind speed, and precipitation. These variables are often forecast for extended periods, such as 2020, 2050, and 2080. The results of the Global Climate Model (GCM), usually presented in a larger size, are transformed to a smaller scale and more suitable for local and regional uses. The downscaling process can be statistical or dynamic, considering local weather conditions and geographical factors to improve accuracy. The program allows users to choose from multiple emissions scenarios, such as RCP4.5 and RCP8.5, representing different amounts of greenhouse gas concentrations in the future. These scenarios affect the magnitude of the consequences of climate change on the meteorological records produced. Subsequently, CCWeatherGen produces weather files that replicate the structure of conventional weather files used in building simulation software. These files include future climate variables modified for various periods and situations. They can be used efficiently with applications such as EnergyPlus and DesignBuilder.

4.2 Analysis of Results

The thesis research is developed in a real building with almost zero energy consumption (nZEB) located on the campus of the University of Valladolid, specifically designed to teach bachelor's and master's degrees in industrial engineering. The building has both LEED and VERDE-GBCe certifications. Certification means a dedication to constructing and operating green and resource-efficient buildings[106], [107]. In addition, the building received the Castilla y León Sustainable Construction Award in the area of equipment. The monitoring data is used to analyze the energy balance, energy indicators, and the performance of the building in its current state. This analysis also considers the expected climate change and how it will affect the building's performance in the near and distant future. In addition, the study explores the possibility of relocating the building to different climatic regions to assess its present and future performance.

An energy simulation of the INDUVA building was created to estimate its performance in short, medium, and long periods. In addition, it calculates the potential savings that can be derived from using passive construction techniques and highly efficient energy systems powered by renewable sources. The DesignBuilder version 7, equipped with the EnergyPlus calculation engine, provides a robust tool for performing dynamic simulations and generating simulation data for the energy analysis of the INDUVA building. DesignBuilder provides sophisticated modeling tools within an easy-to-use interface. EnergyPlus is an old and continuously updated tool for simulating buildings' thermal and energy characteristics. An analysis of the demand and consumption of a model, which has been created and calibrated in simulation software, can be performed for 8,760 hours each year. In addition, this technical advancement makes it possible to quickly obtain precise energy characteristics, such as temperature, humidity, energy consumption, or energy production. This reduces the time required for data collection and simplifies subsequent analysis (Figure 4.16).

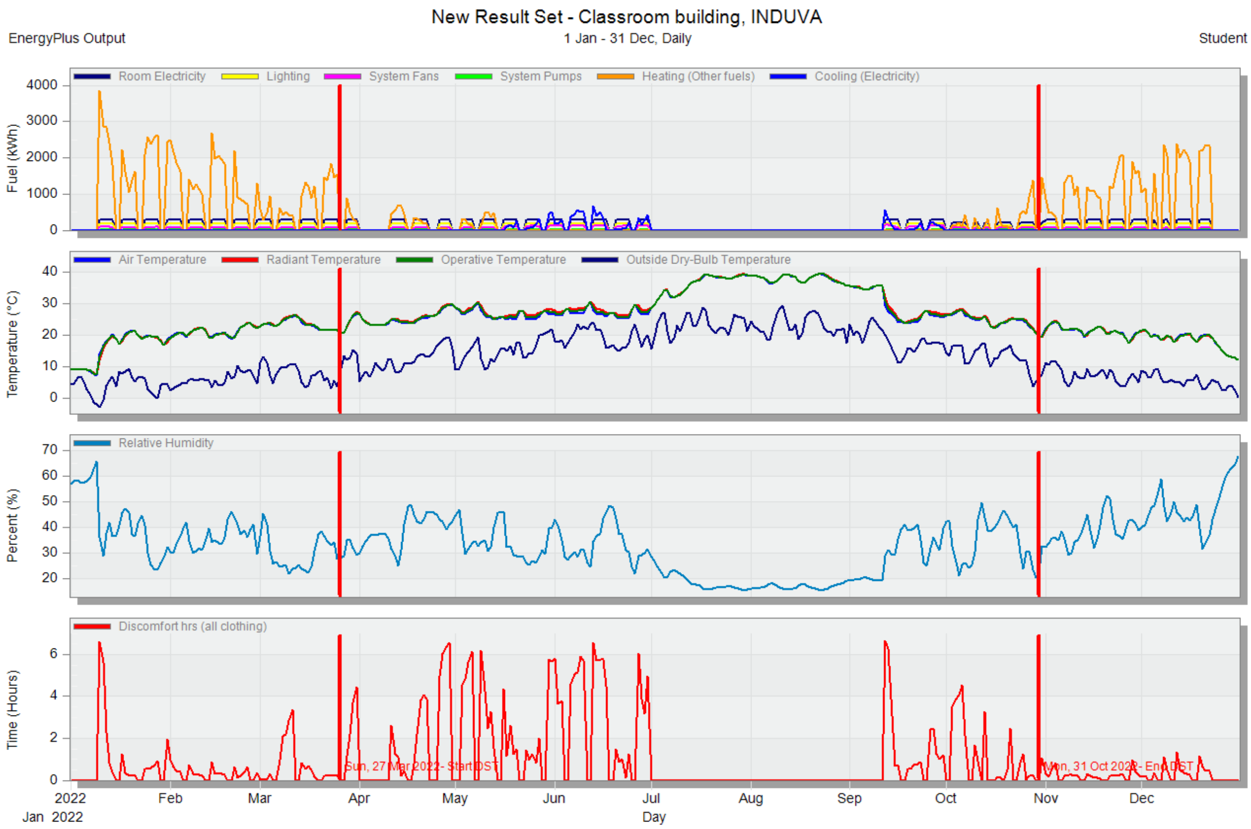


Figure 4.16 Screenshot of DB simulation results

Building a performance simulation starts with creating a three-dimensional model and entering any relevant physical data. This includes information about the structure's envelope, operating procedures, heating and cooling systems, air circulation, and lighting. The weather file is then used to establish the external conditions of the location. The calculation engine uses this data for a year's simulation, producing hourly results for many variables such as energy use, indoor and outdoor temperatures, relative humidity, comfort levels, and CO_2 emissions.

To ensure accuracy, the building model is calibrated using actual energy consumption data acquired from a SCADA monitoring system. The calibration procedure improves the consistency of the results. The simulation uses TMY climate data over several years and cities, which is then adjusted using a mathematical method created by the University of Southampton. Once the model has been verified, the performance of the building in the short, medium, and long term is analyzed. This study considers the potential adverse effects of climate change and location changes. Implementing this proactive study makes it possible to assess the projected energy requirements, the efficiency of the energy systems already installed, and whether the building will reach the prescribed target of nZEB (Nearly Zero Energy Building) for the next period or other locations.

An example of a validation comparison between the data collected by the sensors monitored by SCADA and the data generated by DesignBuilder version 7 is shown in Figures 4.17 and 4.18.

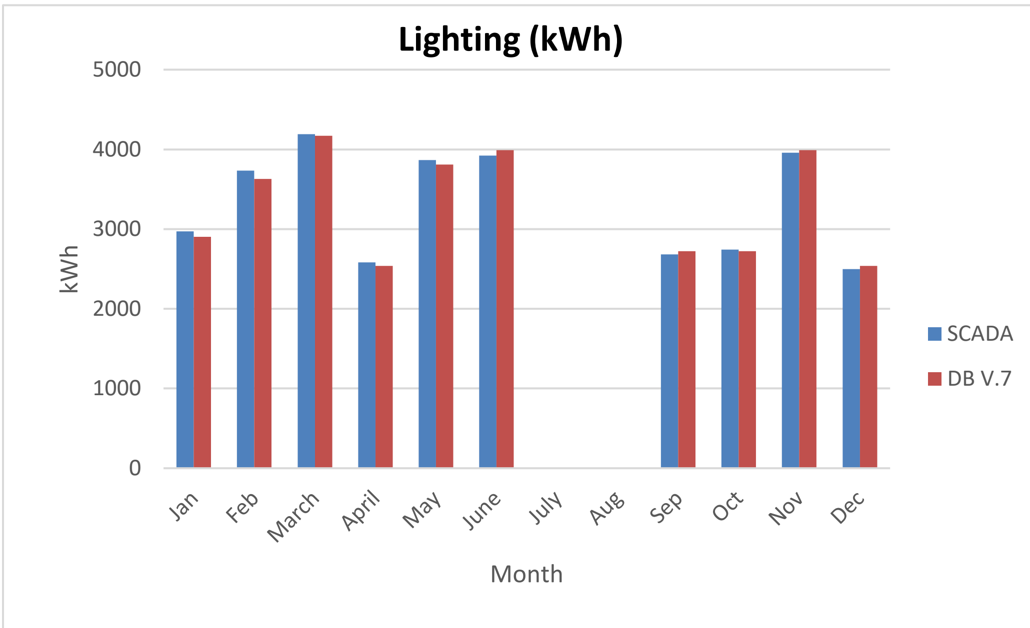


Figure 4.17 Comparison of DB and SCADA simulation lighting data for validation

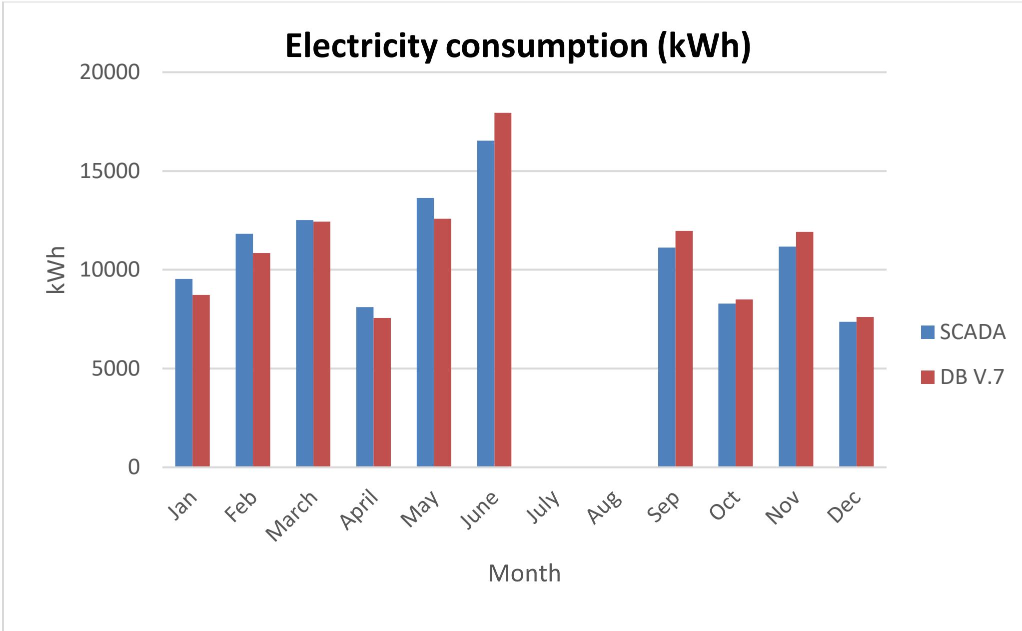


Figure 4.18 Comparison of DB and SCADA simulation electricity consumption data for validation

Using the SCADA system, the controllers and sensors that monitor the building's control compare their findings with those produced by the DesignBuilder V7 simulation program. The results are exported to an Excel file. Subsequently, I validate the closeness to the model, making adjustments within a margin of error not exceeding 9% in some months and less than 1% in the general total, thus agreeing on the difference.

To evaluate the accuracy of the energy simulation model quantitatively, a statistical calibration was conducted using monthly data monitored by SCADA alongside outputs from DesignBuilder. Following the methodology outlined in ASHRAE Guideline 14-2014, two key statistical indicators were applied: the Normalized Mean Bias Error (NMBE) and the Coefficient of Variation of the Root Mean Square Error (CV(RMSE)). These metrics help assess the model's bias and its variability in accurately replicating measured energy performance.

The NMBE is calculated as:

$$NMBE = \frac{\sum_{i=1}^{n}(M_i - S_i)}{(n-1).\bar{M}} \times 100 \qquad \textbf{(4.1)}$$

And (CV(RMSE)) is defined as:

$$\left(\boldsymbol{CV(RMSE)}\right) = \frac{\sqrt{\frac{\sum_{i=1}^{n}(M_i - S_i)^2}{n-1}}}{\bar{M}} \times \mathbf{100} \qquad \textbf{(4.2)}$$

Where:

- $\boldsymbol{M_i}$**:** is the measured energy use (from SCADA).
- $\boldsymbol{S_i}$**:** is the simulated value (from DesignBuilder).
- $\boldsymbol{n}$**:** is the number of monthly time periods.
- $\boldsymbol{\bar{M}}$**:** is the average of the measured values.

According to the lighting data presented in Figure 4.17, the model achieved a Normalized Mean Bias Error (NMBE) of +0.59% and a Coefficient of Variation of the Root Mean Square Error CV(RMSE) of 2.19%. For total electricity consumption, as shown in Figure 4.18, the NMBE was 1.74% and the CV (RMSE) was 7.53%. These results are well within the recommended thresholds set by ASHRAE for calibrated simulations using monthly data, which are ±5% for NMBE and ≤15% for CV(RMSE). This indicates that the model is sufficiently calibrated for both lighting and electricity uses. Statistical validation reinforces the model's reliability for assessing retrofit strategies and climate change scenarios in the following chapters.

Once it was determined that the model accurately represented the actual energy consumption of the building, it was examined using their simulation model. In this thesis, the consumption of kilowatt hours of primary energy per usable area per year for the fixed installations of the building, including cooling, heating, ventilation, geothermal heat exchangers, and lighting, will be analyzed. It will also examine the energy generated on-site, as required by law. Achieve an annual energy balance, measured in kWh/m^2.year, a non-renewable primary energy indicator, and a Renewable Energy Ratio (RER). Obtaining the three indications required by the regulations in force in Europe allows the building to be classified within the nZEB objective. We can identify these structures by linking the energy balances of nZEB buildings and comparing them with the indicators that the

European EPBD has created as a benchmark for nZEB buildings. At the same time, the performance of this building will demonstrate, analyze, and study the economic benefits of reducing carbon emissions through the design of nZEB and the impact of a modified climate year caused by climate change and location change.

Dynamic simulation of the nZEB using DesignBuilder software has yielded three different indications according to the EU's approach to defining an nZEB.

The first indicator, the kWh/m²·year energy consumption ratio, including renewable and non-renewable energy sources, was derived by dynamic simulation using DesignBuilder V7 after validating the building model. It refers to the energy consumption for heating, cooling, lighting, and ventilation, in addition to the heat supplied by district heating systems, as mentioned in Table 4.1. The energy produced by the PV system is sent to the grid, along with heat recovery from the geothermal system. The building's energy consumption ratio of 52.53 kWh/m²·year accurately indicates the building's energy efficiency and the amount of renewable integration.

Table 4-1: Energy Consumption in INDUVA Building

Heating Energy Use	165,293.217 kWh/year
Cooling Energy Use	9,569 kWh/year
Lighting Energy Use	33,016 kWh/year
Ventilation Energy Use	16,656 kWh/year
Computers and Equipment Energy Use	51,011 kWh/year
Geothermal Recovery Heating Energy Use	17,136 kWh/year
Geothermal Recovery Cooling Energy Use	12,518 kWh/year
PV Energy Generation	24,438 kWh/year
Net Floor Area (Conditioned Area)	5,245 m²

Total Electricity Use	110,252 kWh/year
Ep non-renewable, electricity of network	215,432 kWh/year
Ep renewable, District Heating	165,293.217 kWh/year
Ep renewable, PV	24,438.7 kWh/year
Ep renewable, geothermal recovery	29,654 kWh/year
Ep$_{exp}$	0
Ep$_{total\ renewable}$	219,386kWh/year

The second indicator, the primary energy indicator, is calculated and quantifies the value of primary renewable energy in INDUVA nZEB. Using these indicators, we can get an overview of the building's energy production and consumption, comparing it with the maximum and minimum values recommended by the EU. The Primary Energy indicator consolidates all energy supplied and exported into a single measure. The Primary Energy Indicator IEP_p =41.07 kWh/m² is calculated based on the energy supplied and exported, considering a nationally established Primary Energy Factor (PEF), as described in Equation 1, where the factor for electricity consumption is 1.954, and 1 for all renewable consumptions. There is no exported energy; data is mentioned before in Table 4.1.

$$\boldsymbol{IEP_p = \frac{E_{p,nren} - E_{p,exp}}{A_{net}}} \quad \textbf{(4.3)}$$

$$\boldsymbol{E_{p,nren} = \sum_i \left(E_{del,i} f_{del,nren,i}\right) - \sum \left(E_{exp,i} f_{del,exp,i}\right)} \quad \textbf{(4.4)}$$

Where:

IEP_p: Primary Energy Indicator (kWh/m^2.year)

$E_{p,nren}$: Non-renewable primary energy (kWh/year)

A_{net}: Usable area (m^2)

$E_{del,i}$: Energy supplied on-site or in the vicinity (kWh/year) for energy vector i

$f_{del,nren,i}$**:** Non-renewable primary energy factor for the supplied energy vector i

$E_{exp,i}$**:** Energy exported on-site or in the vicinity (kWh/year) for the energy vector i

$f_{del,exp,i}$**:** Non-renewable primary energy factor of the energy supplied offset by the energy exported for the energy vector i

Directive (EU) 2024/1275 on the energy performance of buildings defines precise requirements for nearly zero-energy buildings (nZEBs) in different climate zones to improve energy efficiency and reduce emissions in the EU building sector. This directive highlights the Primary Energy (PE) indicators that fluctuate depending on climate zones and building ratings. According to the regulations, buildings in Mediterranean climates, such as the INDUVA nZEB, categorized as an office building, must have a primary energy consumption of between 80 and 90 kWh/m². The maximum contribution for non-renewable energy is between 20 and 30 kWh/m²·year, accompanied by an on-site renewable energy target of around 60 kWh/m² per year.

The INDUVA building has a primary energy IEP of 41.07 kWh/m².year, demonstrating compliance with the Nearly Zero Energy Building (nZEB) standards in Mediterranean conditions. This rating shows the building's compliance with strict EU regulations, which support the long-term goal of achieving a zero-emission building stock by 2050. The Directive outlines specific values for different climate zones and building types, providing a framework to improve energy efficiency, reduce carbon emissions, and promote sustainable development across the EU. Renewable energy generation amounts to 41.8 kWh/m² per year, compared to the 60 kWh/m² per year suggested by the EU, indicating the need to increase renewable energy generation in the building.

The third indicator, the Renewable Energy Ratio (RER), is used to assess the contribution of renewable energy in the INDUVA building. The RER measures the proportion of the building's total energy consumption supplied by renewable energy sources. This indicator helps determine the extent to which the building's energy needs are met by renewable options, such as solar, geothermal, and biomass, rather than non-renewable sources.

$$RER = \frac{Renewable\ Energy}{Total\ Energy\ Use} \qquad (4.5)$$

The Renewable Energy Ratio, RER = 0,8

This figure means that the building uses renewable energy at a rate that exceeds established standards. In other words, more than two-thirds of the energy the building consumes comes from renewable sources, highlighting its commitment to sustainability and energy efficiency. To accurately calculate the contribution of renewable energy to primary energy, it is essential to account for the combined totals of both renewable and non-renewable energy sources. This equation highlights the importance of integrating both types of energy to understand their respective impacts on overall energy consumption.

$$Renewable\ Contribution\ to\ Primary\ Energy = \frac{Ep_{renewable}}{Ep_{total}} \qquad (4.6)$$

Where:

$Ep_{renewable}$: Primary Energy from Renewable Sources (kWh/m^2.year)

Ep_{total}: Total Primary Energy (Including Non-Renewable) (kWh/m^2.year)

$$Renewable\ Contribution\ to\ Primary\ Energy = 0.5$$

Our study was expanded to examine the resilience and adaptation of the INDUVA building, using its unique design and sustainability attributes in response to climate change. This research sought to evaluate the performance of the building under multiple climate change scenarios, both at its location in Valladolid, Spain, and in potential relocations to other climatic zones. Our goal was to understand the response of a nearly zero-energy building (nZEB) like INDUVA to various climatic circumstances by modeling its energy performance across different periods (2022, 2050, and 2080) and diverse geographic locations. This comprehensive methodology allows us to assess the resilience of nZEB's design principles to maintain energy efficiency and occupant comfort in diverse and changing climatic conditions. The following sections describe our approach, simulation procedure, and ideas for this potential research.

The research study used DesignBuilder version 7 to simulate energy consumption and CO_2 emissions, with EnergyPlus as the computational engine. The CCWeatherGen program was used to forecast future climate scenarios. This application modifies reference weather files according to global circulation models to generate future weather datasets. Specifically, it implements modifications derived from the Hadley Centre Coupled Model, version 3 (HadCM3) created by the United Kingdom Met Office. This program is optimal for producing weather data files compatible with energy modeling software, including predicted temperature, humidity, and more weather factors. Future files for the years 2050 and 2080 were created to augment existing 2022 data for this research. Modeling begins with building a 3D representation of the building. It incorporates all relevant physical characteristics of the building envelope, operating schedules, and various systems, including heating, cooling, ventilation, water heating, and lighting. In addition, a location-specific climate file is included to consider local weather conditions. Using this comprehensive dataset, the simulation engine analyzes the building's thermal and energy performance annually[112], [113].

To examine the impact of climate on building simulations, energy performance, and nZEB design, we first evaluated discrepancies in various meteorological datasets, as shown in the hourly files used in building energy modeling. A preliminary assessment was conducted for an nZEB in Valladolid, Spain. Improvements and expansions were implemented to replicate distinct climates:

Table 4-2: List of Simulated Cities and Climate Group

Climate group	Cities
Temperate	Valladolid, Spain
Tropical	Brasilia, Brazil
Arid	Cairo, Egypt
Continental	Warsaw, Polland
Polar	Juneau-Alaska, United States of America

Five cities in different countries were simulated, representing the five main climate groups across the years based on the Köppen climatic classification, as shown in Table 4-2[114]. The simulations for INDUVA nZEB were run for these countries in 2022, 2050, and 2080. The selection of those countries ensures that the study involves a wide range of global climatic conditions, providing valuable insights into the adaptability of nZEBs across different environments. Those cities demonstrate unique seasonal patterns, temperature ranges, and humidity variations.

This will be ideal for evaluating the dynamic performance of nZEBs in response to diverse climatic challenges. This approach aligns with the study's objective of assessing building resilience and energy efficiency in a relevant context worldwide.

Annual weather data from all regions examined from 2022 to 2080 have been collected and analyzed. The research utilized data from a typical meteorological year (TMY), a standard dataset often employed in software development. The building's energy performance was assessed using sophisticated DesignBuilder version 7 energy modeling software, which uses EnergyPlus as a data calculation engine.

Following the acquisition of climate data and energy simulation data for 2022, 2050, and 2080, the variation of weather and energy consumption patterns for each year within this period was calculated. Consequently, fifteen prospective climate files were derived, reflecting social, economic, and technical advances. The files analyzed the present and prospective energy consumption models, designated as scenarios 2022, 2050, and 2080, with the methodology flowchart illustrated in Figure 4.19.

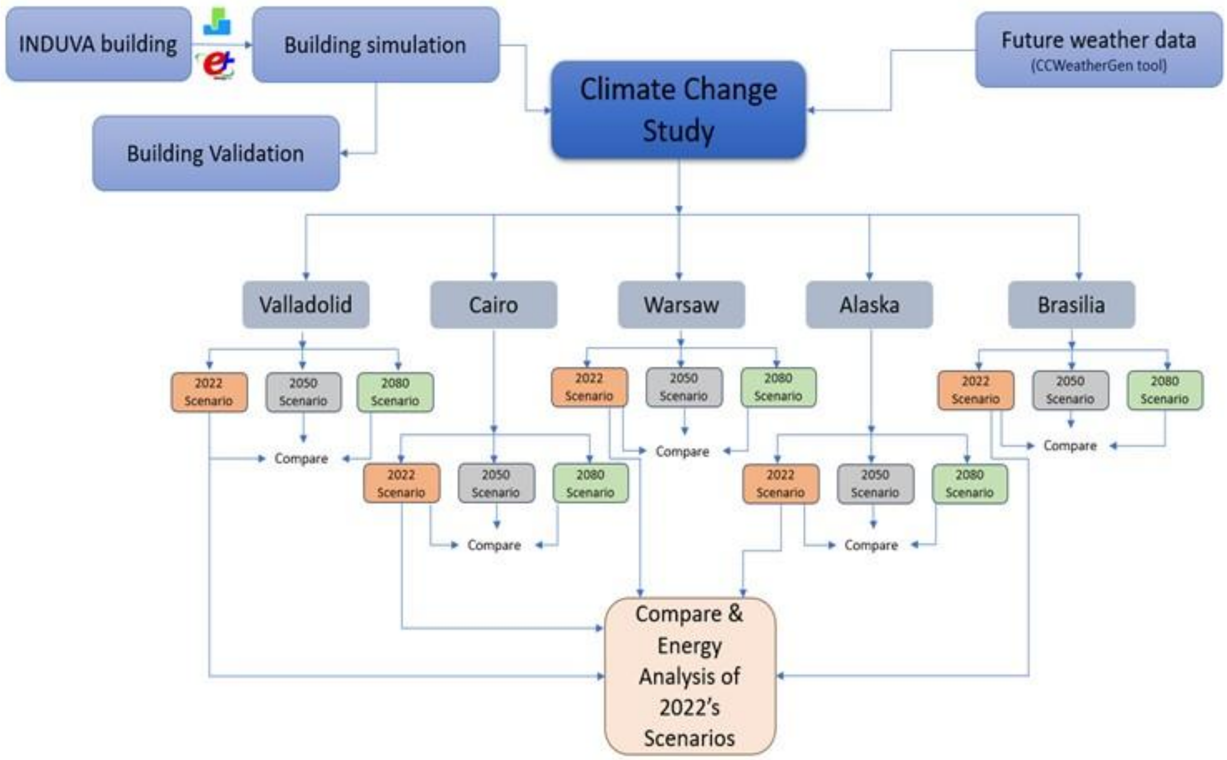


Figure 4.19 Methodology flowchart

This study analyzes changes in the average outdoor temperature, relative humidity, operating temperature, energy consumption, and CO_2 emissions of an nZEB for 2022, 2050, and 2080, considering future climate change impacts and building performance in various climate regions.

The INDUVA building model was simulated using DesignBuilder version 7 software in conjunction with the EnergyPlus modeling engine. The climate data was obtained from the Spanish building standard, and a climate data change was applied to assess the building's energy performance by the end of the century, using the CCweatherGen tool to generate future weather files.

In the base scenario (Valladolid 2022), the behavior of the INDUVA building under future climate change scenarios for 2050 and 2080 indicates a reduction in heating demand of 26% and 29%, respectively. Conversely, CO_2 emissions increased by 10% and 14.5%, correlating with an increase in cooling consumption of 116% and 176%, along with an increase in discomfort hours of 67% and 116%. The predicted temperature increase will lead to a reduction in yield in the future scenarios of 2050 and 2080 compared to 2022. Consequently, the design parameters of buildings must be improved to ensure resilience to climate change. The results indicate that in the 2022 scenario, the performance of the INDUVA building, after the move to Juneau and Warsaw, shows improvements in CO_2 emissions, which are reduced by 5.8% and 4.34%, respectively, and in cooling consumption, which decreases by 93.7% and 50% compared to Valladolid. However, the demand for heating increases by 107% and 87%, and the hours of discomfort increase by 179% and 119%, respectively.

In the 2050 scenario, Juneau and Warsaw show further performance improvements, with decreased CO_2 emissions of 13% and 9%, respectively, and a 92% and 56% reduction in cooling consumption. The building experiences a 32% and 5% increase in hours of discomfort, along with a 159% and 106% increase in heating demand.

In the 2080 scenario, Juneau and Warsaw exhibit significant improvements in performance, with CO_2 emissions reduced by 17% and 9%, cooling usage decreased by 92% and 47%, and hours of discomfort reduced by 24% and 19%, respectively. Heating demand is forecast to increase by 187% in Juneau and 116% in Warsaw.

On the contrary, the building's performance has shown suboptimal results following the move to Cairo and Brasilia in the 2022 scenario. Year-round warm weather decreases heating demand by 95% and 100%, respectively. CO_2 emissions increased by 27% and 14.6%, cooling consumption increased by 316% and 159%, and hours of discomfort increased by 324% and 392%. Future scenarios for 2050 and 2080 will show diminished performance compared to 2022 due to rising temperatures.

Ultimately, future climate change indicates that the design of the INDUVA building needs to be improved to ensure resilience to climate change over the years. The relocation of the INDUVA building to polar and continental climate regions in 2022 will require modifications in thermal insulation and the incorporation of materials with higher thermal mass to ensure internal thermal comfort and decrease heating demand. Long-term performance is improving due to the predominance of cold weather in certain climates throughout the year. As temperatures rise in the future, heat demand is expected to decrease, aligning with current levels of demand in Valladolid. If cold consumption increases at the same rate, it can match the demand for Valladolid in the next century. However, relocating buildings in arid and tropical climates will require substantial modifications in design to accommodate these environmental conditions.

The simulation results indicate that energy demands, particularly for cooling, are expected to increase significantly under projected climatic conditions for 2050 and 2080, especially in warmer regions such as Cairo. This highlights the need for adaptable building envelopes and dynamic ventilation systems in future nZEB designs. The rising cooling loads suggest that strategies such as passive shading, optimizing thermal mass, or implementing more efficient HVAC systems may be necessary to ensure comfort while meeting energy efficiency goals.

In contrast, the scenario for Warsaw showed a decline in heating requirements but an extended shoulder season for mechanical ventilation. These findings emphasize the importance of tailoring nZEB techniques to local climate forecasts, ensuring their effectiveness in the face of climate change.

To better understand the simulation results, Tables 4.3, 4.4, and 4.5 summarize the comparative performance of INDUVA nZEB under varying climatic circumstances and throughout future scenarios. The summarized statistics originate from dynamic simulation, demonstrating the building's adaptability to climatic conditions for heating, cooling energy requirements, and associated CO_2 emissions.

Table 4-3: Total energy consumption, cooling, and heating for 2022

City	**Climate Group**	**Heating Consumption (MWh)**	**Cooling Consumption (MWh)**	**CO_2 Emissions (ton)**
Valladolid	Temperate	165.29	9.268	66.72
Cairo	Arid	7.543	38.545	84.74
Brasilia	Tropical	0	23.978	76.47
Juneau	Polar	342.86	0.5796	62.79
Warsaw	Continental	309.64	4.614	63.82

Table 4-4: Total energy consumption, cooling, and heating for 2050

City	Heating Consumption (MWh)	Cooling Consumption (MWh)	CO_2 Emissions (ton)
Valladolid	122.45	19.99	73.3
Cairo	2.09	43.7	88.25
Brasilia	0	34.6	82.99
Juneau	317.06	1.6	63.53
Warsaw	252.21	8.78	66.55

Table 4-5: Total energy consumption, cooling, and heating for 2080

City	Heating Consumption (MWh)	Cooling Consumption (MWh)	CO_2 Emissions (ton)
Valladolid	100.59	25.59	76.35
Cairo	0.25	43.69	88
Brasilia	0	37.74	84.67
Juneau	288.95	2.04	63.45
Warsaw	216.95	13.65	69.15

In Valladolid, Spain, the baseline scenario, current, and future scenarios indicate a significant shift in energy demands as temperatures rise. Heating consumption is expected to decrease significantly by 2050 and 2080, indicating a reduced need for heating systems. This presents an opportunity to enhance indoor comfort through passive measures such as improved insulation and thermal mass. Conversely, cooling demand is projected to increase sharply, highlighting the need for efficient cooling systems, adaptive shading, and natural ventilation to manage higher indoor temperatures. These trends emphasize the necessity of designing flexible and resilient nZEB that can adapt to changing climate conditions while maintaining energy efficiency and occupant comfort.

For Cairo, Egypt, current and future scenarios indicate a significant increase in cooling demand due to the arid climate and rising temperatures. To adapt buildings after relocation, Egypt's abundant wind resources can be harnessed by integrating wind turbines, which can provide sustainable energy to support cooling systems. Additionally, employing evaporative cooling techniques, which are well-suited to dry climates, can enhance energy efficiency while maintaining indoor comfort.

Incorporating green walls or dense vegetation around the building can help reduce thermal gain and create localized cooling effects. Furthermore, adopting traditional design elements like wind catchers or Mashrabiya-inspired facades can improve natural ventilation and airflow, thereby reducing reliance on mechanical cooling systems. These adaptations align with local climatic conditions and resources, ensuring efficient and sustainable building performance.

Relocating the building to Brasília, Brazil, where the tropical climate highlights the growing demand for cooling due to rising temperatures. This shift in energy requirements calls for a deeper understanding of its impact on energy infrastructure and the capacity for renewable energy in such regions. As the need for cooling increases, the building can implement various strategies to manage energy consumption effectively. These include utilizing nighttime ventilation to leverage thermal mass for reducing daytime cooling loads, employing dynamic shading systems to optimize natural light and airflow while minimizing heat gain, or using stone cladding in facades to reduce the cooling load , and incorporating green roofs or vertical gardens to help mitigate urban heat. However, the heightened reliance on cooling systems may put extra pressure on energy infrastructure, which can be limited in some tropical areas. Harnessing renewable energy sources, especially solar power, is essential to address this challenge. Brazil's high solar potential can support photovoltaic systems, thereby reducing dependence on grid electricity. By combining these strategies with renewable energy solutions, the building can maintain comfort while ensuring energy efficiency and sustainability, even as cooling demands continue to rise in tropical climates.

In Juneau, Alaska, current and future scenarios emphasize the necessity for effective heating solutions due to the region's cold climate. To adapt the building after relocation, it will be essential to enhance insulation in the walls, roofs, and windows to reduce heat loss. Installing triple-glazed windows will significantly improve thermal performance by minimizing heat transfer and boosting energy efficiency. The south-facing facade of the building can be optimized for solar heat gain by minimizing shading during the winter months when the sun is lower in the sky. Adjusting the existing shading structure to allow for greater sunlight penetration in winter will maximize passive heating and reduce reliance on mechanical systems. Additionally, using thermal mass materials to store and release heat will enhance indoor comfort and energy efficiency in cold climates.

Furthermore, integrating geothermal heat pumps can utilize the stable ground temperature for efficient and sustainable heating. Improving the building's air-tightness and incorporating advanced thermal storage systems will also aid in retaining heat during colder periods, thereby reducing reliance on active heating systems. These strategies will ensure that the building remains energy-efficient and comfortable in Juneau's challenging climate.

In Warsaw, Poland, the current and future scenarios indicate that while cooling demand is lower than the baseline in Valladolid, heating demand is significantly higher and requires additional measures to optimize energy performance. To address this issue, installing radiant floor heating systems can provide efficient and uniform indoor heating while reducing energy consumption. Incorporating double-skin facades on walls facing colder directions can create an insulating air layer that minimizes heat loss and improves thermal performance. The roof structure can also be adapted to include integrated thermal storage systems, which capture and retain heat from solar gain during the day for use during colder periods.

To optimize the building's envelope for solar heat gain, it is essential to incorporate design features on south-facing walls that capture and utilize solar energy during winter. Adding sunspaces or conservatories can create buffer zones that trap heat, which can then be transferred to indoor spaces. Additionally, using thermal mass materials such as concrete or stone in areas that receive sunlight can help store solar heat during the day and release it at night, thereby reducing heat loss and maintaining stable indoor temperatures. These strategies reduce reliance on active heating systems, enhance passive heating, and improve overall energy efficiency. They are particularly effective in addressing the high heating demands experienced in Warsaw during the winter, ensuring that the building meets nearly Zero Energy Building objectives in Warsaw's climate.

5 Chapter 5: Comparative study between two classroom buildings on the same Campus, one standard and the other nZEB

5.1 Standard Classroom Building of The UVa Campus

5.1.1 Building Description

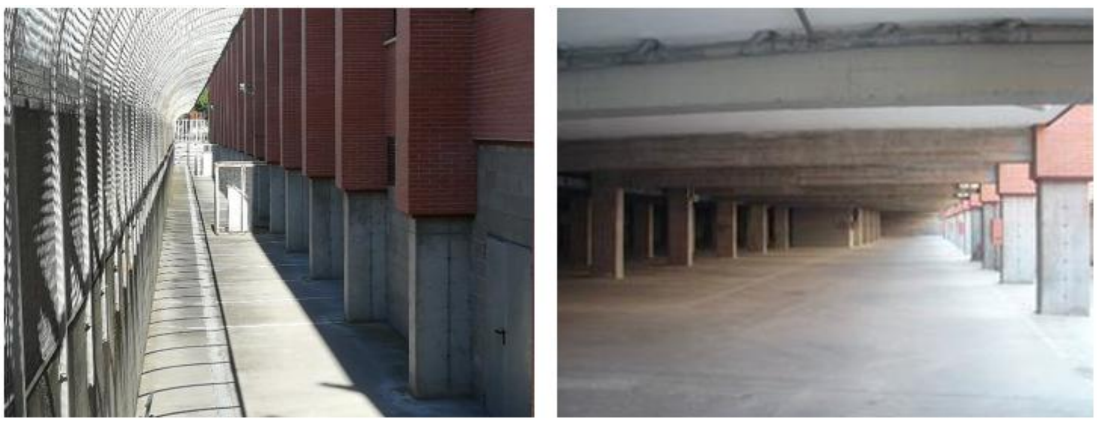
The standard classroom building on the Esgueva campus of the UVa is designed as a classroom building for students at the University of Valladolid (Figure 5.1) [115].

Figure 5.1 Standard Conference Building Location

The rectangular geometry of the building consists of a basement, a ground level, a first floor, and a roof. The basement is used for parking, boiler room housing, and other amenities. The corridor is the same on the ground and first floors, except for the computer and study rooms. Both levels comprise two rectangular wings, each divided by an entrance door. Classrooms and seminars are located in each of these wings, with restrooms at the beginning and end of each. The roof is flat, except for a central roof that runs through the building. Figures 5.2, 5.3, and 5.4 are real images of the standard classroom building.

(a) (b)

Figure 5.2 a) Main façade (south facing) b) Rear façade, with access gallery to the car park



(a) (b)

Figure 5.3 a) Access to the car park b) Visit to the car park (the north to the right of Figure b))

(a) (b)

Figure 5.4 a) Classroom distribution corridor b) Detail of the distribution of luminaires and radiators

As stated above, the building includes a semi-basement and two upper floors. The roof of the first floor is flat, except for the central body, which corresponds to the lobby and has a sloping gabled roof with a height of 3.50 meters. This cover provides access to the cover for maintenance needs (Figure 5.5).

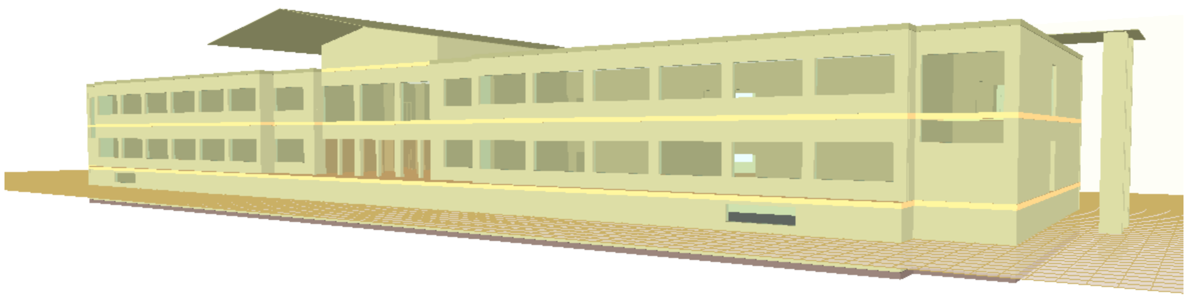


Figure 5.5 Simulated 3D Geometry of the standard conference building

The height of the building is 16 meters, 1.5 meters underground, and 14.5 meters above ground. The lower half corresponds to the basement of the building, which is located 2 meters above ground level and has a total height of 3.5 meters, while the other floors are 4.5 meters high. The classroom building has three floors (Semi-basement Floor, Ground Floor, and First Floor) with an area of 2,786.99 m^2, 2,304.55 m^2, and 2,304.55 m^2, respectively. The semi-basement has 2,786.99 m^2, with 2,585.26 m^2 dedicated to parking with 82 spaces. The remaining 201.73 m^2 is used for the meeting room. Equipment includes boilers, generators, elevators, and building access (Figure 5.6).

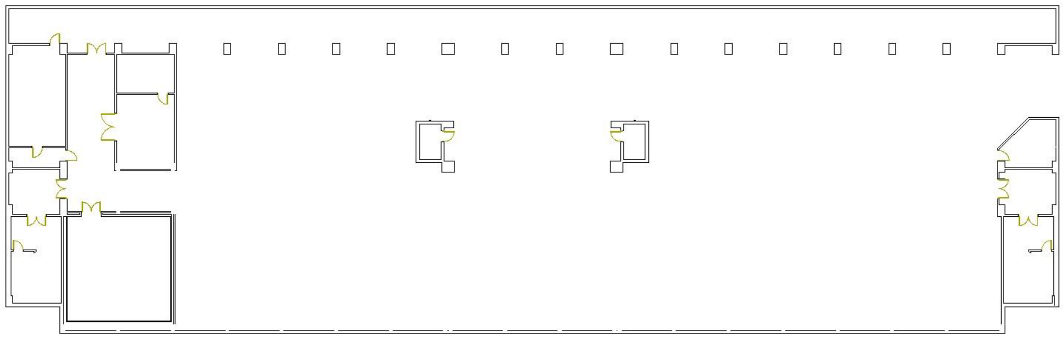


Figure 5.6 Semi-basement distribution

The ground floor has an area of 2,304.55 m^2. The structure is organized into two symmetrical wings with rectangular rooms separated by a corridor and a central staircase. Each wing has a seminary, classrooms, a garage, access to the first floor, bathrooms, and a corridor (Figure 5.7). This floor also houses the center's secretary and an office near the elevators.

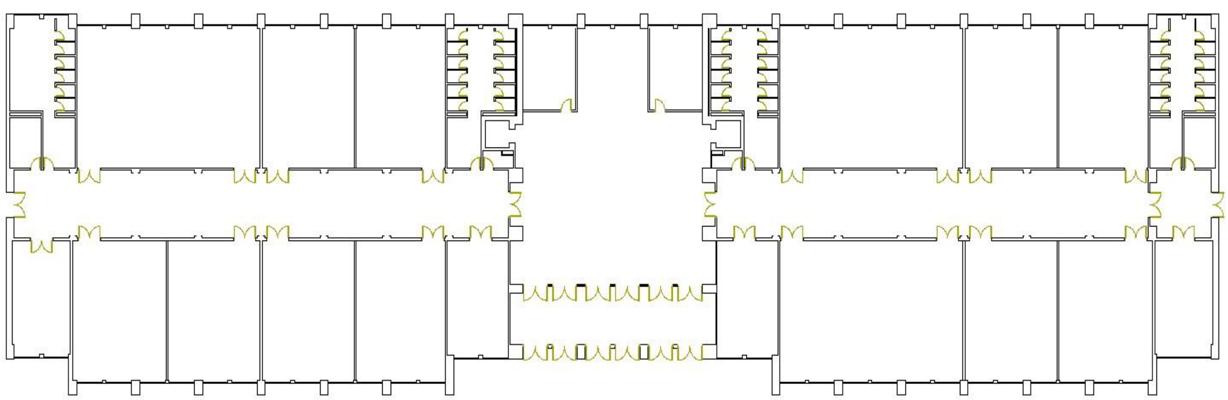


Figure 5.7 Ground floor layout

The first floor measures 2,304.55 m^2 and is identical to the geometry of the ground floor. This floor has a large study area and a computer room, distinguishing it from the other floor (Figure 5.8). The total conditioned area is 4268.93 m^2.

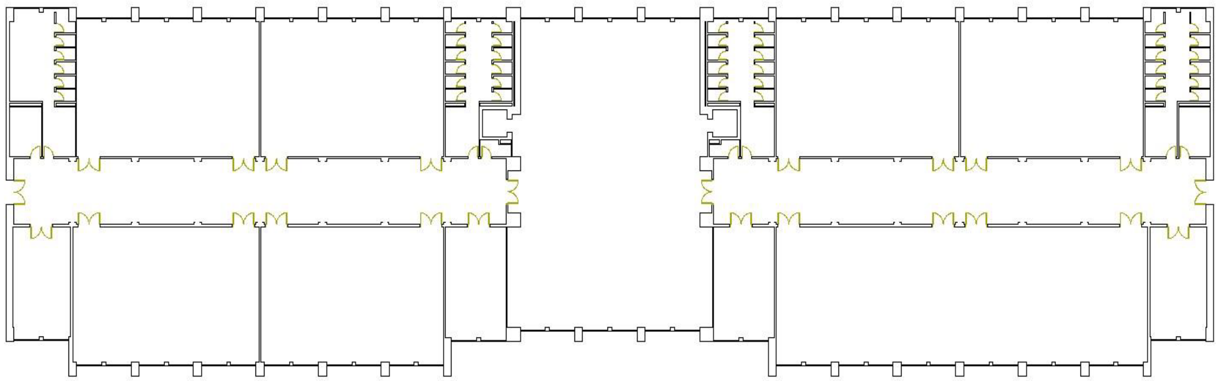


Figure 5.8 The layout of the first floor

5.1.2 Construction Information

The building materials are essential to achieve optimal energy efficiency and establish a robust thermal envelope. Each element of the building's construction, from the exterior walls to the roof, is chosen with a low heat transfer coefficient U, complying with the Spanish regulations 1984.

The exterior walls include two hollow bricks, a bituminous sheet, and a specialized insulating layer, which improves thermal insulation and reduces energy loss. The walls have an unventilated air chamber that improves insulation capacity, which is especially advantageous for regulating the interior temperature and minimizing heat transfer.

The interior partitions consist of a simpler construction made of plaster and double hollow brick layers, making it easier to control the temperature between the interior sections. The roof consists of several materials: polyurethane foam for improved insulation and stainless steel for structural strength. This configuration reduces heat transfer, providing energy savings by improving thermal retention. In addition, the building's windows use double glazing to achieve low U-values and facilitate natural lighting, reinforcing the structure's overall energy efficiency. The red lacquered metal frames enhance durability and integrate aesthetically with the building's façade.

Doors are classified as exterior or interior types, each constructed with materials adapted to their intended use. Exterior doors have metal frames and glass to provide insulation and allow light transmission. Wooden interior doors enhance interior style while satisfying utilitarian needs. In addition, the vents are constructed of red lacquered metal, which ensures a uniform aesthetic for the structure. Selections, including wall compositions and door materials, correspond to energy efficiency requirements, ensuring compliance with designated thermal performance parameters.

5.1.3 Building Facilities

The building includes multiple facilities that ensure comfort and operational efficiency, such as heating, air conditioning, and artificial lighting systems. The heating system uses a network of water radiators distributed in 3 circuits: a north circuit, a south circuit, and a corridor area circuit. It is connected to two different power diesel boilers, each with an efficiency of 0.9 and using diesel. Each boiler operates different circuits within the building, distributing heat through aluminum radiators. These radiators provide uniform heating in various areas and are electronically regulated to optimize heat distribution, which is particularly important during the colder seasons, Figure 5.9.

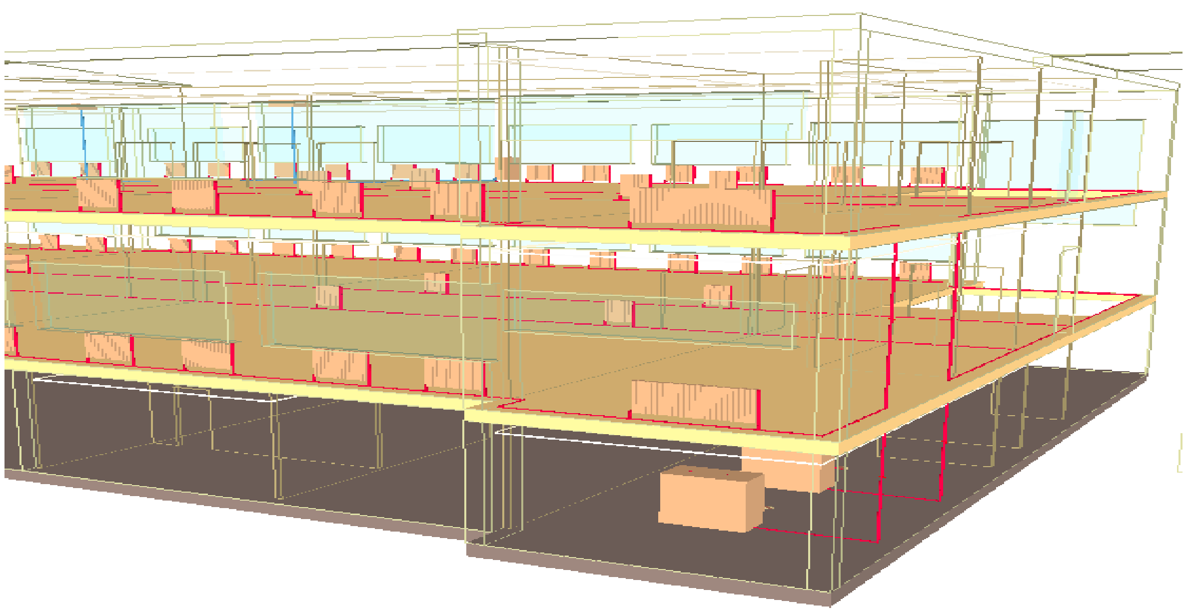


Figure 5.9 Standard classroom building heating system

Air conditioning is provided by direct expansion systems, specifically split systems, consisting of outdoor and indoor units. These units only supply air conditioning to a portion of the building, such as classrooms 21, 22, and 24, and to the study room on the first floor, which is located to provide cooling and dehumidification, particularly in high-occupancy areas. The building does not have a mechanical ventilation system, and therefore, the natural ventilation openings improve air circulation, especially in the warm months, reducing dependence on mechanical cooling systems. The building uses traditional fluorescent luminaires with high energy consumption throughout classrooms and corridors, providing a uniform light distribution suitable for educational environments. The luminaires are positioned according to calculations to ensure optimal visibility and compatibility with energy consumption. Together with natural light sources, the lighting system meets visual comfort standards.

5.2 Comparison of Energy Consumption Between the INDUVA Classroom Buildings (nZEB) and the Campus Standard Building

This section offers a comparative analysis of the energy performance between two classroom buildings with the same climate and close to each other on the same Campus, the INDUVA Nearly Zero Energy Building (nZEB) and a standard building, evaluated in two different scenarios designed to show different characteristics of use and energy efficiency.

However, neither building is equal in size, capacity, number of students, materials, spatial configuration, orientation, HVAC systems, or lighting. The study is of interest to characterize the energy behavior, normalized in final and primary energy indicators kWh/m^2, between two buildings of the same typology (classrooms of a Campus) and the same climatology to analyze the energy and environmental differences between a standard building and a very efficient one nZEB.

In the first scenario, the nZEB and the standard building are analyzed considering that the heating system uses fossil fuel, an actual situation from construction to 2014. This involves thoroughly examining heating energy consumption, electricity use for air conditioning, and lighting consumption. The analysis focuses on the essential differences in energy efficiency between the two buildings. The nZEB for the heating system uses a renewable DH district network with biomass, which is more efficient and has a reduced carbon footprint. In contrast, the standard building heating system uses diesel fuel, which results in higher greenhouse gas emissions [116]

The electricity consumption of the standard building is only from a Split machine that supplies air conditioning to a small part of the building and from the hydraulic pumps that move the heating water, while in the nZEB building, the electricity consumption is divided into the operation of the air conditioning machines for the whole building, the rotary heat recovery motor for the entire building, the ventilation system fans to the whole building for an improvement of the IAQ and the hot water pumps.

The lighting energy consumption in the standard building is that of electromagnetic ballasts, while in the nZEB building, it is high-efficiency LED equipment.

By comparing the data from these two buildings, we gain valuable insights into the design and fuel sources affecting overall energy performance.

The second scenario introduces a crucial modification in the standard building: the replacement of diesel in 2014 with renewable DH heating with biomass as an energy source. This change allows for a more focused comparison in terms of primary energy consumption and CO_2 emissions. By examining energy use patterns and environmental impacts, we can better understand how the change in fuel type influences the building's energy efficiency and overall environmental footprint.

The two scenarios comprehensively evaluate the building's energy demand improvement, achieving more significant energy savings and better thermal comfort. The effectiveness of integrating renewable energy solutions. The introduction of a mechanical ventilation system to achieve good IAQ and therefore guarantee the health of the building's occupants, as well as the improvement of the lighting system with the choice of LED equipment. They highlight the substantial potential benefits of transitioning from conventional energy sources to more sustainable alternatives to achieve further decarbonization, thus advancing the goal of reducing energy consumption and minimizing environmental impacts in the building sector. All the data for the standard building was validated with real data [115], [116].

5.2.1 SCENARIO 1: Comparative Analysis of Energy Consumption Between INDUVA and Standard Building

The graph in Figure 5.10 provides a complete comparison of monthly final heating consumption measured in (kWh/m²) between two types of buildings: a standard building that relies on diesel fuel and a nearly zero-energy (nZEB) building that uses biomass fuel from a DH.

The data reveals a clear trend where the nZEB consistently shows significantly lower energy consumption than the standard building over most of the months analyzed. This trend highlights nZEB's superior energy efficiency, making it an effective alternative to traditional energy sources. The difference in heat consumption is particularly pronounced during the peak winter months of January, February, and December, when the energy demand for the standard building is significantly higher than that of the nZEB. In fact, during these colder months, the heat consumption of the standard building exceeds that of the nZEB building by a high margin.

The notable reduction in energy consumption within the nZEB can be attributed primarily to using renewable biomass. This approach aligns with the core goals of nZEBs, which aim to reduce reliance on fossil fuels and minimize carbon emissions. By employing sustainable biomass as a heating source, nZEB decreases energy consumption and carbon footprint, contributing to a broader effort to promote environmentally friendly practices in construction operations.

Furthermore, these findings exemplify the potential of integrating DH with biomass as a viable solution to improve the energy efficiency of buildings. These systems are critical to the shift towards sustainable practices, demonstrating how innovative approaches to energy consumption in the building sector can significantly reduce total energy demand while also supporting the transition to a more sustainable future.

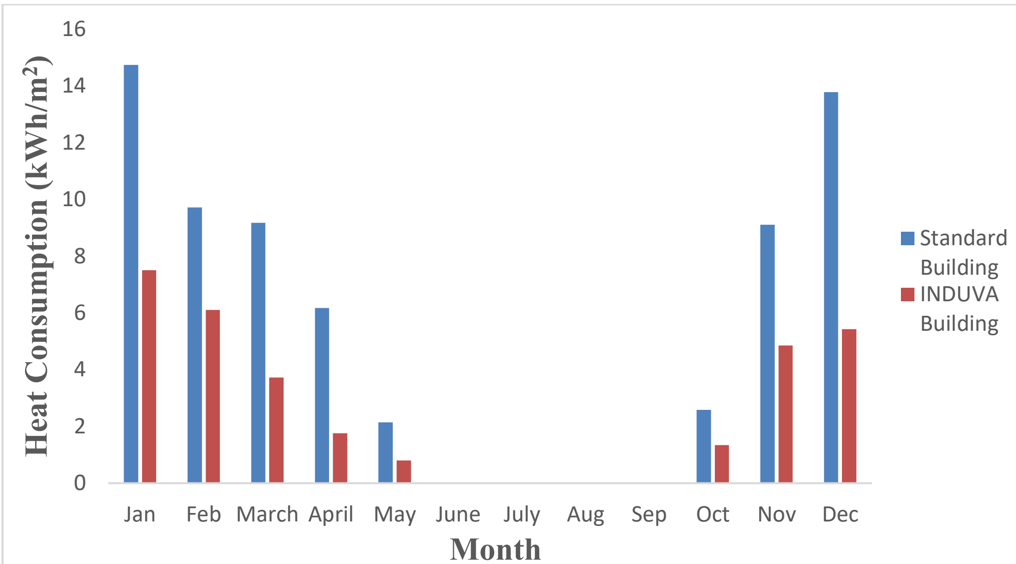


Figure 5.10 Comparison of heating consumption between the standard building and the INDUVA building

Figure 5.11 compares the monthly final electricity consumption for cooling, expressed in kWh/m², between a standard Campus classroom building and the nZEB. During the summer months, especially in June, the INDUVA building has a noticeably higher demand for air conditioning, reaching around 1 kWh/m². This increase in energy consumption can be attributed to the larger conditioned area of the INDUVA building, which is 5,245 m², compared to the standard building's area of 4,268.93 m². In addition, the air conditioning in the nZEB is designed to service the entire building, while in the standard building, it only powered a few classrooms.

In contrast, both buildings show minimal demand for air conditioning during the colder months, from November to April. However, the standard building experiences occasional cooling needs, even in winter. This is due to the high internal thermal loads generated in the study and assembly classrooms, which reach a high occupancy of students at certain times of the day together with a cooling set point of 24 °C. Such a set point can result in fluctuating cooling demands at various times, influenced by occupancy patterns, appliance operation, and other internal heat sources contributing to the overall heat load.

The trends illustrated in the graph highlight the significant impact of several factors, in particular building size, seasonal variations, and thermal comfort set points, on the air-conditioning cooling energy needs of different types of buildings. This analysis emphasizes the importance of understanding these elements to improve energy efficiency in both building design and operational practices.

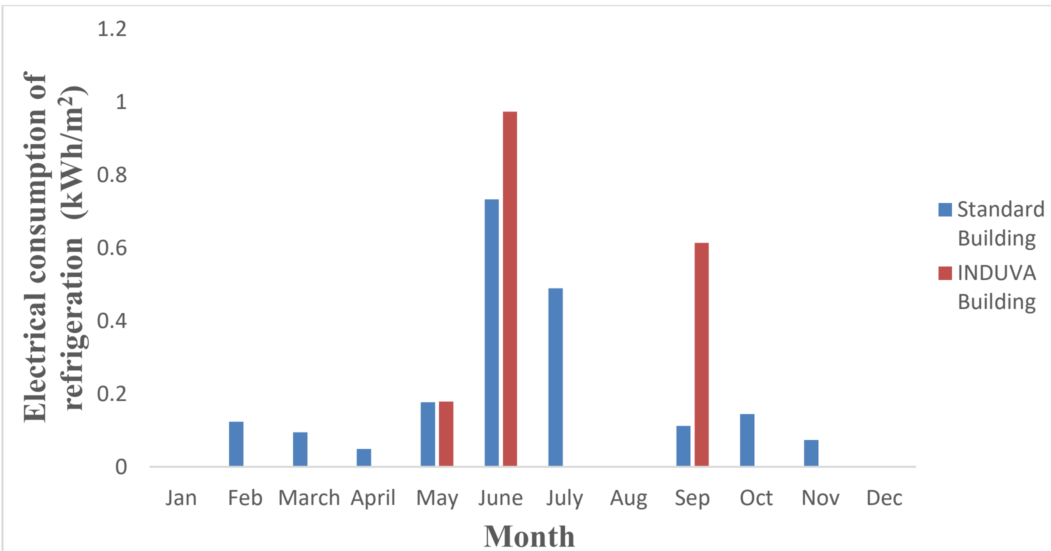


Figure 5.11 Comparison of cooling electricity consumption between the Standard building and the INDUVA building

The graph in Figure 5.12 provides a comparison of the monthly final lighting energy consumption (kWh/m^2) between the standard building and the nZEB over a year. The data indicates that the INDUVA building consistently achieves significantly lower lighting energy consumption than the standard building.

This lower energy consumption can be attributed to the innovative architectural design of the INDUVA building, which effectively maximizes natural light while minimizing reliance on artificial lighting. The classrooms in the INDUVA building are carefully oriented to make the most of the northeast- and southwest-facing windows, allowing generous amounts of natural light to infiltrate the interior spaces. To enhance this natural lighting further, horizontal parasols are strategically placed to reflect external sunlight onto the roofs. Not only does this design feature help distribute light more evenly throughout the room, but it also reduces the need for artificial lighting during daylight hours.

In addition, the building incorporates fully glazed staircases and corridors, which play a crucial role in facilitating the entry of light. The integration of the Parans system is another critical aspect of INDUVA's design; This system uses optical fibers to channel natural light into areas that receive minimal daylight. Together with a DALI control system, these features enable substantial energy savings in lighting, with reductions of up to 75% in energy use.

In addition, all the luminaires in the nZEB are of the highly energy-efficient LED type, while in the standard building, they are electromagnetic ballasts that are less energy-efficient and achieve higher energy consumption.

The standard building lighting system operates on a fixed schedule and does not respond to occupancy levels, leading to inefficiencies. For example, the hallways remain illuminated even when unoccupied, significantly increasing energy consumption. This fundamental design difference between the two buildings underscores the considerable efficiency advantages of the lighting strategy employed in the INDUVA building. By harnessing natural light and using smart technologies, the INDUVA building reduces energy costs and promotes a more sustainable approach to building design.

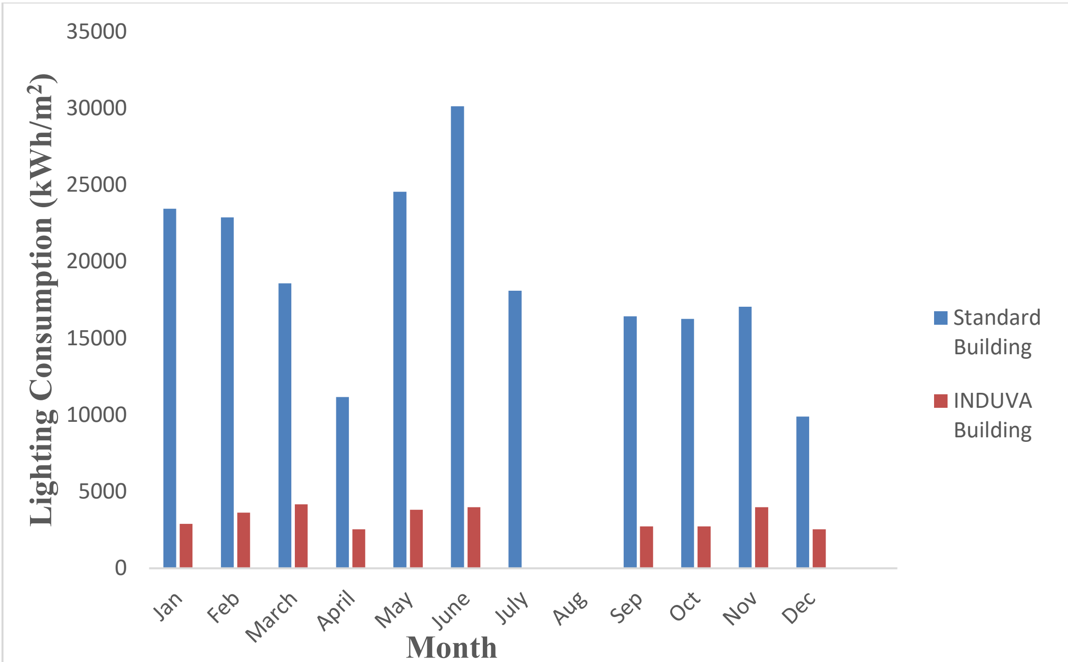


Figure 5.12 Comparison of light consumption between the Standard building and the INDUVA building

5.2.2 SCENARIO 2: Comparative Analysis Between The nZEB and The Standard Building Heated by a Biomass DH

In this case, a refurbishment of the standard building in 2014 by replacing diesel fuel with biomass for the heating system allows us to compare primary energy consumption and CO_2 emissions more closely. By examining energy use patterns and associated environmental impacts, we can better understand that switching from a fossil fuel to a renewable one significantly influences the building's energy efficiency and environmental footprint.

The graph shown in Figure 5.13 compares the primary energy consumption patterns of a standard building versus INDUVA nZEB for one year.

In this new scenario, the standard building heating system uses biomass-powered DH. In addition, we have main electrical power consumption for the split refrigeration machines that supply the air conditioning in a single part of the building and support the electric motors of the water pumps and lighting.

In contrast, in the INDUVA nZEB building, in addition to the heating and air conditioning system, we have mechanical ventilation that works all year round, feeding a variable flow to the entire building. At the same time, this design leads to increased energy use during the summer months, when cooling demands are at their peak. The efficient systems within the INDUVA building are designed to optimize energy utilization, allowing it to effectively handle periods of high energy demand in winter.

It should be noted that, for most of the year, the INDUVA building consumes less energy than the standard building. This comparison underscores the substantial advantages of nZEB strategies, which focus on minimizing primary energy demand by integrating sustainable technologies and efficient building practices.

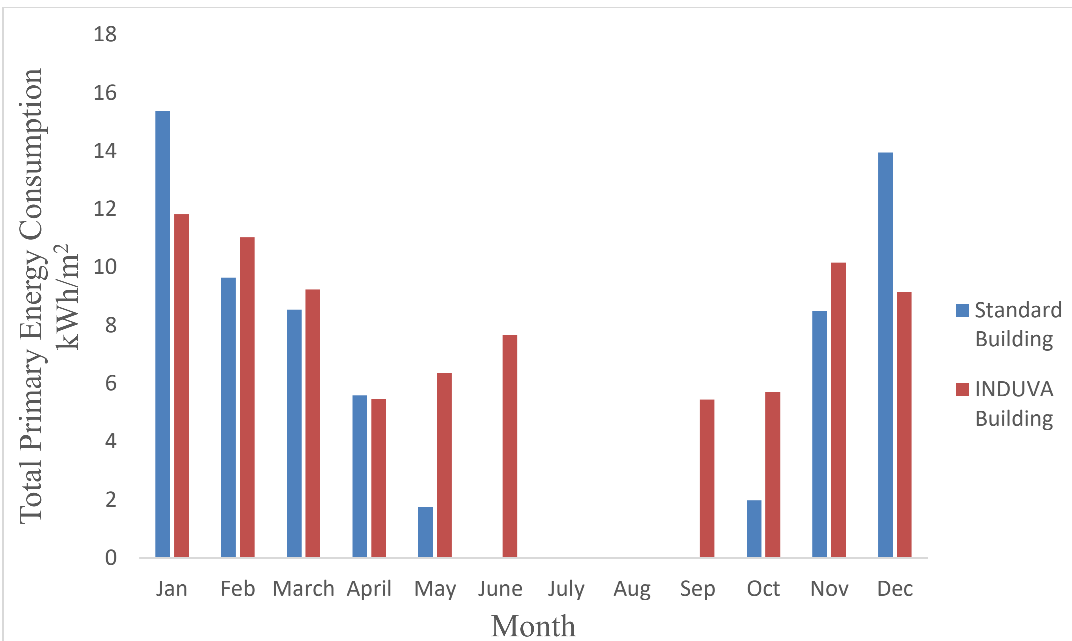


Figure 5.13 Comparison of total primary energy between the Standard building and the INDUVA building

The analysis of CO_2 emissions between INDUVA and the Standard Building, as presented in Figure 5.14, reveals apparent differences in their emission profiles, mainly shaped by their architectural design and operating methods. For this comparison, both buildings exclude emissions from lighting systems, which typically account for a significant portion of a building's total emissions.

Despite these exclusions, INDUVA continues to show consistently higher CO_2 emissions than the Standard Building in most months of the year. This increase in the level of emissions can be attributed mainly to INDUVA's dependence on mechanical ventilation systems and the consumption of air conditioning throughout the building. The ventilation system is critical to maintaining indoor air quality IAQ and comfort, but they require a substantial amount of energy to operate; despite the energy savings through heat recovery systems such as the rotary recuperator and the geothermal air system installed in the building, we have to consider that DCV mechanical ventilation, controlled by sensors, it is operating as long as the building is open, which causes a corresponding increase in CO_2 emissions.

The data indicates that INDUVA emissions peaks occur during peak energy consumption periods, particularly in summer and September. These spikes are driven by increased operational demands for mechanical ventilation, fans circulating air, and refrigeration machines for air conditioning. This scenario contrasts sharply with the standard building, which uses natural ventilation without energy consumption. As a result, the standard building shows significantly lower CO_2 emissions throughout the year. However, when comparing it to the nZEB, we must consider the absence of systems such as air conditioning throughout the building and the DCV mechanical ventilation system. This means a reduced IAQ and thermal comfort that would be unfeasible under the new EPBD Directive 2024 in new and refurbished buildings [92].

In addition, the standard building has made great strides in reducing its carbon footprint by replacing the use of diesel fuel with renewable ones such as biomass through DH for its heating system. This change has contributed to decarbonization, minimizing the building's overall emissions profile.

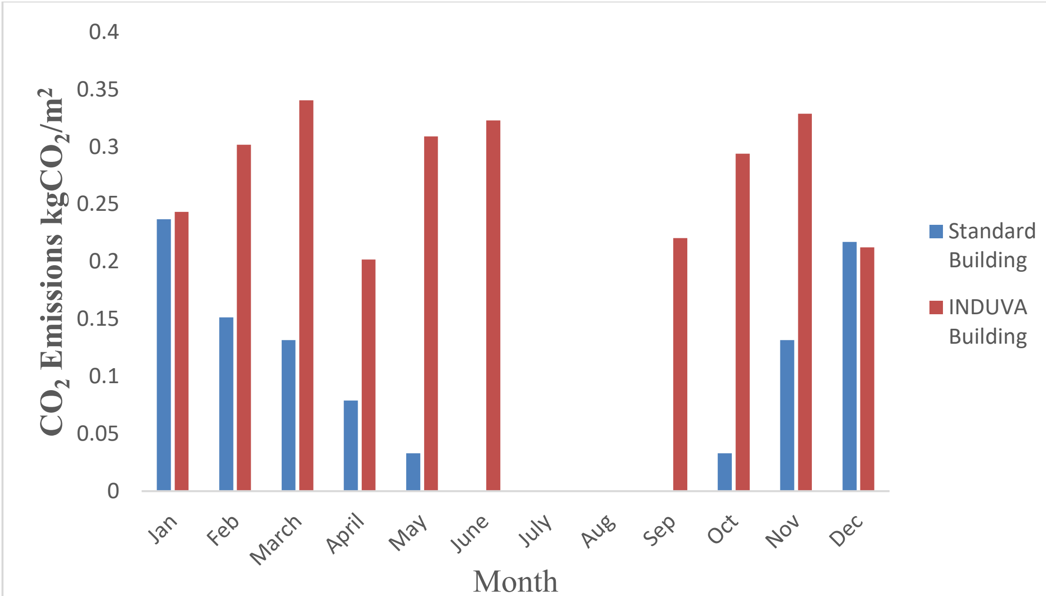


Figure 5.14 Comparison of CO_2 emissions between the Standard building and the INDUVA building

A comprehensive overview of the comparative results between the INDUVA nZEB and the Standard building is shown in Table 5-1. These results demonstrate enhancements in energy efficiency, pollution reduction, and indoor air quality attained with nZEB design.

Table 5-1: Key Performance Indicators: INDUVA vs. Standard Building

	Standard Building	**INDUVA**
Heat Consumption ($kWh/m^2.yr$)	67.4	31.5
Electrical consumption of Refrigeration ($kWh/m^2.yr$)	1.997	1.76
Lighting Consumption ($kWh/m^2.yr$)	208,487	33,016
Total Primary Energy Consumption ($kWh/m^2.yr$)	65.2	81.9
CO_2 Emissions $kgCO_2/m^2.yr$	1.013	2.77

In summary, while the advanced systems employed at INDUVA are designed to optimize the quality of the indoor environment and the comfort of its occupants, the high energy demands associated with these systems ultimately translate into higher levels of CO_2 emissions compared to the standard building that uses a renewable energy resource for its heating. This comparison underscores the premise that implementing the principles of nearly zero-energy buildings can lead to significant energy savings and a lower carbon footprint, even when mechanical systems are part of the design.

Retrofitting standard buildings to comply with nZEB standards necessitates a detailed strategy that integrates energy efficiency, renewable energy, and occupant engagement. Essential phases encompass evaluating the building's existing performance, enhancing the envelope through insulation, airtight windows, high-performance glass, and shading and renovating HVAC systems with efficient heat pumps , sensors and smart controls. Integrating renewable energy sources, such as PV, with energy-efficient lights and appliances, further decreases energy consumption. Continuous monitoring, post-retrofit commissioning, and occupant education guarantee that the facility operates as designed.

The results highlight the importance of considering energy efficiency and environmental impact when designing new or refurbished buildings.

6 Chapter 6: Health and Indoor Environmental Quality (IEQ)

6.1 Introduction

This chapter aims to optimize Indoor Environment Quality (IEQ) and reduce energy demand by examining the ventilation systems in various School of Industrial Engineering classrooms. It focuses on defining requirements, defining parameters, describing the methodology for evaluating each parameter, and defining experimental data collection parameters. The study proposes a methodology for collecting data on the main parameters affecting indoor environmental quality, conducting the data collection process on selected classrooms, analyzing results, and making recommendations based on the findings. The findings will help identify shortcomings in each classroom and help improve ventilation systems in the future.

6.2 Indoor Environmental Quality Assessment

Buildings' Indoor Environmental Quality (IEQ) is evaluated following the approach outlined in the UNE 171330-1 standard for Indoor Environmental Quality [117], [118]

Part 1: Evaluation of the indoor environment. Essential characteristics that must be managed to determine Indoor Air Quality (IAQ) include:

A) Temperature and relative humidity.

B) Carbon dioxide: determination of the ventilation rate.

C) Carbon monoxide.

D) Particulate matter ($PM_{2.5}$)

E) Particle counting.

And other Additional parameters:

F) Ambient lighting.

G) Environmental noise.

H) Electromagnetic field.

I) Electric field.

J) Static electricity.

K) Formaldehyde (HCHO).

L) Ozone.

M) Total volatile organic compounds (TVOC).

N) Suspended fibers (asbestos, glass fibers, etc.)

O) Thermal comfort analysis.

The methods of analysis and assessment criteria of the standard mentioned above are set out in Annex 1 [119] [105], [120], [121], [122],[123][124][125][126],[127][128], [129][129],[130],[131][132],[133]

6.3 Assessment Criteria for This Study

6.3.1 Ventilation

6.3.1.1 Ventilation According to RITE

Ventilation, according to RITE in IT 1.1.4.2.3, proposes five methods to achieve the indoor air category [105]:

A) Indirect method of outdoor airflow per person

When people have an average metabolic activity of 1.2 met, when pollution from sources other than humans is minimal, and when smoking is prohibited, the numbers in Annex 2 should be applied. Into Spanish buildings now is forbidden.

B) Direct method by perceived air quality

In this method, based on the UNE-CR 1752 IN:2008 report (olfactory method), the values to be used are those in Annex 2 [134].

C) Direct method by CO_2 concentration

The CO_2 concentration method, a reliable indication for human bioeffluent emissions, can be utilized in locations with high metabolic activity (party halls, sports, physical activity venues, etc.) where smoking is prohibited. Annex 2 provides the values.
The information in Annex 2 can be utilized for locations with high pollutant production (such as swimming pools, restaurants, cafés, bars, some types of businesses, etc.), but if the composition and flow rate of the pollutants is known, the dilution approach, which equates to the analytical method, is advised.

D) Indirect method of air flow per unit area

For spaces not devoted to permanent human occupation, the values in Annex 2 shall apply.

E) Method of dilution

The dilution method must be utilized in rooms where known emissions of harmful elements are present. This is consistent with an analytical approach that relies on a mass balance of the investigated premises. The concentration for each pollutant must be lower than the level established by the health authority while considering the concentration in the SUP supply air and the emissions from the exact location.

6.3.1.2 Ventilation According to the UNE-EN 16798-1:2020 Standard

The result is an expression that is a function of the generation of pollutants, the external and internal concentration of the pollutant under study, and the efficiency of the diffusion system, taking into account that secondary air, recirculated air, and the filter efficiency are disregarded in the standards and the various regulations:

$$q_{ODA} = \frac{1}{\varepsilon_V} X \frac{N}{(C_{INT} - C_{EXT})} \qquad (6.1)$$

Where:
q_{ODA}: Outside Air Flow Rate

N: Number of Persons

ε_V: Ventilation Efficiency

C_{INT}: Internal Concentration

C_{EXT}: External concentration

The minimum total air flow rate per person must never be less than 4 L/s because calculating the outdoor air flow rate analytically necessitates knowledge of numerous parameters, many of which change over time. The determination of the outdoor air ventilation air flow rate has been calculated, and the regulations provide reference values for various cases where perfect ventilation efficiency is assumed ($\varepsilon_V = 1$).

The UNE-EN 16798-1:2020 standard proposes three ways to calculate the ventilation rate for non-residential buildings[135].

- Method 1: method based on perceived air quality.
- Method 2: method using the concentration limit values of substances.
- Method 3: method based on predefined ventilation flow rates.

6.3.1.3 Method Based on Perceived Air Quality UNE-EN 16798-1:2020

For various categories associated with the percentage of dissatisfaction, the approach suggests a ventilation rate to remove bioeffluent emissions from building occupants and a ventilation rate to remove emissions from the building. The two terms are added to get the overall air flow rate, and the values suggested by the standard are shown in Annex 3. Design ventilation rates for dilution of emissions from different types of buildings are presented in Annex 4 [135].

Design ventilation rates for sedentary people, adults, and people not adapted for the dilution of emissions (bio effluent) of people in different categories.

6.3.1.4 Method Using Substance Concentration Limit Values UNE-EN 16798-1:2020

The abbreviated phrase established above is utilized for any substance released in the study area, regardless of whether any additional contaminants are present. The National Institute for Safety and Health at Work (INSHT) published the occupational exposure limits for chemical agents in Spain 2021. To find these values, one needs to know the concentration of the above pollutant in the outside air and then use this expression [135].

$$q_{ODA} = \frac{N}{(C_{INT} - C_{EXT})} \qquad \textbf{(6.2)}$$

The rule specifies the CO_2 concentration limitations as a sign of human habitation, and it is reasonable to presume that these limits correspond to an average outdoor CO_2 concentration of between 420 and 450 ppm. The CO_2 exposure limit values determined by this regulation are shown in Annex 5.

Default design CO_2 concentrations above the outdoor concentration, assuming a standard CO_2 emission of 20 l/h per person.

6.3.1.5 Method Based on Predefined Ventilation Flow Rates UNE-EN 16798-1:2020

The data listed in Annex 6 are for an office with an occupancy of one person per 10 square meters. Two techniques are considered, one for occupancy and one for surface area, and the one that results in the highest ventilation flow rate is used. This method is based on perceived air quality[135].

Additionally, it suggests ventilation airflow rates for times when no one is around:

The ventilation system is turned off, and by default, 1 volume of the vented space must be supplied every two hours of minimal airflow before occupancy. In all rooms, the total airflow for dilution of building emissions should be 0.15 $l/s.m^2$ of floor area, even if ventilation is lowered during unoccupied times.

6.3.2 Assessment of Ventilation in This Work

The indirect method of outdoor airflow per person and air flow per unit area of RITE for occupied classrooms and UNE-EN 16798 for unoccupied classrooms are applied.

A building with indoor air quality IDA 2 (good air quality) has been considered, considering two scenarios:

- No occupancy: by default, the minimum air flow rate to be supplied before occupancy is 1 volume of the ventilated zone every 2 hours.
- With occupancy: 12.5 l/(s-person)

6.3.3 Thermal Comfort

6.3.3.1 Regulation on Thermal Installations in Buildings (RITE)

Operating temperature and relative humidity conditions according to RITE in IT 1.1.4.1.2 [105].

Based on the metabolic activity of the people, their level of clothing, and the estimated percentage of dissatisfaction (PPD), the indoor design parameters of operational temperature and relative humidity shall be determined as follows:

(a) The values of the operating temperature and relative humidity, assuming a low air velocity level (0,1 m/s), for persons with a sedentary metabolic activity of 1,2 met, with a clothing level of 0,5 Clo in summer and 1 Clo in winter, and a PPD (Percentage of Dissatisfied Persons) of less than 10%, shall be within the limits given in Annex 7.

For the sizing of heating systems, a design temperature of 21 °C shall be used for indoor conditions. For cooling systems, the design temperature shall be 25 °C.

(b) For values other than metabolic activity, degree of clothing, air velocity, and PPD in the preceding section, the standard UNE-EN ISO 7730 method can be used to calculate the operating temperature and relative humidity.

6.3.3.2 UNE-EN-ISO 7730 (2006) Ergonomics of The Thermal Environment

This standard makes it possible to determine the Predicted Mean Vote (PMV) and the Percentage of People in Discomfort PPD [136]. Based on six variables:

- Met: Metabolic level.
- Clo: Clothing index.
- T_a: Air temperature.
- P_V: A partial vapor pressure of air.

- V_a: Air speed.
- T_r: Mean radiant temperature

6.3.4 Thermal Comfort Assessment of This Work

The Mean Vote (PMV) and the Percentage of People in Discomfort (PPD) will be calculated using the TESTO Comsoft 3 Software. Following the ventilation criterion, 20% of people experiencing discomfort are considered unfavorable when the (PPD) value is > 20%.

6.3.5 Indoor Air Quality

The following two regulations are under consideration:

- WHO Global Air Quality Guidelines, Particulate Matter ($PM_{2,5}$ and PM_{10}), Ozone, Nitrogen Dioxide, Sulphur Dioxide and Carbon Monoxide, Executive Summary 2021[137]. ISBN 978-92-4-003546-1 (electronic version).
- Royal Decree 102/2011, of 28 January, on improving air quality. Annex 8 compares the limit values for some pollutants in both regulations [128], [132].

6.3.6 Indoor Air Quality Assessment of This Work

A) Particles

The UNE- EN-ISO 14664-1 Cleanroom and Annexed buildings, Part 1 classification of air cleanliness, is used to assess the presence of particles in the classrooms. Annex 9 lists the various rooms' categories based on the total particle count. Classrooms in this project have been configured to ISO class 9 [129].

B) Carbon dioxide (CO_2)

The limit value is established by EN 15251:2007: Indoor environment parameters to be considered for the design and assessment of the energy performance of buildings, including indoor air quality, thermal conditions, lighting, and noise [138]. Annex 10 lists the values for this standard.

In this case, category II has been taken so that, considering an outdoor concentration of 450 ppm, the permitted limit would be:

$$(CO_2) < 950 \text{ ppm.}$$

C) Other gases

The following two laws control gas concentration:

- The Royal Decree 102/2011, of January 28, addresses air quality improvement [128].
- National Institute of Safety and Health at Work (INSHT), Professional Exposure Limit Chemical Agents in Spain 2022, Ministry of Labour and Social Economy.

D) Carbon monoxide (CO)

For this case, the INSHT Daily Exposure Limit Value for carbon monoxide is taken as the Daily Exposure Limit Value for carbon monoxide:

$$(CO) < 20 \text{ ppm}$$

E) Formaldehyde (HCHO)

For this case, the INSHT Daily Exposure Limit Value for formaldehyde is taken:

$$(HCHO) < 3 \text{ ppm}$$

F) Nitrogen dioxide (NO_2)

The hourly limit value for the protection of human health (lower assessment threshold) for nitrogen dioxide of RD 102/2011 is taken for this case:

$$(NO_2) < 100 \text{ µg/m}^2 \text{ (50 ppm)}$$

G) Ozone (O_3)

For this case, the INSHT ozone Daily Exposure Limit Value is taken:

$$(O_3) < 0{,}1 \text{ ppm}$$

H) Volatile Organic Compounds (VOCs)

Since many different volatile organic compounds can have negative health effects at low concentrations, it is challenging to determine the concentration limit for VOCs. In the study Indoor air quality: volatile organic compounds, smells, and comfort, INSHT established a value for Total Volatile Organic Compounds (TVOC), which indicate sensory characteristics (odor) created by the presence of people in the room.

$$(VOC) < 200\ \mu g/m^3\ (280\ ppb)$$

6.3.7 Lighting Comfort

The following standards for indoor lighting enable evaluation of its quality:

- CTE-DB-HE3, Conditions for lighting installations [133].
- UNE 12464-1: Artificial lighting in indoor environments [139].
- UNE 17037: Natural light in buildings [140].
- UNE 15193: Energy efficiency of lighting installations [141].
- EN 15251:2007, Indoor environment parameters are to be considered for the design and assessment of the energy performance of buildings, including indoor air quality, thermal conditions, lighting, and noise [138].

6.3.8 Assessment of The Lighting in This Work

The values of EN 15251:2007, Indoor environmental parameters to be considered for the design and assessment of energy performance of buildings, including indoor air quality, thermal conditions, lighting, and noise, are used as the standard's reference values [138]. Annex 11 lists the values for this standard.

Where reference is made to:
E_m: Mean surface illuminance in lux.
UGR: (Unified Glare Rating)
R_a: Uncorrected UGR value.
In this case, measurements of E (lux) are taken on the student's desks and are considered compliant when E (lux) is measured:

E > 300 lux.

6.3.9 Acoustics

Several standards in the field of acoustics deal with emissions, insulation, and allowable limitations. Among these, we will mention CTE-DB-HR and Protection against Noise. Royal Decree 1371/2007, of 19 October (BOE 23/10/2007), approved the articles of this Basic Document. Subsequently, the following provisions were added [142][143][144][130][145][146][147]:

- Correction of errors in Royal Decree 1371/2007, of 19 October (BOE 20/12/2007).
- The 17 October 2008 royal decree amending the 18 October 2008 BOE royal decree 1371/2007.
- The order VIV/984/2009, dated April 15 (BOE, April 23, 2009).
- Correction of typographical and factual mistakes in Order VIV/984/2009 of April 15 (BOE September 23, 2009).
- Royal Decree 732/2019 of December 20, 2019 (BOE December 27, 2019).
- The Royal Decree 1367/2007 of October 19, 2007, which implements Law 37/2003 of November 17, 2003, on Noise in terms of acoustic zoning, quality goals, and acoustic emissions.

6.3.10 Assessment of The Acoustic Quality of This Work

The limit values for indoor areas are obtained from RD 1367/2007 [148], Annex II "Noise Quality Objectives for Noise Applicable to Habitable Indoor Space of Buildings Intended for Housing, Residential, Hospital, Educational or Cultural Use," Annex 12.

The permissible noise indices are considered to be compliant:

L < 40 dB(A)

6.4 EQUIPMENT

6.4.1 Particle Counter

The HANDHELD 3016 particle counter, Figure 6.1, includes six channels for particle sizes ranging from 0.3 microns to 10 microns, and it operates at a flow rate of 0.1 CFM (2.83 l/min). A laser diode light source powers the device. The laser diode's light is scattered by particles. An optical particle collection device then focuses the light onto a photodiode, which turns the light burst into electrical pulses. The pulse height determines the particle size. The results of the pulse counting are shown as particle counts in the designated size channel. Annex 13 displays the equipment's technical specifications.

Figure 6.1 The LIGHTHOUSE particle counter, model Handheld 3016

6.4.2 Indoor Air Quality

A GrayWolf device model, DirectSense II, Figure 6.2, measures indoor air quality. It has an Android smartphone that serves as both a screen and a recorder of data from eight intelligent sensors that are all connected to the same probe to measure things like ambient T and RH, total volatile organic compounds (TVOC) (PID sensor), and CO_2 (NDIR sensor). Additionally, it has electrochemical sensors to monitor formaldehyde (HCHO), CO, O_3, and NO_2. Annex 14 displays the equipment's technical specifications.

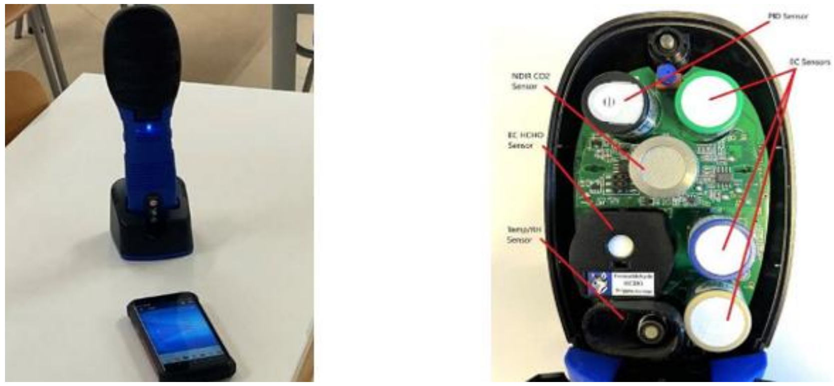


Figure 6.2 GreyWolf model DirectSense

6.4.3 Balometer

The TSI Accubalance 8375 digital balometer was used to measure the volumetric air flow rates in the diffusers and grilles of the classrooms. The technical characteristics are shown in Figure 6.3.

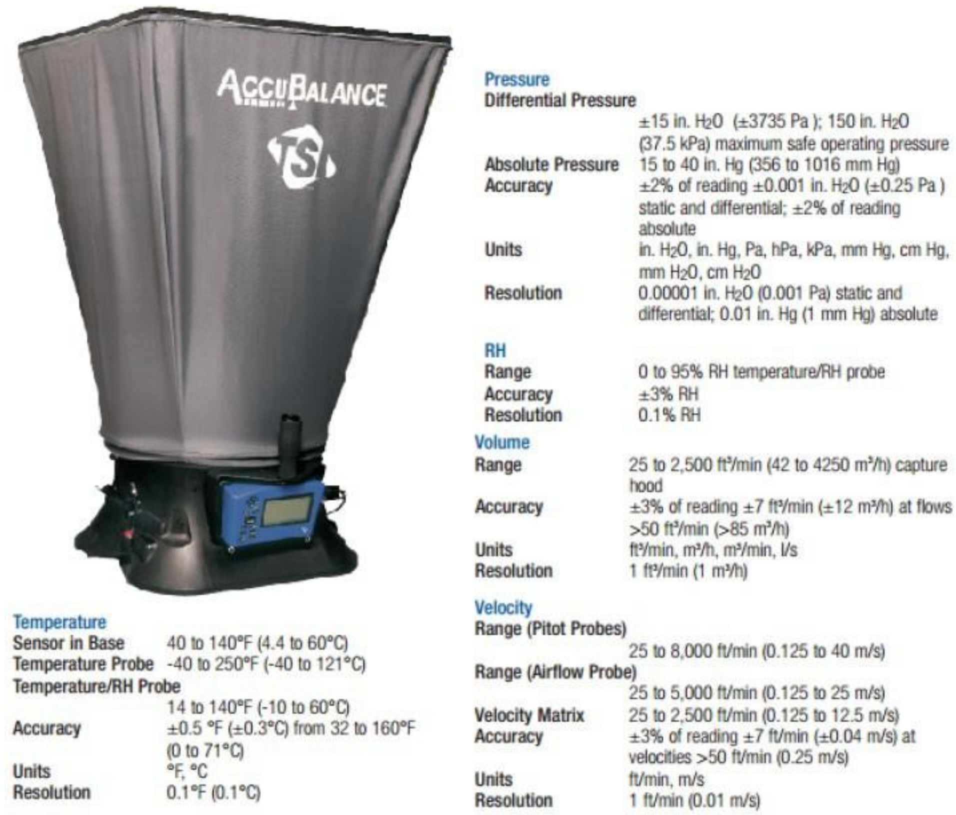


Figure 6.3 characteristics of the Accubalance 8375 equipment

6.4.4 Sound Level Meter

The ISO-TECH model SLM-1352A sound level meter, Figure 6.4, is particularly well suited for measuring industrial, health, safety, and environmental noise. The frequency of a sound affects how loud humans perceive it in addition to the sound pressure level. A sound is perceived as quieter at high or low frequencies than at the same volume in the mid-range. The A-frequency weighting in this device corrects for this impact and yields measurement results that are reasonably similar to the perceived sound level. Model MC-21 microphone (27pF capacitance) and Model AP-21 Microphone Preamplifier are included in the gadget. It is made to adhere to UNE-EN 61672-1 standard.

Electroacoustics. Sound level meters: Specifications and the technical characteristics of the equipment are shown in Annex 15.

Figure 6.4 ISO-TECH model SLM-1352A sound level meter

6.4.5 Luxmeter

To assure productivity, performance, and health at work, the Testo 545 small digital luxmeter, Figure 6.5, can easily, quickly, and correctly measure the illuminance of all familiar light sources (according to their V-lambda curve). The spectrum of uses is fairly broad because it is compatible with practically all ordinary LEDs (apart from blue LEDs). It functions in. According to Annex B of DIN 5032-7/EN 13032-1. Annex 16 lists the device's technical specifications.

Figure 6.5 Testo 545 luxmeter

6.4.6 Thermal Quality of The Environment

Testo 435, Figure 6.6, a multipurpose measuring device with a 5" full HD display (Model: 0560 0400). This device is perfect for analyzing the thermal comfort of the surrounding area. Using the testo 435, it is possible to determine whether an air cooling or heating system is operating as efficiently as possible from an energy standpoint. A globe thermometer is suitable for measuring radiant heat, for example, in the context of standard-compliant comfort level measurement at the workplace, and it features probes for detecting relative humidity, ambient temperature, and radiant heat. Annex 17 presents the device's technical specifications.

Figure 6.6 Testo 435 multifunctional device

The results shown in this report are obtained after using the TESTO Comsoft 3 thermal stress and comfort software (PPD and PMV) Comsoft 3, according to EN-UNE-ISO 7730.

6.5 Scope of Survey Data Collection

Measurements of Indoor Environmental Quality (IQ) were made in three distinct classrooms at the University of Valladolid's School of Industrial Engineering:

- The first classroom is on the Paseo del Cauce campus
- The second is in the INDUVa building (lecture hall)
- The third is in the northern part of the main building of the Mergelina campus.

In each classroom, two IAC determinations were made:

A) Check the IAC's starting conditions after more than 8 hours without activity.

B) With the doors and windows closed after a 50-minute lesson.

The conditions, dates, and data collection times are detailed in Table 6.1 below.

Table 6-1: Classrooms, conditions, day and time of data collection

1st) Classroom B1, at the Paseo del Cauce site

A) Unoccupied		**B) With occupation**	
Day	time	Day	time
04/05/2023	11:40	10/05/2023	19:00

2nd) Classroom 33 (IndUVa lecture hall) Mergelina Headquarters

A) Unoccupied		**B) With occupation**	
Day	time	Day	time
16/05/2023	9:30	16/05/2023	14:00

3º) Classroom 3247 (North area of the main building) Sede Mergelina.

A) Unoccupied		**B) With occupation**	
Day	time	Day	time
22/05/2023	9:50	22/05/2023	14:00

6.6 Data Collection Process

Although the equipment has a rapid response time, a sampling duration of between 2 and 5 minutes is utilized, and each parameter is given the mean value of the values recorded in the sample period to make the values recorded for each parameter as informative as possible.

The number of measures per classroom is determined by the area of occupation, which is obtained by deducting the surface area of the excluding perimeter—the region that students are not permitted to occupy from the classroom's overall surface area.

Each classroom is characterized by:

- Geometric dimensions.
- Constructive elements.
- Furniture and equipment.

- Air conditioning and ventilation system.
- Supply and extract air flow rates.
- Overpressure.
- Particle counting.
- Chemical pollutants in the classroom air.
- Thermal comfort.
- Lighting comfort
- Acoustic comfort.

6.7 Indoor Air Quality Measurement

(University of Valladolid, Dr Julio San Jose, Dr Yolanda Arroyo)

6.7.1 School of Industrial Engineering (Headquarters Paseo del Cauce) (unoccupied)

Table 6-2: Measure 1ºA) ROOM: B1 School of Industrial Engineering (Headquarters Paseo del Cauce) (1/5)

Status: **Unoccupied**		Date and time: **04/05/2023 (11:40)**			
Location: **Ground floor**	Capacity (seats): **70**	Height above ground level: **4 m**			
		Long	Width	High	Volume
		12,12	**13,085**	**3,197**	**507,013**
		Windows			
		Exteriors		Inside	
		Surface area $(m)^2$	**24,3**	Surface $(m)^2$	**6,74**
		Type	**Aluminium practicable**	Type	**Aluminium Not practicable**
		Remarks: **The exterior carpentry has a very high air permeability.**			
		Doors			
		Number	Surface $(m)^2$	Type	Opening
		2	**3,95**	**Wood**	**Folding**
		Remarks: **Two-leaf doors, one fixed of 0,634 m**			
Wall finishing:	**Plastic paint on plaster.**				
Ceiling finishing:	**Plastic paint on false plaster ceiling.**				
Floor finish:	**Terrazzo in the students' area and flooring under the slate covered with linoleum.**				
Furniture (type and quantity):	**70 chairs and 35 tables, consisting of melamine and lacquered steel, 1 melamine table and metal cupboard on a platform and 1 melamine cupboard.**				
Equipment:	**Computer, projector and speakers.**				
Type of slate:	**Illuminated chalk board with fluorescent line**				

Table 6-3: Measure 1ºA) ROOM: B1 School of Industrial Engineering (Headquarters Paseo del Cauce) (2/5)

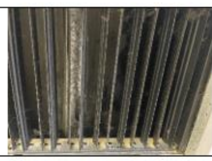
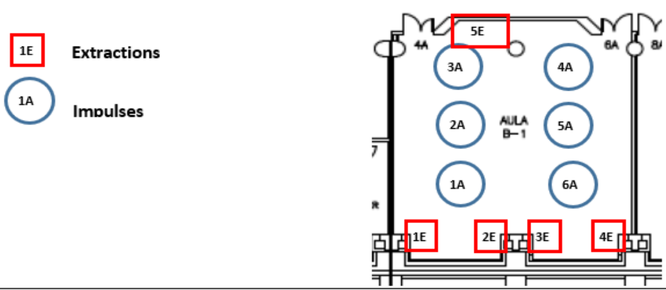
Visual Inspection Air Handling Units (AHUs)		
		The air handling unit, consisting of two fans with belts, one for supply air and one for extract air, had a mixing box for return air and ventilation air, which has been modified to take ventilation air directly from the outside. The mixing box is equipped with a damper drive system to regulate the outside air flow and the return air flow. In addition, the AHU consists of a water heating coil, a heating resistor and a filtering system. The indoor air quality monitoring is of type IDA-C1. Although the room is equipped with a CO_2
		
Ducts		
		The ducts are the same as those installed when the building was completed and have not undergone any apparent changes, except for the outside air intake.

Table 6-4: Measure 1ºA) ROOM: B1 School of Industrial Engineering (Headquarters Paseo del Cauce) (3/5)

Independent air-conditioning system	Independent ventilation system	Integrated air-conditioning and ventilation system
No	No	(UTA) supply air by swirl diffusers and extract grilles



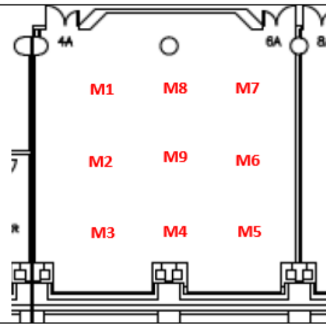
Air supply: type, dimensions and flow rate (Diffuser)										
(A1)	(A2)	(A3)	(A4)	(A5)	(A6)					Total
Φ40	Φ40	Φ40	Φ40	Φ40	Φ40					
(m^3/h)	(m^3/h)	(m^3/h)	(m^3/h)	(m^3/h)	(m^3/h)					(m^3/h)
0	0	0	0	0	0					0
Exhaust air: type, dimensions and flow rate (Grille)										
(E1)	(E2)	(E3)	(E4)	(E5)						Total
0,38X0,29	0,38X0,29	0,38X0,29	0,38X0,29	1,77X0,38						
(m^3/h)	(m^3/h)	(m^3/h)	(m3/h)	(m^3/h)						(m^3/h)
0	0	0	0	0						0

Determination of the ventilation flow rate	(m^3/h)	254[1]	Complies:	Yes □ No X

[1] 0.5 renewals per hour without occupancy

Table 6-5: Measure 1ºA) ROOM: B1 School of Industrial Engineering (Headquarters Paseo del Cauce) (4/5)

Local area: **158.6** (m)^2	Number of measures: $\sqrt{S - A_{perimetro}} = 9$



Particulates (p/m)^3	0,3 (µm)	0,5 (µm)	1,0 (µm)	3,0 (µm)	5,0 (µm)	10 (µm)
M1	**5.950.874,4**	**1.360.320,9**	**434.370,4**	**68.863,6**	**28.958,0**	**12.360,1**
M2	**5.697.668,2**	**1.215.530,8**	**375.748,0**	**50.146,8**	**13.772,7**	**4.237,8**
M3	**5.908.496,8**	**1.234.600,7**	**370.450,8**	**45.555,9**	**16.951,0**	**6.003,5**
M4	**5.625.273,2**	**1.181.628,7**	**340.433,4**	**48.381,1**	**14.832,2**	**4.237,8**
M5	**5.690.958,5**	**1.169.974,9**	**357.031,3**	**40.965,0**	**10.241,3**	**3.178,3**
M6	**5.626.685,8**	**1.191.516,8**	**333.370,4**	**41.318,2**	**9.888,1**	**2.825,2**
M7	**5.572.654,3**	**1.209.527,3**	**363.387,9**	**49.793,7**	**15.185,3**	**3.178,3**
M8	**5.736.867,5**	**1.270.268,5**	**397.996,3**	**55.090,9**	**16.597,9**	**6.709,8**
M9	**5.811.028,3**	**1.267.796,5**	**391.992,8**	**57.916,1**	**18.716,8**	**5.650,3**
Media	**5.735.611,9**	**1.233.462,8**	**373.864,6**	**50.892,4**	**16.127,0**	**5.375,7**
Maximum	**5.950.874,4**	**1.360.320,9**	**434.370,4**	**68.863,6**	**28.958,0**	**12.360,1**
Minimum	**5.572.654,3**	**1.169.974,9**	**333.370,4**	**40.965,0**	**9.888,1**	**2.825,2**
Average deviation	**130.357,5**	**59.159,9**	**31.100,0**	**8.779,9**	**5.633,8**	**2.953,5**

Table 6-6: Measure 1ºA) ROOM: B1 School of Industrial Engineering (Headquarters Paseo del Cauce) (5/5)

Gaseous pollutants										
Gases	M1	M2	M3	M4	M5	M6	M7	M8	M9	Media
CO_2 (ppm)	**428**	**438**	**447**	**473**	**506**	**499**	**500**	**463**	**439**	**465,9**
CO (ppm)	**0,8**	**0,8**	**0,8**	**0,8**	**0,8**	**0,775**	**0,7**	**0,7**	**0,7**	**0,76**
HCHO (ppb)	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
NO_2 (ppm)	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
O_3 (ppm)	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
VOC (µg/m)^3	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Thermal comfort										
Parameters	M1	M2	M3	M4	M5	M6	M7	M8	M9	Media
T dry (°C)	**23,6**	**23,6**	**23,5**	**23,4**	**23,5**	**23,5**	**23,4**	**23,4**	**23,4**	**23,48**
Humidity (%)	**38,2**	**38,1**	**38**	**38,8**	**39,1**	**38,1**	**38,4**	**38,9**	**38,7**	**38,48**
T Globe(°C)	**23,7**	**23,8**	**23,8**	**23,8**	**23,8**	**23,8**	**23,8**	**23,7**	**23,7**	**23,77**
Speed (m/s)	**0,04**	**0,01**	**0,01**	**0,01**	**0,03**	**0,04**	**0,06**	**0,00**	**0,03**	**0,03**
Clo	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
Met	**0,9**	**0,9**	**0,9**	**0,9**	**0,9**	**0,9**	**0,9**	**0,9**	**0,9**	**0,9**
VMP	**-0,21**	**-0,23**	**-0,21**	**-0,2**	**-0,21**	**-0,21**	**-0,2**	**-0,18**	**-0,18**	**-0,20**
PPD (%)	**5,93**	**6,06**	**5,96**	**5,8**	**5,88**	**5,95**	**5,82**	**5,68**	**5,69**	**5,86**
Acoustic comfort										
N. Noise (dBA)	**40,5**	**41,2**	**44,2**	**39,8**	**40,2**	**42,3**	**39,8**	**40,8**	**40,1**	**40,99**
Light level										
Illumination (lux)	**297**	**396**	**340**	**443**	**688**	**418**	**384**	**311**	**371**	**405,33**

6.7.2 School of Industrial Engineering (Headquarters Paseo del Cauce) (occupied)

Table 6-7: Measure 1ºB) ROOM: B1 School of Industrial Engineering (Headquarters Paseo del Cauce) (1/3)

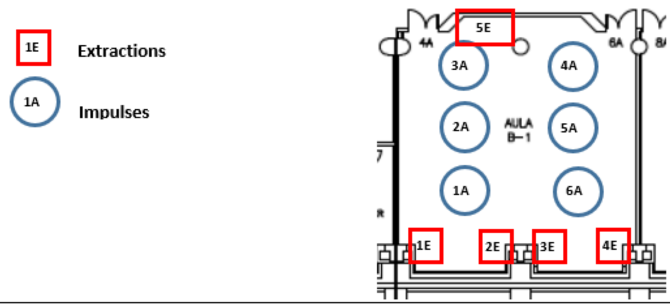
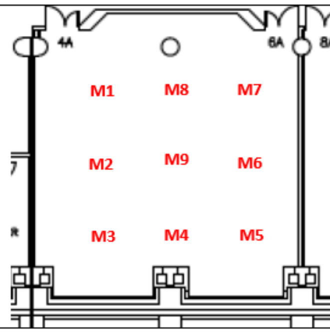
Status: **occupied (34 students)**			Date and time: **10/05/2023 (19:00)**						
									
Air supply: type, dimensions and flow rate (Diffuser)									
(A1)	**(A2)**	**(A3)**	**(A4)**	**(A5)**	**(A6)**				**Total**
Φ40	**Φ40**	**Φ40**	**Φ40**	**Φ40**	**Φ40**				
(m^3/h)	(m^3/h)	(m^3/h)	(m^3/h)	(m^3/h)	(m^3/h)				(m^3/h)
0	**0**	**0**	**0**	**0**	**0**				**0**
Exhaust air: type, dimensions and flow rate (Grille)									
(E1)	**(E2)**	**(E3)**	**(E4)**	**(E5)**					**Total**
0,38X0,29	**0,38X0,29**	**0,38X0,29**	**0,38X0,29**	**1,77X0,38**					
(m^3/h)	(m^3/h)	(m^3/h)	(m^3/h)	(m^3/h)					(m^3/h)
0	**0**	**0**	**0**	**0**					**0**
Determination of the ventilation flow rate				**(m^3/h)**	**1.575**[2]	**Complies:**		**Yes □ No X**	
Overpressure with the outside				**(Pa)**	**0**				

Table 6-8: Measure 1ºB) ROOM: B1 School of Industrial Engineering (Headquarters Paseo del Cauce) (2/3)

Local area: **158.6** (m)^3 | Number of measures: $\sqrt{S - A_{perimetro}} = 9$



Particulates (p/m)^3	0,3 (µm)	0,5 (µm)	1,0 (µm)	3,0 (µm)	5,0 (µm)	10 (µm)
M1	**16.182.592,6**	**3.913.924,5**	**1.215.884,0**	**251.440,4**	**88.286,7**	**35.667,8**
M2	**16.129.267,5**	**3.840.116,8**	**1.162.558,8**	**232.017,4**	**80.870,6**	**30.723,8**
M3	**15.919.851,5**	**3.722.165,8**	**1.064.030,9**	**200.940,5**	**61.094,4**	**22.248,2**
M4	**15.819.911,0**	**3.694.267,2**	**1.043.548,4**	**193.171,2**	**60.034,9**	**24.720,3**
M5	**15.977.767,6**	**3.741.942,0**	**1.045.667,3**	**185.755,1**	**54.737,7**	**21.541,9**
M6	**15.431.096,5**	**3.574.550,5**	**967.621,9**	**167.038,4**	**46.615,4**	**21.541,9**
M7	**15.472.767,8**	**3.468.606,5**	**919.593,9**	**152.559,4**	**39.905,6**	**14.832,2**
M8	**15.181.421,9**	**3.442.120,5**	**846.139,4**	**122.541,9**	**22.601,4**	**7.416,1**
M9	**15.312.792,4**	**3.483.438,7**	**896.286,2**	**143.024,4**	**42.024,5**	**18.363,6**
Media	**15.714.163,2**	**3.653.459,2**	**1.017.925,6**	**183.165,4**	**55.130,1**	**21.895,1**
Maximum	**16.182.592,6**	**3.913.924,5**	**1.215.884,0**	**251.440,4**	**88.286,7**	**35.667,8**
Minimum	**15.181.421,9**	**3.442.120,5**	**846.139,4**	**122.541,9**	**22.601,4**	**7.416,1**
Average deviation	**370.477,0**	**169.877,3**	**122.558,3**	**41.764,4**	**20.481,3**	**8.276,4**

Table 6-9: Measure 1ºB) ROOM: B1 School of Industrial Engineering (Headquarters Paseo del Cauce) (3/3)

Gaseous pollutants										
Gases	M1	M2	M3	M4	M5	M6	M7	M8	M9	Media
CO_2 (ppm)	**936,6**	**1.059,6**	**1.001,4**	**941,1**	**911,0**	**878,8**	**868,6**	**835,0**	**806,7**	915,42
CO (ppm)	**0,33**	**0,34**	**0,35**	**0,35**	**0,35**	**0,35**	**0,33**	**0,30**	**0,29**	0,33
HCHO (ppb)	**0,0**	**0,0**	**0,0**	**0,0**	**0,0**	**0,0**	**0,0**	**0,0**	**0,0**	0,00
NO_2 (ppm)	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**	0,00
O_3 (ppm)	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**	0,00
VOC (µg/m)^3	**196,1**	**227**	**209,4**	**194,5**	**187,7**	**180,1**	**172,8**	**167,4**	**162,0**	188,56
Thermal comfort										
Parameters	M1	M2	M3	M4	M5	M6	M7	M8	M9	Media
T dry (ºC)	**25,6**	**27,0**	**27,7**	**28,1**	**28,5**	**28,1**	**27,9**	**27,7**	**27,7**	**27,6**
Humidity (%)	**33,8**	**31,9**	**30,4**	**29,7**	**28,3**	**29,0**	**29,5**	**29,2**	**29,5**	**30,1**
T Globe(ºC)	**24,5**	**26,0**	**27,0**	**27,8**	**28,3**	**28,7**	**28,5**	**28,1**	**27,8**	**27,4**
Speed (m/s)	**0,01**	**0,01**	**0,02**	**0,02**	**0,02**	**0,04**	**0,04**	**0,02**	**0,05**	**0,03**
Clo	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1,0**
Met	**0,9**	**0,9**	**0,9**	**0,9**	**0,9**	**0,9**	**0,9**	**0,9**	**0,9**	**0,9**
VMP	**1,37**	**1,58**	**1,75**	**1,81**	**1,81**	**1,81**	**1,79**	**1,74**	**1,72**	**1,71**
PPD (%)	**43,99**	**55,34**	**59,31**	**64,20**	**67,62**	**67,32**	**66,36**	**63,73**	**62,67**	**62,11**
Acoustic **comfort**										
N. Noise (dBA)	**35,2**	**35,1**	**35**	**38**	**40**	**34,6**	**36,0**	**34,1**	**35,4**	**35,93**
Light level										
Illumination (lux)	**367**	**559**	**1849**	**729**	**2105**	**869**	**504**	**469**	**631**	**898**

6.7.3 ROOM: 33 School of Industrial Engineering (INDUVA) (unoccupied)

Table 6-10: Measure 2ºA) ROOM: 33 School of Industrial Engineering (INDUVA) (1/5)

<table>
<tr><td colspan="2">Status: Unoccupied</td><td colspan="4">Date and time: 16/05/2023 (9:30)</td></tr>
<tr><td>Location: Third floor</td><td>Capacity (seats): 64</td><td colspan="4">Height above ground level: 15.1</td></tr>
<tr><td colspan="2" rowspan="11"></td><td>Long</td><td>Width</td><td>High</td><td>Volume</td></tr>
<tr><td>11,59</td><td>10,94</td><td>2,89</td><td>365,9</td></tr>
<tr><td colspan="4">Windows</td></tr>
<tr><td colspan="2">Exteriors</td><td colspan="2">Inside</td></tr>
<tr><td>Surface area $(m)^2$</td><td>26,52</td><td>Surface $(m)^2$</td><td>0</td></tr>
<tr><td>Type</td><td>Non-openable wall</td><td>Type</td><td></td></tr>
<tr><td colspan="4">Remarks: The glass wall is not permeable to air.</td></tr>
<tr><td colspan="4">Doors</td></tr>
<tr><td>Number</td><td>Surface $(m)^2$</td><td>Type</td><td>Opening</td></tr>
<tr><td>2</td><td>6,55</td><td>Melamine double door</td><td>Swing out</td></tr>
<tr><td colspan="4">Observations: The doors have two equal leaves, one of which is fixed.</td></tr>
<tr><td>Wall finishing:</td><td colspan="5">Plastic paint on plasterboard</td></tr>
<tr><td>Ceiling finishing:</td><td colspan="5">Detachable false ceiling made of fibreglass</td></tr>
<tr><td>Floor finish:</td><td colspan="5">Linoleum, linoleum-lined flooring.</td></tr>
<tr><td>Furniture (type and quantity):</td><td colspan="5">64 chairs, 33 melamine and metal tables and a teacher's table made of chipboard and plywood.</td></tr>
<tr><td>Equipment:</td><td colspan="5">One computer and two projectors.</td></tr>
<tr><td>Type of slate:</td><td colspan="5">Chalk.</td></tr>
</table>

Table 6-11: Measure 2ºA) ROOM: 33 School of Industrial Engineering (INDUVA) (2/5)

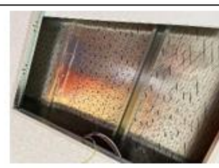
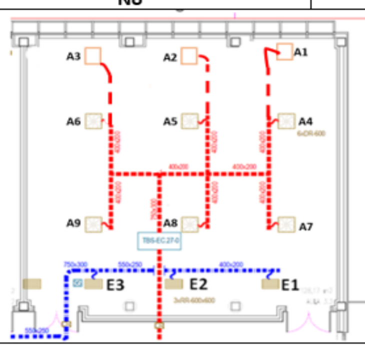
<table>
<tr><th colspan="3">Visual Inspection Air Handling Units (AHUs)</th></tr>
<tr><td></td><td></td><td rowspan="2">The Aulario Tower (INDUVa) has an air conditioner at the top of the building that pre-treats the ventilation air that is fed to the whole building.
The air conditioner has two fans, two air inlets, one direct from the outside and the other coming from Canadian wells, the exhaust air passes through a rotary recuperator, which allows the recovery of energy from the exhaust air.
The supply air is treated in each room by an air handling unit to the conditions required in the room.
The control system is ID-C6 with CO_2 probe$_2$ from Sedical.</td></tr>
<tr><td></td><td></td></tr>
<tr><th colspan="3">Ducts</th></tr>
<tr><td></td><td></td><td>The ducts that distribute the air are Climaver ducts, made of sheet metal and flexible.
They are in good condition, although some sections have had to be repaired.</td></tr>
</table>

Table 6-12: Measure 2ºA) ROOM: 33 School of Industrial Engineering (INDUVA) (3/5)

Independent air-conditioning system	Independent ventilation system	Integrated air-conditioning and ventilation system
No	No	All-air system with heating coils

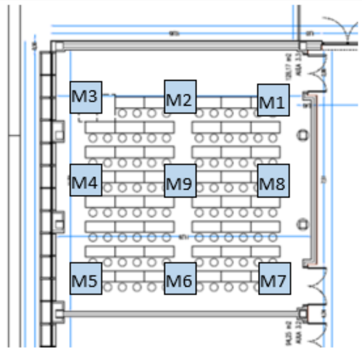


Air supply: type, dimensions and flow rate (Diffuser)									
(A1)	(A2)	(A3)	(A4)	(A5)	(A6)	(A7)	(A8)	(A9)	Total
Swirl diffusers Ø 460 mm in false ceiling 600x600 mm									
(m^3 /h)	(m^3 /h)	(m^3 /h)	(m^3 /h)	(m^3 /h)	(m^3 /h)	(m^3 /h)	(m^3 /h)	(m^3 /h)	(m^3 /h)
102	**98**	**92**	**92**	**106**	**99**	**87**	**91**	**94**	**861**
Air extraction: type, dimensions and flow rate (Grille)									
(E1)	(E2)	(E3)							Total
600x600 mm louvred grilles with slats.									
(m^3 /h)	(m^3 /h)	(m^3 /h)							(m^3 /h)
204	**209**	**294**							**707**
Determination of the ventilation flow rate	(m^3 /h)	**183**[3]	Complies:	Yes x No □					
Overpressure with the outside	(Pa)	**+ 2 Pa**							

[3] No occupancy 0.5 renewals per hour.

Table 6-13: Measure 2ºA) ROOM: 33 School of Industrial Engineering (INDUVA) (4/5)

Local area: **130.85** (m)[2]	Number of measures: $\sqrt{S - A_{perimetro}} = 9$



Particulates (p/m)[3]						
	0,3 (µm)	0,5 (µm)	1,0 (µm)	3,0 (µm)	5,0 (µm)	10 (µm)
M1	**1.268.149,66**	**251.440,42**	**92.877,57**	**30.017,47**	**15.185,31**	**6.709,79**
M2	**1.175.272,09**	**174.454,45**	**63.213,25**	**21.895,09**	**12.006,99**	**7.416,08**
M3	**1.323.593,69**	**243.318,05**	**93.937,01**	**24.720,27**	**11.653,84**	**4.590,91**
M4	**1.188.691,66**	**185.402,00**	**75.573,39**	**22.601,39**	**8.122,37**	**3.178,32**
M5	**1.167.502,86**	**170.922,98**	**64.978,99**	**18.010,48**	**8.828,67**	**4.237,76**
M6	**1.180.216,14**	**200.940,45**	**90.758,69**	**30.370,61**	**15.538,45**	**7.769,23**
M7	**1.267.796,52**	**212.947,44**	**84.048,91**	**26.486,00**	**10.594,40**	**7.062,93**
M8	**1.223.300,04**	**184.342,56**	**84.048,91**	**29.311,17**	**15.891,60**	**7.062,93**
M9	**1.206.349,00**	**200.587,30**	**87.227,23**	**33.548,93**	**14.125,87**	**6.709,79**
Media	**1.222.319,07**	**202.706,18**	**81.851,55**	**26.329,05**	**12.438,61**	**6.081,97**
Maximum	**1.323.593,69**	**251.440,42**	**93.937,01**	**33.548,93**	**15.891,60**	**7.769,23**
Minimum	**1.167.502,86**	**170.922,98**	**63.213,25**	**18.010,48**	**8.122,37**	**3.178,32**
Average deviation	**53.388,77**	**28.683,25**	**11.494,61**	**4.953,85**	**2.910,93**	**1.635,36**

Table 6-14: Measure 2ºA) ROOM: 33 School of Industrial Engineering (INDUVA) (5/5)

Gaseous pollutants										
Gases	M1	M2	M3	M4	M5	M6	M7	M8	M9	Media
CO_2 (ppm)	**494,80**	**498,90**	**485,90**	**510,90**	**494,40**	**511,80**	**515,60**	**501,50**	**501,73**	**501,73**
CO (ppm)	**0,60**	**0,60**	**0,60**	**0,60**	**0,70**	**0,60**	**0,60**	**0,60**	**0,61**	**0,61**
HCHO (ppb)	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**
NO_2 (ppm)	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**
O_3 (ppm)	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**
VOC (µg/m)[3]	**147,70**	**131,60**	**120,70**	**112,20**	**101,00**	**90,00**	**84,40**	**77,40**	**108,13**	**108,13**
Thermal comfort										
Parameters	M1	M2	M3	M4	M5	M6	M7	M8	M9	Media
T dry (°C)	**20,7**	**20,3**	**20,1**	**20,2**	**20,6**	**20,7**	**20,2**	**20,1**	**20,1**	**20,33**
Humidity (%)	**36,8**	**31,7**	**37,3**	**37,1**	**36,7**	**36,2**	**37,0**	**37,4**	**37,4**	**36,40**
T Globe(°C)	**21,3**	**20,9**	**20,7**	**20,6**	**20,8**	**21,3**	**21,1**	**20,8**	**20,7**	**20,91**
Speed (m/s)	**0,02**	**0,02**	**0,02**	**0,04**	**0,03**	**0,03**	**0,03**	**0,03**	**0,02**	**0,03**
Clo	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1,00**
Met	**0,9**	**0,9**	**0,9**	**0,9**	**0,9**	**0,9**	**0,9**	**0,9**	**0,9**	**0,90**
VMP	**-1,06**	**-1,18**	**-1,18**	**-1,19**	**-1,08**	**-1,07**	**-1,16**	**-1,2**	**-1,18**	**-1,14**
PPD (%)	**28,79**	**34,34**	**34,47**	**34,55**	**29,43**	**28,98**	**33,25**	**35,14**	**34,44**	**32,60**
Acoustic **comfort**										
N. Noise (dBA)	**33,0**	**33,6**	**34,0**	**32,1**	**32,4**	**33,6**	**33,8**	**32,9**	**32,7**	**33,12**
Light level										
Illumination (lux)	**709**	**616**	**1.123**	**1.360**	**4.193**	**857**	**737**	**811**	**819**	**1.247,22**

6.7.4 ROOM: 33 School of Industrial Engineering (INDUVA)(occupied)

Table 6-15: Measure 2ºB) ROOM: 33 School of Industrial Engineering (INDUVA) (1/3)

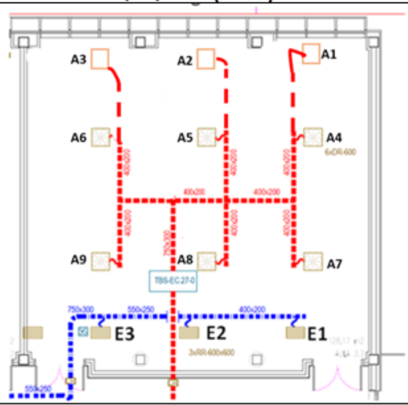
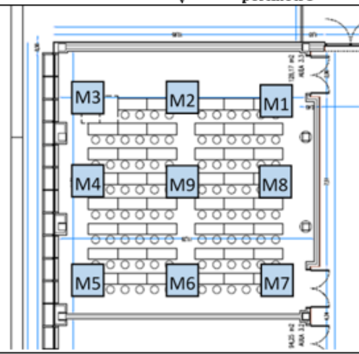
Status: **occupied (24 students)**			Date and time: **16/05/2023 (14:00)**						
									
Air supply: type, dimensions and flow rate									
(A1)	**(A2)**	**(A3)**	**(A4)**	**(A5)**	**(A6)**	**(A7)**	**(A8)**	**(A9)**	**Total**
Swirl diffusers Ø 460 mm in false ceiling 600x600 mm									
(m^3/h)	(m^3/h)	(m^3/h)	(m^3/h)	(m^3/h)	(m^3/h)	(m^3/h)	(m^3/h)	(m^3/h)	(m^3/h)
111,5	**102**	**95**	**96**	**113**	**94**	**93**	**103**	**101**	**908,5**
Air extraction: type, dimensions and flow rate (Grille)									
(E1)	**(E2)**	**(E3)**							**Total**
600x600 mm louvred grilles with slats.									
(m^3/h)	(m^3/h)	(m^3/h)							(m^3/h)
198	**210**	**285**							**693**
Determination of the ventilation flow rate			**(m^3/h)**	**1.080**[4]		**Complies:**		**Yes □ No X**	
Overpressure with the outside			**(Pa)**	**5,5 Pa**					

Table 6-16: Measure 2ºB) ROOM: 33 School of Industrial Engineering (INDUVA) (2/3)

Local area: (m)[2]	Number of measures: $\sqrt{\mathbf{S}-\mathbf{A}_{\mathbf{perimetro}}}=\mathbf{9}$					



Particulates (p/m)[3]						
	0,3 (µm)	0,5 (µm)	1,0 (µm)	3,0 (µm)	5,0 (µm)	10 (µm)
M1	**2.687.446,10**	**663.915,72**	**339.727,09**	**116.538,40**	**45.555,92**	**17.657,33**
M2	**2.439.537,14**	**592.226,95**	**339.020,80**	**122.541,89**	**50.146,83**	**20.835,65**
M3	**2.307.107,14**	**482.751,49**	**264.506,85**	**95.349,60**	**35.314,67**	**10.947,55**
M4	**2.220.939,36**	**433.664,10**	**225.660,72**	**81.930,03**	**26.132,85**	**8.475,52**
M5	**2.218.467,33**	**414.594,18**	**215.419,46**	**78.751,71**	**22.954,53**	**5.650,35**
M6	**2.219.879,92**	**411.062,71**	**210.122,26**	**73.807,65**	**25.779,71**	**11.300,69**
M7	**2.080.033,84**	**362.328,48**	**180.811,09**	**60.034,93**	**18.716,77**	**6.709,79**
M8	**2.133.358,98**	**348.202,61**	**159.975,44**	**54.737,73**	**16.597,89**	**6.709,79**
M9	**2.084.271,60**	**278.985,86**	**134.195,73**	**39.552,43**	**13.419,57**	**6.003,49**
Media	**2.265.671,27**	**443.081,35**	**229.937,72**	**80.360,48**	**28.290,97**	**10.476,68**
Maximum	**2.687.446,10**	**663.915,72**	**339.727,09**	**122.541,89**	**50.146,83**	**20.835,65**
Minimum	**2.080.033,84**	**278.985,86**	**134.195,73**	**39.552,43**	**13.419,57**	**5.650,35**
Average deviation	**193.984,51**	**120.914,06**	**72.667,26**	**27.603,73**	**12.816,41**	**5.425,14**

Table 6-17: Measure 2ºB) ROOM: 33 School of Industrial Engineering (INDUVA) (3/3)

Gaseous pollutants										
Gases	M1	M2	M3	M4	M5	M6	M7	M8	M9	Media
CO_2 (ppm)	**501,74**	**485,88**	**478,58**	**444,20**	**462,28**	**504,10**	**458,16**	**445,90**	**448,25**	**469,90**
CO (ppm)	**0,60**	**0,60**	**0,60**	**0,56**	**0,50**	**0,58**	**0,60**	**0,60**	**0,60**	**0,58**
HCHO (ppb)	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**
NO_2 (ppm)	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**
O_3 (ppm)	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**
VOC (µg/m)[3]	**39,42**	**37,80**	**37,23**	**32,10**	**31,33**	**31,30**	**33,76**	**51,78**	**46,35**	**37,90**
Thermal comfort										
Parameters	M1	M2	M3	M4	M5	M6	M7	M8	M9	Media
T dry (°C)	**22,0**	**22,0**	**21,9**	**21,8**	**21,8**	**21,8**	**21,7**	**21,6**	**21,6**	**21,80**
Humidity (%)	**32,7**	**32,7**	**32,2**	**31,9**	**32,0**	**32,0**	**32,1**	**32,0**	**31,8**	**32,16**
T Globe(°C)	**22,2**	**22,2**	**22,2**	**22,1**	**22,0**	**22,0**	**21,9**	**21,9**	**21,8**	**22,03**
Speed (m/s)	**0,04**	**0,04**	**0,04**	**0,04**	**0,01**	**0,02**	**0,01**	**0,01**	**0,02**	**0,03**
Clo	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1,00**
Met	**0,9**	**0,9**	**0,9**	**0,9**	**0,9**	**0,9**	**0,9**	**0,9**	**0,9**	**0,90**
VMP	**-0,71**	**-0,71**	**-0,7**	**-0,77**	**-0,76**	**-0,76**	**-0,83**	**-0,82**	**-0,8**	**-0,76**
PPD (%)	**15,65**	**15,65**	**15,36**	**17,63**	**17,14**	**17,14**	**19,48**	**19,03**	**18,59**	**17,30**
Acoustic **comfort**										
N. Noise (dBA)	**33,4**	**32,6**	**33,0**	**30,5**	**32,3**	**32,3**	**31,9**	**32,4**	**31,6**	**32,22**
Light level										
Illumination (lux)	**838**	**643**	**332**	**470**	**1.283**	**589**	**708**	**692**	**613**	**685,33**

6.7.5 ROOM: 3247 School of Industrial Engineering (Sede Mergelina) (unoccupied)

Table 6-18: Measure 3ºA) ROOM: 3247 School of Industrial Engineering (Sede Mergelina) (1/5)

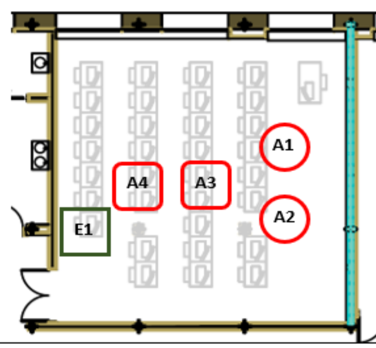
<table>
<tr><td colspan="2">Status: Unoccupied</td><td colspan="4">Date and time: 22/05/2023 (9:50)</td></tr>
<tr><td>Location: Third floor</td><td>Capacity (seats): 24</td><td colspan="4">Height above ground level: 15.1</td></tr>
<tr><td colspan="2" rowspan="13"></td><td>Long</td><td>Width</td><td>High</td><td>Volume</td></tr>
<tr><td>8,74</td><td>9,20</td><td>2,58</td><td>207,23</td></tr>
<tr><td colspan="4">Windows</td></tr>
<tr><td colspan="2">Exteriors</td><td colspan="2">Inside</td></tr>
<tr><td>Surface area (m)^2</td><td>8,81</td><td>Surface (m)^2</td><td>No</td></tr>
<tr><td>Type</td><td>practicable</td><td>Type</td><td></td></tr>
<tr><td colspan="4">Remarks:</td></tr>
<tr><td colspan="4">Doors</td></tr>
<tr><td>Number</td><td>Surface (m)^2</td><td>Type</td><td>Opening</td></tr>
<tr><td>1</td><td>3,29</td><td>Melamine double door</td><td>Swing out</td></tr>
<tr><td colspan="4">Remarks: Door with two equal leaves, one fixed</td></tr>
<tr><td>Wall finishing:</td><td colspan="5">Plastic paint on plasterboard</td></tr>
<tr><td>Ceiling finishing:</td><td colspan="5">Detachable false ceiling made of fibreglass</td></tr>
<tr><td>Floor finish:</td><td colspan="5">Linoleum.</td></tr>
<tr><td>Furniture (type and quantity):</td><td colspan="5">24 chairs, 12 melamine and metal tables and a plywood and plywood teacher's table.</td></tr>
<tr><td>Equipment:</td><td colspan="5">25 computers and a projector.</td></tr>
<tr><td>Type of slate:</td><td colspan="5">Vileda</td></tr>
</table>

Table 6-19: Measure 3ºA) ROOM: 3247 School of Industrial Engineering (Sede Mergelina) (2/5)

Visual Inspection Air Handling Units (AHU)		
		The classroom has a treated outside air system, which is diffused into the classroom by two swirl diffusers. The outside air is taken in and treated by an air conditioner located on the roof of the building, which is distributed through vertical ducts and ducts with horizontal branches in different rooms. Thermal comfort is provided by two VRV cassettes, with external air intake, which are controlled by a room controller. The control system is ID-C6 with CO_2 probe from Sedical.
		
Ducts		
		The air distribution ducts are Climaver ducts, made of sheet metal and flexible.

Table 6-20: Measure 3ºA) ROOM: 3247 School of Industrial Engineering (Sede Mergelina) (3/5)

Independent air-conditioning system	Independent ventilation system	Integrated air-conditioning and ventilation system
Yes	Yes	



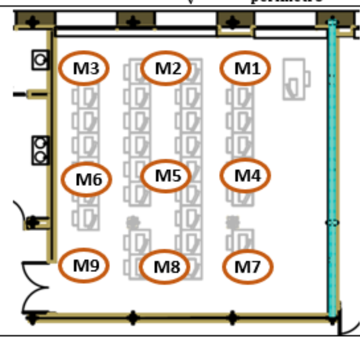
Air discharge: type, dimensions and flow rate (Diffuser)									
(A1)	(A2)	(A3)	(A4)						Total
Rotational ϕ 45		60x60 cm cassette							
(m^3/h)	(m^3/h)	(m^3/h)	(m^3/h)						(m^3/h)
95	**93**	**0**	**0**						**188**
Air extraction: type, dimensions and flow rate (Grille)									
(E1)									Total
45x 45 cm grid									
(m^3/h)									(m^3/h)
269									**269**

Determination of the ventilation flow rate	(m^3/h)	104[5]	Complies:	Yes □ No □
Overpressure with the outside	(Pa)	00		

[5] No occupancy 0.5 renewals per hour.

Table 6-21: Measure 3ºA) ROOM: 3247 School of Industrial Engineering (Sede Mergelina) (4/5)

Local area: 80.35 (m)² | Number of measures: $\sqrt{\mathbf{S}-\mathbf{A}_{\mathbf{perimetro}}}=\mathbf{9}$



Particulates (p/m)³

	0,3 (µm)	0,5 (µm)	1,0 (µm)	3,0 (µm)	5,0 (µm)	10 (µm)
M1	**5.167.948**	**643.433**	**208.357**	**76.633**	**35.315**	**11.301**
M2	**5.027.749**	**600.349**	**225.661**	**84.402**	**28.958**	**10.241**
M3	**5.678.598**	**753.615**	**314.301**	**122.189**	**41.318**	**15.185**
M4	**4.985.725**	**619.772**	**232.017**	**84.402**	**35.315**	**8.122**
M5	**5.716.032**	**727.482**	**268.745**	**97.468**	**34.962**	**9.888**
M6	**5.455.410**	**657.912**	**278.633**	**102.059**	**48.381**	**15.538**
M7	**5.396.434**	**675.923**	**248.968**	**81.930**	**28.958**	**7.063**
M8	**5.294.375**	**698.877**	**284.636**	**107.003**	**39.199**	**15.185**
M9	**6.304.021**	**776.570**	**285.696**	**100.647**	**38.493**	**16.598**
Media	**5.167.948**	**643.433**	**208.357**	**76.633**	**35.315**	**11.301**
Maximum	**5.027.749**	**600.349**	**225.661**	**84.402**	**28.958**	**10.241**
Minimum	**5.678.598**	**753.615**	**314.301**	**122.189**	**41.318**	**15.185**
Average deviation	**4.985.725**	**619.772**	**232.017**	**84.402**	**35.315**	**8.122**

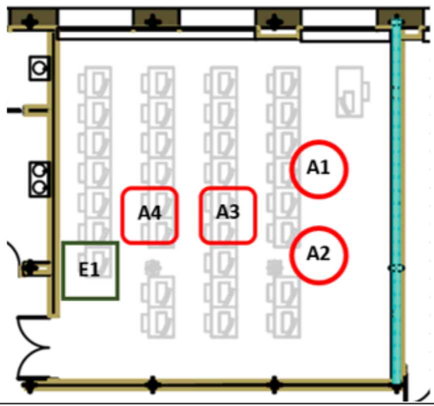
Table 6-22: Measure 3ºA) ROOM: 3247 School of Industrial Engineering (Sede Mergelina) (5/5)

Gaseous pollutants										
Gases	M1	M2	M3	M4	M5	M6	M7	M8	M9	Media
CO_2 (ppm)	**521,4**	**546,2**	**517,9**	**522,6**	**580,3**	**564,8**	**568,2**	**575,7**	**582,7**	**553,3**
CO (ppm)	**0,7**	**0,8**	**0,8**	**0,8**	**0,8**	**0,8**	**0,8**	**0,8**	**0,8**	**0,8**
HCHO (ppb)	**0**	**0,0**	**0,0**	**0,0**	**0,0**	**0,0**	**0,0**	**0,0**	**0,0**	**0,0**
NO_2 (ppm)	**0**	**0,0**	**0,0**	**0,0**	**0,0**	**0,0**	**0,0**	**0,0**	**0,0**	**0,0**
O_3 (ppm)	**0**	**0,0**	**0,0**	**0,0**	**0,0**	**0,0**	**0,0**	**0,0**	**0,0**	**0,0**
VOC (µg/m)³	**231,4**	**206,0**	**181,8**	**169,1**	**168,8**	**167,2**	**151,3**	**148,5**	**133,6**	**173,1**
Thermal comfort										
Parameters	M1	M2	M3	M4	M5	M6	M7	M8	M9	Media
T dry (°C)	**22,5**	**22,5**	**22,5**	**22,6**	**22,7**	**22,8**	**22,8**	**22,8**	**22,8**	**22,67**
Humidity (%)	**38,6**	**38,4**	**39,1**	**39,3**	**39,3**	**39,7**	**39,7**	**39,5**	**39,8**	**39,27**
T Globe(°C)	**22,3**	**22,5**	**22,6**	**22,6**	**22,7**	**22,7**	**22,8**	**22,9**	**22,9**	**22,67**
Speed (m/s)	**0,03**	**0,04**	**0,02**	**0,02**	**0,00**	**0,03**	**0,02**	**0,04**	**0,01**	**0,02**
Clo	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1,00**
Met	**0,9**	**0,9**	**0,9**	**0,9**	**0,9**	**0,9**	**0,9**	**0,9**	**0,9**	**0,90**
VMP	**-0,55**	**-0,58**	**-0,49**	**-0,5**	**-0,43**	**-0,46**	**-0,46**	**-0,47**	**-0,47**	**-0,49**
PPD (%)	**11,31**	**12,04**	**10,05**	**10,28**	**8,91**	**9,34**	**9,34**	**9,64**	**9,59**	**10,06**
Acoustic **comfort**										
N. Noise (dBA)	**35,2**	**35,1**	**34,7**	**37,0**	**34,9**	**34,4**	**35,3**	**35,2**	**35,5**	**35,26**
Light level										
Illumination (lux)	**475**	**636**	**448**	**461**	**586**	**546**	**323**	**285**	**354**	**457,11**

6.7.6 ROOM: 3247 School of Industrial Engineering (Sede Mergelina) (occupied)

Table 6-23: Measure 3ºB) ROOM: 3247 School of Industrial Engineering (Sede Mergelina)(1/3)

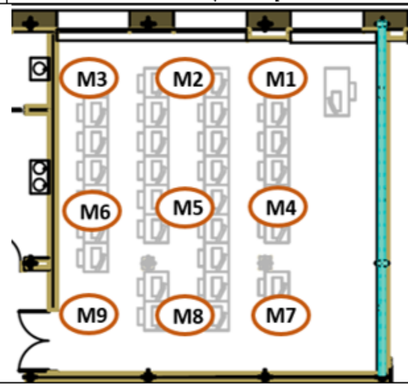
Status: **occupied (12 students)**	Date and time: **22/05/2023 (14:00)**



Air supply: type, dimensions and flow rate									
(A1)	**(A2)**	**(A3)**	**(A4)**						**Total**
Rotational ϕ 45		60x60 cm cassette							
(m^3 /h)	(m^3 /h)	(m^3 /h)	(m^3 /h)						(m^3 /h)
264	**265**	**0**	**0**						**529**
Air extraction: type, dimensions and flow rate (Grille)									
(E1)									**Total**
45x45 cm grid									
(m^3 /h)									(m^3 /h)
460									**460**
Determination of the ventilation flow rate				**(m^3 /h)**	**585**[6]	**Complies:**		**Yes □ No X**	
Overpressure with the outside				**(Pa)**	**1 Pa**				

Table 6-24: Measure 3ºB) ROOM: 3247 School of Industrial Engineering (Sede Mergelina)(2/3)

Local area: 80.35 (m)[2]	Number of measures: $\sqrt{S - A_{perimetro}} = 9$					



Particulates (p/m)[3]						
	0,3 (µm)	0,5 (µm)	1,0 (µm)	3,0 (µm)	5,0 (µm)	10 (µm)
M1	**2.816.698**	**493.346**	**259.210**	**120.423**	**71.689**	**37.434**
M2	**2.877.439**	**473.923**	**245.084**	**106.650**	**55.091**	**25.780**
M3	**2.749.247**	**450.968**	**245.437**	**105.591**	**45.556**	**20.836**
M4	**2.303.223**	**320.657**	**166.332**	**71.336**	**34.608**	**15.538**
M5	**2.416.229**	**321.717**	**155.738**	**67.098**	**32.489**	**12.007**
M6	**2.291.569**	**313.594**	**160.682**	**69.923**	**33.196**	**15.892**
M7	**2.197.985**	**256.738**	**125.014**	**50.500**	**25.073**	**11.301**
M8	**2.221.293**	**280.045**	**140.906**	**64.979**	**25.780**	**9.535**
M9	**2.127.002**	**245.437**	**132.783**	**54.031**	**22.601**	**8.476**
Media	**2.444.520**	**350.714**	**181.243**	**78.948**	**38.454**	**17.422**
Maximum	**2.877.439**	**493.346**	**259.210**	**120.423**	**71.689**	**37.434**
Minimum	**2.127.002**	**245.437**	**125.014**	**50.500**	**22.601**	**8.476**
Average deviation	**290.340**	**95.921**	**53.278**	**25.255**	**16.205**	**9.333**

Table 6-25: Measure 3ºB) ROOM: 3247 School of Industrial Engineering (Sede Mergelina)(3/3)

Gaseous pollutants										
Gases	M1	M2	M3	M4	M5	M6	M7	M8	M9	Media
CO_2 (ppm)	**625,5**	**613,1**	**633,8**	**581,4**	**574,1**	**562,7**	**531,5**	**716,8**	**543,5**	**598,0**
CO (ppm)	**0,8**	**0,8**	**0,8**	**0,8**	**0,8**	**0,8**	**0,8**	**0,8**	**0,8**	**0,8**
HCHO (ppb)	**0,0**	**0,0**	**0,0**	**0,0**	**0,0**	**0,0**	**0,0**	**0,0**	**0,0**	**0,0**
NO_2 (ppm)	**0,0**	**0,0**	**0,0**	**0,0**	**0,0**	**0,0**	**0,0**	**0,0**	**0,0**	**0,0**
O_3 (ppm)	**0,0**	**0,0**	**0,0**	**0,0**	**0,0**	**0,0**	**0,0**	**0,0**	**0,0**	**0,0**
VOC (µg/m)[3]	**114,7**	**109,7**	**107,4**	**104,4**	**100,8**	**97,9**	**95,7**	**95,9**	**94,3**	**102,3**
Thermal comfort										
Parameters	M1	M2	M3	M4	M5	M6	M7	M8	M9	Media
T dry (°C)	**23,6**	**24,1**	**24,3**	**24,3**	**24,4**	**24,3**	**24,4**	**24,4**	**24,5**	**24,26**
Humidity (%)	**38,4**	**37,1**	**37,0**	**35,4**	**35,2**	**36,0**	**35,2**	**35,3**	**35,3**	**36,10**
T Globe(°C)	**23,1**	**23,6**	**23,9**	**24,1**	**24,2**	**24,1**	**24,3**	**24,3**	**24,4**	**24,00**
Speed (m/s)	**0,08**	**0,11**	**0,04**	**0,06**	**0,04**	**0,04**	**0,04**	**0,02**	**0,02**	**0,05**
Clo	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1,00**
Met	**0,9**	**0,9**	**0,9**	**0,9**	**0,9**	**0,9**	**0,9**	**0,9**	**0,9**	**0,90**
VMP	**-0,31**	**-0,16**	**-0,04**	**-0,08**	**-0,02**	**-0,08**	**-0,03**	**-0,03**	**0,04**	**-0,08**
PPD (%)	**6,96**	**5,5**	**5,04**	**5,15**	**5,01**	**5,13**	**5,02**	**5,02**	**5,03**	**5,32**
Acoustic **comfort**										
N. Noise (dBA)	**41,0**	**40,1**	**39,5**	**40,0**	**40,0**	**37,0**	**38,6**	**38,0**	**37,1**	**39,03**
Light level										
Illumination (lux)	**772**	**936**	**567**	**378**	**558**	**423**	**327**	**363**	**382**	**522,89**

6.8 Results Analysis

The results from the three classrooms examined under the two study conditions without teaching activity and after a 50-minute lesson are analyzed in the following section.

Three issues are covered in the analysis:

a. Operation of the air conditioning/ventilation installation
b. Quality of the indoor environment
c. Energy consumption

6.8.1 ROOM: B1 School of Industrial Engineering (Headquarters Paseo del Cauce)

At the Paseo del Cauce headquarters, this is a classroom. Since it was first used in 1986, this classroom has maintained its basic structure and layout, except for some adjustments to the furniture and the regulation of sunlight.

6.8.1.1 Operation of The Air Conditioning and Ventilation System

A few changes have been made to the air conditioning system since it was used to clean and distribute air in this part of the building. The ventilation air intake has been moved to the outside of the casement where the air conditioner is because of the pandemic of COVID. A heat recovery system and the ability to chill the air are absent from the air conditioning unit.

Since the airflow into the classroom is continuous, its conditions cannot be adjusted in response to those in the room. There are returns on the walls near the window area and on the ceiling near the inner wall, and the air is ducted into the classroom and spread by circular diffusers positioned in the ceiling.

The Master's Degree in Industrial Engineering was taught in the afternoon during the academic year 2022–2023, and no air was given to the classroom during the two measurement processes that were conducted.

6.8.1.2 Quality of The Indoor Environment

The noise level in the classroom is above 40 dB(A). When the classroom curtains are drawn to minimize reflections that might obscure the projection screen, there are some spots where the brightness does not reach 300 lux. The CO_2 levels in the empty classroom (condition A) are similar to outside levels, at about 450 ppm, and the TVOCs have a minimum reading. In condition B (50 minutes of class with windows and doors closed), it is shown that the TVOC has significantly increased, and the CO_2 concentration has doubled, approaching values that are near the highest recommended levels. Despite being satisfactory, these numbers demonstrate that the classroom is solely ventilated via infiltration through the carpentry, which accounts for the considerable ambient noise in the classroom, as it has a high air permeability.

6.8.1.3 Energy consumption

The values of the measured indoor conditions, Valladolid's weather at the time of measurement (obtained from InfoRiego), the airflow rates specified by regulations, and the measurements made in the two predetermined situations (A and B) are used to calculate the energy consumption for ventilation. A summary is shown in table 6.26:

Table 6-26: Ventilation power of classroom B1 Paseo del Cauce Headquarters

	Indoor conditions			**External conditions**			**Flow rate**	**Power**
	T (°C)	**RH (%)**	**h (kJ/kg)**	**T (°C)**	**RH (%)**	**h (kJ/kg)**	**(m^3 /h)**	**(kW)**
Unoccupied (A)	23,48	38,48	43,1	18,3	45,77	35,0	By rule 254	0,69
							Measured 0	0
With occupation (B)	27,6	30,1	46,9	18,1	30,94	29,2	1.575	(1)
							Measured 0	0

(1) In this case, the outside air would be used to air-condition the classroom.

6.8.2 ROOM: 33 School of Industrial Engineering (INDUVA)

This classroom is located in the INDUVa lecture hall of the Mergelina Headquarters, which started offering its services in 2018. It was built following the Technical Building Code and hasn't changed since it began operating.

6.8.2.1 Operation of The Air Conditioning and Ventilation System

Air is distributed throughout the building via a network of ducts to low silhouette air handling units with a double coil (4 pipes) and no fan, which clean the air before it is introduced into the classrooms via terminal units.

Each room has a proportionate monitoring damper on the supply and extract air in order to control and balance the system. A CO_2 probe (occupancy principle) that is 1.5 meters high and positioned at the rear of each classroom controls the airflow supply in those spaces. Depending on the CO_2 concentration in the classroom, the ventilation will operate automatically, always maintaining at least 30% of the maximum occupancy. The CO_2 sensor put in the classrooms is shown in Figure 6.7.

Figure 6.7 CO_2 Sensor

A damper system controls the exhaust airflow in the classrooms depending on the overpressure of the classroom with the corridors.

6.8.2.2 Quality of The Indoor Environment

The results of the measurements indicate that there are thermal comfort problems (low T) while the classroom is empty, with a PPD > 20%. However, when the classroom is full, the level of discomfort drops, returning to acceptable values of PPD = 17%. Other measured variables fall within the bounds established in scenarios A and B.

6.8.2.3 Energy consumption

The method given for classroom B1 is used to determine the energy usage for ventilation. Table 6.27 provides an overview of the information analyzed.

Table 6-27: Ventilation power of classroom 33 INDUVA

	Indoor conditions			**External conditions**			**Flow rate**	**Power**
	T (°C)	**RH (%)**	**h (kJ/kg)**	**T (°C)**	**RH (%)**	**h (kJ/kg)**	**(m^3 /h)**	**(kW)**
Unoccupied (A)	20,33	36,40	35,1	12,63	52,10	25,6	By rule 183	0,48
							Measured 707	1,87

With occupation (B)	21,80	32,16	36,2	16,35	39,18	28,9	Per standard 1.080	2,19
							Measured 693	1,41

6.8.3 ROOM: 3247 School of Industrial Engineering (Sede Mergelina)

This computer room, in the north wing of the main Mergelina Headquarters building, has been in operation since 2021 and was built following the Technical Building Code. It has not undergone any modifications since that time. These areas weren't given a clear purpose when they were created.

6.8.3.1 Operation of The Air Conditioning and Ventilation System

The pre-treated ventilation air is delivered to the classroom through the system's two swirl diffusers at the room's head. It has two VRV cassettes with an external air supply distributed along the classroom axis and averaged to service the entire area. These cassettes are in charge of preserving the hygrothermal conditions of the classroom. A CO_2 sensor from Sedical is installed in the classroom, and it controls the ventilation air according to the level of (CO_2) there.

6.8.3.2 Quality of The Indoor Environment

The measurements in room 3247, unoccupied and occupied, were carried out without the VRV cassettes operating.

Volatile Organic Compounds (VOC) issues with indoor air quality only surfaced when the classroom was empty. After 50 minutes of instruction, it was found that the ventilation airflow had increased, and the majority of the chemical pollutants in the air had decreased in concentration compared to when the classroom was empty. The concentration of particles was also reduced for particles larger than 1µm and even 3 times lower for those smaller than 1µm. Additionally, due to the air supply system's performance, values that were very near the limit of acoustic comfort conditions were discovered. Other measured variables fall within the bounds established in scenarios A and B.

6.8.3.3 Energy Consumption

The energy consumption for ventilation is obtained in the same way as described for the previous classrooms (B1 and A33). A summary of the data involved is shown in Table 6.28.

Table 6-28: Ventilation power of classroom 3247 Mergelina Headquarters

	Indoor conditions			**External conditions**			**Flow rate**	**Power**
	T (°C)	**RH (%)**	**h (kJ/kg)**	**T (°C)**	**RH (%)**	**h (kJ/kg)**	**(m^3 /h)**	**(kW)**
Unoccupied (A)	22,67	39,27	39,8	10,12	68,45	23,0	By rule 104	0,6
							Measured 269	1,5
With occupation (B)	24,26	36,10	40,0	16,70	35,48	30,1	By rule 585	1,9
							Measured 460	1,5

A summary table shows the results obtained for the three classrooms studied in the two conditions analyzed:

a) classroom with no teaching activity
b) classroom after 50 minutes of teaching

Table 6-29: Environmental quality parameters in three classrooms of the School of Industrial Engineering of the University of Valladolid

Classrooms	Particles[a]	CO_2 (ppm)	CO (ppm)	HCHO (ppb)	NO_2 (ppm)	O_3 (ppm)	VOCT (ppb)	PPD (%)
B1 (A)[b]	In accordance with	465,6	< 1	0	0	0	0	40,99
B1 (B)	In accordance with	915,4	< 1	0	0	0	188,6	62,11
A33 (A)	In accordance with	501,7	< 1	0	0	0	108,1	32,60
A33 (B)	In accordance with	469,9	< 1	0	0	0	37,9	17,30
A3247 (A)	In accordance with	553,3	< 1	0	0	0	173,1	10,06
A3247 (B)	In accordance with	598	< 1	0	0	0	102,3	5,32

[a]Conforms to UNE-EN-ISO 14664-1. ISO Class 9; [b] The sound level of the empty B1 classroom is higher than 40 dB.

7. Chapter 7: Conclusion

This thesis has enabled an exhaustive analysis of the design and energy performance of the INDUVA classroom building at the University of Valladolid, focusing on the concept of nearly zero energy consumption buildings (nZEB). Throughout this study, various energy efficiency strategies have been explored, from optimizing HVAC and lighting systems to integrating renewable energies and advanced energy management using BMS systems. Through simulations and a comprehensive approach, the significant impact of these measures on carbon footprint reduction, occupant comfort, and long-term sustainability has been demonstrated.

7.1 Key Findings Aligned with Objective and Hypothesis

7.1.1 Advances in energy efficiency and sustainability

The results confirm that the INDUVA building represents a significant advance in energy efficiency and sustainability compared to a conventional classroom building on the same university campus. Integrating renewable energy sources, such as biomass for district heating and DH, and implementing an efficient architectural design have significantly reduced energy consumption. According to previous studies [149],the use of biomass as a heating source can decrease CO_2 emissions and reduce long-term operating costs in energy-efficient buildings such as nZEBs.

7.1.2 Impact of ventilation and power generation strategies

This study has underlined the relevance of mechanical ventilation on demand (VMD) strategies in nZEB buildings, significantly improving indoor air quality (IAQ) and thermal comfort of occupants. However, energy consumption has also been increased due to the intensive use of electric motors in the fans. According to Santamouris et al. [150], VMD systems are an effective tool for monitoring air quality, but their energy impact must be carefully managed. Technologies such as motors with variable frequency drives and heat recovery systems were used to mitigate this consumption, which has proven to be effective in reducing overall energy consumption [151]. Heat recuperators, such as the enthalpic wheel and geothermal systems, allow for greater efficiency in heat exchange, minimizing the heating and cooling load.

7.1.3 Optimization of architectural design and lighting

The architectural design of the INDUVA building is distinguished by its ability to maximize the use of natural light and reduce the load of artificial lighting. The Parans system for the distribution of natural light has proven to be an effective solution to reduce the energy consumption associated with artificial lighting by up to 75%. According to Ghaffarianhoseini et al[152], integrating daylighting systems contributes significantly to energy efficiency and improves occupant comfort, reducing dependence on non-renewable energy sources.

7.1.4 Prediction of future changes and climate adaptation

The study used dynamic simulations with DesignBuilder and the EnergyPlus calculation engine to model the effects of climate change on INDUVA's energy consumption. A reduction in final heating energy consumption is expected, but an increase in cooling needs for air conditioning due to global warming. This finding is consistent with studies by Papadopoulos et al. [153], who stated that buildings should be designed to adapt to changing weather conditions, focusing on the efficiency of cooling systems to mitigate increased energy demand during heat peaks. The ability of the INDUVA building to adapt to these scenarios demonstrates the importance of integrating passive design technologies and energy-efficient cooling solutions, such as heat recovery and free-cooling.

7.1.5 Resilience and adaptability to geographical and climatic conditions

This study has also addressed how contextual factors, such as local climate and the availability of solar radiation, influence the energy performance of nZEBs. Previous research has shown that the performance of nZEB buildings is highly dependent on geographical conditions, underscoring the need for contextualized architectural design that optimizes the use of available natural resources, such as solar radiation and wind. This approach is crucial for creating resilient buildings that are not only energy-efficient but also capable of adapting to predicted climate changes, thereby contributing to the long-term sustainability of cities [154].

7.1.6 Indoor environmental quality and occupant comfort

Regarding indoor environmental quality (IEQ), it has been verified that the INDUVA building meets or exceeds the regulations in Spain. On-demand mechanical ventilation systems, equipped with CO_2 sensors and advanced flow controls, have ensured occupants a healthy and comfortable environment. According to the research of Toftum et al. [155]. VMD systems improve air quality and optimize energy consumption by dynamically adjusting to ventilation needs based on occupancy.

7.2 Study Limitations

Despite the comprehensive nature of this work, it is important to recognize several limitations:

- The findings derive from a singular case study building, which constrains generalizability to alternative types of buildings or climatic zones without modification.
- A comprehensive economic analysis (capital costs, ROI, payback) wasn't included due to the lack of system-level financial data, hence constraining practical investment decision-making assistance.
- Some indoor environmental data was presented in accumulated form lacking comprehensive statistical analysis (e.g., absence of standard deviation, t-tests, or confidence intervals), hence undermining the statistical robustness of the IEQ findings.
- Overventilation and system inefficiencies were observed, but energy penalties were not quantified due to the absence of zone-level HVAC energy breakdowns.

7.3 Recommendations for Practice and Policy

Based on the findings of this study, several recommendations can be made to inform design strategies, operational improvements, and policy development in the context of nearly zero energy buildings (nZEBs):

- Implementing CO_2-based demand-controlled ventilation (DCV) in the INDUVA building improved indoor air quality during occupancy, maintaining concentration levels well below typical regulatory limits. However, ventilation data revealed that airflow rates during unoccupied hours in certain rooms, such as Room 33, substantially exceeded the design minimums by more than 280%. This discrepancy indicates a performance gap between the actual system behavior and the intended control settings. To enhance efficiency, it is recommended that DCV systems incorporate occupancy-linked scheduling and dynamic setback strategies, minimizing energy use when spaces are vacant without compromising air quality when occupied. The integration of daylight transport systems, such as the Parans optical fiber setup, has led to a significant reduction in reliance on artificial lighting. According to the data monitored, the lighting energy demand was reduced by approximately 75% during daytime occupancy compared to baseline estimates. This supports the broader implementation of architectural daylighting solutions in university buildings, especially in spaces with limited access to façade openings.

- Climate-based simulations revealed that cooling demands are expected to increase under future climate scenarios, with warmer cities like Cairo showing a shift toward dominant cooling loads by 2080. To address this, nZEB designs should integrate adaptable façade shading, enhanced passive ventilation, and high-efficiency cooling technologies to maintain thermal comfort and limit energy use in hot climates.
- To enable more accurate system tuning and performance validation, it is recommended that future public building projects incorporate zone-level sub-metering for HVAC, lighting, and ventilation. This would allow building managers to detect system inefficiencies (such as overventilation) and implement targeted operational improvements supported by empirical data.
- At the policy level, national building codes should not only align with European directives but also mandate dynamic climate resilience assessments during the design phase. This would ensure that new constructions remain within energy targets and comfort standards under evolving climatic conditions, reducing the need for premature retrofits.

7.4 Broader Relevance and Future Application

7.4.1 Challenges and recommendations for the future

Despite advances in energy efficiency, reliance on mechanical ventilation and cooling systems in nZEB buildings generates additional energy consumption. This study highlights the need for innovative solutions that improve the efficiency of mechanical systems, such as inverter systems, on-demand airflow control, and heat recovery systems. These strategies are essential to reduce mechanical systems' energy impact and balance energy efficiency, comfort, and sustainability.

7.4.2 Towards the transition to zero-carbon buildings

The transition to zero-carbon buildings, in line with the new EPBD 2024 directive, is crucial for meeting European climate targets. nZEB buildings, such as INDUVA, are a fundamental step towards reducing the carbon footprint in the construction sector, as pointed out by Gagliardi et al. [156]. The integration of renewable technologies, together with the optimization of energy management, will make it possible to achieve the objectives of zero emissions, benefiting both the environment and the well-being of the occupants.

7.4.3 Extrapolation and relevance for the design of buildings on university campuses

Finally, the findings of this research are very relevant to the design and energy management of standard classroom buildings on university campuses. Adopting energy efficiency and renewable energy strategies, such as those implemented at INDUVA, can be replicated in other buildings for academic use, design, and management, contributing to creating more sustainable and healthy educational environments [157]

References

[1] B. Lin and Z. Chen, "Net zero energy building evaluation, validation and reflection – A successful project application," *Energy Build*, vol. 261, Apr. 2022, doi: 10.1016/j.enbuild.2022.111946.

[2] J. N. Castillo, V. F. Resabala, L. O. Freire, and B. P. Corrales, "Modeling and sensitivity analysis of the building energy consumption using the Monte Carlo method," *Energy Reports*, vol. 8, pp. 518–524, Dec. 2022, doi: 10.1016/j.egyr.2022.10.198.

[3] U. Von Der Leyen, "A Union that strives for more My agenda for Europe."

[4] "CELEX_52013DC0169_EN_TXT".

[5] F. Ascione, R. F. De Masi, F. de Rossi, S. Ruggiero, and G. P. Vanoli, "Optimization of building envelope design for nZEBs in Mediterranean climate: Performance analysis of residential case study," *Appl Energy*, vol. 183, pp. 938–957, Dec. 2016, doi: 10.1016/j.apenergy.2016.09.027.

[6] R. K. Jaysawal, S. Chakraborty, D. Elangovan, and S. Padmanaban, "Concept of net zero energy buildings (NZEB) - A literature review," Dec. 01, 2022, *Elsevier Ltd*. doi: 10.1016/j.clet.2022.100582.

[7] N. Azimi Fereidani, E. Rodrigues, and A. R. Gaspar, "A review of the energy implications of passive building design and active measures under climate change in the Middle East," Jul. 10, 2021, *Elsevier Ltd*. doi: 10.1016/j.jclepro.2021.127152.

[8] T. Douthat, J. D. Morgan, H. Alibašić, and A. Grant, "Passive building characteristics, and summertime residential energy use: A spatial analysis of energy efficiency in Gainesville, FL," *Build Environ*, vol. 169, Feb. 2020, doi: 10.1016/j.buildenv.2019.106542.

[9] M. Hu, K. Zhang, Q. Nguyen, and T. Tasdizen, "The effects of passive design on indoor thermal comfort and energy savings for residential buildings in hot climates: A systematic review," May 01, 2023, *Elsevier B.V.* doi: 10.1016/j.uclim.2023.101466.

[10] A. Khaled Mohammad and A. Ghosh, "Exploring energy consumption for less energy-hungry building in UK using advanced aerogel window," *Solar Energy*, vol. 253, pp. 389–400, Mar. 2023, doi: 10.1016/j.solener.2023.02.049.

[11] N. Abdou, Y. EL Mghouchi, S. Hamdaoui, N. EL Asri, and M. Mouqallid, "Multi-objective optimization of passive energy efficiency measures for net-zero energy building in Morocco," *Build Environ*, vol. 204, Oct. 2021, doi: 10.1016/j.buildenv.2021.108141.

[12] Diana D'Agostino, Luisa Daraio, Concetta Marino, and Francesco Minichiello, "Cost-optimal methodology and passive strategies for building energy efficiency: a case-study," *Archit Sci Rev*, vol. 61, no. 6, pp. 400–409, Jul. 2018.

[13] A. Goenaga-Pérez, M. Álvarez-Sanz, J. Terés-Zubiaga, and A. Campos-Celador, “Cost-effectiveness and minimum requirements of nZEB for residential buildings under the new Spanish Technical Building Code,” *Energy Build*, p. 112986, Mar. 2023, doi: 10.1016/j.enbuild.2023.112986.

[14] R. M. Reffat and R. Ezzat, “Impacts of design configurations and movements of PV attached to building facades on increasing generated renewable energy,” *Solar Energy*, vol. 252, pp. 50–71, Mar. 2023, doi: 10.1016/j.solener.2023.01.040.

[15] K. Shono, Y. Yamaguchi, U. Perwez, T. Ma, Y. Dai, and Y. Shimoda, “Large-scale building-integrated photovoltaics installation on building façades: Hourly resolution analysis using commercial building stock in Tokyo, Japan,” *Solar Energy*, vol. 253, pp. 137–153, Mar. 2023, doi: 10.1016/j.solener.2023.02.025.

[16] A. S. Abdelrazik, B. Shboul, M. Elwardany, R. N. Zohny, and A. Osama, “The recent advancements in the building integrated photovoltaic/thermal (BIPV/T) systems: An updated review,” Dec. 01, 2022, *Elsevier Ltd*. doi: 10.1016/j.rser.2022.112988.

[17] D. D’Agostino, F. Minelli, M. D’Urso, and F. Minichiello, “Fixed and tracking PV systems for Net Zero Energy Buildings: Comparison between yearly and monthly energy balance,” *Renew Energy*, vol. 195, pp. 809–824, Aug. 2022, doi: 10.1016/j.renene.2022.06.046.

[18] A. H. Hamzah and Y. I. Go, “Design and assessment of building integrated PV (BIPV) system towards net zero energy building for tropical climate,” 2022, doi: 10.1016/j.prime.2022.100105.

[19] D. D’Agostino, S. Mazzella, F. Minelli, and F. Minichiello, “Obtaining the NZEB target by using photovoltaic systems on the roof for multi-storey buildings,” *Energy Build*, vol. 267, Jul. 2022, doi: 10.1016/j.enbuild.2022.112147.

[20] B. Ceran, J. Jurasz, A. Mielcarek, and P. E. Campana, “PV systems integrated with commercial buildings for local and national peak load shaving in Poland,” *J Clean Prod*, vol. 322, Nov. 2021, doi: 10.1016/j.jclepro.2021.129076.

[21] M. Krarti, “Evaluation of PV integrated sliding-rotating overhangs for US apartment buildings,” *Appl Energy*, vol. 293, Jul. 2021, doi: 10.1016/j.apenergy.2021.116942.

[22] M. Ahangari and M. Maerefat, “An innovative PCM system for thermal comfort improvement and energy demand reduction in building under different climate conditions,” *Sustain Cities Soc*, vol. 44, pp. 120–129, Jan. 2019, doi: 10.1016/j.scs.2018.09.008.

[23] W. Ke, J. Ji, C. Zhang, H. Xie, Y. Tang, and C. Wang, “Effects of the PCM layer position on the comprehensive performance of a built-middle PV-Trombe wall system for building application in the heating season,” *Energy*, vol. 267, Mar. 2023, doi: 10.1016/j.energy.2022.126562.

[24] R. Kalbasi, B. Samali, and M. Afrand, "Taking benefits of using PCMs in buildings to meet energy efficiency criteria in net zero by 2050," *Chemosphere*, vol. 311, Jan. 2023, doi: 10.1016/j.chemosphere.2022.137100.

[25] M. Terhan and G. Ilgar, "Investigation of used PCM-integrated into building exterior walls for energy savings and optimization of PCM melting temperatures," *Constr Build Mater*, vol. 369, Mar. 2023, doi: 10.1016/j.conbuildmat.2023.130601.

[26] S. Abbasian-Naghneh and R. Kalbasi, "Implementation of ANN and GA on building with PCM at various setpoints, PCM types, and installation locations to boost energy saving and CO2 saving," *Eng Anal Bound Elem*, vol. 144, pp. 110–126, Nov. 2022, doi: 10.1016/j.enganabound.2022.08.006.

[27] Q. Al-Yasiri and M. Szabó, "Incorporation of phase change materials into building envelope for thermal comfort and energy saving: A comprehensive analysis," Apr. 01, 2021, *Elsevier Ltd*. doi: 10.1016/j.jobe.2020.102122.

[28] J. Jia, B. Liu, L. Ma, H. Wang, D. Li, and Y. Wang, "Energy saving performance optimization and regional adaptability of prefabricated buildings with PCM in different climates," *Case Studies in Thermal Engineering*, vol. 26, Aug. 2021, doi: 10.1016/j.csite.2021.101164.

[29] H. Wang, W. Lu, Z. Wu, and G. Zhang, "Parametric analysis of applying PCM wallboards for energy saving in high-rise lightweight buildings in Shanghai," *Renew Energy*, vol. 145, pp. 52–64, Jan. 2020, doi: 10.1016/j.renene.2019.05.124.

[30] B. A. Cherkose, S. Issa, H. Saibi, and K. ElHaj, "Building a geospatial model to identify potential geothermal sites in Ayrobera: Afar depression, NE Ethiopia," *Geothermics*, vol. 110, p. 102689, May 2023, doi: 10.1016/j.geothermics.2023.102689.

[31] L. Wang, X. Huang, M. Babaei, Z. Liu, X. Yang, and J. Yan, "Full-scale utilization of geothermal energy: A high-efficiency CO2 hybrid cogeneration system with low-temperature waste heat," *J Clean Prod*, p. 136866, Mar. 2023, doi: 10.1016/j.jclepro.2023.136866.

[32] J. Li, C. Jimenez-Bescos, J. K. Calautit, and J. Yao, "Evaluating the energy-saving potential of earth-air heat exchanger (EAHX) for Passivhaus standard buildings in different climates in China," *Energy Build*, p. 113005, Mar. 2023, doi: 10.1016/j.enbuild.2023.113005.

[33] R. Stasi, F. Ruggiero, and U. Berardi, "The efficiency of hybrid ventilation on cooling energy savings in NZEBs," *Journal of Building Engineering*, vol. 53, Aug. 2022, doi: 10.1016/j.jobe.2022.104401.

[34] D. D'Agostino, F. Minichiello, F. Petito, C. Renno, and A. Valentino, "Retrofit strategies to obtain a NZEB using low enthalpy geothermal energy systems," *Energy*, vol. 239, Jan. 2022, doi: 10.1016/j.energy.2021.122307.

[35] B. Hebbal, Y. Marif, M. Hamdani, M. M. Belhadj, H. Bouguettaia, and D. Bechki, “The geothermal potential of underground buildings in hot climates: Case of Southern Algeria,” *Case Studies in Thermal Engineering*, vol. 28, Dec. 2021, doi: 10.1016/j.csite.2021.101422.

[36] D. D’Agostino, F. Esposito, A. Greco, C. Masselli, and F. Minichiello, “The energy performances of a ground-to-air heat exchanger: A comparison among köppen climatic areas,” *Energies (Basel)*, vol. 13, no. 11, Jun. 2020, doi: 10.3390/en13112895.

[37] Diana D’Agostino, Concetta Marino, and Francesco Minichiello, “Earth-to-Air Versus Air-to-Air Heat Exchangers: A Numerical Study on the Energetic, Economic, and Environmental Performances for Italian Office Buildings,” *Heat transfer engineering*, vol. 41, no. 12, pp. 1040–1051, 2019.

[38] L. H. Yang, J. W. Hu, Y. C. Chiang, and S. L. Chen, “Performance analysis of building-integrated earth-air heat exchanger retrofitted with a supplementary water system for cooling-dominated climate in Taiwan,” *Energy Build*, vol. 242, Jul. 2021, doi: 10.1016/j.enbuild.2021.110949.

[39] “2021 GLOBAL STATUS REPORT FOR BUILDINGS AND CONSTRUCTION Towards a zero-emissions, efficient and resilient buildings and construction sector.” [Online]. Available: www.globalabc.org.

[40] M. Da Ma, M. X. Chen, W. Feng, and J. W. Huo, “What decarbonized the residential building operation worldwide since the 2000s,” *Pet Sci*, vol. 19, no. 6, pp. 3194–3208, Dec. 2022, doi: 10.1016/j.petsci.2022.10.016.

[41] S. Zhang, M. Ma, X. Xiang, W. Cai, W. Feng, and Z. Ma, “Potential to decarbonize the commercial building operation of the top two emitters by 2060,” *Resour Conserv Recycl*, vol. 185, Oct. 2022, doi: 10.1016/j.resconrec.2022.106481.

[42] A. Nuñez-Jimenez and N. De Blasio, “Competitive and secure renewable hydrogen markets: Three strategic scenarios for the European Union,” *Int J Hydrogen Energy*, vol. 47, no. 84, pp. 35553–35570, Oct. 2022, doi: 10.1016/j.ijhydene.2022.08.170.

[43] Y. Xu *et al.*, “Optimization research on energy-saving and life-cycle decarbonization retrofitting of existing school buildings: A case study of a school in Nanjing,” *Solar Energy*, vol. 254, pp. 54–66, Apr. 2023, doi: 10.1016/j.solener.2023.03.006.

[44] M. Alhuyi Nazari *et al.*, “An updated review on integration of solar photovoltaic modules and heat pumps towards decarbonization of buildings,” Feb. 01, 2023, *Elsevier B.V.* doi: 10.1016/j.esd.2022.12.018.

[45] H. Amini Toosi, M. Lavagna, F. Leonforte, C. Del Pero, and N. Aste, “Building decarbonization: Assessing the potential of building-integrated photovoltaics and thermal energy storage systems,” *Energy Reports*, vol. 8, pp. 574–581, Dec. 2022, doi: 10.1016/j.egyr.2022.10.322.

[46] X. Yang, M. Hu, C. Zhang, and B. Steubing, "Key strategies for decarbonizing the residential building stock: Results from a spatiotemporal model for Leiden, the Netherlands," *Resour Conserv Recycl*, vol. 184, Sep. 2022, doi: 10.1016/j.resconrec.2022.106388.

[47] D. Borge-Diez, D. Icaza, D. F. Trujillo-Cueva, and E. Açıkkalp, "Renewable energy driven heat pumps decarbonization potential in existing residential buildings: Roadmap and case study of Spain," *Energy*, vol. 247, May 2022, doi: 10.1016/j.energy.2022.123481.

[48] F. Padovani, N. Sommerfeldt, F. Longobardi, and J. M. Pearce, "Decarbonizing rural residential buildings in cold climates: A techno-economic analysis of heating electrification," *Energy Build*, vol. 250, Nov. 2021, doi: 10.1016/j.enbuild.2021.111284.

[49] F. Kazemi and R. Mohorko, "Review on the roles and effects of growing media on plant performance in green roofs in world climates," Apr. 01, 2017, *Elsevier GmbH*. doi: 10.1016/j.ufug.2017.02.006.

[50] L. Kosareo and R. Ries, "Comparative environmental life cycle assessment of green roofs," *Build Environ*, vol. 42, no. 7, pp. 2606–2613, Jul. 2007, doi: 10.1016/j.buildenv.2006.06.019.

[51] D. J. Sailor, "A green roof model for building energy simulation programs," *Energy Build*, vol. 40, no. 8, pp. 1466–1478, 2008, doi: 10.1016/j.enbuild.2008.02.001.

[52] N. Ketut Acwin Dwijendra, I. Muda, C. B. Milanes, N. Bharath Kumar, A. S. Abosinnee, and R. Akhmadeev, "How do green roofs affect per capita energy consumption in residential buildings under various climate conditions?," *Sustainable Energy Technologies and Assessments*, vol. 56, Mar. 2023, doi: 10.1016/j.seta.2023.103127.

[53] A. Hussien, N. Jannat, E. Mushtaha, and A. Al-Shammaa, "A holistic plan of flat roof to green-roof conversion: Towards a sustainable built environment," *Ecol Eng*, vol. 190, May 2023, doi: 10.1016/j.ecoleng.2023.106925.

[54] R. Zahedi, S. Daneshgar, O. N. Farahani, and A. Aslani, "Thermal analysis model of a building equipped with green roof and its energy optimization," *Nature-Based Solutions*, vol. 3, p. 100053, Dec. 2023, doi: 10.1016/j.nbsj.2023.100053.

[55] S. Algarni, K. Almutairi, and T. Alqahtani, "Investigating the performance of energy management in office buildings by using a suitable green roof design to reduce the building's energy consumption," *Sustainable Energy Technologies and Assessments*, vol. 54, Dec. 2022, doi: 10.1016/j.seta.2022.102825.

[56] M. A. Alim, A. Rahman, Z. Tao, B. Garner, R. Griffith, and M. Liebman, "Green roof as an effective tool for sustainable urban development: An Australian perspective in relation to stormwater and building energy management," Aug. 15, 2022, *Elsevier Ltd*. doi: 10.1016/j.jclepro.2022.132561.

[57] F. Tariku and S. Hagos, “Performance of green roof installed on highly insulated roof deck and the plants’ effect: An experimental study,” *Build Environ*, vol. 221, Aug. 2022, doi: 10.1016/j.buildenv.2022.109337.

[58] M. Abuseif, K. Dupre, and R. Michael, “The effect of green roof configurations including trees in a subtropical climate: A co-simulation parametric study,” *J Clean Prod*, vol. 317, Oct. 2021, doi: 10.1016/j.jclepro.2021.128458.

[59] I. Andric, A. Kamal, and S. G. Al-Ghamdi, “Efficiency of green roofs and green walls as climate change mitigation measures in extremely hot and dry climate: Case study of Qatar,” *Energy Reports*, vol. 6, pp. 2476–2489, Nov. 2020, doi: 10.1016/j.egyr.2020.09.006.

[60] A. Ebrahimi-Moghadam and M. Farzaneh-Gord, “A sustainable optimal biomass waste-driven CCHP system to boost the nearly zero energy building concept,” *Energy Convers Manag*, vol. 277, Feb. 2023, doi: 10.1016/j.enconman.2023.116669.

[61] R. Volpe, M. Gonzalez Alriols, N. Martelo Schmalbach, and A. Fichera, “Optimal design and operation of distributed electrical generation for Italian positive energy districts with biomass district heating,” *Energy Convers Manag*, vol. 267, Sep. 2022, doi: 10.1016/j.enconman.2022.115937.

[62] J. Sajid *et al.*, “Energetic, economic, and greenhouse gas emissions assessment of biomass and solar photovoltaic systems for an industrial facility,” *Energy Reports*, vol. 8, pp. 12503–12521, Nov. 2022, doi: 10.1016/j.egyr.2022.09.041.

[63] E. Moretti, M. Barbanera, D. Foschini, C. Buratti, and F. Cotana, “Energy and Environmental Performance Analysis of Biomass-fuelled Combined Cooling and Heating System for Commercial Building Retrofit: An Italian Case Study,” in *Energy Procedia*, Elsevier Ltd, Nov. 2016, pp. 376–383. doi: 10.1016/j.egypro.2016.11.048.

[64] M. Carpio, M. Zamorano, and M. Costa, “Impact of using biomass boilers on the energy rating and CO2 emissions of Iberian Peninsula residential buildings,” *Energy Build*, vol. 66, pp. 732–744, 2013, doi: 10.1016/j.enbuild.2013.07.079.

[65] J. V. Bakke, G. Wieslander, D. Norback, and B. E. Moen, “Eczema Increases Susceptibility to PM_{10} in Office Indoor Environments,” *Arch Environ Occup Health*, vol. 67, no. 1, pp. 15–21, Jan. 2012, doi: 10.1080/19338244.2011.564236.

[66] V. S. Chithra and S. M. Shiva Nagendra, “Indoor air quality investigations in a naturally ventilated school building located close to an urban roadway in Chennai, India,” *Build Environ*, vol. 54, pp. 159–167, Aug. 2012, doi: 10.1016/j.buildenv.2012.01.016.

[67] P. V. Dorizas, M. N. Assimakopoulos, C. Helmis, and M. Santamouris, “An integrated evaluation study of the ventilation rate, the exposure and the indoor air quality in naturally ventilated

classrooms in the Mediterranean region during spring," *Science of the Total Environment*, vol. 502, pp. 557–570, Jan. 2015, doi: 10.1016/j.scitotenv.2014.09.060.

[68] A. Datta, R. Suresh, A. Gupta, D. Singh, and P. Kulshrestha, "Indoor air quality of non-residential urban buildings in Delhi, India," *International Journal of Sustainable Built Environment*, vol. 6, no. 2, pp. 412–420, Dec. 2017, doi: 10.1016/j.ijsbe.2017.07.005.

[69] P. Kapalo, S. Vilčeková, L. Mečiarová, F. Domnita, and M. Adamski, "Influence of indoor climate on employees in office buildings-A case study," *Sustainability (Switzerland)*, vol. 12, no. 14, Jul. 2020, doi: 10.3390/su12145569.

[70] Z. Cheng, N. Lei, Z. Bu, H. Sun, B. Li, and B. Lin, "Investigations of indoor air quality for office buildings in different climate zones of China by subjective survey and field measurement," *Build Environ*, vol. 214, Apr. 2022, doi: 10.1016/j.buildenv.2022.108899.

[71] A. Amengual *et al.*, "Projections of heat waves with high impact on human health in Europe," *Glob Planet Change*, vol. 119, pp. 71–84, 2014, doi: 10.1016/j.gloplacha.2014.05.006.

[72] Y. H. Yau and S. Hasbi, "A review of climate change impacts on commercial buildings and their technical services in the tropics," 2013. doi: 10.1016/j.rser.2012.10.035.

[73] "European Commission," Causes of climate change. [Online]. Available: https://climate.ec.europa.eu/climate-change/causes-climate-change_en

[74] P. Kr. Chaturvedi, N. Kumar, and R. Lamba, "Identification of climate adaptive multivariate optimization methodologies for the design of NZEB in India: a holistic review," *Frontiers in Energy Efficiency*, vol. 2, Sep. 2024, doi: 10.3389/fenef.2024.1430647.

[75] L. Rodríguez *et al.*, "Life cycle assessment in net zero energy building scenarios in a tropical country," *Discover Civil Engineering*, vol. 1, no. 1, Jun. 2024, doi: 10.1007/s44290-024-00019-5.

[76] L. M. López-Ochoa, J. Las-Heras-Casas, M. Carpio, and E. Sagredo-Blanco, "Adaptation of rural residential buildings in a Mediterranean climate to climate change: A case study of La Rioja (Spain)," *Journal of Building Engineering*, vol. 94, Oct. 2024, doi: 10.1016/j.jobe.2024.109913.

[77] L. Pajek, M. Možina, P. D. Nadarajah, M. K. Singh, and M. Košir, "Future-proofing a naturally ventilated log house: A case study of adaptive thermal comfort under climate change impact," *Energy Build*, vol. 307, Mar. 2024, doi: 10.1016/j.enbuild.2024.113951.

[78] T. Ashrafian, "Enhancing school buildings energy efficiency under climate change: A comprehensive analysis of energy, cost, and comfort factors," *Journal of Building Engineering*, vol. 80, Dec. 2023, doi: 10.1016/j.jobe.2023.107969.

[79] S. Idrissi Kaitouni, R. Chahboun, Z. Bouhssine, M. Cakan, J. Brigui, and M. Ahachad, "Simulation-based assessment of the climate change impact on future thermal energy load and indoor

comfort of a light-weight ecological building across the six climates of Morocco," *Thermal Science and Engineering Progress*, p. 102137, Oct. 2023, doi: 10.1016/j.tsep.2023.102137.

[80] Z. Jalali, A. Y. Shamseldin, and A. Ghaffarianhoseini, "Impact assessment of climate change on energy performance and thermal load of residential buildings in New Zealand," *Build Environ*, vol. 243, Sep. 2023, doi: 10.1016/j.buildenv.2023.110627.

[81] S. Sayadi, J. Akander, A. Hayati, and M. Cehlin, "Analyzing the climate-driven energy demand and carbon emission for a prototype residential nZEB in central Sweden," *Energy Build*, vol. 261, Apr. 2022, doi: 10.1016/j.enbuild.2022.111960.

[82] A. Janssens, E. Vandenbussche, K. van den Brande, W. Bracke, and M. Delghust, "Influence of climate change on the energy performance assessment of NZEB houses," in *Journal of Physics: Conference Series*, IOP Publishing Ltd, Dec. 2021. doi: 10.1088/1742-6596/2069/1/012064.

[83] D. D'Agostino, D. Parker, I. Epifani, D. Crawley, and L. Lawrie, "How will future climate impact the design and performance of nearly zero energy buildings (NZEBs)?," *Energy*, vol. 240, Feb. 2022, doi: 10.1016/j.energy.2021.122479.

[84] S. Attia and C. Gobin, "Climate change effects on belgian households: A case study of a nearly zero energy building," *Energies (Basel)*, vol. 13, no. 20, Oct. 2020, doi: 10.3390/en13205357.

[85] S. Summa, L. Tarabelli, G. Ulpiani, and C. Di Perna, "Impact of climate change on the energy and comfort performance of nzeb: A case study in Italy," *Climate*, vol. 8, no. 11, pp. 1–16, Nov. 2020, doi: 10.3390/cli8110125.

[86] J. Chai, P. Huang, and Y. Sun, "Differential evolution - based system design optimization for net zero energy buildings under climate change," *Sustain Cities Soc*, vol. 55, Apr. 2020, doi: 10.1016/j.scs.2020.102037.

[87] J. Chai, P. Huang, and Y. Sun, "Investigations of climate change impacts on net-zero energy building lifecycle performance in typical Chinese climate regions," *Energy*, vol. 185, pp. 176–189, Oct. 2019, doi: 10.1016/j.energy.2019.07.055.

[88] J. M. Rey-Hernández, C. Yousif, D. Gatt, E. Velasco-Gómez, J. San José-Alonso, and F. J. Rey-Martínez, "Modelling the long-term effect of climate change on a zero energy and carbon dioxide building through energy efficiency and renewables," *Energy Build*, vol. 174, pp. 85–96, Sep. 2018, doi: 10.1016/j.enbuild.2018.06.006.

[89] Y. Cui, D. Yan, T. Hong, C. Xiao, X. Luo, and Q. Zhang, "Comparison of typical year and multiyear building simulations using a 55-year actual weather data set from China," *Appl Energy*, vol. 195, pp. 890–904, 2017, doi: 10.1016/j.apenergy.2017.03.113.

[90] P. Shen and N. Lior, “Vulnerability to climate change impacts of present renewable energy systems designed for achieving net-zero energy buildings,” *Energy*, vol. 114, pp. 1288–1305, Nov. 2016, doi: 10.1016/j.energy.2016.07.078.

[91] “DIRECTIVE (EU) 2018/844 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency (Text with EEA relevance).”

[92] P. Office of the European Union L- and L. Luxembourg, “DIRECTIVE (EU) 2024/1275 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 24 April 2024 on the energy performance of buildings (recast) (Text with EEA relevance).” [Online]. Available: http://data.europa.eu/eli/dir/2024/1275/oj

[93] C. Xia-Bauer *et al.*, “Comparative analysis of residential building decarbonization policies in major economies: insights from the EU, China, and India,” *Energy Effic*, vol. 17, no. 5, Jun. 2024, doi: 10.1007/s12053-024-10225-w.

[94] “Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings.”

[95] “POLICY BRIEFING NEARLY ZERO: A REVIEW OF EU MEMBER STATE IMPLEMENTATION OF NEW BUILD REQUIREMENTS.” [Online]. Available: https://ec.europa.eu/clima/policies/strategies/2050_en

[96] S. A. Kalogirou, “Building integration of solar renewable energy systems towards zero or nearly zero energy buildings,” *International Journal of Low-Carbon Technologies*, vol. 10, no. 4, pp. 379–385, Dec. 2015, doi: 10.1093/ijlct/ctt071.

[97] G. Paoletti, R. Pascual Pascuas, R. Pernetti, and R. Lollini, “Nearly Zero Energy Buildings: An Overview of the Main Construction Features across Europe,” *Buildings*, vol. 7, no. 2, p. 43, May 2017, doi: 10.3390/buildings7020043.

[98] P. Office of the European Union, “I (Legislative acts) DIRECTIVES DIRECTIVE (EU) 2023/1791 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 13 September 2023 on energy efficiency and amending Regulation (EU) 2023/955 (recast) (Text with EEA relevance).”

[99] “COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS.”

[100] “Energy Union New impetus for coordination and integration of energy policies in the EU.” Accessed: Nov. 11, 2025. [Online]. Available: https://www.europarl.europa.eu/RegData/etudes/BRIE/2015/551310/EPRS_BRI(2015)551310_EN.pdf

[101] "DIRECTIVES DIRECTIVE (EU) 2018/2001 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 11 December 2018 on the promotion of the use of energy from renewable sources (recast) (Text with EEA relevance)."

[102] "CTE Sección HE 1 Condiciones para el control de la demanda energética".

[103] "MINISTERIO DE TRANSPORTES, MOVILIDAD Y AGENDA URBANA."

[104] D. Básico, "MINISTERIO DE VIVIENDA Y AGENDA URBANA."

[105] "Reglamento De Instalaciones Termicas En Los Edificios (RITE) Julio 2021," Jul. 2021.

[106] "LEED certificate ." [Online]. Available: https://www.usgbc.org/projects/aulario-induva

[107] "VERDE certificate ." [Online]. Available: http://www2.gbce.es/en/edificio/torre-aulario-induva

[108] "Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings."

[109] "Documento Básico HE Ahorro de energía HE 1. Condiciones para el control de la demanda energética Sección HE 1 Condiciones para el control de la demanda energética."

[110] "Compliance Forms | Building Envelope Compliance Forms-Building Envelope."

[111] "DesignBuilder." Accessed: Dec. 13, 2023. [Online]. Available: https://designbuilder.co.uk/

[112] "Met Office Hadley Centre for Climate Science and Services." Accessed: Dec. 13, 2023. [Online]. Available: https://www.metoffice.gov.uk/weather/climate/met-office-hadley-centre/index

[113] M. Hulme and Tyndall Centre for Climate Change Research., *Climate change scenarios for the United Kingdom : the UKCIP02 scientific report*. Tyndall Centre for Climate Change Research, School of Environmental Sciences, University of East Anglia, 2002.

[114] C. Beck, J. Grieser, M. Kottek, F. Rubel, and B. Rudolf, "CHARACTERIZING GLOBAL CLIMATE CHANGE BY MEANS OF KÖPPEN CLIMATE CLASSIFICATION."

[115] M. López Lorenzo, "Simulacion Db Aulario 2017-eng," UNIVERSITY OF VALLADOLID, Valladolid, Spain, 2017.

[116] D. Fernández Cheliz, "TFM-simulation standar lecture ," UNIVERSIDAD DE VALLADOLID, 2021.

[117] C. Editor and D. Anna Krawczyk, "Sustainable buildings – designing and management of cost-effective and eco-friendly systems," 2020, doi: 10.24427/978-83-67185-29-5_3.

[118] "Spanish Association for Standardization (AENOR), 2014. UNE 171330-1: Indoor environmental quality. Part 1: Assessment of indoor air quality in buildings. Madrid: AENOR.," 2014.

[119] “Spanish Association for Standardization (AENOR), 2005. UNE 100012: Hygiene of ventilation and air-conditioning systems. Madrid: AENOR.,” 2005.

[120] “RITE (Royal Decree 10272007, of 20 July.”.

[121] B. W. Olesen and K. C. Parsons, “Introduction to thermal comfort standards and to the proposed new version of EN ISO 7730,” *Energy Build*, vol. 34, no. 6, pp. 537–548, Jul. 2002, doi: 10.1016/S0378-7788(02)00004-X.

[122] B. Oficial Del Estado, “Government of Spain, 1997. Royal Decree 486/1997 of 14 April, establishing minimum health and safety requirements in workplaces. Official State Gazette (BOE), Spain.”

[123] “International Organization for Standardization (ISO), 1995. UNE-EN ISO 7733: Ergonomics of the thermal environment – Analytical determination and interpretation of thermal comfort using calculation of PMV and PPD indices and local thermal comfort criteria. Geneva: ISO.,” 1995.

[124] “Spanish Association for Standardization (AENOR), 2005. UNE-EN 13779: Ventilation for non-residential buildings – Performance requirements for ventilation and room-conditioning systems. Madrid: AENOR.,” 2005.

[125] “National Institute for Occupational Safety and Health (INSST), 2019. Technical guides and criteria for occupational risk prevention. Madrid: Ministry of Labour and Social Economy, Spain.,” 2019.

[126] Núm, “Government of Spain, 2021. Royal Decree 178/2021 of 20 July, concerning thermal insulation of buildings. Official State Gazette (BOE), Spain.” [Online]. Available: https://www.boe.es

[127] M. DE Sanidad Y Política Social, “Government of Spain, 2011. Royal Decree 02/2011. Official State Gazette (BOE), Spain.” [Online]. Available: http://www.boe.es

[128] “Government of Spain, 2011. Royal Decree 102/2011 of 28 January, concerning the improvement of air quality. Official State Gazette (BOE), Spain”.

[129] “International Organization for Standardization (ISO), 2000. UNE-EN ISO 14644-1: Cleanrooms and associated controlled environments – Part 1: Classification of air cleanliness. Geneva: ISO.,” 2000.

[130] L. Ley, “Government of Spain, 2019. Royal Decree 732/2019 of 20 December, amending the Technical Building Code (CTE). Official State Gazette (BOE, 27 December 2019), Spain.” [Online]. Available: https://www.boe.es

[131] “International Organization for Standardization (ISO), 2015. UNE-EN ISO 14644-1: Cleanrooms and associated controlled environments – Classification of air cleanliness by particle concentration. Geneva: ISO.,” 2015.

[132] "World Health Organization (WHO), 2021. WHO Global Air Quality Guidelines: Particulate Matter ($PM_{2.5}$ and PM_{10}), Ozone, Nitrogen Dioxide, Sulfur Dioxide and Carbon Monoxide. Geneva: World Health Organization. ISBN 978-92-4-003546-1.," 2021.

[133] "Ministry of Housing and Urban Agenda, 2019. CTE DB-HE3: Energy saving – Conditions for lighting installations. Official State Gazette (BOE), Spain.," 2019.

[134] "Spanish Association for Standardization (AENOR), 2008. UNE-CR 1752 IN: Ventilation for buildings – Design criteria for the indoor environment. Madrid: AENOR.," 2008.

[135] "Spanish Association for Standardization (AENOR), 2020. UNE-EN 16798-1: Energy performance of buildings – Ventilation for buildings – Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics. Madrid: AENOR.," 2020.

[136] "International Organization for Standardization (ISO), 2006. UNE-EN ISO 7730: Ergonomics of the thermal environment – Analytical determination and interpretation of thermal comfort using calculation of PMV and PPD indices and local thermal comfort criteria. Geneva: ISO.," 2006.

[137] P. M. Ortiz-Grisales, L. Gutiérrez-León, E. Duque-Grisales, and C. D. Zuluaga-Ríos, "Dynamic Modeling Under Temperature Variations for Sustainable Air Quality Solutions: PM2.5 and Negative Ion Interactions," *Sustainability*, vol. 17, no. 1, p. 70, Dec. 2024, doi: 10.3390/su17010070.

[138] "European Committee for Standardization (CEN), 2007. EN 15251: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics. Brussels: CEN.," 2007.

[139] "Spanish Association for Standardization (AENOR), 2012. UNE 12464-1: Light and lighting – Lighting of work places – Part 1: Indoor work places. Madrid: AENOR.," 2012.

[140] "Spanish Association for Standardization (AENOR), 2018. UNE 17037: Daylight in buildings. Madrid: AENOR.," 2018.

[141] "Spanish Association for Standardization (AENOR), 2009. UNE 15193: Energy performance of buildings – Energy requirements for lighting. Madrid: AENOR.," 2009.

[142] Núm, "Government of Spain, 2007. Royal Decree 1371/2007 of 19 October, approving the Basic Document DB-HR 'Protection against Noise' of the Technical Building Code (CTE). Official State Gazette (BOE, 23 October 2007), Spain." [Online]. Available: http://www.boe.es

[143] "Government of Spain, 2008. Royal Decree of 17 October 2008 amending Royal Decree 1371/2007 of 19 October. Official State Gazette (BOE, 18 October 2008), Spain.".

[144] "Government of Spain, 2007. Correction of errors in Royal Decree 1371/2007 of 19 October. Official State Gazette (BOE, 20 December 2007), Spain." [Online]. Available: http://www.boe.es

[145] Núm, "Government of Spain, 2007. Royal Decree 1367/2007 of 19 October, implementing Law 37/2003 on Noise regarding acoustic zoning, quality objectives, and acoustic emissions. Official State Gazette (BOE, 19 October 2007), Spain." [Online]. Available: http://www.boe.es

[146] "Government of Spain, 2009. Correction of typographical and factual mistakes in Order VIV/984/2009 of 15 April. Official State Gazette (BOE, 23 September 2009), Spain." [Online]. Available: http://www.boe.es

[147] "23. Government of Spain, 2009. Order VIV/984/2009 of 15 April, establishing basic conditions for accessibility and non-discrimination for access and use of buildings and public spaces. Official State Gazette (BOE, 23 April 2009), Spain.," Apr. 2009.

[148] B. Oficial Del Estado, "BOE 254 de 23/10/2007 Sec 1 Pag 42952 a 42973," 2007.

[149] Bertoldi et al, "The role of renewable energy in building heating.," *Energy Policy*, pp. 426–437, 2019.

[150] Santamouris et al., "Ventilation strategies in sustainable buildings.," *Building Research & Information*, vol. 45, no. 6, pp. 718–734, 2017.

[151] Ramos et al, "Energy savings in HVAC systems through advanced heat recovery technologies," *Journal of Energy Engineering*, vol. 35, no. 4, pp. 657–667, 2021.

[152] Ghaffarianhoseini et al, "Energy-efficient lighting systems for buildings," *Renewable and Sustainable Energy Reviews*, vol. 58, pp. 1299–1312, 2016.

[153] Papadopoulos et al, "Future building performance in a changing climate: A simulation study.," *Energy Build*, vol. 225, p. 110329, 2020.

[154] Ghosh et al, "Urban resilience and energy efficiency in building design," *Journal of Climate Adaptation*, vol. 12, no. 5, pp. 124–137, 2020.

[155] Toftum et al, "Dynamic ventilation systems for indoor air quality in nZEBs," *indoor air* , vol. 28, no. 5, pp. 779–789, 2018.

[156] Gagliardi et al, "Zero-carbon buildings in Europe: Challenges and opportunities.," *Renewable and Sustainable Energy Reviews*, vol. 134, pp. 110–143, 2021.

[157] Costa et al., "Sustainable campus design: Best practices and lessons learned. ," *Journal of Sustainable Architecture*, vol. 45, no. 3, pp. 321–336, 2019.

Annexes

Annex 1: Methods of Analysis and Endpoints for Study

		Assessment criteria		
Parameter	**Method**	**A comfort criterion of up to 25% over achievement is accepted.**	**Endpoint upper limit**	**Reference standard/regulation**
Hygienic assessment of air-conditioning systems	Visual inspection of AHUs	Absence of visible dirt	Not applicable	UNE 100012
	Duct requirements	According to standard UNE 100012	Not applicable	UNE 100012
Ventilation	Air flow rate	RITE	Not applicable	RITE
Temperature and humidity (Thermal comfort)	Direct measuring equipment	Spring-summer: 23 - 25 °C 30 - 70 %RH Autumn - Winter 21 - 23 °C 30 - 70 %RH	PPD < 20%.	RITE (Royal Decree 1027/2007, of 20 July. Limit values Royal Decree 486/1997. UNE-EN-ISO 7733
CO_2	Direct measurement by an infrared probe	Indoor-outdoor < 500 ppm	Maximum limit value: 2,500 ppm	UNE-EN 13779.2005 VLA 50%. (INSHT)
CO	Electrochemical cell	< 5 ppm	Maximum limit value: 9 ppm	Royal Decree 02/2011 VLA 75% (INSHT)
Particulate matter ($PM_{2,5}$)	Gravimetry NIOSH Direct measurement .		Maximum limit value	Royal Decree 102/2011 VLA 10 % (INSHT)

	Laser beam diffraction equipment	< 20 µg/m^3	1000 µg/m^3	
Particle counting		ISO Class 9	<35,200,000 part of 0.5 µm/m^3. < 293.000 part of 5 mm/m^3	UNE-EN-ISO 14644-1:2000
Ambient lighting	Photocell	According to tasks: Low: 100 lux. Moderate: 200 lux. High: 500 lux. Very high 1,000 lux.	Not applicable	Royal Decree 486/1997 CTE-HE3
Environmental noise	a microphone and a preamplifier	According to tasks: Optimal range: 55 - 65 dBA	Not applicable	Royal Decree 732/2019 CTE-HR
Formaldehyde	Electrochemical sensor	0.12 mg/ m^3	0.3 mg/m^3	VLA (INSHT) (WHO)
Ozone	Electrochemical sensor	< 0,1 ppm	< 0,2 ppm	VLA (INSHT)
TVOC	Electrochemical sensor	< 200 µg/ m^3	< 3,000 µg/ m^3	Criteria based on the studies: - Comfort < 200 µg/ m^3. - Multifactorial 200 to 3,000 µg/ m^3. - Discomfort 3,000 to 25,000 µg/ m^3. - Toxic > 25,000 µg/ m^3
NO_2	Electrochemical sensor	0.2 mg/m^3	Not applicable	WHO Recommendation

Annex 2: Methods to achieve the desired indoor air category according to RITE

	Indirect method for outdoor airflow per person	**Direct method for perceived air quality**	**Direct CO_2 concentration Method**	**Indirect method of air flow rate per unit area**
Category	**dm^3 / s-person**	**dp**	**ppm (*)**	**dm^3 /(s.m)^3**
IDA 1	20	0,8	350	Not applicable
IDA 2	12,5	1,2	500	0,83
IDA 3	8	2,0	800	0,55
IDA 4	5	3,0	1200	0,28
(*) above outside air concentration				

Annex 3: Perceived air quality-based method

Category	**Expected percentage of dissatisfied**	**Flow rate per person not adapted (l/(s-Person))**
I	15	10
II	20	7
III	30	4
IV	40	2,5

Annex 4: Design ventilation rate for dilution of emissions from different types of buildings

Category	**Very low polluting building LPB-1 (l/(s.m^2))**	**Low polluting building LPB-2 (l/(s.m^2))**	**LPB-3 non-polluting building (l/(s.m^2))**	**Very low polluting building LPB-1 (l/(s.m^2))**
I	0,5	1,0	2,0	0,5
II	0,35	0,7	1,4	0,35
III	0,2	0,4	0,8	0,2
IV	0,15	0,3	0,6	0,15

Annex 5: The method used for substance concentration limit values.

Category	**CO_2 concentration above outdoor concentration for non-adapted persons (ppm)**
I	550
II	800
III	1.350
IV	1.350

Annex 6: Method based on predefined ventilation flow rates

Category	**(l/s per person)**	**(l/ (s.m²))**
I	20	2
II	14	1,4
III	8	0,8
IV	5,5	0,55

Annex 7: limits indicated by RITE

Season	**Operating Temperature (°C)**	**Relative Humidity (%)**
Summer	23 to 25	40 to 80
Winter	20 to 23	40 to 60

Annex 8: WHO and RD 102/2011 limit values

WHO Quality Guide

PM_{10}		**$PM_{2,5}$**		**NO_2**		**SO_2**		**O_3**
Media 24 h	Annual average	Media 24 h	Annual average	Media 1 h	Annual average	Media 10 min.	Media 24 h	Media 8 h
50µg/m^3	20µg/m^3	25 µg/m^3	10µg/ m^3	200µg/ m^3	40µg/ m^3	500µg/ m^3	20µg/ m^3	100µg/ m^3

RD 102/2011 on the improvement of air quality

PM_{10}		**$PM_{2,5}$**		**NO_2**		**SO_2**			**O_3**
Media 24 h	Annual average	Annual average	Media 1 h	Annual average	Media 1 h	Media 24 h	Media annual	Average 8 h	Media 24 h
50µg/ m3	40µg/m3	20µg/ m3	200µg/ m3	40µg/ m3	350µg/ m3	125µg/ m3	20µg/ m3	120µg/ m3	50µg/ m3
It may not be exceeded more than 35 times a year			It may not be exceeded more than 18 times a year.		It may not be exceeded more than 24 times a year.	May not be exceeded more than 3 times a year.	Calendar year or winter	May not be exceeded more than 325 times per year.	It may not be exceeded more than 35 times a year.

Annex 9: Classification of rooms according to airborne particulate matter concentration (UNE-EN-ISO 14664)

6.8.3.4 *ISO classification number N*	***Maximum value of particles/m³ of air equal to or larger than the sizes indicated in the table below***					
	0,1 µm	**0,2 µm**	**0,3 µm**	**0,5 µm**	**1 µm**	**5 µm**
ISO Class 1	10	2	-	-	-	-
ISO Class 2	100	24	10	4	-	-
ISO Class 3	1.000	237	102	35	8	-
ISO Class 4	10.000	2.370	1.020	352	83	-
ISO Class 5	100.000	23.700	10.200	3.520	830	29
ISO Class 6	1.000.000	237.000	102.000	35.200	8.320	293
ISO Class 7	-	-	-	352.000	83.200	2.930
ISO Class 8	-	-	-	3.520.000	832.000	29.300
ISO Class 9	**-**	**-**	**-**	**35.200.000**	**8.320.000**	**293.000**

Annex 10: Recommended CO_2 concentrations according to the category of premises (EN 15251:2007)

Category	**CO_2 above outside in ppm for energy calculations**
I	350
II	500
III	800
IV	< 800

Annex 11: Recommended lighting criteria: EN 15251:2007

Type of building	Space	Lighting maintained, Em in work areas, lux	UGR	Ra	Remarks
Office buildings	Single office	500	19	80	at 0.8 m
	Open-plan office	500	19	80	at 0.8 m
	Conference room	500	19	80	at 0.8 m
Educational buildings	Classes	300	19	80	at 0.8 m
	Adult education classes	500	19	80	at 0.8 m
	Assembly hall	500	19	80	at 0.8 m

Annex 12: Indoor limit values RD 1367/2007, Annex II

Use of the building	Enclosure type	Noise index		
		Ld	La	Ln
Housing or residential use	Stay	45	45	35
	Bedroom	40	40	30
Hospital	Living areas	45	45	35
	Bedrooms	40	40	30
Educational or cultural	Classrooms	40	40	40
	Reading room	35	35	35

Annex 13: Technical characteristics of the LIGHTHOUSE particle counter, model Handheld 3016

Parameters	
Particle size	0.3, 0.5, 1.0, 3.0, 5.0, 10.0 µm
Flow rate	0.1 CFM (2.83 l/min)
Level 0 particles	<1 particle/5min, according to ISO 21501-4 Annex C
Laser Source	Diode laser
Environmental sensors	T (0-50 ºC) ± 0.5 ºC
	HR (15-90%) ± 2 % HR (15-90%) ± 2 % HR (15-90%) ± 2
Regulations it complies with	FS-209E (ft), FS-209E (m), ISO 14664-1, EU GMP
Sample output	HEPA internal filter (>99,997 % for 3 µm)

Annex 14: Technical characteristics of DirectSense II equipment

Parameters	**Sensor**	**Range**	**Accuracy**	**Three answer(s)**
RH (%)	Capacitive	0 to 100	±2% (RH < 80%) ±3% (RH>80%).	immediate
T (ºC)	PT100	-25 to+70	±0,3	immediate
CO (ppm)	Electrochemical	0 to 500	±1	<30
CO_2 (ppm)	NDIR	0 to 10000	±35 (35-2000) ± 3% (>2000)	<20
TVOC (ppb)	PID	0 to 20000	±5	<8
O3	Electrochemical	0-1	<0,02	<60

NO_2	Electrochemical	0-20	<0,02	<80

Annex 15: Technical characteristics of the ISO-TECH sound level meter, model SLM- 1352A

Parameters	
Measuring ranges (dB)	low: 30 - 80 Medium:50 - 100 Height:80 -130 Auto: 30 - 130
Dynamic range (dB)	50
Accuracy (dB)	±1,4
Resolution (dB)	0,1
Frequency range (Hz)	31,5-8000

Annex 16: Technical characteristics of the Testo 545 luxmeter

Parameters	
Measuring ranges (lux)	0-100.000
Accuracy	F1 = 6% = adaptation V(of lambda) F1 = 5% = value as cosine law. Total ≤ 15%. ± 3% of v.m. ±1 digit
Resolution (lux)	0.1 lux (<10,000 lux) 1 lux (≥ 10,000 lux)

Annex 17: Technical characteristics of the Testo 435 multifunctional device

Parameters	**Probe diameter Ø (mm)**	**Range**	**Accuracy**
T (°C)	12	-20 to +70	±0,3
RH (%)		0-100	±2
T globe (TP probe type K)	150	0-120	Class 1[a]

It conforms to ISO 7243, ISO 7726, DIN EN 27726, and DIN 33403.